MINERALOGY CONCEPTS FOR RESEARCH AND TEACHING: THE MINERALOGY OF THE RAU PEGMATITE GROUP, ITS IMPLICATIONS FOR PEGMATITE CONTAMINATION, AND A CONCEPT INVENTORY TO ASSESS STUDENT UNDERSTANDING

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Mineralogy concepts for research and teaching: the mineralogy of the Rau pegmatite group, its implications for pegmatite contamination, and a concept inventory to assess student understanding

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ABSTRACT

This dissertation presents a two-component study: (1) the effect of contamination on the mineralogy of the Rau pegmatite group and implications for pegmatite contamination and (2) a statistically validated concept inventory that can assess understanding of mineralogy concepts.

The Rau pegmatite group, which is made up of 10 F-rich, barren to mixed NYF + LCT pegmatite dikes, is located in the Yukon Territory, Canada. The dikes are hosted in dolostone of the Bouvette Formation and were derived from the nearby Rackla pluton: a ~63 Ma, weakly peraluminous biotite-muscovite granite. The most evolved pegmatites of the group contain abundant rare element phases such as columbite group minerals, fluorcalciomicrolite, and REE-bearing fluoro-carbonate minerals. Elevated F activity during pegmatite crystallization is evident from F enrichment in multiple pegmatite zones.

The Rau pegmatite dikes show clear evidence of being contaminated by their dolostone host rocks. Primary Ca-bearing minerals as well as carbonate pockets are present throughout the pegmatite dikes. Stable C and O isotopic signatures of carbonate minerals indicate that the pegmatite dikes were subjected to pre-emplacement contamination, whereas the presence of endo-contact skarns at the borders of some pegmatite dikes is evidence for post-emplacement contamination.

An extensive meta-analysis of the pegmatite literature suggests that pegmatite contamination that can modify the mineralogy of a pegmatite is a much more common mechanism than is currently recognized. Future studies of pegmatites should include a more thorough investigation of the host rocks, and results should be interpreted while considering the potential influence of the host rock composition on pegmatite mineralogy.

The Mineralogy Concept Inventory (MCI) is a statistically validated assessment that can be used to measure learning gains in introductory mineralogy courses. Development of the MCI was an iterative process involving expert consultation, student interviews, and statistical analysis. The MCI was implemented in undergraduate mineralogy courses at two different Canadian universities that employ different pedagogies: student-centred and instructor-centred. Although average pre-assessment scores were approximately the same, normalized learning gains were significantly higher in the course that uses a student-centred pedagogy. These results suggest that the use of a student-centred pedagogy can significantly increase learning of mineralogy concepts.

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LAY SUMMARY

Pegmatites are coarse-grained igneous rocks that commonly contain distinctive textures and rare element-bearing minerals. Contamination is the idea that the mineralogy and chemical signature of a pegmatite can be influenced by its host rocks and *vice versa*. Contamination has not been well studied and many questions remain about how contamination can influence the mineralogy of a pegmatite.

This dissertation demonstrates that the Rau pegmatite group was contaminated and that the mineralogy of its host rocks was also modified by the pegmatites. Through an extensive analysis of previously published literature, contamination is shown to be a much more common mechanism than is currently recognized.

The Mineralogy Concept Inventory is a statistically validated assessment that can measure students' understanding of mineralogy concepts. During development the assessment was implemented in two mineralogy courses that use different teaching methods. This implementation showed that a more active teaching method promotes the learning of mineralogy concepts.

PREFACE

This dissertation is the original work of the author, Emily Scribner, under the supervision of Drs. Lee Groat and Sara Harris. I identified all research areas in consultation with Drs. Groat and Harris, and I designed all research programmes. Dr. Lee Groat edited Chapters 1–5 and 7, and assisted with data interpretation in Chapter 2 and 4. Dr. Sara Harris edited Chapter 1 and 6–7, and assisted with data interpretation in Chapter 6. Dr. Jan Cempírek edited and assisted with data interpretation in Chapter 6. Dr. Jan Cempírek edited and assisted with data interpretation in Chapter 6. Dr. Jan Cempírek edited and assisted with data interpretation in Chapter 6. Dr. Jan Cempírek edited and assisted with data interpretation in Chapter 2. Some data collection was conducted by third parties and is identified at the appropriate location in the dissertation.

I selected all samples for electron microprobe analysis and chose analysis points. I also incorporated some data on the Rau 1 dike collected by Dr. Cempírek before I became involved with the project. The analyses were performed by Edith Czech at the University of British Columbia (UBC) and Dr. Radek Škoda at Masaryk University. I prepared pucks for laser ablation inductively coupled mass spectrometry (LA-ICP-MS) and selected analysis points. Analyses were performed by Dr. Marghaleray Amini at the Pacific Centre for Isotopic and Geochemical Research (PCIGR), UBC. I performed data reduction with assistance from Rhy McMillan. Cathodoluminescence imaging of quartz was performed by B.Sc. student Jackson Malone at Acadia University under the supervision of Dr. Michael Robertson, but I selected all samples and analysis locations, and interpreted all the images.

The content of Chapter 2 forms the basis of a manuscript that has been submitted for publication to an international journal:

Scribner, E. D., Groat, L. A., & Cempírek, J. (submitted). Petrology and geochemistry of the Rau pegmatite group, Yukon Territory, Canada, and the effect of contamination on its mineralogy.

The content of Chapter 2 was also presented at an international conference and published in the conference proceedings as an extended abstract:

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Ethics approval was obtained for the research presented in Chapter 6 (certificate numbers H16-00976, H19-00025, and GEXT-022-16). This chapter forms the basis of a talk that was presented at two international conferences: the Earth Educators' Rendezvous 2018 in Lawrence, Kansas, U.S.A. in July 2018, and the 2018 Annual Meeting of the Geological Society of America, Indianapolis, Indiana, U.S.A. in November 2018. The material has also been submitted to an international journal for publication:

Scribner, E. D., & Harris, S. E. (submitted). The Mineralogy Concept Inventory: a statistically validated assessment to measure learning gains.

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Abbreviation or Acronym	Complete term	Abbreviation or Acronym	Complete term
apfu	atoms per formula unit	mg	milligram
ASI	alumina saturation index	MIA	Mineral Isotope Analyzer
BSE	Back-scattered electron	mJ	millijoule
CL	Cathodoluminescence	mm	millimeter
cm	centimeter	n	number in a trial; sample size
DIF	Differential Item Functioning	nA	nanoampere
EMP	Electron Microprobe	NYF	niobium, yttrium, fluorine
FCI	Force Concept Inventory	OA-ICOS	Off-axis integrated cavity output spectroscopy
g	gram	PCIGR	Pacific Centre of Isotopic and Geochemical Research
GCI	Geoscience Concept Inventory	ppm	parts per million
HREE	heavy rare earth element	p-value	probability value
Hz	hertz	REE	rare earth element
ICP-ES	Inductively coupled plasma emission spectrometry	S	second
ICP-MS	Inductively coupled plasma mass spectrometry	s.d.	standard deviation
km	kilometer	t crit.	t critical value
kV	kilovolt	t stat.	t statistic
LA-ICP-MS	Laser ablation inductively coupled plasma mass spectrometry	UBC	University of British Columbia
LCT	lithium, cesium, tantalum	μm	micrometer
LIFT	Landscape Identification and Formation Test	UX	University X
LREE	light rare earth element	UY	University Y
m	meter	VPBD	Vienna Pee Dee Belemnite
Ма	million years; million years ago	VSMOW	Vienna Standard Mean Ocean Water
MCI	Mineralogy Concept Inventory	wt.%	weight percent

LIST OF ABBREVIATIONS AND ACRONYMS
LIST OF MINERAL ABBREVIATIONS

Symbol	Mineral name	Symbol	Mineral name	Symbol	Mineral name
Ab	Albite	Exn	Euxenite	Pcl	Pyrochlore
Act	Actinolite	Fac	Ferro-actinolite	Phl	Phlogopite
Aln	Allanite	Fclmcr	Fluorcalciomicrolite	Prg	Pargasite
Amp	Amphibole	Fclprc	Fluorcalciopyrochlore	Prs	Parisite
An	Anorthite	Fed	Ferro-edenite	Qz	Quartz
Ann	Annite	Fe ox	Fe oxide minerals	Rt	Rutile
Ар	Apatite	Fe sul	Fe sulphide minerals	Sch	Scheelite
Brl	Beryl	Fhb	Ferro-hornblende	Smr	Samarskite
Brt	Barite	FI	Fluorite	Snc	Synchysite
Bst	Bastnäsite	Flb	Fluoborite	Srl	Schorl
Bt	Biotite	Flc	Fluocerite	Sps	Spessartine
Cal	Calcite	Gdl	Gadolinite	Thr	Thorite
Chl	Chlorite	Grt	Garnet	Tlc	Talc
Chr	Chondrodite	Hng	Hingganite	Tnt	Tantalite
Clc	Clinochlore	Kfs	K-feldspar	Tr	Tremolite
Col	Columbite	Mhb	Magnesio- hornblende	Ttn	Titanite
Czo	Clinozoisite	Mnz	Monazite	Tur	Tourmaline
Dol	Dolomite	Ms	Muscovite	Zrc	Zircon
Ep	Epidote				

Abbreviations follow Whitney & Evans (2010).

Abbreviations in italic font are those introduced by the author.

Mineral names in bold font are supergroup names, group names, or informal names.

GLOSSARY

Aplite: a fine grained igneous rock, commonly of granitic composition.

Concept inventory: a statistically validated multiple-choice assessment.

Contamination: the modification of the mineralogy and/or geochemical signature of a pegmatite by its host rocks.

Differential item functioning: when an assessment question performs differently based on the demographics of the respondent.

Dolostone: a carbonate sedimentary rock that contains a high percentage of dolomite [CaMg(CO₃)₂].

Endo-contact skarn: a skarn formed by contact metamorphism and/or metasomatism within the igneous intrusion.

Exo-contact skarn: a skarn formed by contact metamorphism and/or metasomatism within the host rock of the igneous intrusion.

Fractional crystallization: the process by which chemical elements are removed from the residual magma by crystallizing minerals.

Hydrothermal contamination: the modification of the mineralogy and/or geochemical signature of a pegmatite by fluids from its host rocks after the pegmatite has solidified.

Instructor-centred pedagogy: a pedagogy in which students have a passive role in their learning and their instructor delivers the content.

Measure: a score that is scaled based on difficulty.

Meta-analysis: the synthesis of data from a large number of studies that have already been completed in an attempt to draw new conclusions.

Pedagogy: the study and practice of teaching.

Pegmatite: an essentially igneous rock, commonly of granitic composition, that is distinguished by its extremely coarse but variable grain size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth habits (London, 2008).

Pluton: a body of igneous rock that crystallized from magma within the Earth.

Porphyritic: a rock texture consisting of at least one mineral whose grains are larger than the finer-grained surrounding minerals.

Pre-assessment: an assessment given prior to instruction of the material.

Pre-emplacement contamination: the modification of the mineralogy and/or geochemical signature of a pegmatite as the pegmatite melt is propagating through the host rocks from the parental granite to its place of solidification.

Protolith: the unmetamorphosed rock that a metamorphic rock is formed form (i.e., the parent rock).

Post-assessment: an assessment given following instruction of the material.

Post-emplacement contamination: the modification of the mineralogy and/or geochemical signature of a pegmatite *in situ* by the host rocks.

Rasch analysis: a form of item response modeling that more accurately reflects the degree to which a student possesses the ability being measured because the scores are scaled to reflect difficulty.

Scaled score: a score that is scaled to take into account the difficult of the assessment question.

Skarn: a calc-silicate rock, generally formed by regional or contact metamorphism followed by metasomatism.

Student-centred pedagogy: a pedagogy in which students have an active role and are given responsibility for their own learning.

Think-aloud interview: an interview in which the interviewee is prompted to verbalize their thinking.

Unidimensionality: whether correct responses on an assessment depend only on the ability being measured.

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CHAPTER 1

Introduction

1.1 Pegmatites: Definition and Formation

A pegmatite is generally thought of as an intrusive igneous rock with coarse grain size, but many pegmatites have several other characteristics that are a product of the special set of conditions under which they crystallize. These include graphic texture formed by the intergrowth of quartz and perthitic microcline, crystals with strongly directional growth habits, and in some cases the presence of rare minerals with unusual chemical compositions. For the purposes of this study, a pegmatite will be defined as "an essentially igneous rock, commonly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse but variable grain size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth habits. Pegmatites generally occur as sharply bounded homogeneous to zoned bodies within igneous or metamorphic host-rocks." (London, 2008). Pegmatites can be generated from composition and therefore most of the nomenclature and classification schemes pertain to them (London, 2008).

With all their diverse features pegmatites clearly cannot be formed by the slow equilibrium crystallization of a silicate melt at depth, which would be expected to produce mineralogically and texturally homogeneous igneous rocks. To explain these features, several models of pegmatite formation have been proposed. One of the most cited models was proposed by London (2008). A model by London (2008) that starts with fractional crystallization and involves strong undercooling and rapid crystallization from a volatile-enriched magma is currently the most widely accepted by the scientific community, although most researchers agree that there is not yet a model that adequately explains all the diverse features of granitic pegmatites. Additional research is needed to fill in the gaps and produce a universally acceptable model of pegmatite genesis.

In the early stages of fractional crystallization, common rock-forming elements are removed from the melt, leaving it enriched in incompatible elements and molecules including B, P, F, and H₂O. These act as fluxes that allow larger crystals to form (London, 2008). They do so

by reducing the viscosity of the melt, thereby increasing element diffusion rates and suppressing the formation of crystallization nuclei. The consequence of this is that the number of competing crystal nuclei is reduced, which allows for a relatively small number of crystals to grow to a large size. After crystallization these incompatible elements and compounds can be re-dissolved, creating further fluctuations in the geochemistry of the melt, which could potentially allow a diverse new set of minerals to crystallize (London, 2008; 2014; Thomas *et al.*, 2012).

Undercooling occurs when a melt is subjected to temperatures below its solidus but does not solidify. As a pegmatitic magma propagates away from its parental granite it enters progressively cooler host rocks at shallower depths. This cooler and shallower environment prevents a highly evolved, viscous magma from flowing despite its liquid state and causes the overall temperature of the magma to drop below its solidus.

The combined effects of undercooling and enrichment in incompatible elements and molecules cause the magma to rapidly crystallize from the wall zones inward. In an undercooled melt, rapid crystallization produces a narrow boundary layer of excluded fluxes and volatiles between the growing crystals and the central magma body, which allows for the exchange of ions; incompatible components are expelled from the growing crystals, whereas compatible elements are extracted from the magma and incorporated into the crystals in a process termed constitutional zone refining (Fig. 1.1). If the boundary layer liquid becomes oversaturated in incompatible components it may re-dissolve some of the newly formed crystals. Crystals that are not dissolved by the boundary layer liquid will continue to grow, with some attaining the large sizes for which pegmatites are known.

As crystallization progresses the boundary layers advancing from the wall zones on either side of the dike can merge in the center, and crystallization then occurs from this liquid instead of the bulk melt. The final composition of this liquid depends on both the initial concentration of fluxing and incompatible elements in the bulk melt and the amount of melt that it has processed via constitutional zone refining. The final composition of a boundary layer liquid that has processed more melt (i.e., crystallization of a thicker pegmatite dike, or a thicker portion of a dike) will have a higher concentration of exotic components, crystallizing a final suite of minerals with a higher degree of chemical fractionation. If the liquid is completely depleted in both compatible and incompatible elements, other than Si and O, it will crystallize into a monomineralic quartz core.

One of the competing models of pegmatite formation involves the crystallization of pegmatites from a flux-rich silicate liquid (e.g., Thomas et al., 2012; Thomas et al., 2000), as opposed the H₂O-undersaturated haplogranitic melt of London (2014). The main evidence for a flux-rich melt are melt inclusions with average H₂O concentrations of \sim 20% (g/g) and extreme H₂O concentrations of up to 50% (g/g), as well as percent to tens of percent concentrations of melt structure modifiers such as up to 11,025 ppm Be. These melt inclusions are interpreted to be primary and therefore reflect the pegmatite forming magma (Thomas et al., 2012). Unlike the London model, which limits fluxing elements to F, P, and B (London, 2008), Thomas proposes that melt structure modifiers can also include H₂O, OH⁻, CO₂, SO₄²⁻, Li, Na, and K, among others. Primary melt inclusions with up to tens of percent concentrations of these elements have been found in primary melt inclusions (Thomas et al., 2012). The high concentration of melt structure modifiers would cause the melt to have very low viscosity and high diffusion rates, causing crystallization to proceed from the margins to the centre of the dike. The composition of the minerals that crystallize in the pegmatite depends on which elements, including melt structure modifiers, are available, and also on changes in the pressure, temperature, and composition of the crystallizing fluid (Thomas et al., 2012).



Figure 1.1. A depiction of constitutional zone refining via crystal growth through a boundary layer liquid. (a) Compatible elements (blue: O; green: Si, Al, Na, K) in the bulk melt diffuse towards the growing quartz and feldspar, whereas incompatible elements – fluxes (maroon: H, B, P, F) and rare metals (black: Li, Rb, Cs. Be, Nb, Ta) – are excluded and accumulate in the boundary layer liquid adjacent to the growing crystals. (b) As crystallization continues the bulk melt is consumed and (c) exotic mineral assemblages are crystallized from the remaining flux- and rare element-rich boundary layer liquid (London, 2014).

1.2 The Current State of Pegmatite Classification

Pegmatites are particularly difficult to classify because bulk chemistry, a characteristic commonly used for classifying rocks, cannot be used as a standard measured criterion for pegmatite classification due to their large grain size. To this day, bulk chemistry and other inferred or presumed criteria such as crystallization temperature and depth are used to classify pegmatites instead of measurable criteria such as mineral content, and mineral and isotope chemistries (Müller *et al.*, 2018).

Currently, the most widely accepted classification scheme for pegmatites is that of Černý (1991a), which was later modified by Černý & Ercit (2005). It groups granitic pegmatites into five classes based on pressure conditions of their host-rocks: abyssal, muscovite, muscovite–rare-element, rare-element, and miarolitic. Each of these classes, with the exception of the muscovite class, can be further subdivided into subclasses, which are distinguished by fundamental differences in their geochemical signatures. Furthermore, some of these subclasses are split into types and subtypes, mostly based on differences in mineral assemblages, geochemical signature, and/or conditions of consolidation (Černý & Ercit, 2005). Commonly in conjunction with the class scheme, pegmatites are further classified using petrogenetic families in an attempt to deal with the provenance of pegmatites that are derived from igneous differentiation from a plutonic source (Černý, 1991a). Three families are defined based on the elements that are the dominant products of fractionation: NYF, LCT, and mixed NYF + LCT (a hybrid of the NYF and LCT families).

Of particular interest to this study are granitic pegmatites of the rare-element class and mixed NYF + LCT family. According to the classification scheme, pegmatites in the rareelement class are emplaced at shallow to intermediate depths and at low to moderate temperatures, and accumulate lithophile rare elements (Černý & Ercit, 2005). As the name implies, pegmatites of the mixed NYF + LCT family have mixed geochemical and mineralogical characteristics, and can have a vast array of genetic origins. The LCT component of the geochemical signature is usually minor and can occur as trace elements in rock-forming minerals or as accessory phases in dominantly NYF mineral assemblages (Černý & Ercit, 2005). It has been suggested that mixed NYF + LCT pegmatites can be formed in three different ways: (1) contamination of a NYF-type magma by undepleted LCT-type supracrustal lithologies (Černý, 1991a); (2) formation from a crustal protolith that was only partially depleted (Whalen *et al.*, 1987); and (3) from a range of depleted and undepleted protoliths that were affected by anatexis (Whalen *et al.*, 1987).

Although this classification scheme is the most widely accepted, there have been numerous other schemes proposed beginning as early as 1920, with the most recent being that of Dill (2016), which focuses on the economic aspects of pegmatites. However, all of these classification schemes, including that of Černý & Ercit (2005), have fundamental problems such as being based on presumed or inferred instead of measured criteria (e.g., Černý & Ercit, 2005;

Ginsburg & Rodionov, 1960), or requiring the application of multiple schemes for complete classification (Müller *et al.*, 2018).

The need for an updated pegmatite classification scheme is recognized by many members of the pegmatite community. During the 2015 bi-annual pegmatite meeting in Ksiaz, Poland, attendees discussed shortcomings of the current classification scheme and possible attributes that would be required of a new classification scheme. The majority of the pegmatite researchers present at this meeting agreed that either the current classification scheme requires significant modification or an entirely new classification scheme is required. However, there was substantial disagreement about the specific modifications or the new classification scheme required to address the shortcomings of the current scheme.

In their recent paper, Müller *et al.* (2018) argue that although the classification scheme first introduced by Černý (1991a) and revised by Černý & Ercit (2005) is widely used, it violates some of the fundamental requirements of a classification scheme. For example, each level of the classification should not have more than one classification criterion, the minimum modal proportion of a mineral or element required to classify a pegmatite should be specified, and it is unclear if the accessory minerals used to classify pegmatites should be macroscopically or microscopically observed (Müller *et al.*, 2018). Müller *et al.* (2018) also noted that an increasing number of pegmatites do not fit into the Černý & Ercit (2005) classification scheme, particularly those that belong to the NYF-type family. They did not comment on the validity of the mixed NYF + LCT family, though they did note that redefinition of the NYF- and LCT-type families is required if they are to continue to be used. One could presume that this redefinition would attempt to eliminate the need for a mixed-type family and instead all pegmatites would be classified relative to these end-member geochemical signatures.

1.3 Pegmatite Contamination

Researchers are beginning to recognize that the geochemical signature of a pegmatite can be influenced by its host rocks and that this may affect the classification of the pegmatite (e.g., Martin & De Vito, 2005). Some hypothesize that many pegmatites that have both diagnostic NYF- and LCT-type element enrichment could have formed due to contamination of an NYFtype magma by LCT-type fluids (Černý & Ercit, 2005; Martin & De Vito, 2005) or by undepleted supracrustal lithologies (Novák *et al.*, 2012). Novák *et al.* (2012) also present two

other hypotheses for the genesis of mixed-type pegmatites: crystallization from a magma generated from crust that was only partially depleted, or anatexis of a range of depleted to undepleted magmas. Clearly more research is needed to determine if mixed-type pegmatites are solely a product of contamination, and the mechanism(s) by which that contamination occurs, or if they can be generated simply through fractionation.

Unraveling the history of pegmatite contamination is very complex because contamination can occur at three distinct stages of pegmatite evolution: (1) pre-emplacement—as the pegmatite melt propagates from the fertile granite to the place of solidification, (2) post-emplacement—*in* situ by the host rocks, and (3) hydrothermal—alteration by fluids from the host rocks after pegmatite solidification (Novák, 2007). Furthermore, determining the degree of contamination can also be difficult, because in most cases the exact composition of the pegmatite melt at the time of separation from the parental magma, as well as the distance and pathway that the pegmatite melt travelled to its place of crystallization, are not known. Fortunately, certain factors are known to control the degree of pre- and post-emplacement contamination and these can be used to hypothesize how the pegmatite has been affected. Pre-emplacement contamination is controlled by distance and velocity of propagation of the pegmatite melt from the parental granite, as well as by the mechanical properties and reactivity of the host rocks through which it travelled. Post-emplacement contamination is controlled by the thickness and internal structure of the pegmatite, the contrasting temperature and composition of the pegmatite and host rock, and the reactivity with the host rock (Novák, 2007). Many of these factors can be easily determined in the field, or by simple petrographic examination of the pegmatite and host rock. The occurrence of individual minerals, commonly those with unusual compositions [e.g., bastnäsite (Ce,La,Nd,Y)(CO₃)F], as well as the chemical compositions of minerals that can incorporate a variety of elements into their structures (e.g., tourmaline), can also be used to determine the degree and timing of contamination (Novák, 2007).

1.4 Scope and Rationale

Pegmatites are extremely complex rocks and a global source of technologically important rare elements (primarily Li, Be, Ta, Nb, W, and Sn) and gems (Simmons, 2007). Although thousands of scientific papers have been published about pegmatites, they remain the subject of significant debate in the scientific community. Much of this debate involves how pegmatites are

classified (e.g., Hanson, 2016; Martin & De Vito, 2005; Müller et al., 2018; Simmons, 2005) which relates back to the remaining questions about how they form. Currently, the most widely accepted classification scheme divides pegmatites into petrogenetic families based on the elements that are the dominant products of fractionation: NYF (niobium, yttrium, fluorine) and LCT (lithium, cesium, tantalum) (Černý, 1991a; Černý & Ercit, 2005). A mixed NYF + LCT petrogenetic family that displays characteristics of both the NYF and LCT families has also been distinguished; however, there is a wide range of possibilities for the genesis of pegmatites in this family including the contamination of NYF-type magma by depleted supracrustal lithologies (Černý, 1991b), genesis from a partially depleted crustal protolith (Whalen *et al.*, 1987), and anatexis of a mixed range of depleted and undepleted protoliths (Whalen et al., 1987). Further complicating the definition of this category is the fact that only a limited number of scientific studies of mixed-type pegmatites having been completed (e.g., Ercit *et al.*, 2003; De Vito *et al.*, 2006; Novák et al., 2012). It has been recognized that as more pegmatites continue to be described, an increasing number of them will not fit into the NYF or LCT petrogenetic families (Simmons, 2005). The controversy surrounding pegmatite classification and the problematic mixed NYF + LCT family highlights the need for more comprehensive scientific studies of mixed-type pegmatites.

Another facet of pegmatite genesis that is greatly understudied is pegmatite contamination, or the idea that the chemical signature of a pegmatite can be influenced by its host rocks. Although contamination is recognized as a process by which the geochemical signature of a pegmatite can be modified (e.g., Černý, 1991c), very little research has been conducted on when contamination can occur during the formation of a pegmatite and exactly how it might affect its mineralogy and geochemical signature (Novák, 2007). The effect of contamination on the geochemical signature of a pegmatite could be particularly important when the host rocks have a very different composition than that of the pegmatite. Furthermore, pegmatite contamination is rarely mentioned in scientific studies of pegmatites with the exception of pegmatites of the Moldanubian zone in the Czech Republic (e.g., Novák, 2007; Novák *et al.*, 2013), and the McCombe pegmatite (Tindle *et al.*, 2005), Pakeagama Lake, and Separation Lake areas in northwestern Ontario (Tindle *et al.*, 2002). This dissertation includes a meta-analysis of pegmatite literature that shows the vast majority of pegmatite studies regard the pegmatite and their host rocks separately, and fail to consider the impact that propagation through a host rock

and crystallization in a host rock of contrasting chemical composition could have on the composition of the pegmatite.

To address these gaps in pegmatite knowledge, this dissertation focuses on a previously unstudied pegmatite occurrence: the Rau pegmatite group in the Yukon Territory. This locality was selected because it is proposed to have a mixed-type geochemical signature and possesses unique characteristics that are not present at most other pegmatite occurrences. Specifically, the Rau pegmatite group was emplaced into dolostone host rocks, resulting in the formation of endoand exo-contact skarns and likely influencing its rare element mineralogy. This dissertation represents the first comprehensive study of this pegmatite occurrence and provides new data on mixed-type pegmatites that are needed to ascertain the validity of this petrogenetic family. It is also one of the first studies to consider the effect of host rock composition on pegmatite mineralogy, which will provide insight into the occurrence and timing of pegmatite contamination, and its influence on the geochemical signature of a pegmatite.

Addressing complex questions such as the validity of the pegmatite classification scheme and the influence of contamination on pegmatite mineralogy requires a solid foundation in mineralogy that is mainly acquired in an undergraduate mineralogy course. Mineralogy is a foundational course in all undergraduate geological sciences programs and is commonly the first geological sciences course that students are required to take above the 100-level (Dyar *et al.*, 2004). In spite of its importance, a variety of pedagogical approaches across a spectrum from instructor- to student-centred are employed to teach mineralogy. To ensure that students are learning key mineralogy concepts, which will help prepare them to tackle complex research in mineralogy at the graduate level, an assessment is required that can reliably evaluate learning in undergraduate mineralogy courses.

For this reason, this dissertation also includes research in the field of Geoscience Education, specifically the creation of a statistically validated, multiple-choice assessment, i.e., a concept inventory, for introductory mineralogy courses. As part of the development process, the concept inventory was deployed in two undergraduate mineralogy courses at two different universities that have similar course content but employ different pedagogies: student-centred and instructor-centred. The results of this deployment were used to assess the impact of pedagogical methods on student learning of mineralogy concepts. The concept inventory can be implemented in any introductory mineralogy course to measure student learning gains, providing

instructors with a reliable way to ensure that their students understand key mineralogy concepts necessary for complex studies such as those described above involving pegmatites.

CHAPTER 2

The Rau Pegmatite Group

2.1 Introduction

The Rau pegmatite group is unusual as it is one of the few pegmatite occurrences in the world hosted by carbonate rocks. These host rocks have resulted in the formation of several features, such as biotite-bearing endo-contact skarns (a skarn formed within the pegmatite dike), a diverse assemblage of rare earth element (REE)- bearing carbonate minerals within the pegmatite dikes, and F-rich exo-contact skarns (a skarn formed within the host rocks). Furthermore, most of the pegmatite dikes contain calcite-filled pockets. Due to their emplacement into rocks of a contrasting chemical composition and the unusual features that have formed, researchers have hypothesized that the Rau pegmatite dikes were contaminated as fluids were exchanged between the cooling pegmatite dikes and their dolostone host rocks (Cempírek & Groat, 2014). However, the following questions remain unanswered: (1) What was the effect of host rock contamination on the mineralogy of the Rau pegmatite dikes? (2) What was the effect of the intrusion of the Rau pegmatite melts on the composition of the dolostone host rocks? (3) What was the timing of fluid exchange between the pegmatite dikes and their host rocks? and (4) What was the source of the CO₂-bearing fluids that crystallized the carbonate minerals in the Rau pegmatite dikes? This study seeks to answer these questions as well as to provide the first comprehensive examination of the Rau pegmatite group.

2.1.1 Pegmatites hosted by carbonate rocks

There are only two other regions in which rare-element pegmatites emplaced into carbonate rocks have been studied in detail: the Czech Republic and Madagascar. In the Czech Republic, the Bližná elbaite-subtype pegmatite intrudes dolomite-calcite marble in the Moldanubian Zone, southern Bohemia. This unusual situation resulted in the crystallization of intermediate elbaite-schorl-dravite and elbaite-dravite solid solutions, due to the mixing of Ca-Mg-rich fluids from the host rock with Na-Al-Li-F-B-rich pegmatite fluids (Novák *et al.*, 1999). The pegmatite also contains primary REE-bearing minerals such as bastnäsite-(Ce), parisite-(Ce), and allanite-(Ce), as well as Ca- and Mg-rich minerals (Novák *et al.*, 2012). Novák *et al.*

(2012) concluded that, although the geochemical signature of Bližná is consistent with the mixed NYF + LCT family, it is not a truly mixed-type pegmatite, but a special type of contaminated LCT-type pegmatite, with its unique mineralogy and geochemistry being obtained through the pre-emplacement contamination of a LCT-type pegmatite-forming melt with carbonatite-like marbles with a NYF-type signature (Novák *et al.*, 2012).

In Madagascar, at least eight of the main pegmatite fields in the Itremo region have been emplaced into marbles, and these comprise almost all of the gem-bearing pegmatites in the region. There are three different groups of pegmatites hosted in the marbles, each with a different geochemical signature: NYF-type pegmatites that are close to the granitic intrusions, mixed-type pegmatites, and narrow, locally miarolitic pegmatites that are highly evolved and LCT-type. The pegmatites crystallized from NYF-type pegmatitic liquids but were significantly contaminated to various degrees, particularly with Ca from B-bearing, LCT-type fluids that were expelled from the metasedimentary sequence. Like the Rau pegmatite dikes, pegmatites of the Itremo region developed exo-contact zones containing skarn minerals such as pyroxenes, amphiboles, and micas (Pezzotta, 2005).

2.2 Regional Geology

The Rau pegmatite group occurs within a regional Jurassic-Cretaceous fold and thrust belt that marks the boundary between rocks of the Selwyn Basin and the Mackenzie Platform (Fig. 2.1) (Abbott *et al.*, 1986). The Selwyn Basin covers an area of approximately 700 by 200 km in the central Yukon Territory and southwestern Northwest Territories. It is defined as a succession of shelf, slope, and basinal strata that accumulated from the Neoproterozoic to Jurassic (Gabrielse, 1967). The northwestern portion of the Selwyn Basin mostly consists of slope to basin facies strata including coarse quartz sandstone, shale, and carbonates (Gordey & Anderson, 1993). The Yukon-Tanana Terrane was isolated from the autochthonous Selwyn Basin when rifting was initiated during the Early to Middle Devonian, forming the Slide Mountain Ocean (Mair *et al.*, 2006; Mortensen, 1992). This caused rocks of the Earn Group to be deposited within fault-bounded basins in a restricted deep marine setting, forming complex internal stratigraphy (Gordey *et al.*, 1991).

In contrast to these basinal successions, the Mackenzie Platform stratigraphy is dominated by shallow water carbonate and clastic shelf facies rocks (Lenz, 1972). Proterozoic rocks of the

Mackenzie Platform sediments consist of the Wernecke, Pinguicula, Mackenzie Mountains, and Windermere supergroups (Aitken & McMechan, 1992; Narbonne & Aitken, 1995), but are undifferentiated in the study area (Fig. 2.2). The Cambrian to Devonian Bouvette Formation is also part of the Mackenzie Platform sediments and consists of a thick sequence of dolostones and limestones (Morrow, 1999).

Regional northeasterly directed compression during the Late Triassic imbricated and folded the Selwyn Basin and Mackenzie Platform strata (Murphy, 1997), producing a series of large-scale thrust fault systems in the Early Jurassic to Early Cretaceous (Figs. 2.1 and 2.2) (Abbott *et al.*, 1986). The Dawson, Tombstone, and Robert Service thrust faults are the three major thrust faults that occur in the region (Mair *et al.*, 2006). The Dawson thrust broadly separates the basinal strata of the Selwyn Basin to the south from the shallow water carbonates of the Mackenzie Platform to the north (Murphy, 1997). The Rau pegmatite group occurs in the footwall of this thrust, within carbonate rocks of the Bouvette Formation (Fig. 2.2).

Two different suites of intrusive rocks occur in the vicinity of the Rau pegmatite group: the 90–94 Ma Tombstone intrusions and the 64–67 Ma McQuesten intrusions (Murphy, 1997). The Tombstone intrusions are a group of hornblende-bearing plutons that comprise part of the larger Selwyn Plutonic Suite (Gordey & Anderson, 1993). They were emplaced during a period of granitic magmatism caused by a tectonic change from convergent-oblique to subduction-dextral strike-slip movement (Murphy, 1997). The McQuesten intrusions form a small east-northeast-trending belt in the Keno Hill District that was generated during the formation of the Mackenzie Mountains (Murphy, 1997). They are generally composed of medium- to coarse-grained, potassium-feldspar megacrystic, biotite \pm muscovite granite and quartz monzonite (Murphy, 1997). The Tombstone and McQuesten intrusions look very similar to one another and geochronology is required to distinguish between the two (Murphy, 1997).



Figure 2.1. (a) Regional geology of the northwestern Selwyn Basin, including the Rau pegmatite group and several Cretaceous intrusions. (b) The inset shows the local geology of the Rau pegmatite group (modified from Thiessen *et al.*, 2016).



Figure 2.2. Generalized regional stratigraphy of the area surrounding the Rau pegmatite group, including the relationship between stratigraphic units, regional structures, and intrusive units. The stratigraphic position of the Rau pegmatite group is indicated by a star (modified from Thiessen *et al.*, 2016).

2.3 Local Geology

The Rau pegmatite group is located approximately 100 km northeast of Mayo, Yukon Territory, in the Keno Hill District (Fig. 2.3). It falls within the Rau property, which also covers the Tiger zone of Au-bearing carbonate replacement mineralization, discovered by ATAC Resources Ltd. in 2008. This same exploration program led to the discovery of the Rau pegmatite dikes (Thiessen *et al.*, 2012; Thiessen *et al.*, 2016). The pegmatites are associated with the Rackla pluton, described by Panton (2008) as a weakly metaluminous, I-type granodiorite. A diameter of approximately 1 km is exposed, but aeromagnetic surveys indicate a large magnetic anomaly that suggests the pluton is considerably larger below the surface (Kingston *et al.*, 2010). Due to the poor exposure of the pluton, it has been mapped and sampled based mainly on float and minor outcrops; however, Panton (2008) describes it as a primarily coarse-grained biotitemuscovite granite with common finer aplitic phases near the margins. Spessartine garnet, fluorite, and schorl were noted in aplite at the contact with the host dolostone (Panton, 2008). This contact was not observed during the 2015 field season when I visited the Rau property. A porphyritic granite that is rich in rare element-bearing minerals was observed in the field ~105 m west of an outcrop of the Rackla pluton, within the mapped extent of the Rackla pluton. This unit is interpreted to be the uppermost, porphyritic phase of the Rackla pluton.

The Rackla pluton was originally determined to have a minimum emplacement age of ~61 Ma (unpublished U-Pb zircon data, Mortensen & Abbott), which, in addition to its geographic location, led to the initial inference that it was related to the 65.2 ± 2.0 Ma (Murphy, 1997) McQuesten Plutonic Suite (Kingston *et al.*, 2010). However, more precise dates obtained using 40 Ar/³⁹Ar step-heating (62.3 ± 0.6 Ma; Kingston *et al.*, 2010) and U-Pb dating of zircon (62.9 ± 0.5 Ma; V. Bennett, unpublished data in Thiessen *et al.*, 2012) indicate that the pluton is early Paleocene in age and represents a later magmatic event than that which generated the McQuesten Plutonic Suite (Kingston *et al.*, 2010).

The pegmatite dikes and the Rackla pluton are hosted by the carbonate Bouvette Formation (Figs. 2.1 and 2.2). In the study area, the age of the Bouvette Formation is Silurian to Middle Devonian (Colpron *et al.*, 2013). It consists of light- to medium-grey beds that are <1 to ~50 cm thick and dip to the northwest. Some pegmatites are rimmed by a narrow zone of green silicate (endo-contact) skarn followed by a white calcite (exo-contact) skarn in the grey host dolostone; veins of the calcite exo-contact skarn oriented perpendicular and oblique to one of the dikes (Rau 9) were locally observed.

The Rau pegmatite group was originally defined as comprising seven pegmatite dikes, separated into two groups based on composition and distance from the Rackla pluton. The two subparallel and subhorizontal pegmatite dikes of Group 1 are located closer to the Rackla pluton, are elbaite- and amazonite-bearing, and are associated with abundant rare element mineralization (Li, Be, Nb, Ta, W, Sn, Sc, Zr, Hf, U, Th). In contrast, the five pegmatite dikes of Group 2 are located farther away from the pluton. Compositionally, they are a mix of mostly barren dikes with fluorite veinlets and low-temperature fracture mineralization, and F-rich dikes with rare element mineralization (Cempírek & Groat, 2014).

During the 2015 field season, three additional pegmatite dikes and two aplite dikes were discovered. One of the pegmatite dikes is similar to the barren pegmatite dikes with fluorite veinlets of Group 2, and the other two dikes contain rare element-bearing minerals. The pegmatite dikes are located relatively close to Group 1, even though they exhibit features of Group 2. The two aplite dikes contain abundant rare element mineralization and are located near both the Group 1 and the newly discovered pegmatite dikes. These newly discovered pegmatite

dikes appear to invalidate the previous distinctions made between Group 1 and 2. All pegmatite dikes in the area surrounding the Rackla pluton are now considered to be parts of a single pegmatite group, with associated aplite dikes (Fig. 2.4; Table 2.1).

The individual pegmatite dikes are 0.10-2.0 m wide, with mappable strike lengths of up to 60 m. Their strikes range from $80-168^{\circ}$, their dips range from subvertical to shallow (~15°), and most appear concordant to bedding in the carbonate host rocks. They show variable types of zoning. Symmetrical concentric zoning with a graphic pegmatite (K-feldspar + quartz + albite) wall zone that gradually increases in grain size from ~ 1 mm at the border to ~ 10-15 cm in a blocky zone in the center of the dike was observed in the most evolved Rau 1 dike. In this dike the blocky (amazonitic) K-feldspar is surrounded by quartz as well as pockets with quartz and tourmaline crystals that are filled by calcite and exsolved Fe-oxides. The core of dike Rau 1 is locally partially replaced by a saccharoidal albite. The Rau 3–9 dikes are irregularly zoned, either with similar grain size and mineralogy throughout the dike (Rau 4, 6, 7, and 9), or with quartz (usually < 2 cm) and conical K-feldspar crystals (up to 20 cm long) enclosed in a fine-grained "line-rock" (thin layers of albite, quartz, and minor K-feldspar) (Rau 3, 5, 5U, and 8). In dikes 3, 5, 5U, and 8, if a core or pocket zone is present it can be either in the pegmatite center or located assymmetrically. In addition to major albite and/or quartz these zones contain common fluorite, K-feldspar crystals, and, in carbonate-filled pockets, also tourmaline.

Previous studies of the Rau property primarily focused on the tin-tungsten and gold skarns (Panton, 2008) and gold-rich carbonate replacement deposit within the Tiger zone (Kingston, 2009; Kingston *et al.*, 2010; Thiessen *et al.*, 2012; Thiessen 2013; Thiessen *et al.*, 2016) that occur on the property. Panton (2008) described the general geology of the Rau property, including its economic aspects, and interpreted the deposit mechanisms of the Au, W, and Pb-Zn-Ag mineralization. The genesis of the gold-rich carbonate replacement deposit was partially constrained when it was determined that the Pb in the sulphide mineralization was genetically related to the Rackla pluton and associated dikes and sills, with a variable contribution of Pb from the host rocks (Kingston, 2009; Kingston *et al.*, 2010). Using ⁴⁰Ar/³⁹Ar step-heating, Kingston *et al.* (2010) determined that the Rackla pluton and related dikes and sills formed during a distinct magmatic event unrelated to the McQuesten suite intrusions. Lead isotopic compositions indicated that the McQuesten suite intrusions and the Rackla pluton were not derived by melting of the same source rocks (Kingston *et al.*, 2010). Thiessen *et al.* (2012)

defined two stages of gold mineralization in the Tiger zone and linked the mineralization to multistage fluid flow that was at least in part associated with the emplacement and cooling of the Rackla pluton. This mineralization was then classified as a Tertiary-aged intrusion-related gold deposit (Thiessen, 2013). Finally, the genesis of the gold deposit was further constrained by Thiessen *et al.* (2016). The authors determined that arsenopyrite-hosted gold formed early from a high-temperature, immiscible, CO₂-bearing fluid sourced from the Rackla pluton. Free gold hosted in fractures formed later due to the introduction of a meteoric fluid and subsequent cooling of the magmatic-hydrothermal system (Thiessen *et al.*, 2016).

The first and only study of the Rau pegmatites was conducted by Cempírek & Groat (2014). They focused on the Rau I pegmatite (hereafter re-defined as Rau 1) and determined that it was a mixed-type pegmatite containing amazonite, fluor-elbaite, Nb- and Ta-bearing minerals, and REE-bearing minerals. They concluded that Rau 1 had been subjected to *in situ* pegmatite contamination, resulting in the formation of a B- and F-rich exo-contact skarn and high contents of carbonates and sulphides in the pegmatite (Cempírek & Groat, 2014). On first examination, the other Rau pegmatite dikes seem to be less evolved than Rau 1 in that they do not appear to contain evolved minerals such as amazonite and elbaite in hand sample. However, several of the pegmatite dikes are bordered by endo-contact skarns and contain pockets of euhedral calcite and Fe oxide minerals. There is also an exo-contact skarn similar to the one described by Cempírek & Groat (2014) that is associated with one of the pegmatite dikes. This suggests that at least some of the other dikes in the Rau pegmatite group have been contaminated.



Figure 2.3. Location of the Rau pegmatite group (modified from Kingston et al., 2010).



Figure 2.4. Local geological map of the Rau pegmatite group and associated units. The mapped extent of the Rackla pluton is represented by a dotted boundary with the dolostone (modified from Panton, 2008).

Unit	Coordinates
Rau 1	N64° 11.563' W134° 22.219'
Rau 3	N64° 11.497' W134° 22.743'
Rau 4	N64° 11.462' W134° 22.645'
Rau 5	N64° 11.485' W134° 22.612'
Rau 5U	N64° 11.514' W134° 22.585'
Rau 6	N64° 11.501' W134° 22.601'
Rau 7	N64° 11.507' W134° 22.590'
Rau 8	N64° 11.513' W134° 22.408'
Rau 9	N64° 11.473' W134° 22.396'
Rau 10	N64° 11.598' W134° 22.100'
Aplite dike 1	N64° 11.508' W134° 22.288'
Aplite dike 2	N64° 11.578' W134° 22.082'
Porphyritic phase	N64° 11.392' W134° 21.911'
Rackla pluton	N64° 11.513' W134° 21.288'

Table 2.1. Coordinates of all pegmatite dikes and associated units.

2.4 Analytical Methods

2.4.1 Whole rock geochemical analysis

Whole rock geochemical analysis was performed on one sample each of dike Rau 3, 4, 5, 6, 7, 8, 9, and 10, as well as an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton itself. These samples were taken as much as possible from fresh parts of the pegmatites and if weathered rims were present they were removed used a diamond-bladed rock saw.

All whole rock geochemical analyses were completed by Bureau Veritas Commodities Canada Ltd. in Vancouver using a combination of inductively coupled plasma emission spectrometry (ICP-ES) analysis for major and minor elements, and inductively coupled plasma mass spectrometry (ICP-MS) analysis for trace elements. Additionally, all samples were analysed for trace level F by specific ion electrode, Li by four-acid digestion with ICP-ES analysis, and B by Na₂O₂ fusion and ICP-MS analysis.

2.4.2 Electron microprobe analysis

Feldspars in the host rocks and all pegmatite dikes, micas in the host rocks, endo-contact skarns and all pegmatite dikes, amphibole in the host rocks and exo-contact skarn, titanite in the

host rocks, and carbonates, fluoborite and norbergite in the exo-contact skarn were analysed using a CAMECA SX-50 electron microprobe (EMP) operating in wavelength-dispersion mode at UBC. In addition, beryl, columbite, and microlite in the Rau 6 pegmatite dike were analysed at UBC because of time constraints at Masaryk University (see below). Data reduction was done using the 'PAP' $\Phi(\rho Z)$ method (Pouchou & Pichoir, 1985). The following analytical conditions were used: acceleration voltage 15 kV, beam current 20 nA (10 nA for carbonates), peak counting time 20 s (50 s for beryl; 40 s for Rb, Cs in feldspar and mica; 40 s for F in mica, amphibole, titanite, fluoborite, norbergite, columbite, and microlite; 40 s for Cl in mica; 40 s for Sr in carbonates), background count time 10 s (20 s for Rb, Cs in feldspar and mica; 20 s for F in mica, amphibole, titanite, fluoborite, norbergite, columbite, and microlite; 20 s for Cl in mica; 20 s for Sr in carbonates; 20 s for Na, Al, Si in beryl and 25 s for all other elements in beryl), spot diameter 5 µm (10 µm for mica and carbonates). The following standards were used for each mineral (all X-ray lines were K_{α} unless otherwise stated): feldspar (albite, Na, TAP; anorthite, Al, TAP; diopside, Mg, TAP; anorthite, Si, TAP; orthoclase, K, PET; anorthite, Ca, PET; rhodonite, Mn, LIF; fayalite, Fe, LIF; RbTiOPO4, RbLa, TAP; pollucite, CsLa, PET; barite, BaL_α, PET); mica (phlogopite, F, Mg, Si, TAP; phlogopite, K, PET; albite, Na, TAP; kyanite, Al, TAP; scapolite, Cl, PET; diopside, Ca, PET; rutile, Ti, PET; magnesiochromite, Cr, LIF; rhodonite, Mn, LIF; fayalite, Fe, LIF; RbTiOPO₄, RbL_α, TAP; pollucite, CsL_α, PET; barite, BaL_{α} , LIF); amphibole (phlogopite, F, TAP; albite, Na, TAP; kyanite, Al, TAP; diopside, Mg, Si, TAP; diopside, Ca, PET; scapolite, Cl, PET; orthoclase, K, PET; rutile, Ti, PET; magnesiochromite, Cr, LIF; rhodonite, Mn, LIF; fayalite, Fe, LIF; cassiterite, SnL_{α} , PET); titanite (topaz, F, TAP; albite, Na, TAP; diopside, Mg, Si, TAP; diopside, Ca, PET; orthoclase, Al, TAP; rutile, Ti, LIF; rhodonite, Mn, LIF; fayalite, Fe, LIF; columbite, NbL α , PET; CePO₄, CeL_{α} , LIF; cassiterite, SnL_{α}, PET; microlite, TaL_{α}, LIF); carbonates (dolomite, Mg, TAP; calcite, Ca, PET; rhodochrosite, Mn, LIF; siderite, Fe, LIF; Sr-titanite, SrL α , TAP; barite, BaL α , PET); fluoborite (phlogopite, F, TAP; kyanite, Al, TAP; olivine, Mg, Si, TAP; diopside, Ca, PET; rutile, Ti, PET; rhodonite, Mn, LIF; fayalite, Fe, LIF); norbergite (phlogopite, F, TAP; kyanite, Al, TAP; olivine, Mg, Si, TAP; diopside, Ca, PET; rutile, Ti, PET; rhodonite, Mn, LIF; fayalite, Fe, LIF); beryl (albite, Na, TAP; albite, Al, Si, TAP; diopside, Mg, TAP; rhodonite, Mn, LIF; fayalite, Fe, LIF; pollucite, CsL_{α} , PET); columbite and microlite (topaz, F, TAP; albite, Na, TAP; diopside, Mg, Si, TAP; diopside, Ca, PET; orthoclase, Al, TAP; Sc-phosphate, Sc, LIF;

rutile, Ti, LIF; rhodonite, Mn, LIF; fayalite, Fe, LIF; zircon, ZrL $_{\alpha}$, PET; columbite, NbL $_{\alpha}$, PET; cassiterite, SnL $_{\alpha}$, PET; microlite, TaL $_{\alpha}$, LIF; scheelite, WL $_{\alpha}$, LIF; ThO₂ glass, ThM $_{\alpha}$, PET; UO₂ glass, UM $_{\alpha}$, PET).

Allanite, bastnäsite, beryl, columbite, euxenite, garnet, mica, monazite, scheelite, titanite, tourmaline, and xenotime were analysed at Masaryk University using a Cameca SX-100 instrument operating in wavelength-dispersion mode. The following analytical conditions were applied: acceleration voltage 15 kV, beam current 20 nA (10 nA for bastnäsite, beryl, mica, and tourmaline), spot diameter 8 μ m for bastnäsite, 5 for μ m allanite, beryl and mica, < 1 μ m for columbite and scheelite, 3 µm for euxenite, garnet and tourmaline, 2 µm for monazite, titanite and xenotime. The following standards were used (all X-ray lines were Ka unless otherwise stated): allanite (albite, Na, TAP; almandine, Fe, LLIF; spessartine, Mn, LLIF; monazite-(Nd), NdL_{β}, LLIF; PrPO₄, PrL_{β}, LLIF; monazite-(La), LaL_{α}, PET; monazite-(Ce), CeL_{α}, PET; anatase, Ti, PET; sanidine, Si, Al, TAP; sanidine, K, LPET; xenotime-(Y), YL $_{\alpha}$, TAP; monazite-(Sm), SmL_{β} , LLIF; DyPO₄, DyL_{\beta}, LLIF; GdPO₄, GdL_{\beta}, LLIF; ErPO₄, ErL_{\alpha}, LLIF; wollastonite, Ca, LPET; vanadinite, Cl, LPET; vanadinite, VK_{β}, LPET; vanadinite, PbM_{α}, LPET; brabantite, ThM_{α}, LPET; uranium, UM_{β}, LPET; topaz, F, PC1; forsterite, Mg, TAP; zircon, ZrL_{α}, TAP; tin, SnL_{α} , LPET; ScVO₄, Sc, PET; fluorapatite, P, LPET; chromite, Cr, PET; celestine, SrL_{α}, TAP; barite, BaL_α, PET; TbPO₄, TbL_α, LLIF; HoPO₄, HoL_β, LLIF; YbPO₄, YbL_α, LLIF; TmPO₄, TmL_{α} , LLIF; EuPO₄, EuL_{\beta}, LLIF); bastnäsite (albite, Na, TAP; monazite-(Ce), CeL_{\beta}, LLIF; monazite-(Nd), NdL_{β}, LLIF; PrPO₄, PrL_{β}, LLIF; monazite-(La), LaL_{α}, PET; barite, BaL_{α}, PET; anatase, Ti, PET; sanidine, Si, Al, TAP; sanidine, K, LPET; xenotime-(Y), YL_{α}, TAP; celestine, SrL_{α} , TAP; monazite-(Sm), SmL_{β} , LLIF; DyPO4, DyL_{\beta}, LLIF; GdPO4, GdL_{\beta}, LLIF; ErPO4, ErL_{α} , LLIF; spessartine, Mn, LLIF; hematite, Fe, LLIF; wollastonite, Ca, LPET; vanadinite, Cl, PbM_α, LPET; brabantite, ThM_α, LPET; uranium, UM_β, LPET; PrF₃, F, PC1; forsterite, Mg, TAP; zircon, ZrL_α, TAP; ScVO₄, Sc, PET; fluorapatite, P, LPET; TbPO₄, TbL_α, LLIF; HoPO₄, HoL_β, LLIF; YbPO₄, YbL_{α}, LLIF; TmPO₄, TmL_{α}, LLIF; EuPO₄, EuL_{β}, LLIF); beryl and mica (albite, Na, TAP; sanidine, Si, Al, TAP; sanidine, K, PET; Rb-leucite, RbL $_{\alpha}$, TAP; pyrope, Mg, TAP; titanite, Ti, LPET; pollucite, CsL_a, LPET; vanadinite, Cl, LPET; barite, BaL_a, LPET; fluorapatite, P, LPET; chromite, Cr, LPET; wollastonite, Ca, PET; almandine, Fe, LLIF; spessartine, Mn, LLIF; gahnite, Zn, LLIF; topaz, F, PC1; ScVO4, Sc, PET); columbite (); euxenite (albite, Na, TAP; almandine, Fe, LLIF; TiO, Ti, PET; titanite, Ca, PET; sanidine, K,

PET; sanidine, Al, TAP; sanidine, Si, LPET; monazite-(La), LaL_{α}, PET; monazite-(Ce), CeL_{α}, PET: xenotime-(Y), YL_{α}, TAP: CrTa₂O₆, TaM_{α}, TAP: spessartine, Mn, LLIF; PrPO₄, PrL_{β}, LLIF; monazite-(Nd), NdL_{β}, LLIF; monazite-(Sm), SmL_{α}, LLIF; columbite, NbL_{α}, LPET; topaz, F, PC1; pyrope, Mg, TAP; uranium, UM_{β}, LPET; brabantite, ThM_{α}, LPET; ScVO₄, Sc, PET; zircon, ZrL_α, TAP; GdPO₄, GdL_β, LLIF; DyPO₄, DyL_β, LLIF; ErPO₄, ErL_α, LLIF; fluorapatite, P, PET; lammerite, AsL_{α}, TAP; TbPO₄, TbL_{α}, LLIF; HoPO₄, HoL_{β}, LLIF; YbPO₄, YbL_{α}, LLIF; TmPO₄, TmL_{α}, LLIF; tungsten, WL_{α}, LLIF; vanadinite, PbM_{β}, LPET; bismuth, BiM_{β}, LPET; LuPO₄, LuM_{β}, TAP); garnet (albite, Na, TAP; wollastonite, Si, TAP; wollastonite, Ca, PET; sanidine, Al, TAP; sanidine, K, PET; pyrope, Mg, TAP; titanite, Ti, LPET; chromite, Cr, LPET; almandine, Fe, LLIF; spessartine, Mn, LLIF; vanadinite, V, LLIF; gahnite, Zn, LLIF; topaz, F, PC1; fluorapatite, P, LPET; YAG, YL α , TAP); monazite (albite, Na, TAP; xenotime-(Y), YL α , TAP; sanidine, Si, TAP; celestine, SrL_{α} , TAP; Celestine, S, LPET; fluorapatite, P, PET; fluorapatite, Ca, LPET; PrPO₄, PrL_β, LLIF; uranium, UM_β, LPET; monazite-(La), LaL_α, PET; monazite-(Ce), CeL_{α}, PET; monazite-(Nd), NdL_{β}, LLIF; monazite-(Sm), SmL_{β}, LLIF; EuPO₄, EuL_{β} , LLIF; GdPO₄, GdL_{\beta}, LLIF; DvPO₄, DvL_{\alpha}, LLIF; ErPO₄, ErL_{\alpha}, LLIF; brabantite, ThM_{\alpha}, LPET: vanadinite, PbMa, LPET; lammerite, AsLa, TAP; almandine, Fe, LLIF; TiO, Ti, PET; zircon, ZrL_{α} , TAP; ScVO4, Sc, LPET); scheelite (albite, Na, TAP; CrTa₂O₆, TaM_{α}, TAP; gahnite, Al, TAP; gahnite, Zn, LLIF; spinel, Mg, TAP; columbite, NbL $_{\alpha}$, LPET; columbite, Fe, LLIF; vanadinite, PbM_{α}, LPET; sanidine, Si, LPET; molybdenum, MoL_{α}, PET; TiO, Ti, PET; ZnWO₄, WL_α, LLIF; tephroite, Mn, LLIF; ScVO₄, Sc, LLIF; topaz, F, PC1; wollastonite, Ca, PET); titanite (albite, Na, TAP; CrTa₂O₆, TaL_{α}, LLIF; almandine, Fe, LLIF; wollastonite, Ca, PET; sanidine, K, PET; sanidine, Al, TAP; monazite-(La), LaL_α, PET; monazite-(Ce), CeL_α, PET; titanite, Si, TAP; titanite, Ti, LPET; xenotime-(Y), YL α , TAP; PrPO4, PrL β , LLIF; monazite-(Nd), NdL_β, LLIF; tin, SnL_α, LPET; topaz, F, PC1; pyrope, Mg, TAP; columbite, NbL_{α}, LPET; brabantite, ThM_{α}, LPET; zircon, ZrL_{α}, TAP; ScVO₄, Sc, LLIF); tournaline (albite, Na, TAP; wollastonite, Si, TAP; wollastonite, Ca, PET; sanidine, Al, TAP; sanidine, K, PET; pyrope, Mg, TAP: vanadinite, Cl, LPET: vanadinite, V, LLIF; titanite, Ti, LPET; barite, BaL_{α} , LPET; chromite, Cr, LPET; almandine, Fe, LLIF; spessartine, Mn, LLIF; gahnite, Zn, LLIF; topaz, F, PC1; Ni₂SiO₄, Ni, LLIF); xenotime (fluorapatite, P, PET; fluorapatite, Ca, LPET; monazite-(La), LaL_{α}, PET; monazite-(Ce), CeL_{α}, PET; celestine, S, PET; brabantite, ThM_{α}, LPET; uranium, UM_{β}, LPET; xenotime-(Y), YL_{α}, TAP; sanidine, Si, Al, TAP; lammerite, AsL_{α},

TAP; YbPO4, YbLα, LLIF; ErPO4, ErLα, LLIF; DyPO4, DyLα, LLIF; GdPO4, GdLα, LLIF; monazite-(Sm), SmLα, LLIF; monazite-(Nd), NdLβ, LLIF; tephroite, Mn, LLIF; almandine, Fe, LLIF; ScVO4, Sc, LPET; TbPO4, TbLα, LLIF; HoPO4, HoLβ, LLIF; TmPO4, TmLα, LLIF; LuAg, LuMβ, TAP; EuPO4, EuLα, LLIF; PrPO4, PrLβ, LLIF; vanadinite, PbMα, LPET; topaz, F, PC1; zirconium, ZrLβ, LPET).

2.4.3 Cathodoluminescence

Cathodoluminescence (CL) images of quartz were obtained using a Gatan MonoCL3 CL system mounted on a scanning electron microscope (SEM) model JEOL LV-5900 at Acadia University. The following analytical conditions were applied: accelerating potential 10 kV (periodically increased to 20 kV to improve CL signal), beam current 3 nA (10 nA at 20 kV accelerating potential).

2.4.4 Laser ablation inductively coupled mass spectrometry

LA-ICP-MS analyses were carried out using an ArF excimer laser ablation system (193 nm; Resolution M-50LR, ASI Australia) connected to a Quadrupole ICP-MS (Agilent 7700x) at the Pacific Centre for Isotopic and Geochemical Research at UBC. Measurements were performed at a repetition rate of 8 Hz and using a spot size of 120 μ m. Energy density on the sample was 15 mJ/cm². Helium served as the carrier gas and was admixed with N₂ for signal enhancement. The mass spectrometer was tuned for sensitivity, ThO/Th < 0.3% and a mass bias with 238/232 < 110%. Calibration was carried out using the silicate glass standard SRM NIST612 as external standard and the standard wt.% Si in quartz (46.74 wt.% Si). SRM NIST610, SRM NIST641, and basaltic BCR2-G were cross-checked as quality control. Data reduction was performed using the Iolite 3.4 software (Paton *et al.*, 2011).

After the analyses were completed all of the ablation craters were examined using a binocular microscope. Data was removed from further analysis if the crater was not clean and/or had broken the surrounding quartz grain. Any spot analyses with a 2RSE (relative standard error) greater than 10% were removed on the basis of poor internal precision (instrumental error).

2.4.5 Carbon and oxygen isotope analysis

Carbon and O isotopic analysis was completed using the Mineral Isotope Analyzer (MIA) in the Mineral Deposits Research Unit at UBC. A total of eight samples of fresh, translucent

calcite in pockets and veins in pegmatite dikes, seven samples of calcite with Fe oxide minerals in pockets in pegmatite dikes, nine samples of the host rock, and one whole rock sample of an aplite dike were successfully analysed. Seventeen whole rock samples of pegmatite dikes and one sample of an altered host rock did not contain enough carbonate to be analysed. A translucent calcite pocket in Rau 8 did not provide sufficient sample for analysis.

Carbonate samples were obtained using a Dremel[©] rotary drill tool equipped with a tungsten carbide bit. Approximately 30 mg of powdered carbonate was collected on weighing paper and transferred to glass sample vials. Larger samples of powdered carbonate were collected when available. The tungsten carbide bit was cleaned with 10% HCl followed by ethanol between each sample.

Powdered carbonate samples were analysed for ${}^{13}\text{C}/{}^{12}\text{C}$ and ${}^{18}\text{O}/{}^{16}\text{O}$ using the MIA, an offaxis integrated cavity output spectroscopy (OA-ICOS) unit. The analytical procedure followed that outlined by Beinlich *et al.* (2017). In-house standards used were BN13 ($\delta^{13}\text{C}_{\text{VPDB}}$ = 1.82‰; $\delta^{18}\text{O}_{\text{VSMOW}}$ = 13.72‰) and Sigma ($\delta^{13}\text{C}_{\text{VPDB}}$ = -14.18‰; $\delta^{18}\text{O}_{\text{VSMOW}}$ = 10.22‰). These were inserted into the analytical sequence every 10 samples to normalize errors. Pure CO₂ gas was inserted every five samples as blanks to calculate instrument drift. Three calcite standards and two gas blanks were also inserted at the beginning and end of each analytical sequence.

2.5 **Results**

2.5.1 Whole rock geochemical analysis

Samples of the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, as well as an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton itself, were analysed for major and trace elements to assess their degree of chemical fractionation. It is difficult to obtain a representative bulk sample of a pegmatite dike for whole rock geochemical analysis because the coarse grain size requires a large amount of sample to be analysed to ensure it includes all components of the pegmatite. However, much of the Rau pegmatite dikes are relatively fine-grained and therefore there is greater confidence that the samples obtained are representative of the overall composition of the pegmatite dikes.

Using the three-tiered classification scheme for granitic rocks of Frost *et al.* (2001), most of the units are ferroan whereas the Rau 7, 8, and 9 pegmatite dikes and an aplite dike are magnesian (Fig. 2.5a), and all of the units are alkalic except for the Rau 10 pegmatite, which is

alkali-calcic, and the Rackla pluton, which is calc-alkalic (Fig. 2.5b). The aluminum saturation index [ASI; ASI = molar Al₂O₃ / (Na₂O + K₂O + CaO – $1.67 \times P_2O_3$)] of pegmatites can be expected to increase with increasing fractionation (Chappell & White, 1992). The ASI of all analysed pegmatite dikes is close to 1.00 (the boundary between metaluminous and peraluminous), with the exception of the Rau 8 pegmatite dike which is anomalously peraluminous (1.29). An aplite dike is the most peraluminous unit with an ASI of 1.42. (Fig 2.6). The Rackla pluton is also weakly peraluminous (ASI = 1.08), and its porphyritic phase is peraluminous (ASI = 1.12). All analysed units are rich in Ga and Zr and plot in the A-type granite field of Whalen *et al.* (1987) (Fig. 2.7).

The major element contents of most of the pegmatite dikes is similar with the exception of the Rau 9 pegmatite dike, which contains less Si and K, and more Al, Na, and Ca than the other pegmatite dikes (Table 2.2). The Rau 10 pegmatite dike is the most similar in major element composition to the Rackla pluton. An aplite dike has a unique composition from the pegmatite dikes: it is enriched in Al and Ca, and relatively poor in Si and Na. This reflects the overall mineralogy of this dike, portions of which are rich in muscovite and calcite.

In terms of trace elements, all analysed pegmatite dikes contain elevated Nb compared to the average trace element composition of the upper continental crust (Rudnick & Gao, 2003) (ranging from 9 ppm in Rau 3 to 145 ppm in Rau 10), Ta (ranging from 68 ppm in Rau 10 to 508 ppm in Rau 9), Rb (ranging from 593 ppm in Rau 9 to above the detection maximum of 1000 ppm in Rau 3, 4, 6, and 7), and F (ranging from 138 ppm in Rau 4 to 3698 ppm in Rau 5). Beryllium and B are also relatively enriched in the pegmatite dikes, attaining 81 ppm Be and 96 ppm B in Rau 9. The Rau 3 and 4 pegmatite dikes both have the lowest contents of these elements, with 3 ppm Be in both dikes, and 9 and 11 ppm B in Rau 3 and 4 respectively (Table 2.3). The Rau 10 pegmatite dike is the richest in REEs, containing a total of 97 ppm total REEs, whereas the Rau 4 pegmatite dike has the lowest contents with 3 ppm total REEs (Fig. 2.8).

Element ratios such as Zr/Hf, Nb/Ta, Na/K, Rb/Sr, Rb/Cs, and Rb/Ba can be used to indicate the relative degree of fractionation of a pegmatite. However, any ratios involving Rb cannot be used to evaluate fractionation trends in these data because the Rb contents of the Rau 3, 4, 6, and 7 pegmatite dikes are above that which can be accurately measured. Decreases in Zr/Hf, Nb/Ta, and Na/K indicate increasing fractionation in metaluminous to peraluminous granites and pegmatites (London, 2008). The lowest Zr/Hf and Nb/Ta values occur in the Rau 9

pegmatite, whereas the highest occur in the Rau 10 pegmatite (Zr/Hf = 3.1 and 8.1; Nb/Ta = 0.2 and 2.1 respectively). An aplite dike, the Rackla pluton, and the porphyritic phase of the Rackla pluton also show high Zr/Hf and Nb/Ta, with Zr/Hf = 8.5 and Nb/Ta = 2.4 in an aplite dike, Zr/Hf = 9.4 and Nb/Ta = 3.8 in the Rackla pluton, and Zr/Hf = 7.5 and Nb/Ta = 1.5 in its porphyritic phase. The Na/K ratio is not consistent with these element ratios: the lowest values of Na/K occur in the Rau 4 and 6 pegmatite dikes (Na/K = 0.03), whereas the highest occurs in Rau 9 (Na/K = 2.86).

Volatile elements such as F and B are elevated in many of the analysed units. Of the pegmatite dikes, the Rau 5 pegmatite dike has the highest contents of F (3698 ppm) and also contains elevated B (43 ppm). The Rau 9 pegmatite dike has the highest B contents with 96 ppm. An aplite dike contains the highest F and B of all analysed units, with 4670 ppm F and 371 ppm B. In comparison, the Rackla pluton contains 252 ppm F and 8 ppm B, which are some of the lowest contents of all analysed units.

Sample	R3-2c	R4-2d	R5-E	R6-1a	R7-A	R8-1a	R9b-2	R10-1c	Apl-3b	Hrn-1	Gra-2c
Unit	Rau 3	Rau 4	Rau 5	Rau 6	Rau 7	Rau 8	Rau 9	Rau 10	Aplite	Porphyritic phase	Rackla pluton
P ₂ O ₅ (wt.%)	<0.01	<0.01	0.00	<0.01	<0.01	<0.01	0.00	0.01	<0.01	<0.01	<0.01
SiO ₂	62.85	65.51	71.45	63.76	63.38	72.67	58.70	77.66	57.10	69.78	75.92
TiO ₂	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Al ₂ O ₃	17.94	17.64	14.90	18.09	17.77	14.65	20.84	12.48	22.34	15.34	13.79
Cr ₂ O ₃	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Fe ₂ O ₃	1.90	0.75	0.52	0.73	0.93	1.67	1.71	0.65	1.30	1.91	0.73
MgO	0.24	0.18	0.08	0.07	0.45	0.69	1.20	0.06	0.72	0.45	0.08
CaO	0.14	0.09	1.45	0.56	1.01	0.74	3.03	0.46	4.16	1.32	0.49
MnO	0.03	<0.01	0.02	0.01	0.04	0.02	0.04	0.07	0.06	0.03	0.44
BaO	0.08	0.10	0.03	0.15	0.08	0.02	0.01	0.01	0.03	0.13	0.00
Na ₂ O	0.82	0.45	2.58	0.46	1.19	3.26	7.64	3.98	0.06	4.06	5.63
K ₂ O	14.43	14.70	7.66	14.84	13.35	4.29	2.67	4.15	7.32	4.24	2.44
F*	0.02	0.01	0.37	0.02	0.06	0.30	0.13	0.02	0.47	0.08	0.02
LOI	1.40	0.40	1.20	1.10	1.15	1.90	4.00	0.40	6.70	2.60	0.40
Total	99.83	99.83	99.86	99.83	99.73	99.87	99.82	99.89	99.85	99.87	99.91

Table 2.2. Whole rock geochemical analysis for major and minor elements in the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton.

*F was determined by specific ion electrode.

Sample	R3-2c	R4-2D	R5-E	R6-1a	R7-A	R8-1A	R9b-2	R10-1c	Apl-3b	Hrn-1	Gra-2c
Unit	Rau 3	Rau 4	Rau 5	Rau 6	Rau 7	Rau 8	Rau 9	Rau 10	Aplite	Porphyritic phase	Rackla pluton
Li* (ppm)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ве	3	3	15.0	<1	3	11	81.0	10.0	3	18	5
B [†]	9	11	43.0	22	15	56	96.0	23.0	371	68	8
Sc	<1	<1	5.0	1	2	20	<1	5.0	1	3	4
V	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8
Со	1.6	0.5	0.3	0.6	0.5	0.9	0.5	0.3	1.2	4.4	<0.2
Ni	9.1	2	0.2	0.8	2.6	0.9	0.5	0.3	1.6	3.4	0.6
Cu	10.5	2.6	1.1	3	2.2	2.8	2.0	1.3	5.4	16.3	2
Zn	7	4	9.0	24	12	7	22.0	13.0	3	38	12
Ga	32.4	36.9	39.6	34.6	39.4	53.5	51.7	32.7	62.1	42.3	33.6
As	1.1	0.6	<0.5	0.8	0.6	<0.5	0.9	<0.5	<0.5	3.5	1
Se	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Rb	>1000.0	>1000.0	971.4	>1000.0	>1000.0	755.2	592.7	661.1	657.6	354.4	358.1
Sr	97.1	92.4	51.2	113.4	77.3	23.6	62.6	13.6	25.3	38	5.2
Y	0.9	0.8	8.0	1.3	6.1	22.3	8.2	30.9	18.1	77.7	86.6
Zr	26.6	30.9	39.6	28.1	55.9	59.5	46.8	81.0	49.2	87.2	149.8
Nb	8.6	40.5	58.5	58.9	51	61	102.4	144.9	54.9	96.2	104.5
Мо	3	1.5	<0.1	2.3	22.2	2.1	0.1	0.3	1.1	2.4	0.8
Ag	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cd	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sn	2	4	10.0	4	10	27	22.0	2.0	321	37	3
Sb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Cs	11.3	8.2	7.0	7.1	11.5	7.6	10.9	4.0	8.2	3.4	3
La	4.9	0.5	4.4	0.9	2.8	6.7	1.6	10.4	2.7	37.1	3.6
Ce	15.1	0.9	13.2	1.8	8	18.2	5.0	26.0	6.6	95.4	7.6

Table 2.3. Whole rock geochemical analysis for trace elements in the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton.

Sample	R3-2c	R4-2D	R5-E	R6-1a	R7-A	R8-1A	R9b-2	R10-1c	Apl-3b	Hrn-1	Gra-2c
Unit	Rau 3	Rau 4	Rau 5	Rau 6	Rau 7	Rau 8	Rau 9	Rau 10	Aplite	Porphyritic phase	Rackla pluton
Pr (ppm)	1.88	0.07	1.77	0.22	1.06	2.59	0.74	3.52	1.09	13.59	0.76
Nd	5.7	0.4	5.7	0.7	2.7	8.6	2.3	11.7	4.7	48.5	2.5
Sm	1.08	0.06	1.40	0.19	0.78	2.36	0.72	2.92	1.67	12.13	0.64
Eu	0.05	<0.02	0.03	0.06	0.04	0.05	0.08	0.03	0.17	0.34	<0.02
Gd	0.37	<0.05	0.70	0.11	0.49	1.42	0.51	2.29	1.48	7.59	1.54
Tb	<0.01	<0.01	0.10	<0.01	0.07	0.22	0.10	0.39	0.23	0.98	0.49
Dy	0.09	0.08	0.51	0.1	0.43	1.36	0.46	2.06	1.38	4.85	4.85
Но	<0.02	<0.02	0.07	<0.02	0.05	0.18	0.09	0.39	0.26	0.74	1.39
Er	<0.03	<0.03	0.31	0.04	0.28	0.84	0.30	1.65	1.07	2.34	6.68
Tm	<0.01	<0.01	0.06	<0.01	0.03	0.17	0.07	0.36	0.2	0.47	1.66
Yb	0.15	0.1	0.75	0.16	0.62	2.2	0.74	3.81	2.22	4.71	17.99
Lu	<0.01	<0.01	0.14	<0.01	0.09	0.38	0.11	0.73	0.4	0.78	3.48
Hf	5.9	7.8	6.8	6.5	13.5	7.9	15.2	10.0	5.8	11.7	15.9
Та	23.8	168.7	121.5	190.2	432.9	53.3	507.9	68.0	22.9	62.8	27.2
W	8.1	2.7	2.8	2.4	2.5	7	3.1	3.2	13.4	4.9	1.5
Au	1.8	<0.5	<0.5	<0.5	1.8	<0.5	<0.5	0.9	<0.5	0.9	<0.5
Hg	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
ТΙ	0.4	0.2	0.2	0.3	0.3	0.6	0.6	0.1	0.2	0.1	<0.1
Pb	4.4	3.4	5.0	5.4	10.1	2	0.9	8.9	1	2.3	5.4
Bi	<0.1	<0.1	1.3	<0.1	<0.1	<0.1	<0.1	3.4	<0.1	0.4	4.8
Th	9.5	4.8	13.2	3.9	5	14.8	6.4	25.7	19.9	31.8	18
U	1.3	5.8	6.0	5.2	7.7	7.9	20.2	9.8	4.7	10	7.6

*Li was determined using four-acid digestion with ICP-ES analysis; [†]B was determined by Na₂O₂ fusion and ICP-MS analysis.



Figure 2.5. Classification of the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton using the three-tiered classification scheme for granitic rocks of Frost *et al.* (2001). (a) Classification using the *Fe*-number showing the boundary between ferroan and magnesian granitic rocks. (b) Classification using the modified alkali-lime index showing the approximate ranges of the alkalic, alkali-calcic, calc-alkalic, and calcic granitic rock series, as well as ideal compositions of K-feldspar and albite.


Figure 2.6. Classification of the bulk whole rock geochemistry of the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton using Shand's index (Maniar & Piccoli, 1989).





Figure 2.7. Plot showing the A-type signature of the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton (Whalen *et al.*, 1987).



Figure 2.8. Chondrite-normalized concentrations of REEs including Y in the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton. Some of these data sets are incomplete because the concentration of some elements was below detection limit.

2.5.2 Mineral chemistry

2.5.2.1 Rackla pluton

The Rackla pluton is composed of quartz, K-feldspar, plagioclase, mica group minerals, and garnet group minerals, with trace columbite group minerals and zircon. K-feldspar has a narrow range of compositions from Or₉₇Ab₃An₀ to Or₈₉Ab₁₁An₀. Plagioclase is nearly pure albite with compositions ranging from Ab₉₂An₇Or₁ to Ab₉₆An₃Or₁. Perthitic exsolution in K-feldspar (Or₉₂Ab₈An₀; n = 2) has an average composition of Ab₉₈An₁Or₁ (n = 2) (Table 2.4). The majority of mica group minerals are Al-rich annite with average Mg / (Mg + Fe) = 0.00 (n = 8); however, minor muscovite occurs in a finer-grained portion of the pluton (Fig. 2.9). Both annite and muscovite have elevated Ti contents with an average of 0.43 wt.% TiO₂ [0.025 atoms per formula unit (*apfu*); n = 8] in annite and 0.35 wt.% TiO₂ (0.018 *apfu*; n = 2) in muscovite. Fluorine and Rb contents are elevated in annite with up to 2.54 wt.% F (0.656 *apfu*) and 0.79 wt.% Rb₂O (0.041 *apfu*). Cesium contents were below the detection limit of the EMP in most samples but three points in annite yielded Cs contents of 0.09–0.16 wt.% Cs₂O (0.003–0.006

apfu) (Table 2.5). Using the biotite discriminant diagram of Abdel-Rahman (1994), the annite compositions plot in the peraluminous field. Garnet group and columbite group minerals were not analysed using the EMP but garnet group minerals appear to be part of the spessartine-almandine series, and columbite group minerals are mostly columbite-(Fe) but range from columbite-(Fe) to columbite-(Mn).



Figure 2.9. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the composition of mica group minerals in the Rackla pluton.

Sample	Gra-1a	Gra-2c	Gra-1a	Gra-2c	Gra-2c	Gra-1a
Linit	Rackla	Rackla	Rackla	Rackla	Rackla	Rackla
Onit	pluton	pluton	pluton	pluton	pluton	pluton
Notes	-	-	Perthitic	_	-	Exsolution
Mineral	*Kfs	Kfs	Kfs	Ab	Ab	Ab
SiO ₂ (wt.%)	65.72	63.67	64.89	68.24	66.80	68.86
Al ₂ O ₃	18.40	18.39	18.12	19.93	20.78	19.61
$Fe_2O_{3(\text{min}}^\dagger$	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	0.00	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	0.72	1.44	0.06
Na ₂ O	1.26	0.38	0.75	10.93	10.52	11.46
K ₂ O	15.45	16.46	16.11	0.17	0.26	0.11
Total	100.83	98.90	99.87	100.05	99.79	100.11
Si ⁴⁺ (apfu)	3.004	2.984	3.004	2.979	2.932	3.000
Al ³⁺	0.991	1.015	0.989	1.026	1.075	1.007
$Fe^{3+}(min)^{\dagger}$	b.d.	0.000	0.000	0.002	b.d.	b.d.
$Fe^{2+}(max)^{\dagger}$	b.d.	0.000	0.000	0.000	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	0.034	0.068	0.003
Na⁺	0.112	0.035	0.067	0.925	0.895	0.968
K+	0.901	0.984	0.951	0.009	0.014	0.006
O ^{2_}	8.000	8.000	8.000	8.000	8.000	8.000

Table 2.4. Representative chemical analyses and structural formulae of feldspar group minerals from the Rackla pluton.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Magnesium, Mn, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	Gra-1a	Gra-1a	Gra-1a	Gra-1a
Unit	Rackla pluton	Rackla pluton	Rackla pluton	Rackla pluton
Mineral	*A	nn	М	s
SiO ₂ (wt.%)	34.71	34.85	45.10	45.52
TiO ₂	0.36	0.53	0.27	0.43
Al ₂ O ₃	19.20	19.25	31.25	30.38
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00
FeO _(max) [†]	29.66	29.58	4.50	5.80
MgO	0.05	0.06	0.08	b.d.
MnO	1.56	1.34	b.d.	b.d.
Na ₂ O	0.10	b.d.	0.14	0.14
K ₂ O	9.44	9.43	11.27	11.13
Rb ₂ O	0.78	0.72	0.06	0.32
Cs ₂ O	0.16	0.09	b.d.	b.d.
F	2.52	2.21	0.49	0.54
CI	0.16	0.21	0.03	b.d.
H_2O^{\ddagger}	2.49	2.63	4.04	4.04
–(O=F,CI)	-1.06	-0.93	-0.21	-0.23
Total	100.13	99.96	97.03	98.07
Si ⁴⁺ (<i>apfu</i>)	2.797	2.803	3.158	3.178
Ti ⁴⁺	0.022	0.032	0.014	0.022
Al ³⁺	1.823	1.825	2.579	2.499
Fe^{3+} (min) †	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.999	1.989	0.264	0.338
Mg ²⁺	0.006	0.008	0.008	0.000
Mn ²⁺	0.106	0.091	0.000	0.000
Na ⁺	0.015	0.000	0.019	0.019
K+	0.970	0.967	1.007	0.991
Rb⁺	0.041	0.037	0.003	0.014
Cs+	0.006	0.003	0.000	0.000
F⁻	0.641	0.561	0.109	0.118
CI⁻	0.021	0.029	0.003	0.000
OH-‡	1.337	1.409	1.888	1.882
vacancy	0.246	0.252	0.976	0.962
O ^{2_}	10.000	10.000	10.000	10.000

Table 2.5. Representative chemical analyses and structural formulae of mica group minerals from the Rackla pluton.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit. Chromium, Ca, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.

2.5.2.2 Porphyritic phase of the Rackla pluton

The uppermost porphyritic part of the Rackla pluton is composed of extremely fine-grained K-feldspar and albite, with abundant but localized concentrations of fine-grained mica and calcite, and quartz phenocrysts (Table 2.6). It contains the most abundant and diverse assemblage of rare element-bearing minerals of all the studied units.

Mica group minerals are minor minerals that form the fine-grained matrix surrounding phenocrysts of quartz. All mica group minerals are muscovite and contain small amounts of Fe²⁺ (up to 2.60 wt.% FeO; 0.150 *apfu*). Muscovite contains trace amounts of F, up to 0.73 wt.% F (0.159 *apfu*) and Na (up to 0.14 wt.% Na₂O; 0.019 *apfu*). It also contains trace amounts of Sc (up to 0.07 wt.% Sc₂O₃) (Table 2.7).

Parisite-(Ce) and synchysite-(Ce) are secondary minerals that replace fine-grained muscovite (Figs. 2.10 and 2.11). Although still Ce-dominant [Ce / (Ce + La + Nd) = 0.55-0.57; n = 3], synchysite-(Ce) has a greater contents of heavy REEs than parisite-(Ce) with an average of 2.82 wt.% Y₂O₃ (0.078 *apfu*), 2.96 wt.% Sm₂O₃ (0.053 *apfu*), 1.19 wt.% Gd₂O₃ (0.020 *apfu*), and 0.44 wt.% Tm₂O₃ (0.007 *apfu*). Parisite-(Ce) contains 0.65 wt.% Y₂O₃ (0.032 *apfu*), 1.88 wt.% Sm₂O₃ (0.059 *apfu*), 0.57 wt.% Gd₂O₃ (0.017 *apfu*), and 0.24 wt.% Tm₂O₃ (0.007 *apfu*; n = 1) (Table 2.8).

Bastnäsite-(Ce) and fluocerite-(Ce) are secondary minerals that occur in the central portion of aggregates of parisite-(Ce) and synchysite-(Ce) that replace fine-grained muscovite (Fig. 2.12). Bastnäsite-(Ce) is Ce-dominant but contains substantial amounts of La and Nd [Ce / (Ce + La + Nd) = 0.55-0.59]. Its HREE contents is low with up to 3.99 wt.% Pr₂O₃ (0.053 apfu), 1.30 wt.% Sm₂O₃ (0.016 apfu), 0.58 wt.% Y₂O₃ (0.011 apfu), 0.49 wt.% Gd₂O₃ (0.006 apfu), and all other HREEs below the detection limit of the EMP (Table 2.8). Fluocerite-(Ce) is Ce-dominant [Ce / (Ce + La + Nd) = 0.54-0.58; n = 3] and also contains minor amounts of Ca (up to 0.50 wt.% CaO; 0.016 apfu) (Table 2.8).

Unlike in other units associated with the Rau pegmatite group, columbite group minerals, rather than pyrochlore supergroup minerals, are the dominant type of Nb,Ta-bearing oxide minerals. They can be associated with parisite-(Ce) and synchysite-(Ce) (Fig. 2.10) but can also occur as isolated subhedral grains within the K-feldspar and albite matrix (Fig. 2.13). All analysed specimens are columbite-(Fe) [Mn / (Mn + Fe_{tot}) = 0.05–0.33 and Ta / (Ta + Nb) = 0.14-0.21; n = 5]. The most Fe-rich grain of columbite-(Fe) [Mn / (Mn + Fe_{tot}) = 0.05; n = 2]

contains elevated W, with an average of 8.01 wt.% WO₃ (0.126 *apfu*). The Sc contents of columbite-(Fe) can also be elevated and attains 0.63 wt.% Sc₂O₃ (0.033 *apfu*) in the rim of a grain, versus 0.05 wt.% Sc₂O₃ (0.002 *apfu*) in the core (Table 2.9).

Extremely small grains (< 10 µm) of monazite-(Ce) occur within the K-feldspar and albite matrix. All analysed specimens are Ce-dominant [Ce / (Ce + La + Nd) = 0.55–0.57]. Although all specimens are monazite-(Ce), there is significant substitution of huttonite/thorite [(Th,U) + Si \leftrightarrow REE + P] and cheralite [Ca + U(Th) \leftrightarrow 2REE] components (Fig. 2.14). Those specimens whose compositions deviate from ideal monazite also have a higher contents of Fe³⁺. The grain with the highest huttonite/thorite component contains 1.20 wt.% Fe₂O₃ (0.038 *apfu*) (Table 2.10).

Samarskite group minerals occur as isolated anhedral grains up to ~80 µm in size within the K-feldspar and albite matrix. One grain is associated with secondary parisite-(Ce) and synchysite-(Ce) (Fig. 2.11). All specimens are samarskite-(Y) and contain a substantial amount of Ta [Nb / (Nb + Ta) = 0.70–0.80; n = 6]. The rims of some grains are altered and have elevated Nb contents [Nb / (Nb + Ta) = 0.87; n = 2] and high Th contents (up to 5.61 wt.% ThO₂; 0.117 *apfu*). All specimens contain minor amounts of W and F. In unaltered specimens, these elements have maximum contents of 1.93 wt.% WO₃ (0.047 *apfu*) and 0.34 wt.% F (0.103 *apfu*) (Table 2.10).

Only one grain of scheelite was observed in the porphyritic phase and it occurs near the outer edge of parisite-(Ce) + synchysite-(Ce) replacement of muscovite (Fig. 2.11). It has a nearly pure end-member composition, with only 0.21 wt.% Nb₂O₅ and 0.10 wt.% FeO (Table 2.9).

Mineral	Abundance in
	porphyritic phase
Kfs*	Х
Qz	Х
Ab	Х
Ms	Μ
Cal	Μ
Bst-(Ce)	Т
Brt	Т
Col-(Fe)	Т
Flc	Т
Mnz-(Ce)	Т
Prs-(Ce)	Т
Pcl	Т
Smr-(Y)	Т
Sch	Т
Snc-(Ce)	Т
Zrc	Т
Fe sul	Т
X = major mineral; M = mineral	or mineral; T = trace

Table 2.6. Presence and abundance of minerals in the porphyritic phase of the Rackla pluton.

Evans (2010); Bst = bastnäsite; Col = columbite; Flc = fluocerite; Prs = parisite; Smr = samarskite; Snc = synchysite; Fe sul = Fe sulphide minerals.

*Abbreviations of mineral names follow Whitney &

mineral; - = not observed.

Table 2.7. Chemical analyses and structural formulae of muscovite from the porphyritic phase of the Rackla pluton.

Sample	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic
Mineral	*Ms	Ms
SiO ₂ (wt.%)	46.53	45.96
TiO ₂	b.d.	0.06
Al ₂ O ₃	33.23	33.21
Sc ₂ O ₃	0.07	0.07
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.54	2.60
MnO	0.04	0.03
Na ₂ O	0.14	0.11
K ₂ O	11.00	10.91
F	0.73	0.65
H_2O^{\ddagger}	4.05	4.05
-(O=F,Cl)	-0.31	-0.27
Total	98.02	97.38
Si ⁴⁺ (<i>apfu</i>)	3.175	3.159
Ti ⁴⁺	b.d.	0.003
Al ³⁺	2.672	2.690
Sc ³⁺	0.000	0.000
$Fe^{3+}(min)^{\dagger}$	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.145	0.150
Mn ²⁺	0.003	0.003
Na ⁺	0.019	0.014
K+	0.957	0.957
F⁻	0.158	0.142
OH-‡	1.842	1.858
vacancy	1.001	0.994
O ²⁻	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + OH) = 2 per formula unit. Phosphorus, Cr, Mg, Zn, Ca, Ba, Cs, Rb, and Cl were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.10. Back-scattered electron (BSE) image of parisite-(Ce) (Prs) and synchysite-(Ce) (Snc) replacing fine-grained muscovite (Ms) in the porphyritic phase of the Rackla pluton. Columbite-(Fe) (Col) is also present within the muscovite.



Figure 2.11. BSE image of anhedral grains of samarskite-(Y) (Smr) and scheelite (Sch) that occur at the outer edge of parisite-(Ce) + synchysite-(Ce) (Prs + Snc) replacement of muscovite (Ms) in the porphyritic phase of the Rackla pluton.

Sample	Hrn-1						
Unit	Porphyritic						
Mineral	*Prs-(Ce)	Snc-(Ce)	Snc-(Ce)	Bst-(Ce)	Bst-(Ce)	Flc	Flc
SiO ₂ (wt.%)	0.43	1.43	0.28	b.d.	b.d.	b.d.	b.d.
ThO ₂	0.55	0.23	0.00	0.16	0.23	0.11	0.69
Al ₂ O ₃	0.09	0.57	b.d.	b.d.	b.d.	b.d.	b.d.
Y ₂ O ₃	0.65	3.38	2.59	0.58	0.50	0.69	0.54
La ₂ O ₃	8.90	6.67	7.22	16.98	17.03	29.44	22.39
Ce_2O_3	29.37	22.87	22.51	39.41	39.59	46.62	49.64
Pr ₂ O ₃	3.51	3.31	3.22	3.99	3.68	3.80	4.56
Nd_2O_3	10.70	11.35	11.30	11.22	10.93	10.95	13.59
Sm ₂ O ₃	1.88	2.94	3.19	1.30	1.19	1.02	1.57
Gd_2O_3	0.57	1.31	1.39	0.49	0.48	0.39	0.47
Dy_2O_3	b.d.	b.d.	0.36	b.d.	b.d.	b.d.	b.d.
Tm ₂ O ₃	0.24	0.40	0.52	b.d.	b.d.	b.d.	b.d.
CaO	11.05	15.77	17.05	0.37	0.55	0.22	0.50
K ₂ O	b.d.	0.26	b.d.	b.d.	b.d.	b.d.	b.d.
F	4.64	4.49	4.49	7.39	7.13	34.42	34.32
CO_2^\dagger	24.09	28.46	27.74	19.83	19.67	_	_
H_2O^{\ddagger}	1.09	3.69	3.55	0.55	0.64	_	_
-(O=F)	-1.95	-1.89	-1.89	-3.11	-3.00	-14.50	-14.45
Total	95.81	105.27	103.51	99.16	98.62	113.16	113.83
Si ⁴⁺ (<i>apfu</i>)	0.039	0.074	0.015	b.d.	b.d.	b.d.	b.d.
Th ⁴⁺	0.011	0.003	0.000	0.001	0.002	0.001	0.004
Al ³⁺	0.010	0.035	b.d.	b.d.	b.d.	b.d.	b.d.
Y ³⁺	0.032	0.093	0.073	0.011	0.010	0.010	0.008
La ³⁺	0.299	0.127	0.141	0.228	0.228	0.299	0.228

Table 2.8. Representative chemical analyses and structural formulae of parisite-(Ce), synchysite-(Ce), bastnäsite-(Ce), and fluocerite-(Ce) from the porphyritic phase of the Rackla pluton.

Sample	Hrn-1						
Unit	Porphyritic						
Mineral	*Prs-(Ce)	Snc-(Ce)	Snc-(Ce)	Bst-(Ce)	Bst-(Ce)	Flc	Flc
Ce ³⁺ (<i>apfu</i>)	0.981	0.431	0.435	0.525	0.527	0.470	0.502
Pr³⁺	0.117	0.062	0.062	0.053	0.049	0.038	0.046
Nd ³⁺	0.348	0.209	0.213	0.146	0.142	0.108	0.134
Sm ³⁺	0.059	0.052	0.058	0.016	0.015	0.009	0.015
Gd ³⁺	0.017	0.022	0.024	0.006	0.006	0.003	0.004
Dy ³⁺	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.
Tm ³⁺	0.007	0.006	0.009	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	1.079	0.870	0.965	0.014	0.021	0.006	0.015
K+	b.d.	0.017	b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	1.339	0.731	0.749	0.850	0.820	3.000	3.000
C ^{4+†}	3.000	2.000	2.000	1.000	1.000	_	_
OH ^{-‡}	0.661	1.269	1.251	0.150	0.180	_	_
O ²⁻	9.316	6.220	6.150	3.143	3.170	-	-

The formulae for parisite-(Ce) were calculated on the basis of 3 *A* and *B* site cations, synchysite-(Ce) on the basis of 2 *A* and *B* site cations, bastnäsite-(Ce) on the basis of 1 *A* and *B* site cations, and fluocerite-(Ce) on the basis of 3 anions per formula unit.

Phosphorus, Ti, Zr, Fe, U, Eu, Er, Mg, Pb, Ba, Sr, and Na in parisite-(Ce), synchysite-(Ce), bastnäsite-(Ce), and fluocerite-(Ce), Mn in bastnäsite-(Ce) and fluocerite-(Ce), and Sc in fluocerite-(Ce) were sought but were below the detection limit of the EMP in all analyses.

*Prs = parisite; Snc = synchysite; Bst = bastnäsite; Flc = fluocerite; $^{+}CO_2$ was fixed at 3 *apfu* C in parisite-(Ce), 2 *apfu* C in synchysite-(Ce), and 1 *apfu* C in bastnäsite-(Ce); $^{+}H_2O$ contents based on stoichiometry; b.d. = below detection limit.



Figure 2.12. BSE image of (a) parisite-(Ce) (Prs) and synchysite-(Ce) (Snc) replacing fine-grained muscovite in the porphyritic phase of the Rackla pluton. (b) Bastnäsite-(Ce) (Bst) and fluocerite-(Ce) (Flc) occur near the centre of this replacement.



Figure 2.13. BSE image of isolated grains of columbite-(Fe) (Col) in the K-feldspar (Kfs), albite (Ab), and quartz (Qz) matrix. Secondary baryte (Brt) is abundant in this part of the porphyritic phase of the Rackla pluton. The aggregate of bright minerals in the bottom left corner of this image are shown in detail in Figs. 2.11a and 2.11b.

Sample	Hrn-1	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic	Porphyritic
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Sch
WO ₃ (wt.%)	8.17	0.06	2.43	78.04
Nb ₂ O ₅	55.90	55.34	58.30	0.21
Ta ₂ O ₅	15.45	24.46	19.34	b.d.
SiO ₂	0.10	0.04	0.06	b.d.
TiO ₂	0.22	0.73	0.04	b.d.
ZrO ₂	b.d.	0.08	b.d.	-
SnO ₂	0.01	0.08	b.d.	-
ThO ₂	0.01	b.d.	0.02	-
UO ₂	0.06	b.d.	b.d.	-
Al ₂ O ₃	0.01	0.00	0.01	b.d.
$Fe_2O_{3(min)}^{\dagger}$	2.47	2.39	2.42	0.00
FeO _(max) †	17.75	10.97	16.89	0.10
Sc ₂ O ₃	0.05	0.63	0.05	b.d.
Y_2O_3	0.00	0.03	b.d.	-
Bi ₂ O ₃	0.24	b.d.	0.14	-
MgO	0.02	0.16	0.01	b.d.
CaO	b.d.	b.d.	0.07	19.36
MnO	1.13	6.20	1.44	b.d.
PbO	0.06	b.d.	b.d.	b.d.
Na ₂ O	0.01	b.d.	0.02	b.d.
Total	101.65	101.19	101.24	97.71
W ⁶⁺ (<i>apfu</i>)	0.128	0.001	0.038	0.971
P ⁵⁺	_	-	-	-
Nb ⁵⁺	1.525	1.520	1.590	0.004
Ta ⁵⁺	0.254	0.404	0.317	b.d.
Si ⁴⁺	0.006	0.003	0.004	b.d.
Ti ⁴⁺	0.010	0.033	0.002	b.d.
Zr ⁴⁺	b.d.	0.002	b.d.	-
Sn ⁴⁺	0.000	0.002	b.d.	-
Th ⁴⁺	0.000	b.d.	0.000	-
U ⁴⁺	0.001	b.d.	b.d.	-
Al ³⁺	0.001	0.000	0.001	b.d.
Fe ³⁺ (min) [†]	0.112	0.109	0.110	0.000
Fe ²⁺ (max) [†]	0.896	0.557	0.853	0.004
Sc ³⁺	0.003	0.033	0.002	b.d.
Y ³⁺	0.000	0.001	b.d.	_

Table 2.9. Representative chemical analyses and structural formulae of columbite-(Fe) and scheelite from the porphyritic phase of the Rackla pluton.

Sample	Hrn-1	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic	Porphyritic
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Sch
Bi ³⁺	0.004	b.d.	0.002	-
Mg ²⁺	0.002	0.015	0.001	b.d.
Ca ²⁺	b.d.	b.d.	0.005	0.996
Mn ²⁺	0.058	0.319	0.074	b.d.
Pb ²⁺	0.001	b.d.	b.d.	b.d.
Na ⁺	0.001	b.d.	0.002	b.d.
O ²⁻	6.000	6.000	6.000	3.923

The formulae for columbite-(Fe) were calculated on the basis of 6 O atoms and scheelite on the basis of 4 Ca atoms per formula unit. Zinc, Sb, and F in columbite-(Fe), and Zn, Mo, and F in scheelite were

sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit; - = not analysed.

Sample	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic
Mineral	*Smr-(Y)	Smr-(Y)	Smr-(Y)	Mnz-(Ce)	Mnz-(Ce)	Mnz-(Ce)
WO ₃ (wt.%)	_	_	_	1.93	0.59	2.03
P ₂ O ₅	19.11	21.80	30.50	0.06	0.06	0.05
Nb ₂ O ₅	-	-	_	30.91	35.83	41.37
Ta ₂ O ₅	-	-	_	21.79	16.52	9.89
SiO ₂	4.86	6.26	0.52	0.25	0.34	0.17
TiO ₂	b.d.	b.d.	0.00	0.22	0.05	0.04
ZrO ₂	0.34	0.27	0.45	b.d.	b.d.	b.d.
ThO ₂	25.67	15.50	1.82	0.26	3.44	5.61
UO ₂	0.30	0.25	b.d.	0.10	1.29	0.87
$Fe_2O_{3(min)}^{\dagger}$	0.30	1.20	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.00	0.00	0.00	b.d.	b.d.	b.d.
Sc ₂ O ₃	b.d.	b.d.	0.00	b.d.	b.d.	b.d.
As ₂ O ₃	b.d.	0.05	0.08	0.00	0.03	0.01
Y_2O_3	0.86	0.44	0.38	31.22	28.07	27.16
La ₂ O ₃	6.29	6.70	11.95	b.d.	b.d.	b.d.
Ce ₂ O ₃	19.42	24.15	33.65	0.57	0.64	0.45
Pr ₂ O ₃	2.98	3.65	4.72	0.31	b.d.	0.34
Nd ₂ O ₃	9.59	11.86	15.13	1.99	2.23	1.79
Sm ₂ O ₃	1.69	2.05	2.22	2.44	2.28	1.74
Gd ₂ O ₃	0.67	0.57	0.37	3.01	2.36	1.96
Tb ₂ O ₃	-	-	-	0.39	0.28	0.24
Dy ₂ O ₃	0.17	b.d.	b.d.	1.96	0.92	1.32
H02O3	-	-	-	0.25	b.d.	b.d.
Er_2O_3	0.12	b.d.	b.d.	0.72	0.30	0.86
Tm ₂ O ₃	-	-	-	0.71	0.47	0.50
Lu_2O_3	-	-	-	0.30	0.23	0.42
Yb ₂ O ₃	-	-	-	0.95	0.34	1.81
CaO	3.31	0.43	0.22	0.12	1.14	1.54
PbO	0.07	0.07	0.00	b.d.	b.d.	b.d.
Na ₂ O	b.d.	b.d.	0.00	b.d.	b.d.	b.d.
F	-	-	-	0.29	0.34	0.25
-(O=F)	_	_	_	-0.12	-0.14	-0.11
Total	95.73	95.24	102.01	100.60	97.58	100.33
W ⁶⁺ (apfu)	_	-	_	0.047	0.015	0.048
P ⁵⁺	0.701	0.771	0.990	0.005	0.004	0.004
Nb ⁵⁺	_	-	_	1.328	1.543	1.709

Table 2.10. Representative chemical analyses and structural formulae of samarskite-(Y) and monazite-(Ce) from the porphyritic phase of the Rackla pluton.

Sample	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic
Mineral	*Smr-(Y)	Smr-(Y)	Smr-(Y)	Mnz-(Ce)	Mnz-(Ce)	Mnz-(Ce)
Ta⁵+ (<i>apfu</i>)	-	-	_	0.563	0.428	0.246
Si ⁴⁺	0.210	0.262	0.020	_	-	-
Ti ⁴⁺	b.d.	b.d.	0.000	0.015	0.004	0.003
Zr ⁴⁺	0.007	0.006	0.008	0.000	0.000	0.000
Th ⁴⁺	0.253	0.147	0.016	0.006	0.074	0.117
U ⁴⁺	0.003	0.002	b.d.	0.002	0.027	0.018
$Fe^{3+}(min)^{\dagger}$	0.01	0.04	0.00	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.00	0.00	0.00	b.d.	b.d.	b.d.
Sc ³⁺	b.d.	b.d.	0.00	-	-	-
As ³⁺	b.d.	0.00	0.00	0.000	0.002	0.00
Y ³⁺	-	-	-	1.578	1.423	1.321
La ³⁺	0.100	0.103	0.169	b.d.	b.d.	b.d.
Ce ³⁺	0.308	0.370	0.472	0.020	0.022	0.015
Pr ³⁺	0.047	0.056	0.066	0.011	0.00	0.011
Nd ³⁺	0.148	0.177	0.207	0.068	0.076	0.059
Sm ³⁺	0.025	0.030	0.029	0.080	0.075	0.055
Gd ³⁺	0.010	0.008	0.005	0.095	0.074	0.059
Tb ³⁺	-	-	_	0.012	0.009	0.007
Dy ³⁺	0.00	b.d.	b.d.	0.06	0.03	0.039
Ho ³⁺	-	-	-	0.01	0.00	0.00
Er ³⁺	0.00	b.d.	b.d.	0.02	0.01	0.025
Tm ³⁺	-	-	_	0.02	0.01	0.014
Lu ³⁺	-	-	-	0.01	0.01	0.012
Yb ³⁺	-	-	_	0.03	0.01	0.050
Ca ²⁺	0.154	0.019	0.009	0.012	0.117	0.151
Pb ²⁺	0.001	0.001	0.000	b.d.	b.d.	b.d.
Na ⁺	b.d.	b.d.	0.000	b.d.	b.d.	b.d.
F⁻	-	-	_	0.088	0.103	0.073
O ²⁻	3.846	3.960	3.992	7.956	7.948	7.963

The formulae for samarskite-(Y) was calculated on the basis of 8 O atoms and monazite-(Ce) on the basis of 2 cations per formula unit.

Europium and K in samarskite-(Y), and Al, Sr, Bi, Mg, Mn, and S in monazite-(Ce) were sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Smr = samarskite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit; - = not analysed.



Figure 2.14. The composition of monazite-(Ce) in the porphyritic phase of the Rackla pluton shown using a REE + Y + P versus Th + U + Si substitution diagram. The straight lines are ideal cheralite and thorite/huttonite substitution vectors (Ondrejka *et al.*, 2012).

2.5.2.3 Pegmatite dikes

All of the pegmatite dikes are composed of K-feldspar, quartz, and albite, but the proportion of these minerals varies between dikes. In the Rau 1, 3, 4, 5, 5U, 8, and 10 pegmatite dikes K-feldspar, quartz, and albite are all major minerals, whereas in the Rau 6 and 7 pegmatite dikes albite only occurs in trace amounts, with the dikes being mostly composed of K-feldspar. In contrast, parts of the Rau 9 pegmatite dike are composed of almost entirely albite. Mica group minerals are major components of some of the pegmatite dikes (Rau 8 and 9), but in most of the dikes they are a minor mineral. Other minor minerals that are present in some of the pegmatite dikes are calcite and fluorite. Specifically, calcite is a minor mineral in Rau 5, 5U, and 9, whereas fluorite is a minor mineral in Rau 3, 5, and 5U. Many of the other pegmatite dikes contain calcite and/or fluorite as a trace mineral (Table 2.11).

Both K-feldspar and albite occur in the pegmatite dikes. K-feldspar is near end-member composition in all pegmatite dikes, ranging from $K_{88}Na_{12}Ca_0$ to $K_{99}Na_1Ca_0$ (n = 287). Albite was only analysed from Rau 1, 3, 4, 9, and 10, but it is also nearly pure end-member composition,

ranging from Na₉₃Ca₆K₁ in Rau 10 to an average of Na₉₉Ca₀K₁ in the other pegmatite dikes. One analysis from the Rau 3 pegmatite dike was anomalous and yielded Na₇₂Ca₁K₂₇. Extensive analyses were made of K-feldspar from all pegmatite dikes because its contents of Rb and Cs can be used as markers of pegmatite fractionation. Rubidium contents were generally below the detection limit of the EMP, but it was detected in several analyses of K-feldspar in the Rau 3 pegmatite dike (up to 0.93 wt.% Rb₂O; n = 17 of 97 total analyses). It was also detected in some K-feldspar samples in the Rau 1 (up to 0.77 wt.% Rb₂O; n = 12 of 21 total analyses), 5 (up to 0.37 wt.% Rb₂O; n = 2 of 63 total analyses), 5U (0.18 wt.% Rb₂O; n = 1 of 57 total analyses), and 10 (0.08 wt.% Rb₂O; n = 1 of 14 total analyses) pegmatite dikes. Cesium was detected in even fewer samples than Rb and was only above the detection limit of the EMP in three analyses of samples from the Rau 3 pegmatite dike, in which 0.06–0.07 wt.% Cs₂O was detected. Significant amounts of other trace elements were not detected in either K-feldspar or albite from any of the pegmatite dikes (Table 2.12).

Mica group minerals mainly exhibit two habits in the pegmatite dikes. Primary mica group minerals form large (up to ~3 mm) elongated crystals in quartz and K-feldspar (Fig 2.15). Aggregates of small, needle-shaped crystals of secondary mica group minerals occur in both Kfeldspar (Fig 2.16) and albite (Figs 2.17 and 2.18). Both primary and secondary mica group minerals generally occur within the same pegmatite dike, and commonly within the same thin section (Table 2.11). All analysed mica group minerals in the pegmatite dikes belong to the muscovite-trilithionite and/or lepidolite (trilithionite-polylithionite) series. There appear to be no compositional differences between the primary and secondary mica group minerals; however, there are slight differences between mica group minerals in different pegmatite dikes (Fig 2.19). Mica group minerals from the larger pegmatite dikes (Rau 3, 5, and 5U) have compositions that evolve from muscovite towards trilithionite and polylithionite (Figs. 2.19b, 2.19d, and 2.19e), whereas mica group minerals in the other pegmatite dikes have a narrower range of compositions. However, this could also be an effect of the sampling size: samples were taken across all three of these pegmatite dikes, whereas sampling was more limited for the other dikes. In the Rau 1 pegmatite dike, mica group minerals evolve towards polylithionite only, with a minimal trend towards trilithionite (Fig 2.19a). Mica group minerals in Rau 4 are the most evolved with compositions close to trilithionite or along the trend towards polylithionite (Fig 2.19c). In contrast, mica group minerals in Rau 10 plot closer to muscovite and only evolve

towards polylithionite, not trilithionite (Fig 2.19j). The composition of primary and secondary mica group minerals in this pegmatite dike do show a slight variation, with primary mica group minerals trending towards polylithionite and secondary mica group minerals having compositions closer to muscovite.

Some grains of mica group minerals (which as shown above are all muscovite) display core-rim zonation. This is most apparent in primary muscovite but larger grains of secondary muscovite can also be zoned. In some pegmatite dikes this zonation is due to a difference in Fe and F contents, with higher contents of these elements in the cores and lower contents in the rims. For example, the cores of a zoned grain of muscovite in Rau 5U contain 5.20 wt.% FeO_{tot} $(0.302 apfu Fe^{2+})$ and 1.50 wt.% F (0.330 *apfu* F), whereas the rims contain an average of 1.27 wt.% FeO_{tot} (0.083 *apfu* Fe²⁺; n = 2) and an average of 1.04 wt.% F (0.229 *apfu* F, n = 2) (Fig 2.20) (Table 2.13).

There are clear differences in the compositions of muscovite in different pegmatite dikes. The highest average Mg:Fe ratio [Mg / (Mg + Fetot)] is found in muscovite in dike Rau 1 (0.82; n = 9), whereas the lowest occurs in muscovite in dike Rau 9 (0.32; n = 6). Muscovite in dikes Rau 3, 4, and 9 have the highest average Rb contents with 0.24 wt.% Rb₂O (0.011 *apfu*; n = 153), 0.23 wt.% Rb₂O (0.010 *apfu*; n = 18), and 0.24 wt.% Rb₂O (0.011 *apfu*; n = 6), respectively. The lowest average Rb contents are found in muscovite from dikes Rau 10 and 6, with 0.10 wt.% Rb₂O (n = 19) and 0.12 wt.% (n = 6) Rb₂O, respectively. Average F contents are highest in muscovite in dikes Rau 1 (1.56 wt.% F; 0.337 *apfu*; n = 2) and 7 (1.50 wt.% F; 0.325 *apfu*; n = 4), and lowest in muscovite in dikes Rau 10 (0.61 wt.% F; 0.130 *apfu*; n = 19) and 9 (0.61 wt.% F; 0.134 *apfu*; n = 6) (Table 2.13).

Samples were taken in transects across three of the larger pegmatite dikes: across the entire Rau 5 and 5U dikes, and from an outer zone to an inner zone of dike Rau 3. In dike Rau 3, muscovite is most enriched in F in the central portions of the pegmatite dike, but F also increases in the outer portions of the dike. The Rb contents of muscovite generally increases from the centre to the edge of the pegmatite, with an average of 0.31 wt.% Rb₂O (0.014 *apfu*; n = 3) in the sample taken closest to the edge of the dike (Fig. 2.21a). In both dikes Rau 5 and 5U, F contents are highest in muscovite near the rims of the pegmatite dikes and contents decrease towards the centre of the dikes. The Rb contents of muscovite in these pegmatite dikes is more variable, with

the highest average Rb contents occurring in one of the middle portions of dike Rau 5 and in a central portion of dike Rau 5U (Figs. 2.21b and 2.21c) (Table 2.13).

Zircon is a trace constituent of all pegmatite dikes but EMP analysis was only conducted on zircon from dike Rau 1, where it occurs as isolated euhedral to anhedral grains and is locally associated with secondary muscovite and fluorite (Figs. 2.18 and 2.22). Some zircon is highly evolved—Hf / (Hf + Zr) is 0.27 and 0.37 in two analyses—whereas in other grains Hf / (Hf + Zr) = 0.05–0.07. Grains that have the highest contents of Hf also have the highest contents of P (average 0.50 wt.% P₂O₅; 0.014 *apfu*), but have the lowest contents of Th (average 0.04 wt.% ThO₂) and Sc (average 0.08 wt.% Sc₂O₃; n = 2). The zircon contains a substantial amount of Y and Sc, with up to 1.40 wt.% Y₂O₃ (0.024 *apfu*) and 0.34 wt.% Sc₂O₃ (0.010 *apfu*) (Table 2.14).

Fluorite is a minor mineral in some pegmatite dikes (Rau 1, 5, 5U, and 6) and a trace mineral or is not observed in others (Table 2.14). Most fluorite forms subhedral to anhedral crystals that are a few mm to < 1 cm in size (Fig. 2.23), but it also occurs as a fracture-filling mineral between feldspar and quartz crystals (Fig. 2.22), and as large masses up to ~10 cm across (Fig. 2.24). It is commonly associated with fine-grained muscovite (Fig. 2.23), but some also occurs in the feldspar and quartz pegmatite. Some fluorite is associated with REE-bearing minerals such as monazite-(Ce), synchysite-(Ce), and bastnäsite-(Ce) (Fig. 2.25). Fluorite from dike Rau 1 has the highest contents of minor elements of analysed fluorite with up to 0.84 wt.% Y_2O_3 (0.008 *apfu*), 0.79 wt.% Ce₂O₃ (0.005 *apfu*), 0.53 wt.% Nd₂O₃ (0.004 *apfu*), 0.34 wt.% La₂O₃ (0.002 *apfu*), and 0.15 wt.% Sm₂O₃ (0.001 *apfu*) (Table 2.14). In two other analyses of fluorite REEs were below the detection limit of the EMP. Due to time constraints on the electron microprobe, fluorite was not analysed from any of the other pegmatite dikes.

Pyrochlore supergroup minerals are present in all of the pegmatite dikes. It is the most common trace mineral in the Rau pegmatite group, with hundreds of small grains occurring in some thin sections (Fig. 2.18). Although a large number of individual grains occur in the dikes, these grains are always extremely small (generally < 100 μ m and commonly < 20 μ m) and therefore the pyrochlore supergroup minerals only occur in trace amounts. The pyrochlore supergroup minerals commonly occur as aggregates of these extremely small grains (Fig. 2.26). Larger, primary grains are zoned and display oscillatory to chaotic growth zonation (Fig. 2.27). Many specimens are associated with and secondary to columbite group minerals (Fig. 2.28).

Pyrochlore supergroup minerals were analysed from all of the pegmatite dikes except (because of time constraints) Rau 5 and 7. All analysed pyrochlore supergroup minerals have F as the dominant anion and are Ca-dominant at the *A* site, meaning that they are calciopyrochlore or calciomicrolite (Fig. 2.29). Some pegmatite dikes contain only fluorcalciomicrolite (Rau 1, 4, 6, and 9), whereas others contain both fluorcalciopyrochlore and fluorcalciomicrolite (Rau 3, 5U, 8, and 10) (Fig. 2.30). It should be noted that the number of analyses obtained from these minerals varies greatly from one pegmatite dike to the next, and therefore the lack of fluorcalciopyrochlore in dikes Rau 1, 4, and 9 could also be due to a smaller sample size.

The pyrochlore supergroup minerals contain a variety of minor elements including Sn (up to 2.12 wt.% SnO₂; 0.067 apfu in dike Rau 8), W (up to 1.25 wt.% WO₃; 0.024 apfu in a middle portion of dike Rau 5U), Sc (up to 0.50 wt.% Sc₂O₃; 0.035 apfu in an inner portion of dike Rau 5U), Bi (up to 0.41 wt.% Bi₂O₃; 0.009 apfu in a middle portion of dike Rau 3), Sb (up to 0.20 wt.% Sb₂O₃; 0.008 apfu in an outer portion of dike Rau 5U), and Y (up to 0.14 wt.% Y₂O₃; 0.006 *apfu* in a middle portion of dike Rau 3). The concentrations of some of these trace elements vary between different pegmatite dikes. Fluorcalciomicrolite and fluorcalciopyrochlore in dike Rau 8 contain on average 1.69 wt.% SnO₂ (0.055 *apfu*; n = 5), which is significantly higher than the average Sn contents of pyrochlore supergroup minerals in dike Rau 1 (average 0.50 wt.% SnO₂; 0.017 apfu; n = 5), dike Rau 3 (average 0.57 wt.% SnO₂; 0.029 apfu; n = 19), dike Rau 5U (average 0.83 wt.% SnO₂; 0.027 *apfu*; *n* = 40), dike Rau 6 (average 0.68 wt.% SnO₂; 0.022 *apfu*; n = 7), and dike Rau 10 (average 0.67 wt.% SnO₂; 0.020 apfu; n = 4) [t statistic (t stat.) = 4.50 > tcritical value (t crit.) = 2.31; probability value (p-value) 0.002 for dike Rau 1¹; t stat. = 6.74 > tcrit. = 2.07; p-value <.001 for dike Rau 3; t stat. = 4.55 > t crit. = 2.02; p-value <.001 for dike Rau 5U; t stat. = 4.60 > t crit. = 2.23; p-value .002 for dike Rau 6; t stat. = 3.60 > t crit. = 2.36; pvalue .009 for dike Rau 10]. Pyrochlore supergroup minerals in dike Rau 10 have the highest average contents W of all analysed samples with 0.61 wt.% WO₃ (0.012 apfu). This is significantly higher than the W contents of pyrochlore supergroup minerals in dikes Rau 1 (average 0.07 wt.% WO₃; n = 5), 3 (average 0.09 wt.% WO₃; n = 19), and 9 (average 0.04 wt.% WO₃; n = 2) (t stat. = 5.76 > t crit. = 2.36; p-value <.001 for dike Rau 1; t stat. = 7.25 > t crit. =

¹ A t-test is used to determine if there is a statistically significant difference between two groups. If the t statistic is greater than the t critical value, the null hypothesis is rejected. The strength of the evidence against the null hypothesis is represented by the p-value: if the test yields a small p-values (≤ 0.05) there is strong evidence that the null hypothesis should be rejected (i.e., there is a significant difference between the two groups being compared).

2.08; p-value <.001 for dike Rau 3; t stat. = 3.99 > t crit. = 2.78; p-value .02 for dike Rau 9) (Table 2.15). There is no apparent relationship between the trace element contents (W, Sn, Sc, Sb, and Y) of pyrochlore supergroup minerals and Ta *versus* Nb.

Columbite group minerals are present as trace minerals in dikes Rau 1, 3, 5, 5U, 6, and 10. They generally form extremely small (~25 μ m) subhedral to anhedral grains (Fig. 2.31), but larger grains (up to ~500 μ m long) are also present. Columbite group minerals are commonly associated with secondary pyrochlore supergroup minerals (Fig. 2.28).

The composition of columbite group minerals ranges from columbite-(Fe) in dikes Rau 5 and 10, to columbite-(Mn) in dike Rau 5U, to tantalite-(Mn) in dike Rau 3 (Fig. 2.32). Higher contents of minor elements, namely Ti, W, Sc, and Y, occur in columbite-(Fe) compared to columbite-(Mn) and tantalite-(Mn). The maximum contents of these elements in columbite-(Fe) are 2.29 wt.% TiO₂ (0.101 *apfu*) in dike Rau 10, 2.13 wt.% WO₃ (0.033 *apfu*) in dike Rau 6, 1.12 wt.% Sc₂O₃ in dike Rau 10 (0.058 *apfu*), and 0.45 wt.% Y₂O₃ (0.014 *apfu*) in dike Rau 10. In contrast, columbite-(Mn) and tantalite-(Mn) contain minor amounts of F [up to 0.45 wt.%; *apfu* in tantalite-(Mn) in dike Rau 3] whereas F was below the detection limit of the EMP in all analyses of columbite-(Fe) (Table 2.16).

Subhedral to euhedral grains of apatite group minerals are usually small (< 50 μ m) but can attain ~300 μ m in size. They occur in dikes Rau 3, 5, 5U, and 9 and are commonly associated with rare element-bearing minerals such as synchysite-(Ce) and thorite (Fig. 2.33). Apatite group minerals in the Rau 3 pegmatite dike are fluorapatite. Most elements, other than those that are essential to its structure, are below the detection limit of the EMP, but one zone of an apatite crystal in the Rau 3 pegmatite dike does contain 1.60 wt.% Ce₂O₃ (0.050 *apfu*), 0.44 wt.% Nd₂O₃ (0.013 *apfu*), 0.31 wt.% La₂O₃ (0.010 *apfu*), and 0.12 wt.% MnO (0.009 *apfu*) (Table 2.16). Due to time constraints on the electron microprobe, no further analyses were completed on apatite group minerals in the other pegmatite dikes.

A variety of REE-bearing carbonate minerals occur in some of the pegmatite dikes. Bastnäsite-(Ce) [Ce(CO₃)F] and synchysite-(Ce) [CaCe(CO₃)₂F] both occur in dikes Rau 3, 5, and 5U, whereas parisite-(Ce) [CaCe₂(CO₃)₃F₂] occurs in dikes Rau 3 and 5U. All REE-bearing carbonate minerals are secondary and most are disseminated in fine-grained muscovite (Figs. 2.34a and 2.34b). Bastnäsite-(Ce) in dike Rau 5U occurs as fine lamellae within parasite-(Ce) that are not large enough to be accurately analysed. Synchysite-(Ce) can form more coherent

grains up to \sim 500 µm in size (Figs. 2.25, 2.35a, and 2.35b). All analysed specimens are Cedominant with Ce / (Ce + La + Nd) in bastnäsite ranging from 0.57 in dike Rau 5 to 0.64 in dike Rau 3, synchysite ranging from an average of 0.59 in dike Rau 3 (n = 10) to 0.62 in dike Rau 5. Parisite is also Ce-dominant with an average Ce / (Ce + La + Nd) of 0.61 in dike Rau 5U (n =17) and 0.63 in dike Rau 3 (n = 3). All bastnäsite-(Ce) has elevated Pr, Sm, and Gd, but the highest concentrations of these elements are found in bastnäsite-(Ce) in dike Rau 5, with 6.31 wt.% Pr₂O₃ (0.083 apfu), 6.04 wt.% Sm₂O₃ (0.075 apfu), and 1.21 wt.% Gd₂O₃ (0.015 apfu). In contrast, bastnäsite-(Ce) in dike Rau 3 contains an average of 4.50 wt.% Pr₂O₃ (0.064 apfu), 2.04 wt.% Sm₂O₃ (0.027 *apfu*), and 0.42 wt.% Gd₂O₃ (0.005 *apfu*; n = 2). Synchysite-(Ce) in all pegmatite dikes contains elevated Pr, Y, and Gd. The highest contents of these elements are an average of 3.77 wt.% Pr_2O_3 (0.071 *apfu*; n = 2) in dike Rau 5U, and an average of 1.72 wt.% Y_2O_3 (0.050 *apfu*) and 0.90 wt.% Gd₂O₃ (0.016 *apfu*; n = 10) in dike Rau 3. The Sm content of synchysite-(Ce) from dike Rau 3 is significantly higher than that from dike Rau 5U, with an average of 2.70 wt.% Sm_2O_3 (0.050 *apfu*; n = 10) in dike Rau 3 and 1.77 wt.% Sm_2O_3 (0.032) *apfu*; n = 2) in dike Rau 5U (t stat. = 3.22 > t crit. = 2.23; p-value .009). Parisite-(Ce) has similar minor element compositions in dikes Rau 3 and 5U. After Ce, Nd, and La, the REE that has the highest concentration in parisite-(Ce) from both pegmatite dikes is Pr, with up to 4.52 wt.% Pr₂O₃ (0.141 apfu) in dike Rau 3 and 4.42 wt.% Pr₂O₃ (0.137 apfu) in dike Rau 5U. This is followed by Sm with up to 2.17 wt.% Sm₂O₃ (0.067 apfu) in dike Rau 3 and 2.04 wt.% Sm₂O₃ (0.060 *apfu*) in dike Rau 5U (Table 2.17).

Euxenite occurs as both primary euhedral crystals that are up to ~300 μ m long (Fig. 2.31) and as small anhedral grains associated with secondary pyrochlore supergroup minerals in dike Rau 10. It also occurs in dike Rau 5 but no specimens were large enough to obtain an accurate EMP analysis. The euxenite is Y-dominant but other elements are also present at the *A* site including U and Th. The euhedral crystals of euxenite-(Y) have a higher contents of these elements than the euxenite-(Y) associated with secondary pyrochlore supergroup minerals, with up to 5.31 wt.% UO₂ and 7.99 wt.% ThO₂ (0.091 *apfu* U and 0.124 *apfu* Th). Euhedral euxenite-(Y) also has higher Fe contents with an average of 5.73 wt.% FeO_{tot} (0.346 *apfu* Fe²⁺; *n* = 5) versus 0.36 wt.% FeO_{tot} (0.022 *apfu* Fe²⁺) in euxenite-(Y) associated with secondary pyrochlore supergroup minerals (Table 2.18).

Monazite is commonly associated with other trace minerals in dikes Rau 3 and 5. In dike Rau 3 it is hosted by apatite group minerals (Figs. 2.35a and 2.35b), whereas in dike Rau 5 it is hosted by fluorite (Fig. 2.36). All of the monazite is Ce-dominant, with Ce / (Ce + La + Nd) = 0.58 in dike Rau 3 and 0.64 in dike Rau 5. The monazite-(Ce) in dike Rau 3 has higher contents of other REEs, with 5.03 wt.% Pr₂O₃ (versus 4.64 wt.% in dike Rau 5), 3.40 wt.% Sm₂O₃ (versus 1.34 wt.%), 0.77 wt.% Gd₂O₃ (versus below the detection limit of the EMP), 0.44 wt.% Y₂O₃ (versus 0.09 wt.%), and 0.14 wt.% Dy₂O₃ (versus below the detection limit of the EMP). In contrast, monazite-(Ce) from dike Rau 5 contains 6.50 wt.% ThO₂ (0.058 *apfu*), whereas monazite-(Ce) in dike Rau 3 only contains 3.63 wt.% ThO₂ (0.032 *apfu*) (Table 2.18).

Beryl is present in trace quantities as a secondary mineral in dikes Rau 1 and 3. In dike Rau 1, it occurs in secondary calcite veinlets, whereas in dike Rau 3 it occurs as small (< 10 μ m) grains between crystals of albite (Fig 2.37). All of the beryl contains trace amounts of Na, Mg, and Rb. The beryl in dike Rau 1 contains 0.17 wt.% Na₂O (0.030 *apfu*), 0.01 wt.% MgO (0.001 *apfu*), and 0.09 wt.% Rb₂O (0.005 *apfu*), whereas the beryl associated with albite in the Rau 3 pegmatite dike has an average contents of 1.38 wt.% Na₂O (0.244 *apfu*), 1.08 wt.% MgO (0.148 *apfu*), and 0.10 wt.% Rb₂O (0.006 *apfu*; *n* = 3). Beryl in dike Rau 1 has a lower Fe²⁺ contents (0.20 wt.% FeO; 0.014 *apfu*), whereas beryl associated with albite in the Rau 3 pegmatite dike contains substantially more Fe²⁺, with an average of 1.63 wt.% FeO (0.124 *apfu*; *n* = 3) (Table 2.19).

Relatively large (~1 mm long) grains of epidote supergroup minerals occur in dike Rau 3 (Fig. 2.38). The crystals display complex oscillatory zoning with compositions ranging from mostly allanite-(Ce) [Ce / (Ce + La + Nd) = 0.59–0.63] with minor clinozoisite in the cores, to a middle zone of epidote, and mostly epidote with minor allanite-(Ce) in the rims (Fig. 2.39). Minor elements that occur in the epidote supergroup minerals include Mn, Th, Sr, and F. Manganese has a maximum content of 0.75 wt.% MnO (0.058 *apfu*) in allanite-(Ce) in the core of a grain. There is not a significant difference between the Mn contents of epidote and allanite-(Ce). Epidote has higher contents of Th, Sr, and F than allanite-(Ce), regardless of whether these minerals form the core or rim of a grain. Epidote contains an average of 5.83 wt.% ThO₂ (0.112 *apfu*), 0.21 wt.% SrO (0.010 *apfu*), and 0.44 wt.% F (0.116 *apfu*; n = 5), whereas allanite-(Ce) contains an average of 1.98 wt.% ThO₂ (0.041 *apfu*), 0.16 wt.% F (0.047 *apfu*; n = 5), and Sr was below the detection limit of the EMP (Table 2.18).

Small grains of scheelite occur between grains of muscovite and quartz, and are associated with fluorite (Fig. 2.40) in dikes Rau 1 and 3. Due to its simple composition, EMP analysis was only conducted on scheelite from dike Rau 1. The scheelite is end-member in composition: Mo was below the detection limit of the EMP in all analyses. It contains trace amounts of Nb (up to 0.78 wt.% Nb₂O₅; 0.017 *apfu*), Fe²⁺ (up to 0.44 wt.% FeO; 0.018 *apfu*), and Mn (up to 0.19 wt.% MnO; 0.008 *apfu*) (Table 2.19).

Garnet group minerals are only present in the Rau 10 pegmatite dike where they form euhedral to subhedral grains hosted by quartz and associated with mica group minerals (Fig. 2.41). All garnet group minerals are spessartine but have a significant almandine component with Mn / (Mn + Fe) ranging from 0.55–0.64 and only minor Ca contents (up to 0.93 wt.% CaO; 0.082 *apfu*). They contain up to 0.84 wt.% F (0.220 *apfu*), 0.18 wt.% Y₂O₃ (0.008 *apfu*), and 0.13 wt.% Na₂O (0.021 *apfu*) (Table 2.19).

Gadolinite subgroup minerals are only found in the Rau 1 pegmatite dike, where they occur as a trace mineral. Analysed specimens have high Ca contents ranging from 9.97–10.56 wt.% CaO (0.797–0.840 *apfu*), but REEs are still dominant at the *A* site and therefore they are classified as hingganites. The specimens have higher contents of light REEs than heavy REEs, classifying them as hingganite-(Ce). However, heavy REEs are still abundant with specimens containing 6.76–9.12 wt.% Y₂O₃ (0.268–0.361 *apfu*). Normalization of the chemical formulae to 2 cations at the *T* site—the preferred normalization method of Bačík *et al.* (2017)—indicates that 0.749–0.772 *apfu* B is present at the *Q* site in place of Be. Minor elements that have elevated concentrations in hingganite-(Ce) are Mg (average 0.93 wt.% MgO; 0.103 *apfu*) and F (0.77 wt.% F; 0.182 *apfu*) (Table 2.18).

Mineral	Rau 1	Rau 3	Rau 4	Rau 5	Rau 5U	Rau 6	Rau 7	Rau 8	Rau 9	Rau 10
Kfs*	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х
Qz	Х	Х	Х	Х	Х	М	М	Х	М	Х
Ab	Х	Х	х	Х	Х	_	Т	Х	Х	Х
Ms	М	Μ	М	М	М	М	Т	Х	Х	М
PhI	_	М	-	_	-	_	-	-	_	-
Cal	_	-	Т	М	М	_	Т	_	М	Т
FI	М	М	-	М	М	М	-	Т	_	Т
Pcl	Т	Т	Т	Т	Т	Т	Т	Т	Т	Т
Zrc	Т	Т	Т	Т	Т	_	_	Т	Т	Т
Col	Т	Т	-	Т	Т	Т	-	_	_	Т
Fe ox	_	Т	Т	Т	Т	_	Т	_	_	_
Ар	_	-	-	Т	Т	_	-	_	Т	_
Chl	_	Т	-	_	-	_	-	_	М	Т
Bst	_	Т	-	Т	Т	_	_	_	_	-
Snc	_	Т	-	Т	Т	_	-	_	_	_
Exn	_	-	-	Т	-	_	-	_	_	Т
Fe sul	_	-	-	Т	-	_	-	_	_	_
Mnz-(Ce)	_	Т	-	Т	-	_	-	_	_	_
Prs	_	Т	_	_	Т	_	_	_	_	_
Sch	Т	Т	-	_	-	_	-	-	_	-
Brl	_	Т	-	_	-	_	-	_	_	-
Dol	_	Т	Т	_	-	_	-	-	_	-
Mn ox	_	Т	-	_	Т	_	-	_	_	-
Thr	_	Т	_	_	Т	_	_	_	_	_
Aln	_	Т	_	_	_	_	-	-	_	_
Brt	_	_	_	_	_	_	_	_	_	_
Flc	_	-	-	_	-	_	_	_	_	-

Table 2.11. Presence and abundance of minerals in all pegmatite dikes.

Mineral	Rau 1	Rau 3	Rau 4	Rau 5	Rau 5U	Rau 6	Rau 7	Rau 8	Rau 9	Rau 10
Grt	_	_	-	_	_	-	_	_	_	Т
Hng	т	_	_	_	_	-	_	_	-	_

X = major mineral; M = minor mineral; T = trace mineral; – = not observed.

*Abbreviations of mineral names follow Whitney & Evans (2010); Fe ox = Fe oxide minerals; Bst = bastnäsite; Snc = synchysite; Exn = euxenite; Fe sul = Fe sulphide minerals; Prs = parisite; Mn ox = Mn oxide minerals; Flc = fluocerite; Hng = hingganite.

Sample	R1-J	R3-2a	R3-3	R5-B1	R10-1c	R2-3	R10-1c
Unit	Rau 1	Rau 3	Rau 3	Rau 5	Rau 10	Rau 1	Rau 10
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Ab	Ab
SiO ₂ (wt.%)	65.22	64.24	65.25	64.42	65.37	68.73	67.79
Al ₂ O ₃	18.36	18.29	18.23	18.71	17.58	19.63	20.39
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.02	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.02	b.d.	b.d.
CaO	0.16	b.d.	b.d.	b.d.	b.d.	0.07	1.19
Na ₂ O	0.65	1.02	0.98	0.92	0.33	11.22	10.83
K ₂ O	15.81	14.88	15.14	15.21	16.82	0.19	0.17
Rb ₂ O	0.77	0.93	0.52	0.37	0.08	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	0.07	b.d.	b.d.	b.d.	b.d.
Total	100.97	99.36	100.20	99.62	100.20	99.85	100.38
Si ⁴⁺ (<i>apfu</i>)	2.998	2.995	3.008	2.985	3.024	3.001	2.955
Al ³⁺	0.995	1.005	0.990	1.022	0.959	1.010	1.048
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.
Ca ²⁺	0.008	b.d.	b.d.	b.d.	b.d.	0.003	0.056
Na ⁺	0.058	0.092	0.088	0.082	0.030	0.950	0.916
K⁺	0.927	0.885	0.890	0.899	0.993	0.011	0.010
Rb⁺	0.023	0.028	0.016	0.011	0.002	b.d.	b.d.
Cs+	b.d.	b.d.	0.001	b.d.	b.d.	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table 2.12. Representative chemical compositions and structural formulae of feldspar group minerals from the Rau 1, 3, 5, and 10 pegmatite dikes.

The formulae were calculated on the basis of 5 O atoms per formula unit.

Magnesium, Mn, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.



Figure 2.15. BSE image of large grains of muscovite (Ms) in quartz (Qz) and associated with K-feldspar (Kfs) in the Rau 5 pegmatite dike.



Figure 2.16. BSE image of fine-grained secondary muscovite (Ms) in K-feldspar (Kfs) in the Rau 5 pegmatite dike.



Figure 2.17. BSE image of extremely fine-grained secondary muscovite (Ms) in albite (Ab) in the Rau 3 pegmatite dike. A single grain of apatite (Ap) is also present.



Figure 2.18. BSE image of secondary muscovite (Ms) and calcite (Cal), and pyrochlore supergroup minerals (Pcl) in albite (Ab) in the Rau 9 pegmatite dike.



Figure 2.19. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the compositions of primary and secondary mica group minerals in the (a) Rau 1, (b) Rau 3, (c) Rau 4, (d) Rau 5, (e) Rau 5U, (f) Rau 6, (g) Rau 7, (h) Rau 8, (i) Rau 9, and (j) Rau 10 pegmatite dikes.



Figure 2.19. (continued) Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the compositions of primary and secondary mica group minerals in the (a) Rau 1, (b) Rau 3, (c) Rau 4, (d) Rau 5, (e) Rau 5U, (f) Rau 6, (g) Rau 7, (h) Rau 8, (i) Rau 9, and (j) Rau 10 pegmatite dikes.



Figure 2.19. (continued) Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the compositions of primary and secondary mica group minerals in the (a) Rau 1, (b) Rau 3, (c) Rau 4, (d) Rau 5, (e) Rau 5U, (f) Rau 6, (g) Rau 7, (h) Rau 8, (i) Rau 9, and (j) Rau 10 pegmatite dikes.



Figure 2.20. BSE image of zoned muscovite (Ms) with Fe-rich cores and Fe-depleted rims in K-feldspar (Kfs) in the Rau 5U pegmatite dike. Grains of thorite (Thr) are present within muscovite.

Sample	R2-3	R3-3	R4-A	R4-2d	R5-A	R5-C	R5-F1
Unit	Rau 1	Rau 3	Rau 4	Rau 4	Rau 5	Rau 5	Rau 5
Generation	Primary	Primary	Primary	Secondary	Primary	Secondary	Primary
Zone	Rim	Rim	_	_	_	-	_
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	50.17	46.84	45.43	50.76	47.51	45.22	47.60
TiO ₂	b.d.	0.25	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	26.67	26.25	27.08	27.43	28.43	35.04	27.07
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.98	3.96	5.02	1.01	2.40	0.28	3.47
MgO	3.59	4.66	3.18	3.07	2.44	0.11	4.37
CaO	b.d.	b.d.	0.04	b.d.	b.d.	0.04	0.04
MnO	b.d.	b.d.	0.08	0.23	b.d.	b.d.	b.d.
Na ₂ O	0.09	0.10	0.22	0.04	0.17	0.61	0.20
K ₂ O	11.27	11.25	11.00	10.89	11.59	10.53	11.29
Rb ₂ O	0.22	0.35	0.26	0.41	0.22	0.57	0.17
F	1.90	2.07	1.66	1.45	1.55	0.49	1.73
CI	b.d.	b.d.	0.07	b.d.	b.d.	b.d.	0.03
H_2O^{\ddagger}	3.49	3.33	3.43	3.75	3.59	4.14	3.53
−(O=F,CI)	-0.80	-0.87	-0.71	-0.61	-0.65	-0.20	-0.74
Total	97.58	98.20	96.73	98.44	97.25	96.83	98.77
Si ⁴⁺ (<i>apfu</i>)	3.428	3.259	3.222	3.431	3.296	3.102	3.273
Ti ⁴⁺	b.d.	0.013	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.148	2.152	2.264	2.185	2.325	2.834	2.194
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.056	0.230	0.298	0.057	0.139	0.016	0.200
Mg ²⁺	0.366	0.483	0.336	0.310	0.252	0.011	0.448
Ca ²⁺	b.d.	b.d.	0.003	b.d.	b.d.	0.003	0.003
Mn ²⁺	b.d.	b.d.	0.005	0.013	b.d.	b.d.	b.d.
Na⁺	0.012	0.014	0.030	0.006	0.023	0.081	0.027
K⁺	0.982	0.999	0.995	0.939	1.026	0.922	0.990
Rb⁺	0.010	0.016	0.012	0.018	0.010	0.025	0.008
F⁻	0.411	0.455	0.371	0.310	0.340	0.105	0.376
Cl⁻	b.d.	b.d.	0.008	b.d.	b.d.	b.d.	0.004
OH-‡	1.589	1.545	1.621	1.690	1.660	1.895	1.620
vacancy	1.003	0.862	0.875	1.004	0.988	1.036	0.885
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Table 2.13. Representative chemical compositions and structural formulae of muscovite from the Rau 1, 3, 4, 5, 5U, 9, and 10 pegmatite dikes.
The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit. Cesium was also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-A	R5U-C	R5U-C	R5U-E	R5U-G	R9b-2c	R10-1c
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 9	Rau 10
Generation	Primary	Primary	Primary	Secondary	Secondary	Primary	Secondary
Zone	NA	Core	Rim	NA	NA	Rim	NA
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	44.80	45.33	48.06	48.50	48.30	44.47	46.26
TiO ₂	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	b.d.
Al ₂ O ₃	29.19	29.58	30.15	31.25	29.24	30.16	35.04
Cr ₂ O ₃	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	6.41	5.19	1.47	2.13	2.97	6.85	0.96
MgO	2.36	2.48	2.69	1.36	2.50	1.48	0.05
CaO	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	0.07
MnO	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
Na ₂ O	0.27	0.24	0.21	0.16	0.17	0.20	0.25
K ₂ O	10.97	11.21	11.43	11.41	11.32	11.12	11.14
Rb ₂ O	0.28	0.27	0.22	0.12	0.20	0.29	0.12
F	1.05	1.50	1.07	0.86	1.20	0.84	0.00
CI	0.07	0.05	0.00	b.d.	0.02	0.09	b.d.
H_2O^{\ddagger}	3.78	3.59	3.92	4.05	3.84	3.87	4.44
-(O=F,CI)	-0.46	-0.64	-0.45	-0.36	-0.51	-0.37	0.00
Total	98.72	98.81	98.86	99.64	99.33	99.00	98.32
Si ⁴⁺ (<i>apfu</i>)	3.130	3.147	3.257	3.258	3.279	3.104	3.126
Ti ⁴⁺	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.
Al ³⁺	2.404	2.420	2.408	2.474	2.340	2.482	2.790
Cr ³⁺	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.374			0.120	0.169	0.400	0.054
Mg ²⁺	0.246	0.256	0.271	0.136	0.253	0.155	0.005
Ca ²⁺	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	0.005
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.
Na⁺	0.036	0.033	0.028	0.020	0.023	0.026	0.033
K⁺	0.978	0.993	0.988	0.978	0.981	0.990	0.960
Rb⁺	0.013	0.012	0.010	0.005	0.009	0.013	0.005
F⁻	0.232	0.330	0.229	0.183	0.257	0.186	0.000
Cl⁻	0.008	0.006	0.000	b.d.	0.003	0.011	b.d.
OH-‡	1.760	1.665	1.771	1.817	1.740	1.804	2.000
vacancy	0.845	0.876	0.976	1.006	0.955	0.860	1.025
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Table 2.13. (Continued) Representative chemical compositions and structural formulae of muscovite from the Rau 1, 3, 4, 5, 5U, 9, and 10 pegmatite dikes.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit. Cesium was also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.21. Rubidium and F contents of muscovite showing variation across pegmatite dikes from the (a) inner to outermost part of the Rau 3 pegmatite and outer to inner to outer parts of the (b) Rau 5 and (c) Rau 5U pegmatite dikes.



Figure 2.22. BSE image showing fluorite (Fl) and associated fine-grained muscovite (Ms) filling fractures between grains of K-feldspar (Kfs), quartz (Qz), and albite (Ab) in the Rau 5 pegmatite dike. Small grains of zircon (Zrc), fluorcalciomicrolite (Fclmcr), and synchysite-(Ce) (Snc) are also present.

Sample	R1-J	R1-J	R1-J	R1-J	R5F-A3	R5F-A3
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 5	Rau 5
Mineral	*Zrc	Zrc	Zrc	FI	FI	FI
P ₂ O ₅ (wt.%)	0.59	0.33	0.13	b.d.	b.d.	0.02
SiO ₂	31.21	31.13	31.76	b.d.	b.d.	b.d.
ZrO ₂	35.71	56.53	57.65	-	_	-
HfO ₂	36.41	5.58	7.98	-	_	-
ThO ₂	0.09	0.48	0.25	b.d.	0.06	0.00
UO ₂	0.64	2.76	2.27	-	_	-
Sc ₂ O ₃	0.09	0.34	0.22	-	-	-
Y ₂ O ₃	0.50	0.94	0.38	0.84	0.11	0.09
La_2O_3	_	-	-	0.34	b.d.	b.d.
Ce ₂ O ₃	_	-	-	0.79	0.44	b.d.
Pr_2O_3	_	-	-	b.d.	0.10	b.d.
Nd ₂ O ₃	_	-	-	0.53	0.33	b.d.
Sm ₂ O ₃	_	-	-	0.15	0.11	b.d.
Dy ₂ O ₃	0.21	0.18	0.10	0.15	b.d.	b.d.
Er ₂ O ₃	0.40	0.15	0.10	b.d.	b.d.	b.d.
Yb ₂ O ₃	0.73	0.62	0.31	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	48.56	50.65	51.36
Na ₂ O	_	-	-	0.12	b.d.	b.d.
F	b.d.	b.d.	b.d.	47.36	48.46	48.67
Total	106.56	99.03	101.15	98.86	100.25	100.15
P⁵+ (<i>apfu</i>)	0.017	0.009	0.003	b.d.	b.d.	0.000
Si ⁴⁺	1.035	1.005	1.006	b.d.	b.d.	b.d.
Zr ⁴⁺	0.577	0.890	0.891	-	-	-
Hf ⁴⁺	0.345	0.051	0.072	-	-	-
Th ⁴⁺	0.001	0.004	0.002	b.d.	0.000	0.000
U ⁴⁺	0.005	0.020	0.016	-	-	-
Sc ³⁺	0.002	0.010	0.006	-	-	-
Y ³⁺	0.009	0.016	0.006	0.008	0.001	0.001
La ³⁺	_	-	-	0.002	b.d.	b.d.
Ce ³⁺	_	-	-	0.005	0.003	b.d.
Pr ³⁺	_	-	-	b.d.	0.001	b.d.
Nd ³⁺	_	-	-	0.004	0.002	b.d.
Sm ³⁺	_	-	-	0.001	0.001	b.d.
Dy ³⁺	0.002	0.002	0.001	0.001	b.d.	b.d.
Er ³⁺	0.004	0.002	0.001	b.d.	b.d.	b.d.
Yb ³⁺	0.007	0.006	0.003	b.d.	b.d.	b.d.

Table 2.14. Representative chemical compositions and structural formulae of zircon and fluorite from the Rau 1 and 5 pegmatite dikes.

Sample	R1-J	R1-J	R1-J		R1-J	R5F-A3	R5F-A3
Unit	Rau 1	Rau 1	Rau 1	_	Rau 1	Rau 5	Rau 5
Mineral	*Zrc	Zrc	Zrc		FI	FI	FI
Ca ²⁺ (apfu)	b.d.	b.d.	b.d.		0.974	0.992	0.999
Na⁺	-	-	-		0.004	b.d.	b.d.
F⁻	b.d.	b.d.	b.d.		2.803	2.802	2.794
O ²⁻	4.000	4.000	4.000		0.000	0.000	0.000

The formulae for zircon were calculated on the basis of 4 O atoms and fluorite on the basis of 1 cation per formula unit.

Titanium, Al and Fe in zircon, and Mg, Sr, Gd, Ba, Pb, K and Cl in fluorite were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit.



Figure 2.23. BSE image showing subhedral to anhedral grains of fluorite (Fl) associated with finegrained muscovite (Ms) in the Rau 5U pegmatite dike. Small grains of fluorcalciomicrolite (Fclmcr) are also present. At this location, the pegmatite dike is mainly composed of muscovite, albite (Ab), and calcite (Cal).



Figure 2.24. Large masses of fluorite (Fl) associated with quartz (Qz) in the Rau 6 pegmatite dike.



Figure 2.25. BSE image of anhedral to subhedral fluorite (Fl) associated with fine-grained muscovite (Ms) and synchysite-(Ce) (Snc) in the Rau 5U pegmatite dike. The pegmatite is mainly composed of K-feldspar (Kfs) and quartz (Qz). A small grain of thorite (Thr) is also present.



Figure 2.26. BSE image of an aggregate of pyrochlore supergroup minerals in the Rau 5U pegmatite dike. The numbers mark the EMP analysis points. The brighter parts of the grains are fluorcalciomicrolite (Fclmcr), whereas the darker parts are fluorcalciopyrochlore (Fclprc). Fluorcalciopyrochlore has higher contents of Ti, W, and Sn.



Figure 2.27. BSE image of a zoned pyrochlore supergroup mineral in the Rau 5U pegmatite dike. The numbers mark EMP analysis points. All zones of this grain are fluorcalciomicrolite but the Ta and Ti contents are higher in the brighter zones.



Figure 2.28. BSE image of tantalite-(Mn) (Tnt) with secondary fluorcalciomicrolite (Fclmcr) in the Rau 3 pegmatite dike.



Figure 2.29. *A* site compositions (Atencio *et al.*, 2010) of pyrochlore supergroup minerals in the pegmatite dikes.



Figure 2.30. *B* site composition (Atencio *et al.*, 2010) of pyrochlore supergroup minerals from the (a) Rau 1, (b) Rau 3, (c) Rau 4, (d) Rau 5U, (e) Rau 8, (f) Rau 9, and (g) Rau 10 pegmatite dikes. Compositions of pyrochlore supergroup minerals in dikes Rau 3 and Rau 5U were analysed from across the dikes and the variation in these compositions with location is shown on the diagrams.



Figure 2.30. (Continued) *B* site composition (Atencio *et al.*, 2010) of pyrochlore supergroup minerals from the (e) Rau 8, (f) Rau 9, and (g) Rau 10 pegmatite dikes. Compositions of pyrochlore supergroup minerals in dikes Rau 3 and Rau 5U were analysed from across the dikes and the variation in these compositions with location is shown on the diagrams.

Sample	R1-J	R3	-2e	R4-2d	R5U-C	R5U-D	R6-1b	R8-1b	R9t	o-2c	R10)-1c
Unit	Rau 1	Ra	u 3	Rau 4	Rau	u 5U	Rau 6	Rau 8	Ra	u 9	Rau	u 10
Mineral	*Fclmcr	Fcl	mcr	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclprc	Fcl	mcr	Fclprc	Fclmcr
WO ₃ (wt.%)	0.20	b.d.	0.01	0.57	1.25	0.57	b.d.	b.d.	b.d.	0.08	0.88	0.48
Nb ₂ O ₅	22.50	10.21	8.92	11.93	31.69	16.34	17.58	31.84	10.83	13.83	30.31	25.00
Ta ₂ O ₅	51.10	66.17	68.03	62.52	40.66	57.35	60.38	37.34	62.31	60.72	32.04	45.78
SiO ₂	0.02	b.d.	0.02	0.06	0.07	0.02	0.55	0.07	0.11	0.31	0.08	0.09
TiO ₂	0.67	1.22	0.76	1.62	1.38	1.98	0.53	0.34	0.11	0.10	5.10	1.79
ZrO ₂	0.05	0.05	b.d.	0.02	0.19	0.57	0.19	0.03	b.d.	0.10	b.d.	0.21
SnO ₂	0.30	0.68	0.81	1.08	0.74	1.09	0.38	1.90	1.55	1.31	0.54	0.77
ThO ₂	0.03	0.01	0.05	0.03	b.d.	0.05	b.d.	b.d.	0.02	b.d.	0.52	0.12
UO ₂	0.55	0.55	0.45	0.20	b.d.	0.07	0.32	2.16	0.84	1.10	3.99	1.24
Al ₂ O ₃	0.16	0.06	0.06	0.03	0.17	0.56	0.04	0.25	0.12	0.22	0.11	0.15
Sc ₂ O ₃	0.04	b.d.	b.d.	0.02	0.28	0.50	b.d.	0.10	0.03	0.01	b.d.	0.02
$Fe_2O_{3(\text{min})}^\dagger$	0.01	0.00	0.01	0.01	b.d.	0.01	b.d.	b.d.	0.01	0.00	0.16	0.04
$FeO_{(max)}^{\dagger}$	0.75	0.27	0.18	0.09	0.49	0.14	0.24	1.00	0.64	0.81	0.72	0.55
Y_2O_3	0.02	0.14	0.05	0.02	0.06	0.01	-	0.05	b.d.	0.03	0.04	b.d.
Sb ₂ O ₃	0.08	0.14	0.18	0.05	0.18	b.d.	-	b.d.	b.d.	0.11	0.02	b.d.
Bi ₂ O ₃	0.20	0.28	0.41	b.d.	b.d.	b.d.	-	0.30	0.05	0.15	0.41	0.28
MgO	0.03	b.d.	0.00	0.03	0.01	b.d.	b.d.	0.01	b.d.	0.04	b.d.	b.d.
CaO	15.88	12.42	12.46	12.74	14.46	13.59	12.13	12.49	13.12	13.93	14.53	15.43
MnO	0.10	b.d.	0.05	b.d.	b.d.	0.05	b.d.	b.d.	0.01	0.03	0.11	0.09
ZnO	0.03	b.d.	0.09	0.06	b.d.	b.d.	-	b.d.	0.04	b.d.	0.04	0.05
PbO	b.d.	b.d.	0.04	b.d.	0.11	0.08	-	0.09	b.d.	b.d.	0.05	b.d.
Na ₂ O	4.37	5.33	5.42	5.38	6.04	5.25	5.05	5.76	4.92	3.58	4.65	3.51
F	3.48	3.69	3.64	3.97	4.38	3.85	3.72	3.64	3.43	2.74	3.18	3.06
–(O=F)	-1.47	-1.55	-1.53	-1.67	-1.85	-1.62	-1.57	-1.53	-1.44	-1.15	-1.34	-1.29

Table 2.15. Representative chemical compositions and structural formulae of pyrochlore supergroup minerals from the Rau 1, 3, 4, 5U, 6, 8, 9, and 10 pegmatite dikes.

Sample	R1-J	R3	-2e	R4-2d	R5U-C	R5U-D	R6-1b	R8-1b	R9t	o-2c	R10	D-1c
Unit	Rau 1	Ra	u 3	Rau 4	Rau	ı 5U	Rau 6	Rau 8	Ra	u 9	Rau	u 10
Mineral	*Fclmcr	Fcl	mcr	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclprc	Fcl	mcr	Fclprc	Fclmcr
Total	99.09	99.66	100.12	98.76	100.31	100.48	99.54	95.83	96.70	98.03	96.12	97.35
W ⁶⁺ (apfu)	0.004	b.d.	0.000	0.012	0.023	0.011	b.d.	b.d.	b.d.	0.002	0.017	0.010
Nb ⁵⁺	0.792	0.384	0.338	0.442	1.034	0.575	0.636	1.109	0.420	0.525	1.027	0.881
Ta⁵+	1.082	1.497	1.552	1.393	0.798	1.213	1.314	0.782	1.452	1.386	0.653	0.970
Si ⁴⁺	0.002	b.d.	0.002	0.005	0.005	0.001	0.044	0.005	0.009	0.026	0.006	0.007
Ti ⁴⁺	0.039	0.077	0.048	0.100	0.075	0.116	0.032	0.020	0.007	0.006	0.287	0.105
Zr ⁴⁺	0.002	0.002	b.d.	0.001	0.007	0.022	0.007	0.001	b.d.	0.004	b.d.	0.008
Sn ⁴⁺	0.009	0.022	0.027	0.035	0.021	0.034	0.012	0.058	0.053	0.044	0.016	0.024
Th ⁴⁺	0.001	0.000	0.001	0.001	b.d.	0.001	b.d.	b.d.	0.000	b.d.	0.009	0.002
U ⁴⁺	0.009	0.010	0.008	0.004	b.d.	0.001	0.006	0.037	0.016	0.020	0.067	0.022
Al ³⁺	0.014	0.006	0.006	0.003	0.014	0.052	0.004	0.022	0.012	0.021	0.010	0.013
Sc ³⁺	0.003	b.d.	b.d.	0.001	0.018	0.034	b.d.	0.007	0.002	0.001	b.d.	0.001
$Fe^{3+}(min)^{\dagger}$	0.001	0.000	0.001	0.001	b.d.	0.001	b.d.	b.d.	0.000	0.000	0.009	0.002
$Fe^{2+}(max)^{\dagger}$	0.049	0.019	0.013	0.006	0.030	0.009	0.016	0.064	0.046	0.057	0.045	0.036
Y ³⁺	0.001	0.006	0.002	0.001	0.002	0.001	-	0.002	b.d.	0.001	0.001	b.d.
Sb ³⁺	0.003	0.005	0.006	0.002	0.005	b.d.	-	b.d.	b.d.	0.004	0.001	b.d.
Bi ³⁺	0.004	0.006	0.009	b.d.	b.d.	b.d.	-	0.006	0.001	0.003	0.008	0.006
Mg ²⁺	0.003	b.d.	0.001	0.004	0.001	b.d.	b.d.	0.002	b.d.	0.005	b.d.	b.d.
Ca ²⁺	1.325	1.107	1.120	1.118	1.118	1.133	1.040	1.031	1.204	1.253	1.167	1.288
Mn ²⁺	0.006	b.d.	0.004	b.d.	b.d.	0.003	b.d.	b.d.	0.001	0.002	0.007	0.006
Zn ²⁺	0.001	b.d.	0.006	0.004	b.d.	b.d.	-	b.d.	0.002	b.d.	0.002	0.003
Pb ²⁺	b.d.	b.d.	0.001	b.d.	0.002	0.002	-	0.002	b.d.	b.d.	0.001	b.d.
Na ⁺	0.659	0.860	0.882	0.855	0.845	0.792	0.783	0.861	0.817	0.582	0.676	0.530
F⁻	0.858	0.970	0.965	1.029	1.000	0.946	0.941	0.887	0.929	0.728	0.754	0.753
O ^{2_}	6.143	6.030	6.036	5.971	6.000	6.055	6.059	6.113	6.071	6.272	6.251	6.248

The formulae were calculated on the basis of 7 anions per formula unit. *Fclmcr = fluorcalciomicrolite; Fclprc = fluorcalciopyrochlore; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit; - = not measured.



Figure 2.31. BSE image of small grains of columbite-(Fe) (Col) and euxenite-(Y) (Exn) associated with calcite (Cal) and muscovite (Ms) in the Rau 10 pegmatite dike. The pegmatite is mostly composed of K-feldspar (Kfs), albite (Ab), and quartz (Qz). The elongated, rectangular-shaped grains were too small to provide accurate chemical compositions.



Figure 2.32. Quadrilateral plot showing the general compositional space of columbite group minerals in the Rau 3, 5, 5U, and 10 pegmatite dikes (Černý *et al.*, 1992).

Sample	R3	-2d	R5F-A3	R5U-F	R6-1b	R10)-1c
Unit	Ra	u 3	Rau 5	Rau 5U	Rau 6	Rau	ı 10
Mineral	*Tnt-	-(Mn)	Col-(Fe)	Col- (Mn)	Col-(Fe)	Col-	(Fe)
WO ₃ (wt.%)	0.12	0.44	1.66	0.01	2.13	0.78	0.42
Nb ₂ O ₅	22.19	24.31	56.45	40.37	57.99	57.77	61.96
Ta_2O_5	59.55	56.52	20.52	41.84	19.42	19.56	14.87
SiO ₂	0.03	0.02	0.14	0.07	0.22	0.06	0.08
TiO ₂	0.68	1.28	1.09	0.34	1.90	2.16	2.29
ZrO ₂	0.18	0.17	b.d.	0.13	b.d.	0.27	0.30
SnO ₂	0.27	0.23	b.d.	b.d.	b.d.	b.d.	0.16
ThO ₂	b.d.	0.01	b.d.	0.02	b.d.	0.04	0.10
UO ₂	b.d.	0.03	b.d.	0.01	b.d.	0.10	0.04
AI_2O_3	0.01	b.d.	b.d.	0.02	b.d.	b.d.	0.00
Sc ₂ O ₃	0.06	0.11	0.18	0.27	0.24	1.12	0.57
$Fe_2O_{3(\text{min})}^\dagger$	0.40	0.59	0.38	0.73	0.00	1.66	2.19
$FeO_{(max)}^{\dagger}$	0.00	0.00	16.42	0.00	16.59	12.07	11.64
Y_2O_3	0.06	0.06	b.d.	0.01	_	0.45	0.37
Sb ₂ O ₃	0.00	0.18	b.d.	b.d.	_	b.d.	0.06
Bi ₂ O ₃	0.12	0.47	b.d.	0.10	_	b.d.	b.d.
MgO	b.d.	b.d.	0.09	0.00	0.22	0.18	0.09
CaO	b.d.	0.72	b.d.	0.64	b.d.	b.d.	b.d.
MnO	16.12	15.67	2.24	17.54	2.16	4.99	5.90
ZnO	0.02	0.03	b.d.	0.04	_	b.d.	b.d.
PbO	b.d.	b.d.	b.d.	0.02	_	b.d.	0.09
Na ₂ O	0.01	0.61	b.d.	0.05	b.d.	0.04	0.02
F	0.10	0.45	b.d.	0.01	b.d.	b.d.	b.d.
-(O=F)	-0.04	-0.19	0.00	-0.01	0.00	0.00	0.00
Total	99.88	101.70	99.17	102.20	100.87	101.23	101.17
W ⁶⁺ (apfu)	0.002	0.008	0.027	0.000	0.033	0.012	0.006
Nb ⁵⁺	0.739	0.777	1.574	1.197	1.572	1.558	1.644
Ta⁵+	1.193	1.087	0.344	0.746	0.317	0.317	0.237
Si ⁴⁺	0.002	0.001	0.009	0.004	0.013	0.003	0.005
Ti ⁴⁺	0.038	0.068	0.051	0.017	0.086	0.097	0.101
Zr ⁴⁺	0.006	0.006	b.d.	0.004	b.d.	0.008	0.009
Sn ⁴⁺	0.008	0.007	b.d.	b.d.	b.d.	b.d.	0.004
Th ⁴⁺	b.d.	0.000	b.d.	0.000	b.d.	0.001	0.001
U ⁴⁺	b.d.	0.000	b.d.	0.000	b.d.	0.001	0.001
Al ³⁺	0.001	b.d.	b.d.	0.001	b.d.	b.d.	0.000

Table 2.16. Representative chemical compositions and structural formulae of columbite group minerals from the Rau 3, 5, 5U, 6, and 10 pegmatite dikes.

Sample	R3	-2d	R5F-A3	R5U-F	R6-1b	R10)-1c
Unit	Ra	u 3	Rau 5	Rau 5U	Rau 6	Rau	u 10
Mineral	*Tnt-	·(Mn)	Col-(Fe)	Col- (Mn)	Col-(Fe)	Col-	(Fe)
Sc ³⁺ (<i>apfu</i>)	0.004	0.007	0.010	0.015	0.013	0.058	0.029
$Fe^{3+}(min)^{\dagger}$	0.022	0.031	0.000	0.005	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.865	0.031	0.832	0.677	0.668
Y ³⁺	0.002	0.002	b.d.	0.000	-	0.014	0.012
Sb ³⁺	0.000	0.005	b.d.	b.d.	-	b.d.	0.002
Bi ³⁺	0.002	0.009	b.d.	0.002	-	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	0.008	0.000	0.019	0.016	0.008
Ca ²⁺	b.d.	0.054	b.d.	0.045	b.d.	b.d.	b.d.
Mn ²⁺	1.005	0.938	0.117	0.974	0.110	0.252	0.293
Zn ²⁺	0.001	0.002	b.d.	0.002	-	b.d.	b.d.
Pb ²⁺	b.d.	b.d.	b.d.	0.000	-	b.d.	0.001
Na⁺	0.002	0.084	b.d.	0.006	b.d.	0.004	0.002
F⁻	0.024	0.101	b.d.	0.003	b.d.	b.d.	b.d.
O ²⁻	5.987	5.914	6.000	6.000	6.000	6.000	6.000

The formulae were calculated on the basis of 6 anions per formula unit.

*Tnt = tantalite; Col = columbite; $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.



Figure 2.33. BSE image of subhedral and anhedral apatite group minerals (Ap) associated with thorite (Thr), Fe oxide minerals (Fe ox), and pyrochlore supergroup minerals (Prc) in the Rau 5U pegmatite dike. At this location, the pegmatite dike is composed of quartz (Qz), heavily altered K-feldspar (Kfs), and muscovite (Ms).



Figure 2.34. BSE image of (a) secondary synchysite-(Ce) (Snc) and (b) thorite (Thr) associated with finegrained muscovite (Ms) in the Rau 3 pegmatite dike.



Figure 2.35. BSE image of synchysite-(Ce) (Snc) with (a) zones of bastnäsite-(Ce) (Bsn) in the Rau 3 pegmatite dike. (b) Synchysite-(Ce) and bastnäsite-(Ce) are associated with fine-grained secondary muscovite (Ms). Monazite-(Ce) (Mnz) is also present and is hosted in fluorapatite (Ap).

Sample	R3-A	R5F-A3	R3-1b	R5F-A3	R5U-F	R3-1b	R5U-C
Unit	Rau 3	Rau 5	Rau 3	Rau 5	Rau 5U	Rau 3	Rau 5U
Mineral	*Bsn- (Ce)	Bsn- (Ce)	Snc- (Ce)	Snc- (Ce)	Snc- (Ce)	Prs-(Ce)	Prs-(Ce)
SiO ₂ (wt.%)	0.18	0.18	0.34	0.96	b.d.	0.43	b.d.
ThO ₂	4.98	0.21	3.19	1.08	1.77	1.39	0.98
AI_2O_3	0.11	b.d.	0.11	0.70	b.d.	0.00	0.18
Fe ₂ O _{3(min)} *	0.00	0.00	0.00	0.32	0.00	0.00	0.00
FeO _(max) *	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.
Y ₂ O ₃	0.55	0.82	3.36	0.84	0.79	0.22	0.38
La ₂ O ₃	9.23	5.80	4.85	7.76	7.74	8.35	9.30
Ce ₂ O ₃	36.32	33.81	23.78	27.61	28.25	35.25	33.25
Pr ₂ O ₃	4.67	6.31	3.74	3.77	3.84	4.52	4.20
Nd ₂ O ₃	11.62	20.02	10.50	9.67	10.41	12.08	11.81
Sm ₂ O ₃	2.06	6.04	3.39	2.06	1.83	1.99	2.04
Gd ₂ O ₃	0.47	1.21	1.48	0.54	0.50	b.d.	0.51
Dy ₂ O ₃	0.23	0.52	b.d.	b.d.	b.d.	b.d.	b.d.
Tm ₂ O ₃	b.d.	b.d.	0.52	b.d.	0.28	b.d.	0.25
CaO	0.65	0.27	14.41	16.29	17.77	10.91	11.64
BaO	b.d.	b.d.	b.d.	0.01	b.d.	b.d.	b.d.
K₂O	-	_	b.d.	b.d.	0.00	0.01	b.d.
F	6.87	8.30	4.18	5.53	5.62	4.69	6.59
CO_2^{\dagger}	18.98	20.19	26.26	28.47	28.61	25.77	25.94
H_2O^{\ddagger}	0.63	0.20	3.39	3.21	3.19	1.29	0.42
-(O=F)	-2.89	-3.50	-1.76	-2.33	-2.37	-1.97	-2.77
Total	94.64	100.38	101.76	106.50	108.22	104.93	104.71
Si ⁴⁺ (<i>apfu</i>)	0.007	0.006	0.019	0.050	b.d.	0.037	b.d.
Th ⁴⁺	0.044	0.002	0.041	0.013	0.021	0.027	0.019
Al ³⁺	0.005	0.000	0.007	0.042	b.d.	0.000	0.018
Fe ³⁺ (min)*	0.000	0.000	0.000	0.012	0.000	0.000	0.000
Fe ²⁺ (max)*	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.
Y ³⁺	0.011	0.016	0.100	0.023	0.021	0.010	0.017
La ³⁺	0.131	0.078	0.100	0.147	0.146	0.262	0.291
Ce ³⁺	0.513	0.449	0.486	0.520	0.530	1.100	1.031
Pr ³⁺	0.066	0.083	0.076	0.071	0.072	0.141	0.130
Nd ³⁺	0.160	0.259	0.209	0.178	0.190	0.368	0.357
Sm ³⁺	0.027	0.075	0.065	0.037	0.032	0.058	0.060
Gd ³⁺	0.006	0.015	0.027	0.009	0.009	b.d.	0.014
Dy ³⁺	0.003	0.006	b.d.	b.d.	b.d.	b.d.	b.d.

Table 2.17. Representative chemical compositions and structural formulae of bastnäsite-(Ce), synchysite-(Ce), and parisite-(Ce) from the Rau 3, 5, and 5U pegmatite dikes.

Sample	R3-A	R5F-A3	R3-1b	R5F-A3	R5U-F	R3-1b	R5U-C
Unit	Rau 3	Rau 5	Rau 3	Rau 5	Rau 5U	Rau 3	Rau 5U
Mineral	*Bsn- (Ce)	Bsn- (Ce)	Snc- (Ce)	Snc- (Ce)	Snc- (Ce)	Prs-(Ce)	Prs-(Ce)
Tm³⁺ (<i>apfu</i>)	b.d.	b.d.	0.009	b.d.	0.004	b.d.	0.007
Ca ²⁺	0.027	0.011	0.861	0.898	0.975	0.996	1.057
Ba ²⁺	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.
K ⁺	-	-	b.d.	b.d.	0.000	0.001	b.d.
F⁻	0.839	0.952	0.738	0.900	0.910	1.264	1.765
C ^{4+†}	1.000	1.000	2.000	2.000	2.000	3.000	3.000
OH-‡	0.161	0.048	1.262	1.100	1.090	0.736	0.235
O ^{2_}	3.173	3.046	6.230	6.126	6.068	9.401	9.099

The formulae for parisite-(Ce) were calculated on the basis of 3 A and B site cations, synchysite-(Ce) on the basis of 2 A and B site cations, and bastnäsite-(Ce) on the basis of 1 A and B site cations per formula unit.

Phosphorus, Ti, Zr, U, Er, Tb, Ho, Yb, Eu, Mg, Pb, Sr, Na, and S in bastnäsite-(Ce), synchysite-(Ce) and parisite-(Ce), Sc and Mn in bastnäsite-(Ce), and As in synchysite-(Ce) and parisite-(Ce) were also sought but were below the detection limit of the EMP in all analyses.

*Bsn = bastnäsite; Snc = synchysite; Prs = parisite; $^{+}CO_2$ was fixed at 3 *apfu* C in parisite-(Ce), 2 *apfu* C in synchysite-(Ce), and 1 *apfu* C in bastnäsite-(Ce); $^{+}H_2O$ contents based on stoichiometry; b.d. = below detection limit.



Figure 2.36. BSE image of an inclusion of monazite-(Ce) (Mnz) in fluorite (Fl) in a quartz-rich (Qz) portion of the Rau 5 pegmatite dike.

Sample	R10-1c	R10-1c	R3-2e	R5F-A3	R3-A	R3-A	R3-A	R1-J	R1-J
Unit	Rau 10	Rau 10	Rau 3	Rau 5	Rau 3	Rau 3	Rau 3	Rau 1	Rau 1
Zone	-	-	-	-	Core	Middle	Rim	-	-
Mineral	*Exn-(Y)	Exn-(Y)	Mnz-(Ce)	Mnz-(Ce)	Aln-(Ce)	Ep	Ep	Hng-(Ce)	Hng-(Ce)
WO₃ (wt.%)	1.46	0.78	-	-	-	-	-	_	-
P_2O_5	b.d.	0.18	29.50	28.76	b.d.	0.06	0.07	b.d.	b.d.
Nb ₂ O ₅	40.94	35.88	-	-	-	-	-	_	-
Ta ₂ O ₅	15.40	18.25	-	-	-	-	-	_	-
SiO ₂	0.14	0.83	0.81	1.47	32.50	37.12	36.17	26.81	26.93
TiO ₂	0.14	0.74	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
ZrO ₂	1.17	b.d.	0.46	b.d.	b.d.	b.d.	b.d.	_	-
ThO ₂	7.88	3.59	3.63	6.50	1.91	6.35	6.08	b.d.	0.29
UO ₂	2.10	0.83	b.d.	b.d.	b.d.	0.15	0.17	b.d.	b.d.
$B_2O_3^\dagger$	-	-	-	-	-	-	-	5.82	6.02
Al ₂ O ₃	b.d.	0.05	-	-	19.61	20.38	19.99	b.d.	b.d.
Sc ₂ O ₃	5.63	b.d.	b.d.	b.d.	0.20	0.24	0.07	b.d.	b.d.
$Fe_2O_{3(min)}^{\ddagger}$	6.09	0.40	0.00	0.00	0.57	8.03	9.43	4.83	2.64
FeO _(max) ‡	0.00	0.00	b.d.	b.d.	8.63	0.00	0.00	1.34	3.21
As_2O_3	0.00	b.d.	0.09	0.08	-	-	-	_	-
Y_2O_3	10.59	13.15	0.44	0.09	0.19	0.18	0.17	6.76	9.12
La ₂ O ₃	b.d.	b.d.	9.21	9.39	2.39	1.39	2.13	2.65	1.99
Ce ₂ O ₃	0.63	0.54	33.29	36.62	10.78	5.52	5.91	12.61	9.97
Pr ₂ O ₃	0.25	b.d.	5.03	4.64	1.56	0.78	0.75	2.47	1.82
Nd_2O_3	1.55	1.91	14.47	11.35	4.39	2.45	1.96	8.16	7.83
Sm ₂ O ₃	0.79	2.05	3.40	1.34	0.70	0.57	0.30	1.94	2.29
Gd_2O_3	0.89	2.19	0.77	b.d.	b.d.	b.d.	b.d.	0.80	1.21
Tb ₂ O ₃	b.d.	0.34	_	_	b.d.	b.d.	b.d.	b.d.	b.d.

Table 2.18. Representative chemical compositions and structural formulae of euxenite-(Y), monazite-(Ce), epidote supergroup minerals, and hingganite-(Ce) from the Rau 1, 3, 5, and 10 pegmatite dikes.

Sample	R10-1c	R10-1c	R3-2e	R5F-A3	R3-A	R3-A	R3-A	R1-J	R1-J
Unit	Rau 10	Rau 10	Rau 3	Rau 5	Rau 3	Rau 3	Rau 3	Rau 1	Rau 1
Zone	-	_	_	-	Core	Middle	Rim	-	-
Mineral	*Exn-(Y)	Exn-(Y)	Mnz-(Ce)	Mnz-(Ce)	Aln-(Ce)	Ep	Ep	Hng-(Ce)	Hng-(Ce)
Dy ₂ O ₃ (wt.%)	0.62	2.06	0.14	b.d.	b.d.	b.d.	b.d.	0.37	0.53
Ho ₂ O ₃	b.d.	0.24	_	-	b.d.	b.d.	b.d.	-	-
Er ₂ O ₃	0.44	1.26	b.d.	b.d.	b.d.	b.d.	b.d.	0.19	0.32
Tm_2O_3	0.35	0.67	_	-	b.d.	b.d.	b.d.	-	-
Yb ₂ O ₃	1.13	2.02	_	-	b.d.	b.d.	b.d.	0.43	0.63
Lu ₂ O ₃	0.31	0.44	_	-	-	_	-	-	-
BeO§	-	-	_	-	-	-	-	6.98	6.88
MgO	b.d.	b.d.	_	-	0.88	0.53	0.41	0.87	0.98
CaO	0.12	4.23	0.34	0.30	12.74	11.03	11.19	9.97	10.56
MnO	1.54	b.d.	_	-	0.75	0.62	0.50	0.29	0.26
SrO	-	-	b.d.	b.d.	0.00	0.20	0.20	b.d.	b.d.
PbO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
Na ₂ O	b.d.	0.56	b.d.	b.d.	b.d.	0.31	0.29	b.d.	b.d.
K ₂ O	b.d.	b.d.	_	-	b.d.	0.02	0.03	0.05	0.14
F	0.17	1.22	_	-	0.13	0.46	0.40	0.82	0.73
CI	-	-	_	-	b.d.	0.02	b.d.	b.d.	b.d.
-(O=F)	-0.07	-0.51	_	-	-0.06	-0.20	-0.17	-0.34	-0.31
H₂O [∥]	-	-	_	-	1.62	5.42	4.59	2.13	2.13
Total	100.25	93.87	101.57	100.53	99.50	101.62	100.70	95.95	96.16
W ⁶⁺ (<i>apfu</i>)	0.025	0.015	_	-	_	_	_	_	_
P ⁵⁺	0.000	0.011	0.973	0.956	b.d.	0.004	0.005	b.d.	b.d.
Nb ⁵⁺	1.243	1.195	_	-	_	_	_	_	_
Ta⁵+	0.281	0.366	_	-	_	-	-	_	-
Si ⁴⁺	0.010	0.061	0.032	0.058	3.000	2.996	2.995	2.000	2.000
Ti ⁴⁺	0.007	0.041	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Sample	R10-1c	R10-1c	R3-2e	R5F-A3	R3-A	R3-A	R3-A	R1-J	R1-J
Unit	Rau 10	Rau 10	Rau 3	Rau 5	Rau 3	Rau 3	Rau 3	Rau 1	Rau 1
Zone	_	-	_	-	Core	Middle	Rim	_	_
Mineral	*Exn-(Y)	Exn-(Y)	Mnz-(Ce)	Mnz-(Ce)	Aln-(Ce)	Ep	Ep	Hng-(Ce)	Hng-(Ce)
Zr ⁴⁺ (apfu)	0.038	0.000	0.009	b.d.	b.d.	b.d.	b.d.	_	_
Th ⁴⁺	0.120	0.060	0.032	0.058	0.040	0.117	0.115	b.d.	0.005
U ⁴⁺	0.031	0.014	b.d.	b.d.	b.d.	0.003	0.003	b.d.	b.d.
B ^{3+†}	_	-	-	-	-	-	_	0.749	0.772
Al ³⁺	0.000	0.005	-	-	2.134	1.939	1.951	b.d.	b.d.
Sc ³⁺	0.330	0.000	b.d.	b.d.	0.016	0.017	0.005	b.d.	b.d.
$Fe^{3+}(min)^{\ddagger}$	0.308	0.022	0.000	0.000	0.039	0.488	0.587	0.271	0.147
$Fe^{2+}(max)^{\ddagger}$	0.000	0.000	b.d.	b.d.	0.666	0.000	0.000	0.084	0.199
As ³⁺	0.00	0.00	0.002	0.002	_	-	_	_	-
Y ³⁺	0.378	0.515	0.009	0.002	0.009	0.008	0.008	0.268	0.361
La³+	0.000	0.000	0.132	0.136	0.081	0.041	0.065	0.073	0.054
Ce ³⁺	0.015	0.015	0.475	0.527	0.364	0.163	0.179	0.344	0.271
Pr ³⁺	0.006	0.000	0.071	0.066	0.052	0.023	0.023	0.067	0.049
Nd ³⁺	0.037	0.050	0.201	0.159	0.145	0.071	0.058	0.217	0.208
Sm ³⁺	0.018	0.052	0.046	0.018	0.022	0.016	0.009	0.050	0.059
Gd ³⁺	0.020	0.053	0.010	b.d.	b.d.	b.d.	b.d.	0.02	0.03
Tb ³⁺	0.000	0.008	-	_	b.d.	b.d.	b.d.	b.d.	b.d.
Dy ³⁺	0.013	0.049	0.002	b.d.	b.d.	b.d.	b.d.	0.009	0.013
Ho ³⁺	0.000	0.006	-	-	b.d.	b.d.	b.d.	_	-
Er ³⁺	0.009	0.029	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	0.007
Tm ³⁺	0.007	0.015	-	_	b.d.	b.d.	b.d.	_	-
Yb ³⁺	0.023	0.045	-	-	b.d.	b.d.	b.d.	0.010	0.014
Lu ³⁺	0.006	0.010	-	-	-	-	_	-	-
Be ^{2+§}	-	-	-	-	-	-	_	1.251	1.228
Mg ²⁺	b.d.	b.d.	_	-	0.121	0.064	0.051	0.097	0.109

Sample	R10-1c	R10-1c	R3-2e	R5F-A3	R3-A	R3-A	R3-A	R1-J	R1-J
Unit	Rau 10	Rau 10	Rau 3	Rau 5	Rau 3	Rau 3	Rau 3	Rau 1	Rau 1
Zone	-	_	_	-	Core	Middle	Rim	-	-
Mineral	*Exn-(Y)	Exn-(Y)	Mnz-(Ce)	Mnz-(Ce)	Aln-(Ce)	Ep	Ep	Hng-(Ce)	Hng-(Ce)
Ca ²⁺ (<i>apfu</i>)	0.009	0.334	0.014	0.013	1.259	0.954	0.993	0.797	0.840
Mn ²⁺	0.087	0.000	_	-	0.058	0.042	0.035	0.019	0.017
Sr ²⁺	-	-	b.d.	b.d.	0.000	0.009	0.010	b.d.	b.d.
Pb ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.
Na ⁺	0.000	0.080	b.d.	b.d.	b.d.	0.049	0.046	b.d.	b.d.
K⁺	0.000	0.000	_	-	b.d.	0.002	0.003	0.005	0.013
F⁻	0.037	0.285	_	-	0.039	0.117	0.106	0.192	0.171
CI⁻	-	_	_	-	b.d.	0.003	b.d.	b.d.	b.d.
OH-II	-	_	-	_	1.000	2.915	2.535	1.059	1.057
O ^{2_}	5.982	5.858	4.000	4.000	12.961	12.881	12.894	6.374	6.386

The formulae for euxenite-(Y) were calculated on the basis of 6 anions, monazite-(Ce) on the basis of 4 oxygen atoms, epidote supergroup minerals on the basis of 3 Si atoms, and hingganite-(Ce) on the basis of 2 Si atoms per formula unit.

Bismuth in euxenite-(Y), Eu and S in monazite-(Ce), and Sn in epidote supergroup minerals were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Exn = euxenite; Hng = hingganite; $^{\dagger}B_2O_3$ was calculated based on the assumption that B = 2 anions – Be; $^{\ddagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{\$}BeO$ was calculated based on assumed 12 total anions; $^{\parallel}H_2O$ contents based on stoichiometry; b.d. = below detection limit; – = not measured.

Sample	R1-J	R3-A	R1-J	R1-J	R10-1c	R10-1c
Unit	Rau 1	Rau 1 Rau 3		Rau 1	Rau 10	Rau 10
Description	With Ab					
Mineral	*Brl	Brl	Sch	Sch	Grt	Grt
WO ₃ (wt.%)	_	_	80.00	78.81	_	_
Nb ₂ O ₅	_	_	0.20	0.78	_	_
Ta ₂ O ₅	_	_	b.d.	0.30	-	_
SiO ₂	68.17	66.15	b.d.	b.d.	35.52	36.01
TiO ₂	0.01	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	18.39	15.83	_	_	20.61	20.38
Cr ₂ O ₃	0.01	b.d.	-	_	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	18.67	17.44
FeO _(max) †	0.20	1.57	0.44	0.31	0.00	3.18
Y_2O_3	_	_	-	_	0.18	b.d.
BeO [‡]	14.19	13.77	_	_	-	_
MgO	0.01	1.21	_	_	b.d.	b.d.
CaO	0.03	b.d.	19.49	19.01	0.93	0.61
MnO	0.02	b.d.	0.09	0.10	25.07	23.50
BaO	0.01	b.d.	_	_	-	_
Na ₂ O	0.17	1.43	_	_	0.13	b.d.
Rb ₂ O	0.09	0.11	_	_	_	-
F	0.02	0.00	_	_	0.76	0.24
-(O=F)	-0.01	0.00	_	_	-0.32	-0.10
Total	101.30	100.07	100.22	99.29	101.54	101.25
W ⁶⁺ (<i>apfu</i>)	_	_	0.990	0.984	_	_
Nb ⁵⁺	_	_	0.004	0.017	_	_
Ta ⁵⁺	_	_	b.d.	0.004	_	_
Si ⁴⁺	6.054	b.d.	b.d.	b.d.	2.947	2.990
Ti ⁴⁺	0.001	0.000	b.d.	b.d.	b.d.	b.d.
Al ³⁺	1.925	1.698	_	_	2.01	1.991
Cr ³⁺	0.001	b.d.	_	_	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.014	0.120	0.000	0.000	1.161	1.125
$Fe^{2+}(max)^{\dagger}$	0.014	0.120	0.018	0.012	0.000	0.183
Y ³⁺	_	_	_	_	0.008	b.d.
Be ^{2+‡}	3.000	3.000	_	_	_	_
Mg ²⁺	0.001	0.163	_	_	b.d.	b.d.
Ca ²⁺	0.003	b.d.	0.997	0.981	0.08	0.054
Mn ²⁺	0.002	b.d.	0.003	0.004	1.755	1.650
Ba ²⁺	0.000	b.d.	_	_	_	_

Table 2.19. Representative chemical compositions and structural formulae of beryl, garnet group minerals, and scheelite from the Rau 1, 3, and 10 pegmatite dikes.

Sample	R1-J	R3-A	R1-J	R1-J	R10-1c	R10-1c
Unit	Rau 1	Rau 3	Rau 1	Rau 1	Rau 10	Rau 10
Description		With Ab				
Mineral	*Brl	Brl	Sch	Sch	Grt	Grt
Na ⁺ (<i>apfu</i>)	0.030	0.252	-	-	0.02	b.d.
Rb⁺	0.005	0.007	-	_	-	-
F⁻	0.005	0.000	_	_	0.20	0.062
O ²⁻	18.032	17.997	4.000	4.000	11.802	11.938

The formulae for beryl were calculated on the basis of 8 *T* and *M* site cations, scheelite on the basis of 4 anions, and garnet on the basis of 12 anions per formula unit. Scandium, V, Zn, K, Cs, S and Cl in beryl, Mo, Sn, Sc and Pb in scheelite, and P, V, K, and Zn in garnet were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]BeO was calculated assuming 3 Be cations per formula unit; b.d. = below detection limit; - = not measured.



Figure 2.37. BSE image of small grains of beryl (Brl) between crystals of albite (Ab) and quartz (Qz) and associated with muscovite (Ms) in the Rau 3 pegmatite dike.



Figure 2.38. BSE image of a zoned grain of an epidote supergroup mineral in muscovite (Ms) in the Rau 3 pegmatite dike. The light-grey zones are allanite-(Ce) (Aln), and the medium-grey and dark-grey zones are epidote (Ep).



Figure 2.39. Epidote classification diagram (modified from Armbruster *et al.*, 2006) showing the composition of epidote supergroup minerals in the Rau 3 pegmatite dike.



Figure 0-1.40. BSE image of anhedral scheelite (Sch) and fluorite (Fl) between muscovite (Ms) and quartz (Qz) crystals in the Rau 3 pegmatite dike.



Figure 2.41. BSE image of euhedral to subhedral grains of spessartine (Sps) hosted in quartz (Qz) and associated with K-feldspar (Kfs) in the Rau 10 pegmatite dike.

2.5.2.3.1 Carbonate-filled pegmatite pockets

Pockets of calcite and other accessory minerals occur in all of the pegmatite dikes except Rau 10. They occur less commonly in the Rau 8 pegmatite dike and were not intersected by any of the thin sections that were made, although they were observed in hand sample. Pockets in the Rau 3, 4, 5U, 6, 7, and 9 pegmatite dikes were examined using EMP analysis. In addition to calcite, all the pockets also contain mica group minerals. The calcite contains variable amounts of exsolved Fe oxide minerals (Fig. 2.42). These pockets can attain sizes of several centimeters across and can contain accessory minerals such as tourmaline supergroup minerals and columbite group minerals (Table 2.20).

The mica group minerals in the pockets are fine-grained (< 1 mm in length) and commonly form elongated grains with highly variable orientations. The pockets in the Rau 3 and 9 pegmatite dikes contain minor biotite–phlogopite series mica group minerals in addition to muscovite (Fig. 2.43a). Pockets in dike Rau 3 contain fluorophlogopite that is highly altered and intergrown with calcite and Fe oxide minerals, whereas pockets in dike Rau 9 mostly contains muscovite but also annite that is intergrown with chlorite group minerals. Fluorophlogopite in pockets in dike Rau 3 contains elevated Rb (up to 0.18 wt.% Rb₂O; 0.009 *apfu*), which is comparable to the Rb contents of muscovite that occurs in pockets within the same part of the pegmatite dike. Unlike the muscovite in the pockets of this pegmatite dike, the fluorophlogopite contains trace amounts of Mn (up to 0.46 wt.% MnO; 0.030 *apfu*). Annite in pockets the Rau 9 pegmatite dike contains 0.30 wt.% Rb₂O (0.016 *apfu*) and 1.34 wt.% F (0.343 *apfu*). Its Ti content is below the detection limit of the EMP (Table 2.21).

Muscovite in the pockets belongs to both the muscovite–trilithionite and trilithionite– polylithionite series. It is more evolved than mica group minerals in the pegmatite dikes, plotting closer to the trilithionite end-member and trending towards the polylithionite end-member (Fig. 2.43a). In Rau 3, samples were taken in a transect across the pegmatite dike. The pockets in the outer parts of the dike contain mica group minerals. Mica group minerals that occur in the outermost part of this dike plot closer to the polylithionite end-member than those that are relatively closer to the centre of the dike (Fig. 2.43b). The Rb and F contents of muscovite-type mica in the pockets is comparable in all pegmatite dikes (Fig. 2.44). Muscovite-type mica in the Rau 6 pegmatite dike has the highest F contents of all muscovite-type mica in the pegmatite pockets (up to 2.040 wt.% F; 0.45 *apfu*). There is a trend towards higher Rb and F contents in muscovite-type mica from an outer part of the Rau 3 pegmatite dike to pockets in its outermost edge (Fig. 2.44).

Tourmaline supergroup minerals are the most common minor mineral in the pegmatite pockets and occur in pockets within the Rau 3, 5U, and 9 dikes. Although alkali elements, specifically Na, are the dominant cations at the X site in all analysed grains, there are compositional differences between the cores and rims of the grains (Fig. 2.45a). In all pegmatite pockets, the cores of tourmaline grains tend to have a greater amount of vacancy at the X site. The vast majority of specimens are OH-dominant at the W site but there is a clear trend towards oxy- and fluor-species in the rims and middle zones of the grains (Fig. 2.45b). The rim of one grain in a Rau 3 pegmatite pocket is oxy-schorl, and the rims of grains in Rau 5U and 9 pockets also approach oxy-dominant compositions. Grains found in pockets in the Rau 9 pegmatite dike have the highest F contents with an average of 0.54 wt.% F (0.029 *apfu*; n = 4) in the rims and middle zones and an average of 0.19 wt.% F (0.010 *apfu*; n = 2) in the cores. The Mg versus Fe content of tourmaline supergroup minerals is less variable. Nearly all tourmaline supergroup specimens are Fe-dominant over Mg, but a middle zone of a grain in a pocket in Rau 9 is Mgdominant and classified as dravite (Fig. 2.45c). All other elements occur in very low concentrations. Titanium was only above the detection limit of the EMP in two analyses of schorl rims in crystals in pockets in dike Rau 5U (average 0.06 wt.% TiO₂; n = 2) (Table 2.22).

A single grain of rutile was identified in a pocket in an outer part of the Rau 3 pegmatite dike. It is not pure end-member composition and contains a significant amount of minor elements including 8.26 wt.% Nb₂O₅ (0.057 *apfu*), 4.15 wt.% WO₃ (0.016 *apfu*), and 2.75 wt.% Ta₂O₅ (0.011 *apfu*).



Figure 2.42. BSE image of pockets of calcite (Cal) with exsolved Fe oxide minerals (Fe ox) in the Rau 4 pegmatite dike. Secondary fine-grained muscovite (Ms) occurs both within the pockets and surrounding them.

Mineral	Rau 3	Rau 4	Rau 5U	Rau 6	Rau 7	Rau 9
Cal*	Х	Х	Х	Х	Х	Х
Fe ox	Х	Х	Т	М	Т	X–M
Ms	Х	Х	-	Х	-	-
Phl	Т	-	_	-	-	Т
Tur	М	-	Μ	_	_	М
Chl	_	-	_	-	-	М
Col	-	Т	_	Т	_	-
FI	Т	-	_	-	Т	-
Ар	Т	-	_	_	_	-
Brl	Т	_	_	_	_	_
Gdl	-	-	-	_	Т	-
Rt	Т	_	_	_	_	_

Table 2.20. Presence and abundance of minerals	s in the pegmatite	ockets.
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*Abbreviations of mineral names follow Whitney & Evans (2010); Fe ox = Fe oxide minerals; Gdl = gadolinite.

X = major mineral; x = accessory mineral; t = trace mineral; – = not observed.



Figure 2.43. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the composition of mica group minerals in (a) the pockets in dikes Rau 3, 4, 5U, 6, and 9. (b) When the outer and outermost parts of the Rau 3 pegmatite dike are distinguished, mica group minerals from the outermost parts of the dike show a trend towards polylithionite.

Sample	R3-A	R3-A	R9b-2c	R3-A	R3-2d	R4-2d	R4-2d
Unit	Rau 3	Rau 3	Rau 9	Rau 3	Rau 3	Rau 4	Rau 4
Mineral	*Fluoro- Phl	Fluoro- Phl	Ann	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	39.10	38.25	34.34	47.42	47.98	46.75	46.24
TiO ₂	0.06	0.05	0.00	0.00	0.13	0.00	0.00
Al ₂ O ₃	13.00	13.55	15.15	31.11	25.37	30.28	29.68
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	18.98	19.74	30.50	3.17	3.57	3.67	4.56
MgO	13.11	12.60	5.52	1.34	5.80	2.00	2.35
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	0.46	0.42	0.22	b.d.	b.d.	0.08	0.06
Na ₂ O	0.13	0.16	0.07	0.21	0.10	0.24	0.20
K ₂ O	9.78	9.77	9.49	11.09	11.09	11.04	11.05
Rb ₂ O	0.18	0.17	0.30	0.14	0.46	0.27	0.27
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.
F	4.39	4.13	1.34	0.98	1.95	1.02	1.29
Cl	0.15	0.16	0.55	b.d.	b.d.	0.05	0.06
H_2O^{\ddagger}	1.79	1.89	2.92	3.94	3.44	3.88	3.72
–(O=F,Cl)	-1.88	-1.77	-0.69	-0.41	-0.82	-0.44	-0.56
Total	99.24	99.12	99.71	98.98	99.06	98.91	98.93
Si ⁴⁺ (<i>apfu</i>)	2.997	2.950	2.786	3.224	3.300	3.204	3.186
Ti ⁴⁺	0.003	0.003	0.000	0.000	0.007	0.000	0.000
Al ³⁺	1.175	1.232	1.448	2.493	2.056	2.445	2.410
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.217	1.273	2.069	0.180	0.205	0.210	0.263
Mg ²⁺	1.498	1.449	0.668	0.135	0.595	0.204	0.241
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	0.030	0.028	0.015	b.d.	b.d.	0.005	0.004
Na ⁺	0.019	0.024	0.011	0.028	0.014	0.032	0.027
K+	0.957	0.962	0.982	0.962	0.973	0.965	0.971
Rb⁺	0.009	0.009	0.016	0.006	0.020	0.012	0.012
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.
F⁻	1.064	1.006	0.343	0.211	0.423	0.222	0.282
Cl⁻	0.019	0.021	0.076	b.d.	b.d.	0.005	0.007
OH⁻‡	0.917	0.973	1.581	1.789	1.577	1.773	1.711
vacancy	0.080	0.066	0.014	0.968	0.838	0.932	0.896
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Table 2.21. Representative chemical compositions and structural formulae of mica group minerals from pockets in the Rau 3, 4, 5U, 6, and 9 pegmatite dikes.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit.
Phosphorus, Cr, V, Sc, Sn, Ba, and S were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); † Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡ H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-I	R5U-I	R6-1b	R6-1b	R9b-2c
Unit	Rau 5U	Rau 5U	Rau 6	Rau 6	Rau 9
Mineral	Ms	Ms	 Ms	Ms	Ms
SiO ₂ (wt.%)	49.09	48.62	 47.50	47.23	44.78
TiO ₂	0.11	0.00	0.24	0.12	0.09
Al ₂ O ₃	30.35	30.03	25.40	27.30	29.73
$Fe_2O_{3(min)}{}^\dagger$	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.90	2.57	3.98	3.48	4.53
MgO	1.30	2.24	5.60	3.61	1.51
CaO	b.d.	b.d.	0.04	0.06	b.d.
MnO	b.d.	b.d.	b.d.	0.14	b.d.
Na ₂ O	0.07	0.12	0.13	0.18	0.12
K ₂ O	11.50	11.58	11.41	11.37	10.99
Rb ₂ O	0.36	0.20	0.19	0.13	0.19
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.
F	1.28	1.45	2.04	1.76	1.30
CI	0.00	0.00	0.03	0.03	0.06
H_2O^{\ddagger}	3.86	3.76	3.37	3.48	3.61
-(O=F,Cl)	-0.54	-0.61	-0.87	-0.75	-0.56
Total	100.29	99.96	99.07	98.15	96.35
Si ⁴⁺ (<i>apfu</i>)	3.295	3.274	3.277	3.271	3.168
Ti ⁴⁺	0.006	0.000	0.013	0.006	0.005
Al ³⁺	2.401	2.383	2.065	2.228	2.479
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.163	0.145	0.230	0.202	0.268
Mg ²⁺	0.130	0.224	0.576	0.372	0.159
Ca ²⁺	b.d.	b.d.	0.003	0.005	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	0.008	b.d.
Na⁺	0.010	0.015	0.017	0.024	0.017
K ⁺	0.985	0.994	1.004	1.005	0.992
Rb⁺	0.016	0.008	0.008	0.006	0.009
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.
F-	0.273	0.309	0.445	0.387	0.291
CI⁻	0.000	0.000	0.004	0.004	0.007
OH-‡	1.727	1.691	1.551	1.610	1.701
vacancy	1.006	0.974	0.840	0.913	0.921
O ^{2_}	10.000	10.000	10.000	10.000	10.000

Table 2.21. (Continued) Representative chemical analyses and structural formulae of mica group minerals from pockets in the Rau 3, 4, 5U, 6, and 9 pegmatite dikes.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit.

Phosphorus, Cr, V, Sc, Sn, Ba, and S were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.44. Rubidium and F contents of muscovite–trilithionite and trilithionite–polylithionite series mica in the pockets. When the outer and outermost parts of the Rau 3 pegmatite dike are distinguished, mica group minerals from pockets in the outermost parts of the dike trend towards higher Rb and F contents.



Figure 2.45. Compositional variation of tourmaline supergroup minerals from pockets in the Rau 3, 5U, and 9 pegmatite dikes. (a) Classification diagram based on the dominant occupancy of the *X* site (Henry *et al.*, 2011). There is a trend towards *X*-vacant group tourmaline species from core to rim. (b) General series of tourmaline supergroup mineral species based on the occupancy of the *W* site (Henry *et al.*, 2011). There is a trend towards oxy- and fluor-species from core to rim. (c) Binary plot of Ca / (Ca + Na) versus Mg / (Mg + Fe²⁺). Most analysed tourmaline supergroup minerals are Fe-dominant, but Mg / (Mg + Fe²⁺) increases from core to rim.

Sample	R3-2c	R3-2c	R5U-I	R5U-I	R9a-4c	R9a-4c
Unit	Rau 3	Rau 3	Rau 5U	Rau 5U	Rau 9	Rau 9
Zone	Core	Rim	Core	Rim	Core	Rim
Mineral	*Srl	Oxy-srl	Srl	Srl	Srl	Srl
SiO ₂ (wt.%)	36.79	36.04	36.66	36.84	37.14	36.50
TiO ₂	b.d.	b.d.	b.d.	0.06	b.d.	b.d.
$B_2O_3^{\dagger}$	10.47	10.31	10.51	10.56	10.61	10.48
Al ₂ O ₃	31.82	30.44	32.05	31.71	32.11	31.70
Fe ₂ O ₃ [‡]	0.00	3.14	0.00	0.00	0.00	0.00
FeO [‡]	11.85	8.90	12.77	11.58	11.37	10.79
MgO	4.08	4.78	3.72	4.78	4.75	5.09
CaO	0.29	0.26	0.11	0.43	0.21	0.49
MnO	0.06	0.10	0.06	0.07	b.d.	b.d.
Na ₂ O	2.33	2.71	1.93	2.40	2.24	2.72
K ₂ O	b.d.	0.06	b.d.	b.d.	b.d.	0.05
F	0.32	0.37	0.14	0.50	0.25	0.59
CI	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
H_2O^{\S}	3.19	2.84	3.54	3.21	3.40	3.00
-(O=F)	-0.13	-0.16	-0.06	-0.21	-0.11	-0.26
Total	101.05	99.81	101.42	101.93	101.99	101.19
Si ⁴⁺ (<i>apfu</i>)	6.109	6.079	6.062	6.065	6.083	6.053
Ti ⁴⁺	0.000	0.000	0.000	0.007	0.000	0.000
B ^{3+†}	3.000	3.000	3.000	3.000	3.000	3.000
Al ³⁺	6.228	6.050	6.246	6.151	6.199	6.194
Fe ³⁺ (min) [‡]	0.000	0.399	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\ddagger}$	1.646	1.255	1.766	1.594	1.558	1.496
Mg ²⁺	1.009	1.202	0.917	1.174	1.160	1.257
Ca ²⁺	0.052	0.048	0.020	0.075	0.037	0.087
Mn ²⁺	0.009	0.015	0.009	0.009	0.000	0.000
Na⁺	0.749	0.887	0.618	0.766	0.712	0.875
K+	0.000	0.012	0.000	0.000	0.000	0.011
F⁻	0.168	0.199	0.072	0.261	0.131	0.310
CI⁻	0.000	0.000	0.000	0.000	0.000	0.010
OH-§	3.533	3.200	3.900	3.528	3.719	3.321
O ^{2_}	30.832	30.801	30.928	30.739	30.869	30.679

Table 2.22. Representative chemical compositions and structural formulae of tourmaline supergroup minerals from pockets in the Rau 3, 5U, and 9 pegmatite dikes.

The formulae were calculated on the basis of 15 Y + Z + T cations [general formula $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$] per formula unit.

Vanadium, Cr, Ni, Zn, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{\dagger}B_2O_3$ was fixed at 3 *apfu* B; $^{\dagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{\$}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

2.5.2.4 Aplite dikes

The two aplite dikes associated with the Rau pegmatite group are composed of quartz, K-feldspar, and albite. Portions of one of the aplite dikes are rich in mica group minerals, calcite, and locally contain significant amounts of beryl. Minerals that are present in trace amounts in the dikes are columbite group minerals, zircon, and Fe sulphide minerals (Table 2.23). This aplite dike was studied in detail.

Mica group minerals are irregularly distributed throughout the dike. Some parts of the dike consist almost entirely of quartz, mica group minerals, and calcite, whereas others are nearly free of mica group minerals. Two habits of mica group minerals are present: (1) larger (1–2 cm) subhedral to anhedral grains that are associated with the beryl-rich part of the dike, and (2) smaller (0.25–1 mm) euhedral grains that are associated with quartz and calcite. Both habits of mica group minerals are muscovite and evolve towards polylithionite with a small trilithionite component (Fig. 2.46). Their minor element contents are very similar: both types of muscovite contain trace Na (up to 0.29 wt.% Na₂O in the coarser-grained muscovite versus up to 0.27 wt.% in the finer-grained muscovite), Rb (up to 0.23 wt.% Rb₂O in the coarser-grained muscovite versus up to 0.13 wt.% in the finer-grained muscovite), and F (up to 1.29 wt.% F in the coarser-grained muscovite). The only noticeable difference is in their Ti contents. The coarser-grained muscovite contains up to 0.14 wt.% TiO₂ (0.007 *apfu*), whereas the Ti content of the finer-grained muscovite is below the detection limit of the EMP. There is a slight difference between the composition of the cores and rims in that the cores tend to be richer in Ti and Rb than the rims (Table 2.24).

Beryl forms large (1.5 mm to 1 cm long) euhedral to anhedral grains in muscovite-rich parts of the aplite dike (Fig. 2.47). The translucent to semi-translucent crystals have a pale blue to medium blue colour. A substantial amount of Fe and Mg substitutes for Al at the *Y* site. The maximum contents of these elements is 0.56 wt.% FeO (0.043 *apfu*) and 0.89 wt.% MgO (0.120 *apfu*) in the rim of a crystal. There is also a large amount of Na and Rb substituting in the channels in the crystal structure, with up to 0.83 wt.% Na₂O (0.146 *apfu*) and 0.11 wt.% Rb₂O (0.007 *apfu*) in two separate parts of the rim of a crystal (Table 2.25).

Columbite group minerals occur in trace amounts in the aplite dike and as small (< 100 μ m) isolated grains within coarse-grained muscovite (Fig. 2.48). They are rich in Fe and Nb, classifying them as columbite-(Fe) [Fe_{tot} / (Fe_{tot} + Mn) = 0.85–0.87 and Nb / (Nb + Ta) = 0.78–

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0.88; n = 2]. Columbite-(Fe) contains a substantial amount of Ti, W, and Sc. Titanium content attains 0.94 wt.% TiO₂ (0.043 *apfu*), and the same grain contains 0.39 wt.% Sc₂O₃ (0.021 *apfu*). The grain of columbite-(Fe) with slightly lower Ti and Sc contents has the highest contents of W, with 0.68 wt.% WO₃ (0.010 *apfu*) (Table 2.25).

Zircon and Fe sulphide minerals also occur only in trace amounts and are also associated with coarser-grained muscovite and form very small isolated grains (Fig. 2.48).

Table 2.23. Presence and abundance of minerals in the aplite dike.

Unit	*Qz	Ms	Cal	Brl	Col	Zrc	Fe sul
Aplite dike	Х	Х	М	M–T	Т	Т	Т
				<u> </u>	(_

*Abbreviations of mineral names follow Whitney & Evans (2010); Fe sul = Fe sulphide minerals.

X = major mineral; x = accessory mineral; t = trace mineral; – = not observed.



Figure 2.46. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the composition of mica group minerals in the aplite dike.

Sample	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1
Grain size	Coarse	Coarse	Coarse	Coarse	Fine	Fine
Zone	Rim	Core	Rim	Core	Rim	Core
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.02	47.23	47.97	46.31	47.19	46.86
TiO ₂	b.d.	0.14	b.d.	b.d.	0.10	0.11
Al ₂ O ₃	32.87	31.88	29.71	34.24	33.29	30.06
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.38	2.58	1.82	1.27	1.51	3.29
MgO	1.14	1.63	2.98	0.77	1.17	2.44
CaO	b.d.	b.d.	b.d.	0.04	b.d.	b.d.
Na ₂ O	0.29	0.22	0.23	0.27	0.26	0.23
K ₂ O	11.35	11.14	11.33	11.36	11.30	11.06
Rb ₂ O	0.16	0.17	0.10	0.13	0.07	0.23
F	0.75	0.56	1.26	b.d.	b.d.	1.29
CI	b.d.	0.02	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	4.07	4.17	3.82	4.44	4.47	3.77
-(O=F,Cl)	-0.32	-0.24	-0.53	0.00	0.00	-0.54
Total	98.72	99.50	98.70	98.82	99.35	98.79
Si ⁴⁺ (<i>apfu</i>)	3.182	3.187	3.259	3.126	3.168	3.206
Ti ⁴⁺	b.d.	0.007	b.d.	b.d.	0.005	0.006
Al ³⁺	2.621	2.536	2.379	2.724	2.634	2.424
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.078	0.146	0.103	0.071	0.085	0.188
Mg ²⁺	0.115	0.164	0.302	0.077	0.117	0.248
Ca ²⁺	b.d.	b.d.	b.d.	0.003	b.d.	b.d.
Na ⁺	0.038	0.029	0.031	0.035	0.033	0.031
K⁺	0.980	0.959	0.982	0.978	0.968	0.966
Rb⁺	0.007	0.007	0.005	0.006	0.003	0.010
F⁻	0.161	0.120	0.271	b.d.	b.d.	0.278
CI⁻	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
OH-‡	1.839	1.878	1.729	2.000	2.000	1.722
vacancy	1.005	0.960	0.957	1.001	0.992	0.927
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000

Table 2.24. Representative chemical compositions and structural formulae of muscovite from the aplite dike.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit. Chromium, Mn, and Cs were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.47. BSE image of a crystal of beryl (Brl) that occurs on the edge of an area of coarser-grained muscovite (Ms) in the aplite dike.

Sample	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1
Zone	Rim	Core	Rim	Core	_	-
Mineral		*	Brl		Col-	·(Fe)
WO ₃ (wt.%)	-	_	_	_	0.58	0.68
Nb ₂ O ₅	-	-	_	_	54.24	63.59
Ta ₂ O ₅	_	_	_	_	24.99	14.31
SiO ₂	66.16	67.26	66.61	67.07	0.04	0.15
TiO ₂	b.d.	b.d.	b.d.	b.d.	0.94	0.62
ZrO ₂	-	-	-	-	0.03	0.05
ThO ₂	-	-	-	-	0.04	0.00
UO ₂	-	-	-	-	0.05	0.07
AI_2O_3	17.22	17.69	18.20	18.24	0.07	0.05
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	3.63	4.57
$FeO_{(max)}^{\dagger}$	0.56	0.50	0.28	0.21	14.16	13.75
Sc ₂ O ₃	b.d.	0.04	b.d.	b.d.	0.39	0.21
Y ₂ O ₃	-	-	-	-	0.02	0.07
Bi ₂ O ₃	-	-	-	-	b.d.	0.09
BeO [‡]	13.77	14.00	13.86	13.96	-	-
MgO	0.89	0.61	0.15	0.05	0.07	0.26
MnO	b.d.	b.d.	b.d.	b.d.	2.47	3.16
Na ₂ O	0.83	0.64	0.24	0.13	0.06	0.02
Rb ₂ O	0.00	0.11	0.11	0.11	_	-
Total	99.43	100.84	99.46	99.75	101.80	101.63
W ⁶⁺ (<i>apfu</i>)	-	_	-	-	0.009	0.010
Nb ⁵⁺	-	-	-	-	1.484	1.665
Ta⁵+	-	-	-	-	0.411	0.225
Si ⁴⁺	5.998	6.014	6.021	6.042	0.002	0.009
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	0.043	0.027
Zr ⁴⁺	-	-	-	-	0.001	0.001
Th ⁴⁺	-	-	-	-	0.001	0.000
U ⁴⁺	-	-	-	-	0.001	0.001
Al ³⁺	1.839	1.864	1.939	1.936	0.005	0.003
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.165	0.199
$Fe^{2+}(max)^{\dagger}$	0.043	0.037	0.021	0.015	0.717	0.666
Sc ³⁺	b.d.	0.003	b.d.	b.d.	0.021	0.011
Y ³⁺	-	-	-	-	0.001	0.002
Bi ³⁺	-	-	-	-	b.d.	0.001
Be ^{2+‡}	3.000	3.000	3.000	3.000	-	-
Mg ²⁺	0.120	0.081	0.020	0.006	0.006	0.022

Table 2.25. Representative chemical compositions and structural formulae of beryl and columbite-(Fe) from the aplite dike.

Sample	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1
Zone	Rim	Core	Rim	Core	-	-
Mineral		*E	Brl		Col-	(Fe)
Mn²+ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	0.127	0.155
Na⁺	0.146	0.11	0.042	0.023	0.007	0.003
Rb⁺	0.000	0.006	0.007	0.006	-	-
O ²⁻	17.991	18.006	18.014	18.025	6.000	6.000

The formulae for beryl were calculated on the basis of 8 T and M site cations and columbite-(Fe) on the basis of 6 O atoms per formula unit.

Phosphorus, Cr, Zn, Ca, Ba, Cs, K, F and Cl in beryl, and Sn, Zn, Sb, Ca, Pb, F and Cl in columbite-(Fe) were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Col = columbite; [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]BeO was calculated based on assumed 3 Be cations; b.d. = below detection limit; - = not measured.



Figure 2.48. BSE image of small, isolated grains of columbite-(Fe) (Col) and Fe sulphide minerals (Fe sul) in coarse-grained muscovite (Ms) and calcite (Cal) in the aplite dike.

2.5.2.5 Endo-contact skarns

Endo-contact skarns are associated with dikes Rau 5, 5U, 6, 7, and 9. The skarns are mainly composed of mica group minerals and calcite, with the exception of the endo-contact skarn bordering dike Rau 6, which also contains amphibole supergroup minerals as a major component. This amphibole supergroup-bearing skarn is distinguished as a different type of skarn, hereafter called "amphibole-type endo-contact skarn" or simply "amphibole-type skarn". The type and abundance of minor and accessory minerals varies both between skarn types and within the same skarn type (Table 2.26).

The biotite-type endo-contact skarns generally occur as a thin layer (1 mm to 2 cm) within the pegmatite dike at the contact with its host rock. Parts of these skarns extend further into the pegmatite dikes where they are associated with pockets of calcite (Fig. 2.49). The amphiboletype endo-contact skarn that borders dike Rau 6 is thicker than the biotite-type skarns, attaining 5 cm in thickness.

There are three different types of boundaries between the endo-contact skarns and the pegmatites. The Rau 5, 5U, and 7 biotite-type endo-contact skarns form an irregular boundary with the pegmatite that is commonly bordered by graphic intergrowths of quartz and K-feldspar (Fig. 2.50). In the Rau 9 endo-contact skarn there is a sharp transition from the skarn to the pegmatite, marked by $\sim 25-100 \mu m$ of muscovite that is coarser-grained than the muscovite within the pegmatite dike (Fig. 2.51). This skarn can also extend further into the pegmatite dike. The transition from pegmatite to skarn is not as sharp in these extensions but it is still marked by an increased abundance and grain size of muscovite (Fig. 2.52). The amphibole-type endo-contact skarn is separated from the Rau 6 pegmatite by a quartz vein (Fig. 2.53).

Biotite–phlogopite series mica occurs in all endo-contact skarns and is always a major mineral. It forms tabular to elongated grains that generally have variable orientations with respect to the boundary of the endo-contact skarn and the pegmatite dike. In the Rau 9 endo-contact skarn, most of the mica has a variable orientation; however, coarser grains near the boundary with the pegmatite dike tend to be oriented perpendicular to that boundary (Fig 2.54). The grain size of biotite–phlogopite series mica is also variable and can vary from < 50 μ m to 7 mm within the same skarn. In the Rau 9 endo-contact skarn, there is a distinct increase in the grain size of annite with proximity to the fine-grained muscovite that borders the pegmatite dike (Fig. 2.54).

In the majority of the biotite-type skarns, the biotite-phlogopite series mica is annite; however, in the Rau 5U biotite-type skarn it is phlogopite (Fig. 2.55). The most Fe-rich annite occurs in the endo-contact skarn bordering dike Rau 9 with an average Fe / (Fe + Mg) of 0.76 (n= 3). Annite in the Rau 7 biotite-type endo-contact skarn has an average Fe / (Fe + Mg) of 0.57(n = 6), whereas photophic in the Rau 5U biotite-type skarn has an average Fe / (Fe + Mg) of 0.48 (n = 2). Annite in the Rau 6 amphibole-type skarn has one of the lowest average Fe / (Fe + Mg) values at 0.51 (n = 2). The Ti contents of all analysed annite is low, but it attains 0.14 wt.% TiO_2 (0.008 *apfu*) in the amphibole-type endo-contact skarn bordering dike Rau 6. In the biotitetype endo-contact skarns, the highest Ti contents occur in annite in the Rau 7 skarn, with 0.14 wt.% TiO₂ (0.008 apfu). Phlogopite from the endo-contact skarn bordering dike Rau 5U has the highest average Rb contents (0.34 wt.% Rb₂O; 0.017 *apfu*; n = 2) of all analysed samples. This is significantly higher than the average Rb contents of annite from the biotite-type endo-contact skarn bordering dike Rau 9 (0.27 wt.% Rb₂O; 0.014 *apfu*; t stat. = 3.92 > t crit. = 3.18; p-value .03), as well as Rau 7 biotite-type and the Rau 6 amphibole-type skarn in which the Rb contents of the annite was below the detection limit of the EMP in all analyses (n = 6 and 2 respectively). There is a negative correlation between the F contents of the biotite-phlogopite series mica and its Fe:Mg ratio, whereas there is a positive correlation between its Cl contents and Fe:Mg ratio (Figs. 2.56a and 2.56b). The most Fe-rich annite that occurs in the Rau 9 endo-contact skarn has the lowest F contents and the highest Cl contents of all analysed biotite-phlogopite series mica. Annite in the Rau 7 endo-contact skarn approaches fluorannite with up to 3.91 wt.% F (0.957 *apfu*); it also contains elevated Cl with up to 0.48 wt.% Cl (0.064 *apfu*) (Table 2.27).

Muscovite occurs in all of the biotite-type endo-contact skarns but it does not occur in the amphibole-type endo-contact skarn. It is a major mineral in the Rau 5U endo-contact skarn where it is more abundant than phlogopite. In the Rau 7 endo-contact skarn, it is highly altered and is associated with calcite that is intergrown with Fe oxide minerals and fluorite (Fig. 2.57). In the Rau 9 endo-contact skarn, increased abundance and grain size of muscovite marks the transition between the endo-contact skarn and the pegmatite. The muscovite in the endo-contact skarn bordering dike Rau 5U contains significantly more Na and Rb than the muscovite in the endo-contact skarn bordering dike Rau 7. Muscovite in the Rau 5U skarn contains an average of 0.18 wt.% Na₂O (0.024 *apfu*) and 0.24 wt.% Rb₂O (0.011 *apfu*; n = 11), whereas muscovite in the Rau 7 skarn contains an average of 0.07 wt.% Na₂O (0.009 *apfu*; n = 3) and Rb was below

the detection limit in all analyses (t stat. = 5.17 > t crit. = 2.18; p-value <.001 for Na; t stat. = 8.08 > t crit. = 2.18; p-value <.001 for Rb). In contrast, muscovite in the skarn bordering dike Rau 5U contains significantly less Ti and F than that bordering dike Rau 7, with an average of 0.04 wt.% TiO₂ (0.002 *apfu*) and 1.26 wt.% F (0.272 *apfu*) in muscovite in the Rau 5U endocontact skarn and an average of 0.16 wt.% TiO₂ (0.008 *apfu*) and 1.93 wt.% F (0.415 *apfu*) in muscovite in the Rau 7 endo-contact skarn (t stat. = 3.35 > t crit. = 2.18; p-value .005 for Ti; t stat. = 4.14 > t crit. = 2.18; p-value .001 for F) (Table 2.28).

Amphibole supergroup minerals only occur in the Rau 6 amphibole-type endo-contact skarn. They form elongated grains that are intergrown with annite and are generally oriented perpendicular to the boundary with the pegmatite dike, but other orientations are present (Fig. 2.53). All specimens are part of the ^W(OH,F,Cl)-dominant amphibole group and the calcium amphibole subgroup and display patchy zonation. Amphibole supergroup species present are magnesio-hornblende, ferro-edenite, ferro-hornblende, ferro-actinolite, and actinolite (Figs. 2.58a and 2.58b). The Mn contents of all species is similar with an average of 0.76 wt.% MnO (0.096 *apfu*). All analysed species contain F and Cl, with an average of 1.28 wt.% F (0.607 *apfu*) and 0.09 wt.% Cl (0.023 *apfu*) and a maximum of 1.60 wt.% F (0.741 *apfu*) in magnesio-hornblende and 0.23 wt.% Cl (0.061 *apfu*) in ferro-edenite (Table 2.29).

Epidote supergroup minerals are present in minor amounts in the biotite-type endo-contact skarns that border dikes Rau 7 and 9, and in the amphibole-type endo-contact skarn that borders dike Rau 6. The grains are relatively large—up to 600 μ m in length in the Rau 7 skarn, 800 μ m in length in the Rau 9 skarn, and 200 μ m in length in the Rau 6 skarn—and display chaotic growth zonation (Fig. 2.59). Most of the epidote supergroup minerals in the Rau 9 biotite-type endo-contact skarn are epidote; however, some of the patchy zones in one grain are clinozoisite. In the Rau 7 biotite-type endo-contact skarn there is a continuum of compositions from epidote to clinozoisite to allanite-(Ce). In the Rau 6 amphibole-type endo-contact skarn the rim of one crystal is clinozoisite, whereas the core is allanite-(Ce) (Fig. 2.60).

Overall, the epidote and clinozoisite in the Rau 9 biotite-type skarn have low minor element contents, with a maximum of 0.77 wt.% MnO (0.060 *apfu*) and 0.06 wt.% F (0.016 *apfu*). Epidote has relatively high Th contents, with up to 6.95 wt.% ThO₂ (0.144 *apfu*) (Table 2.30).

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The chemical composition of epidote supergroup minerals varies from core to rim in the oscillatory zoned crystals that occur in the Rau 7 biotite-type skarn and the Rau 6 amphiboletype skarn. In the Rau 7 biotite-type skarn, the composition oscillates between REE-poor allanite-(Ce) and epidote cores, to an REE-rich allanite-(Ce) zone, to epidote rims (Fig. 2.59). In addition to this variation in REE contents, the middle allanite-(Ce) zone tends to have higher contents of Mg (up to 1.00 wt.% MgO; 0.140 apfu) and Mn (up to 1.06 wt.% MnO; 0.085 apfu). Iron and Th contents increase from core to rim with an average of 10.62 wt.% FeO (0.776 apfu) and 1.10 wt.% ThO₂ (0.022 *apfu*) in the core and 12.40 wt.% FeO (0.913 *apfu*) and 2.38 wt.% ThO₂ (0.048 apfu) in the rim. Scandium contents decrease from core to rim with an average of 0.44 wt.% Sc₂O₃ (0.033 apfu) in the core and 0.08 wt.% Sc₂O₃ (0.006 apfu) in the rim. The F contents are more erratic, but the middle allanite-(Ce) zone has higher F contents than the core, and the outermost epidote rim has the highest F content with 0.30 wt.% F (0.084 apfu) (Fig. 2.61). In the Rau 6 amphibole-type skarn, the allanite-(Ce) cores are relatively enriched in Mg (up to 0.65 wt.% MgO versus 0.27 wt.% in the rims), Mn (up to 0.67 wt.% MnO versus 0.33 wt.% in the rims), Sc (up to 0.19 wt.% Sc_2O_3 versus below the detection limit of the EMP in the rims), and F (up to 0.28 wt.% F versus 0.02 wt.% in the rims), whereas the clinozoisite rims are relatively enriched in Th (up to 1.77 wt.% ThO₂ versus 1.19 wt.% in the cores) (Fig. 2.62) (Table 2.30).

There are no significant differences in the minor element contents of allanite-(Ce) in the Rau 7 biotite-type and Rau 6 amphibole-type endo-contact skarns. Notably, they both contain Sc and F, with up to 0.49 wt.% Sc₂O₃ (0.037 *apfu*) and 0.22 wt.% F (0.065 *apfu*) in allanite-(Ce) in the Rau 7 skarn and 0.19 wt.% Sc₂O₃ (0.015 *apfu*) and 0.28 wt.% F (0.082 *apfu*) in allanite-(Ce) in the Rau 6 skarn (Table 2.30).

Pyrochlore supergroup minerals occur in trace amounts in all of the endo-contact skarns, but EMP analysis was only performed on specimens from the Rau 6 amphibole-type and biotite-type endo-contact skarns because the grain size of pyrochlore supergroup minerals in the other skarns was too small to obtain accurate analyses. In these skarns the pyrochlore supergroup minerals form extremely small grains (< 5 to \sim 20 µm) that can form larger aggregates of grains (Fig. 2.63).

The grains of pyrochlore supergroup minerals in the amphibole-type skarn are zoned with cores of fluorcalciomicrolite [average Ca / (Ca + Na + U) = 0.68 and Ta / (Ta + Nb + Ti) = 0.81;

n = 3] that are rimmed by fluorcalciopyrochlore [average Ca / (Ca + Na + U) = 0.71 and Ta / (Ta + Nb + Ti) = 0.47; n = 3] (Fig. 2.63). The fluorcalciopyrochlore contains a substantial amount of Sn, with a maximum of 2.79 wt.% SnO₂ (0.085 *apfu*), whereas the fluorcalciomicrolite still contains up to 1.56 wt.% SnO₂ (0.056 *apfu*). Other minor elements are more abundant in fluorcalciomicrolite, including Ti with up to 1.06 wt.% TiO₂ (0.072 *apfu*) and W with up to 0.64 wt.% WO₃ (0.015 *apfu*) (Table 2.31).

Grains of pyrochlore supergroup minerals in the Rau 6 biotite-type skarn are extremely small (< 50 μ m) and have a homogeneous composition. They are fluorcalciomicrolite with Ca / (Ca + Na + U) = 0.55–0.63 and Ta / (Ta + Nb + Ti) = 0.54–0.78. Their Sn contents are similar to the fluorcalciomicrolite in the Rau 6 amphibole-type skarn, with up to 1.52 wt.% SnO₂ (0.052 *apfu*). Unlike pyrochlore supergroup minerals in the Rau 6 amphibole-type skarn, the fluorcalciomicrolite has low Ti contents: one analysis yielded 0.51 wt.% TiO₂ (0.030 *apfu*), whereas the Ti content was below the detection limit of the EMP in the other two analyses. That same fluorcalciomicrolite grain also contains 0.65 wt.% WO₃ (0.013 *apfu*), which is the highest observed W content in pyrochlore supergroup minerals from either of the skarn types (Table 2.31).

Columbite group minerals occur in the biotite-type endo-contact skarns bordering dikes Rau 5U, 6, and 9. All specimens are columbite-(Fe) with Nb / (Nb + Ta) = 0.84 in the Rau 5U skarn, 0.79 in the Rau 6 skarn, and 0.86 in the Rau 9 skarn, and Fe / (Fe + Mn) = 0.96 in the Rau 5U skarn, 0.85 in the Rau 6 skarn, and 0.92 in the Rau 9 skarn (Fig. 2.64). Columbite-(Fe) in the Rau 5U endo-contact skarn is rich in Ti and W, with 7.98 wt.% TiO₂ (0.351 *apfu*) and 7.42 wt.% WO₃ (0.112 *apfu*). These elements are also elevated in columbite-(Fe) in the Rau 6 and 9 endocontact skarns, with 2.34 wt.% TiO₂ (0.108 *apfu*) and 1.04 wt.% WO₃ (0.017 *apfu*) in the Rau 6 skarn, and with 1.27 wt.% TiO₂ (0.056 *apfu*) and 1.42 wt.% WO₃ (0.022 *apfu*) in the Rau 9 skarn. All columbite-(Fe) contains Sc, with the highest contents occurring in the Rau 6 and 9 endo-contact skarns [0.40 wt.% and 0.38 wt.% Sc₂O₃ (0.021 and 0.019 Sc *apfu*), respectively] (Table 2.32).

Minerals that occur in trace amounts in only one of the endo-contact skarns are apatite group minerals, scheelite, gadolinite-(Y), and synchysite-(Ce). Apatite group minerals are present in the amphibole-type endo-contact skarn that borders dike Rau 6, where they form small (\sim 100 µm) euhedral crystals in the amphibole-rich portions of the skarn. Their composition is

fluorapatite with F / (F + Cl) = 1.00. The only minor element this apatite contains is 0.19 wt.% Y₂O₃ (0.009 *apfu*) (Table 2.32). Scheelite is present in trace amounts in the Rau 9 biotite-type endo-contact skarn. Its composition is essentially pure, with only trace contents of F (up to 0.10 wt.% F; 0.015 *apfu*) (Table 2.32). A single grain of gadolinite-(Y) occurs in the Rau 6 amphibole-type endo-contact skarn where it fills a fracture in fluorite. In this crystal Y is by far the dominant REE with 22.97 wt.% Y₂O₃ (0.816 *apfu*), followed by 2.01 wt.% Yb₂O₃ (0.041 *apfu*), 1.37 wt.% Gd₂O₃ (0.030 *apfu*), and 1.21 wt.% Dy₂O₃ (0.026 *apfu*). It is Ca-bearing with 13.29 wt.% CaO (0.950 *apfu*) (Table 2.33). Synchysite-(Ce) occurs as an inclusion within epidote in the Rau 9 biotite-type endo-contact skarn. It is Ce-dominant, with Ce / (Ce + La + Nd) = 57.22, but is also rich in Nd, with 10.51 wt.% Nd₂O₃ (0.196 *apfu*). It also contains trace amounts of Th (4.10 wt.% ThO₂; 0.049 *apfu*), Fe (0.25 wt.% FeO_{tot}; 0.011 *apfu*), and Al (0.11 wt.% Al₂O₃; 0.006 *apfu*) (Table 2.33).

Pegmatite	Skarn Type	*Amp	Ann	Phl	Ms	Cal	Qz	FI	Ер	Pcl	Col	Ар	Sch	Gdn	Snc	Fe ox	Mn ox
Rau 5U	Biotite	_	_	М	Х	Х	_	_	_	Т	Т	_	_	_	_	М	Т
Rau 6	Amphibole	Х	Х	_	_	Х	_	Μ	М	Т	-	Т	-	Т	_	_	_
Rau 6	Biotite	_	Х	_	_	Х	Х	-	_	Т	Т	_	_	_	_	_	_
Rau 7	Biotite	_	Х	_	Μ	Х	_	Μ	М	Т	-	_	_	_	_	Μ	_
Rau 9	Biotite	_	Х	_	М	-	_	-	М	Т	Т	_	Т	_	Т	_	_

Table 2.26. Presence and abundance of minerals in the endo-contact skarns bordering dikes Rau 5U, 6, 7, and 9.

X = major mineral; M = minor mineral; T = trace mineral; - = not observed.

*Abbreviations of mineral names follow Whitney & Evans (2010); Gdn = gadolinite; Snc = synchysite; Fe ox = Fe oxide minerals; Mn ox = Mn oxide minerals.



Figure 2.49. A hand sample of the Rau 6 pegmatite dike showing the amphibole-type endo-contact skarn extending into the pegmatite dike and bordered by a quartz vein. A carbonate-filled pocket is present at the top of the sample.



Figure 2.50. BSE image of the contact between the Rau 7 pegmatite dike and its biotite-type endo-contact skarn. The transition from pegmatite to annite (Ann) skarn is marked by graphic intergrowths of quartz (Qz) and K-feldspar (Kfs).



Figure 2.51. BSE image of the contact between the Rau 9 pegmatite dike and its biotite-type endo-contact skarn. The skarn is mostly composed of annite (Ann) but the immediate contact with the pegmatite is lined with muscovite (Ms). At this location the pegmatite is composed of albite (Ab) and muscovite.



Figure 2.52. BSE image of the contact between an extension of the biotite-type endo-contact skarn bordering Rau 9 into the pegmatite dike. The skarn is mostly composed of annite (Ann). The pegmatite is composed of albite (Ab) and muscovite (Ms). The abundance and grain size of the muscovite increases at the contact of the pegmatite and the endo-contact skarn.



Figure 2.53. A thin section scan in plane polarized light of the amphibole-type endo-contact skarn that borders the Rau 6 pegmatite dike. A quartz (Qz) vein separates the skarn from the pegmatite dike. The pale green-grey and brown grains with lower relief are annite (Ann), whereas the darker green grains with higher relief are amphibole supergroup minerals (Amp).



Figure 2.54. A thin section scan in cross polarized light of the biotite-type endo-contact skarn that borders the Rau 9 pegmatite dike. The grain size of the annite (Ann) increases from the edge of the skarn to its boundary with the pegmatite dike. The edge of this boundary is marked by a thin layer of muscovite (Ms). The pegmatite is mostly composed of albite (Ab).



Figure 2.55. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the composition of mica group minerals in the endo-contact skarns.



Figure 2.56. Diagrams showing the compositional variation of annite with a (a) negative correlation between Fe / (Fe + Mg) and F contents and (b) positive correlation between Fe / (Fe + Mg) and Cl contents.

Sample	R5U-G	R5U-G	R6-A	R6-A	R6-1b	R6-1b	R7-A	R7-A	R9b-2c	R9b-2c
Skarn type	Bic	otite	Amph	nibole	Bio	tite	Bio	otite	Bio	otite
Mineral	*Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann
SiO ₂ (wt.%)	37.36	37.25	38.49	38.69	37.76	37.63	37.16	38.00	34.88	34.34
TiO ₂	0.11	b.d.	0.14	0.14	b.d.	b.d.	0.13	0.07	b.d.	b.d.
AI_2O_3	13.04	12.90	11.87	11.67	11.78	12.06	12.89	13.11	15.47	15.15
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	20.49	21.15	22.53	22.23	21.88	23.32	25.16	21.96	31.01	30.50
MgO	12.00	12.49	12.16	12.13	11.58	11.00	9.27	11.90	5.10	5.52
CaO	0.06	0.07	0.08	b.d.	0.05	b.d.	b.d.	0.08	b.d.	b.d.
MnO	0.31	0.37	0.35	0.40	0.38	0.36	0.35	0.39	0.22	0.22
Na ₂ O	0.08	0.12	0.15	b.d.	0.13	0.08	0.13	0.11	0.07	0.07
K ₂ O	9.43	9.62	9.15	9.69	9.71	9.73	9.58	9.76	9.34	9.49
Rb ₂ O	0.35	0.34	b.d.	b.d.	0.28	0.34	b.d.	b.d.	0.26	0.30
F	3.30	3.57	2.64	2.56	3.01	2.58	3.20	3.91	1.49	1.34
Cl	0.26	0.26	0.28	0.32	0.22	0.28	0.45	0.17	0.53	0.55
H_2O^{\ddagger}	2.17	2.07	2.53	2.56	2.30	2.50	2.15	1.98	2.89	2.92
-(O=F,Cl)	-1.45	-1.56	-1.17	-1.15	-1.32	-1.15	-1.45	-1.68	-0.75	-0.69
Total	97.52	98.64	99.19	99.24	97.77	98.73	99.01	99.73	100.51	99.71
Si ⁴⁺ (apfu)	2.946	2.919	2.992	3.009	2.995	2.974	2.947	2.941	2.802	2.786
Ti ⁴⁺	0.007	b.d.	0.008	0.008	b.d.	b.d.	0.008	0.004	b.d.	b.d.
Al ³⁺	1.212	1.192	1.087	1.070	1.101	1.124	1.205	1.196	1.464	1.448
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.351	1.386	1.465	1.446	1.451	1.541	1.669	1.421	2.083	2.069
Mg ²⁺	1.410	1.459	1.410	1.406	1.369	1.296	1.096	1.373	0.611	0.668
Ca ²⁺	0.005	0.006	0.000	b.d.	0.004	b.d.	b.d.	0.006	b.d.	b.d.
Mn ²⁺	0.021	0.025	0.023	0.027	0.026	0.024	0.023	0.025	0.015	0.015

Table 2.27. Representative chemical compositions and structural formulae of annite in the biotite- and amphibole-type endo-contact skarns bordering dikes Rau 5U, 6, 7 and 9.

Sample	R5U-G	R5U-G	R6-A	R6-A	R6-1b	R6-1b	R7-A	R7-A	R9b-2c	R9b-2c	
Skarn type	Bio	tite	Amph	ibole	Bio	Biotite		Biotite		Biotite	
Mineral	*Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	
Na⁺ (<i>apfu</i>)	0.012	0.018	0.023	b.d.	0.020	0.013	0.019	0.016	0.011	0.011	
K ⁺	0.949	0.961	0.907	0.962	0.982	0.981	0.969	0.963	0.958	0.982	
Rb⁺	0.018	0.017	b.d.	b.d.	0.014	0.017	b.d.	b.d.	0.014	0.016	
F⁻	0.823	0.884	0.649	0.629	0.754	0.645	0.802	0.957	0.378	0.343	
Cl⁻	0.035	0.034	0.036	0.042	0.030	0.038	0.061	0.022	0.072	0.076	
OH-‡	1.142	1.082	1.314	1.329	1.216	1.318	1.137	1.021	1.550	1.581	
vacancy	0.053	0.019	0.016	0.034	0.058	0.041	0.052	0.039	0.025	0.014	
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit.

Phosphorus, Cr, V, Zn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-G	R5U-G	R7-A	R7-A
Skarn type	Bio	tite	Biot	ite
Mineral	*Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.29	44.52	51.11	51.40
TiO ₂	b.d.	b.d.	0.20	0.15
AI_2O_3	30.24	29.38	26.32	27.18
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.79	6.04	3.02	2.58
MgO	1.82	2.51	3.91	3.30
CaO	b.d.	b.d.	b.d.	0.08
Na ₂ O	0.22	0.18	0.06	0.08
K ₂ O	11.16	11.04	10.40	10.79
Rb ₂ O	0.27	0.33	b.d.	b.d.
F	0.76	1.46	2.07	1.97
CI	b.d.	0.07	0.03	b.d.
H_2O^{\ddagger}	4.01	3.57	3.48	3.57
-(O=F,CI)	-0.32	-0.63	-0.88	-0.83
Total	98.25	98.49	99.73	100.28
Si ⁴⁺ (<i>apfu</i>)	3.241	3.117	3.426	3.422
Ti ⁴⁺	b.d.	b.d.	0.010	0.008
Al ³⁺	2.443	2.425	2.080	2.133
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.160	0.354	0.169	0.144
Mg ²⁺	0.186	0.262	0.391	0.328
Ca ²⁺	b.d.	b.d.	b.d.	0.006
Na ⁺	0.030	0.025	0.008	0.010
K+	0.976	0.986	0.890	0.916
Rb ⁺	0.012	0.015	b.d.	b.d.
F⁻	0.165	0.324	0.438	0.414
CI⁻	b.d.	0.008	0.004	b.d.
OH-‡	1.835	1.668	1.558	1.586
vacancy	0.971	0.842	0.924	0.966
O ²⁻	10.000	10.000	10.000	10.000

Table 2.28. Representative chemical compositions and structural formulae of muscovite in the biotite-type endo-contact skarns bordering dikes Rau 5U and 7.

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit

Phosphorus, Cr, V, Zn, Mn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010);

 † Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡ H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.57. BSE image of muscovite (Ms) in the biotite-type endo-contact skarn that borders the Rau 7 pegmatite dike. The muscovite is extensively altered and is associated with calcite (Cal), some of which is intergrown with Fe oxide minerals (Fe ox), and fluorite (Fl).



Figure 2.58. Classification diagrams for calcium amphiboles for (a) calcium amphiboles with (Na + K) < 0.5 apfu and (b) calcium amphiboles with (Na + K) > 0.5 apfu (Hawthorne *et al.*, 2012).

Sample	R6-A	R6-A	R6-A	R6-A	R6-A
Unit	Rau 6				
Skarn type	Amphibole	Amphibole	Amphibole	Amphibole	Amphibole
Mineral	*Act	Fac	Fed	Fhb	Mhb
SiO ₂ (wt.%)	51.29	51.47	42.58	46.02	50.73
TiO ₂	0.06	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	3.37	2.58	9.69	7.26	4.07
$Fe_2O_{3(min)}^{\dagger}$	1.86	4.36	3.79	3.25	2.28
$FeO_{(max)}^{\dagger}$	15.18	18.29	19.33	19.07	15.33
MgO	12.63	9.90	7.15	8.21	12.34
CaO	12.35	11.79	11.95	12.03	12.28
MnO	0.75	0.75	0.69	0.84	0.71
Na ₂ O	0.78	0.65	1.34	1.09	0.96
K ₂ O	0.55	0.27	1.56	0.98	0.69
F	1.49	0.96	1.20	1.08	1.60
CI	0.04	0.03	0.23	0.09	0.05
H_2O^{\ddagger}	1.34	1.58	1.32	1.45	1.28
-(O=F,CI)	-0.63	-0.41	-0.56	-0.47	-0.69
Total	101.04	102.22	100.27	100.88	101.62
Si ⁴⁺	7.503	7.562	6.569	6.964	7.405
Ti ⁴⁺	0.007	b.d.	b.d.	b.d.	b.d.
Al ³⁺	0.580	0.447	1.763	1.294	0.700
Fe^{3+} (min) †	0.204	0.482	0.440	0.370	0.250
$Fe^{2+}(max)^{\dagger}$	1.857	2.247	2.494	2.413	1.871
Mg ²⁺	2.755	2.169	1.644	1.851	2.686
Ca ²⁺	1.936	1.856	1.975	1.950	1.920
Mn ²⁺	0.093	0.093	0.090	0.108	0.087
Na⁺	0.221	0.185	0.401	0.320	0.270
K+	0.102	0.050	0.307	0.189	0.129
F⁻	0.688	0.446	0.583	0.516	0.741
Cl⁻	0.009	0.008	0.061	0.022	0.012
$OH^{-\ddagger}$	1.303	1.545	1.356	1.462	1.247
O ^{2_}	22.000	22.000	22.000	22.000	22.000

Table 2.29. Representative chemical compositions and structural formulae of amphibole supergroup minerals in the amphibole-type endo-contact skarn bordering dike Rau 6.

The formulae were calculated on the basis of 13 [Si + Al + Ti + Fe³⁺ + Fe²⁺ + Mn + Mg] cations per formula unit.

Phosphorus, V, Cr, Sc, Zn, and Ni were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of minerals names follow Whitney & Evans (2010); Fhb = ferrohornblende; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.59. BSE image of an epidote supergroup mineral in the Rau 7 biotite-type endo-contact skarn that displays chaotic oscillatory zoning. It has a core of REE-poor allanite-(Ce) (Aln) and epidote (Ep), a middle zone of REE-rich allanite-(Ce), and a rim of epidote.



Figure 2.60. Epidote classification diagram (modified from Armbruster *et al.*, 2006) showing the composition of epidote supergroup minerals in the endo-contact skarns.

Sample	R6-A	R6-A	R7-A	R7-A	R7-A	R9b-2c	R9b-2c
Skarn type	Amph	nibole		Biotite		Bio	tite
Zone	Core	Rim	Core	Middle	Rim	-	-
Mineral	*Aln	Czo	Aln	Aln	Ep	Czo	Ep
SiO ₂ (wt.%)	32.29	33.95	34.26	31.88	34.24	34.71	32.99
ZrO ₂	b.d.	b.d.	0.12	b.d.	b.d.	b.d.	b.d.
ThO ₂	1.19	1.77	0.21	0.74	4.08	1.12	6.95
UO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.21	0.14
Al ₂ O ₃	18.18	19.63	20.46	18.62	19.63	21.35	17.56
Sc ₂ O ₃	0.19	b.d.	0.49	0.26	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	2.22	6.41	6.20	0.00	12.46	5.76	7.26
$FeO_{(max)}^{\dagger}$	9.59	6.39	4.27	10.48	1.53	6.10	6.94
Y ₂ O ₃	b.d.	0.29	0.19	b.d.	0.53	1.76	0.42
La ₂ O ₃	3.60	2.45	2.84	4.44	1.80	0.65	1.81
Ce ₂ O ₃	12.07	8.00	8.85	13.99	5.94	3.62	6.41
Pr ₂ O ₃	1.53	1.05	1.19	1.53	0.71	0.85	0.92
Nd ₂ O ₃	4.72	3.01	3.66	3.90	2.19	3.74	2.41
Sm ₂ O ₃	0.54	0.43	0.64	0.30	0.48	1.38	0.40
Gd ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.48	b.d.
Tm ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.02	b.d.
MgO	0.65	0.27	0.46	1.00	0.24	0.08	0.11
CaO	11.46	15.27	14.76	10.48	13.46	16.51	14.43
MnO	0.66	0.33	0.59	0.99	0.44	0.34	0.77
PbO	b.d.	0.01	b.d.	b.d.	0.03	b.d.	b.d.
Na ₂ O	b.d.	b.d.	b.d.	0.09	0.15	b.d.	b.d.
F	0.28	0.02	0.09	0.22	0.30	b.d.	0.06
CI	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.
H_2O^{\ddagger}	1.61	1.70	1.71	1.44	1.71	1.73	1.65
-(O=F,Cl)	-0.12	-0.01	-0.04	-0.10	-0.13	0.00	-0.02
Total	100.65	100.95	100.94	100.27	99.80	100.39	101.20
Si ⁴⁺ (<i>apfu</i>)	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Zr ⁴⁺	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.
Th ⁴⁺	0.025	0.036	0.004	0.016	0.081	0.022	0.144
U ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	0.003
Al ³⁺	1.991	2.045	2.111	2.065	2.027	2.174	1.882
Sc ³⁺	0.015	b.d.	0.037	0.021	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.155	0.426	0.409	0.000	0.822	0.374	0.497
Fe ²⁺ (max) [†]	0.745	0.472	0.312	0.825	0.112	0.441	0.527

Table 2.30. Representative chemical compositions and structural formulae of epidote supergroup minerals in the amphibole-type endo-contact skarn bordering dike Rau 6, and the biotite-type endo-contact skarns bordering dikes Rau 7 and 9.

Sample	R6-A	R6-A	R7-A	R7-A	R7-A	R9b-2c	R9b-2c
Skarn type	Amphibole		Biotite			Biotite	
Zone	Core	Rim	Core	Middle	Rim	-	
Mineral	*Aln	Czo	Aln	Aln	Ep	Czo	Ep
Y ³⁺ (apfu)	b.d.	0.013	0.009	b.d.	0.025	0.081	0.020
La ³⁺	0.123	0.080	0.092	0.154	0.058	0.021	0.061
Ce ³⁺	0.410	0.259	0.284	0.482	0.191	0.115	0.213
Pr ³⁺	0.052	0.034	0.038	0.053	0.023	0.027	0.030
Nd ³⁺	0.157	0.095	0.114	0.131	0.069	0.115	0.078
Sm³+	0.017	0.013	0.019	0.010	0.014	0.041	0.013
Gd ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.014	b.d.
Tm ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	0.090	0.036	0.060	0.140	0.032	0.010	0.015
Ca ²⁺	1.141	1.446	1.384	1.057	1.264	1.529	1.406
Mn ²⁺	0.052	0.025	0.044	0.079	0.033	0.025	0.060
Pb ²⁺	b.d.	0.000	b.d.	b.d.	0.001	b.d.	b.d.
Na⁺	b.d.	b.d.	b.d.	0.017	0.025	b.d.	b.d.
F⁻	0.082	0.005	0.024	0.065	0.084	b.d.	0.016
CI⁻	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.
OH-‡	1.000	1.000	1.000	0.902	1.000	1.000	1.000
O ^{2_}	12.918	12.995	12.976	12.932	12.916	13.000	12.984

The formulae were calculated on the basis of 3 Si atoms per formula unit.

Phosphorus, Ti, Sn, Tb, Dy, Ho, Er, Yb, Ca, Sr, and K were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.61. Element concentrations in the core and rim of an epidote supergroup mineral from the biotite-type endo-contact skarn of the Rau 7 pegmatite dike: (a) Mg, (b) Fe_{tot}, (c) Th, (d) Mn, (e) Sc, and (f) F.



Figure 2.62. Element concentrations in the core and rim of an epidote supergroup mineral from the amphibole-type endo-contact skarn of the Rau 6 pegmatite dike: (a) Mg, (b) Th, (c) Mn, (d) Sc, and (e) F.



Figure 2.63. BSE image of pyrochlore supergroup minerals in the Rau 6 amphibole-type endo-contact skarn. Aggregates of small grains are fluorcalciomicrolite (Fclmcr) rimmed by fluorcalciopyrochlore (Fclprc).

Sample	R6-A	R6-A	R6-A	R6-A	R6-1b	R6-1b
Skarn type		Amp	Biotite			
Zone	Core	Core	Rim	Rim	-	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr	Fclmcr
WO ₃ (wt.%)	0.25	0.64	0.30	0.28	b.d.	0.65
Nb ₂ O ₅	7.58	7.59	28.53	30.46	11.25	25.28
Ta ₂ O ₅	69.29	65.55	44.23	42.19	66.33	51.11
SiO ₂	0.00	1.85	b.d.	b.d.	0.77	0.52
TiO ₂	0.91	1.06	0.42	0.92	b.d.	0.51
ZrO ₂	b.d.	0.15	b.d.	b.d.	b.d.	b.d.
SnO ₂	1.12	1.56	2.60	2.79	1.52	1.11
UO ₂	0.91	1.36	1.79	2.05	1.87	1.25
Al ₂ O ₃	b.d.	0.27	0.15	b.d.	0.15	0.09
$Fe_2O_{3(\text{min})}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	0.48	1.08	0.99	0.64	0.88	1.51
CaO	14.65	12.48	11.97	14.42	12.29	12.19
MnO	0.17	0.09	0.12	0.13	b.d.	0.10
Na ₂ O	3.16	3.17	3.15	3.20	3.78	5.46
F	3.14	3.13	3.02	3.25	2.85	3.50
–(O=F)	-1.32	-1.32	-1.27	-1.37	-1.20	-1.47
Total	98.79	98.08	98.08	98.95	100.50	101.80
W ⁶⁺ (apfu)	0.006	0.006	0.014	0.005	b.d.	0.013
Nb ⁵⁺	0.992	0.298	0.289	1.046	0.425	0.865
Ta⁵+	0.925	1.640	1.502	0.871	1.508	1.052
Si ⁴⁺	b.d.	b.d.	0.156	b.d.	0.065	0.039
Ti ⁴⁺	0.024	0.060	0.067	0.053	b.d.	0.029
Zr ⁴⁺	b.d.	b.d.	0.006	b.d.	b.d.	b.d.
Sn ⁴⁺	0.080	0.039	0.052	0.084	0.051	0.033
U ⁴⁺	0.031	0.018	0.026	0.035	0.035	0.021
Al ³⁺	0.013	b.d.	0.027	b.d.	0.015	0.008
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.064	0.035	0.076	0.040	0.061	0.096
Ca ²⁺	1.208	1.164	1.081	1.173	1.101	0.989
Mn ²⁺	0.011	0.006	0.008	0.008	b.d.	0.006
Na⁺	0.471	0.535	0.514	0.471	0.612	0.802
F⁻	0.763	0.862	0.805	0.780	0.754	0.837
O ²⁻	6.237	6.138	6.195	6.220	6.246	6.163

Table 2.31. Representative chemical compositions and structural formulae of pyrochlore supergroup minerals in the amphibole- and biotite-type endo-contact skarns bordering dike Rau 6.

The formulae were calculated on the basis of 7 anions per formula unit.
Thorium, Sc, Sb, Y, Bi, Mg, Zn and Pb were also sought but were below the detection limit of the EMP in all analyses.

*FcImcr = fluorcalciomicrolite; FcIprc = fluorcalciopyrochlore; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.



Figure 2.64. Quadrilateral plot showing the general compositional space of columbite group minerals in the endo-contact skarns (Černý *et al.*, 1992).

Sample	R5U-G	R6-1b	R9b-2c	R6-A	R9b-2c
Skarn type	Biotite	Biotite	Biotite	Amphibole	Biotite
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Fluor-Ap	Sch
WO₃ (wt.%)	7.42	1.04	1.42	_	79.43
P ₂ O ₅	-	_	-	41.94	_
Nb ₂ O ₅	50.63	54.76	61.67	-	b.d.
Ta₂O₅	15.65	23.56	16.49	-	b.d.
SiO ₂	0.04	0.25	0.02	0.15	b.d.
TiO ₂	7.98	2.34	1.27	-	b.d.
ZrO ₂	0.06	b.d.	0.10	-	-
SnO ₂	0.18	b.d.	0.27	-	-
ThO ₂	b.d.	b.d.	0.02	b.d.	_
Al ₂ O ₃	0.02	b.d.	0.01	b.d.	b.d.
Sc ₂ O ₃	0.04	0.40	0.38	-	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	18.84	14.53	19.69	0.14	b.d.
Y_2O_3	0.02	b.d.	0.04	0.19	-
Sb ₂ O ₃	b.d.	b.d.	0.08	-	-
Bi ₂ O ₃	0.02	b.d.	b.d.	-	-
MgO	0.09	0.17	0.13	b.d.	b.d.
CaO	b.d.	0.29	b.d.	47.41	19.26
MnO	0.82	2.45	1.64	b.d.	b.d.
PbO	b.d.	b.d.	0.07	-	b.d.
Na ₂ O	0.02	b.d.	b.d.	b.d.	b.d.
F	b.d.	b.d.	b.d.	3.86	0.10
H_2O^{\ddagger}	-	-	-	0.00	-
-(O=F)	-	-	-	-1.63	-0.04
Total	101.80	99.78	103.31	92.06	98.74
W ⁶⁺ (apfu)	0.112	0.017	0.022	-	0.998
P ⁵⁺	-	-	-	3.277	-
Nb ⁵⁺	1.339	1.515	1.625	-	b.d.
Ta⁵⁺	0.249	0.392	0.261	-	b.d.
Si ⁴⁺	0.002	0.015	0.001	0.014	b.d.
Ti ⁴⁺	0.351	0.109	0.056	-	b.d.
Zr ⁴⁺	0.002	b.d.	0.003	-	-
Sn ⁴⁺	0.004	b.d.	0.006	-	-
Th ⁴⁺	b.d.	b.d.	0.000	b.d.	_

Table 2.32. Representative chemical compositions and structural formulae of columbite-(Fe) in the biotite-type endo-contact skarns bordering dikes Rau 5U, 6 and 9, apatite group minerals from the amphibole-type endo-contact skarn bordering dike Rau 6, and scheelite from the biotite-type endo-contact skarn bordering dike Rau 9.

Sample	R5U-G	R6-1b	R9b-2c	R6-A	R9b-2c
Skarn type	Biotite	Biotite	Biotite	Amphibole	Biotite
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Fluor-Ap	Sch
Al ³⁺ (<i>apfu</i>)	0.001	b.d.	0.001	b.d.	b.d.
Sc ³⁺	0.002	0.021	0.019	-	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.921	0.744	0.960	0.011	b.d.
Y ³⁺	0.001	b.d.	0.001	0.009	_
Sb ³⁺	b.d.	b.d.	0.002	-	_
Bi ³⁺	0.000	b.d.	b.d.	_	-
Mg ²⁺	0.007	0.016	0.012	b.d.	b.d.
Ca ²⁺	b.d.	0.019	b.d.	4.689	1.000
Mn ²⁺	0.041	0.127	0.081	b.d.	b.d.
Pb ²⁺	b.d.	b.d.	0.001		b.d.
Na⁺	0.002	b.d.	b.d.	b.d.	b.d.
F⁻	b.d.	b.d.	b.d.	1.127	0.015
OH⁻‡	-	-	_	0.000	-
O ²⁻	6.000	6.000	6.000	12.370	3.985

The formulae for columbite-(Fe) were calculated on the basis of 6 O atoms, apatite on the basis of 8 cations, and scheelite on the basis of 4 anions per formula unit.

Zinc and U in columbite-(Fe), La, Ce, Nd, Sr, Ba, S, and Cl in apatite, and Mo and Zn in scheelite were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Col = columbite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit; - = not measured.

Sample	R6-A	R9b-2c
Skarn type	Amphibole	Biotite
Mineral	*Gdl-(Y)	Snc-(Ce)
SiO ₂ (wt.%)	29.97	0.68
ThO ₂	0.13	4.10
UO ₂	0.20	b.d.
$B_2O_3^{\dagger}$	8.63	-
Al ₂ O ₃	b.d.	0.11
Fe ₂ O _{3(min)} ‡	0.00	0.00
FeO _(max) ‡	9.39	0.25
Y ₂ O ₃	22.97	2.06
La ₂ O ₃	b.d.	7.51
Ce ₂ O ₃	0.56	23.83
Pr ₂ O ₃	0.22	3.47
Nd_2O_3	0.98	10.51
Sm ₂ O ₃	0.64	2.85
Gd ₂ O ₃	1.37	0.90
Tb ₂ O ₃	0.11	b.d.
Dy ₂ O ₃	1.21	b.d.
Ho ₂ O ₃	0.21	b.d.
Er ₂ O ₃	0.71	b.d.
Tm ₂ O ₃	0.14	0.41
Yb ₂ O ₃	2.01	b.d.
BeO§	6.27	-
MgO	0.23	0.08
CaO	13.29	16.01
MnO	0.15	b.d.
PbO	0.16	b.d.
F	0.46	5.21
CO₂ [∥]	-	27.86
-(O=F)	-0.19	-2.19
Total	101.97	103.66
Si ⁴⁺ (<i>apfu</i>)	2.000	0.036
Th ⁴⁺	0.002	0.049
U ⁴⁺	0.003	b.d.
B ^{3+†}	0.994	-
Al ³⁺	b.d.	0.007
Fe ³⁺ (min) [‡]	0.000	0.000

Table 2.33. Chemical compositions and structural formulae of gadolinite-(Y) in the amphibole-type endocontact skarn bordering dike Rau 6, and synchysite-(Ce) from the biotite-type endo-contact skarn bordering dike Rau 9.

Sample	R6-A	R9b-2c
Skarn type	Amphibole	Biotite
Mineral	*GdI-(Y)	Snc-(Ce)
Fe ²⁺ (max) [‡] (<i>apfu</i>)	0.524	0.011
Y ³⁺	0.816	0.058
La ³⁺	b.d.	0.146
Ce ³⁺	0.014	0.459
Pr ³⁺	0.005	0.067
Nd ³⁺	0.023	0.197
Sm ³⁺	0.015	0.052
Gd ³⁺	0.030	0.016
Tb ³⁺	0.002	b.d.
Dy ³⁺	0.026	b.d.
Ho ³⁺	0.004	b.d.
Er ³⁺	0.015	b.d.
Tm ³⁺	0.003	0.007
Yb ³⁺	0.041	b.d.
Be ^{2+§}	1.006	-
Mg ²⁺	0.023	0.007
Ca ²⁺	0.950	0.902
Mn ²⁺	0.008	b.d.
Pb ²⁺	0.003	b.d.
F-	0.097	0.866
C ^{4+∥}	-	2.000
OH⁻¶	0.890	0.134
O ^{2_}	9.013	6.233

The formula for gadolinite-(Y) was calculated on the basis of 2 Si atoms, and synchysite-(Ce) on the basis of 3 cations per formula unit.

Phosphorus, Ti, Zr, Sc, Na, K, and Cl in gadolinite-(Y), and Ti, Sn, Sc, Eu, Ba, Sr, Na, K, and Cl in synchysite-(Ce) were also sought but were below the detection limit of the EMP in all analyses. *Gdl = gadolinite; Snc = synchysite; ${}^{\dagger}B_2O_3$ was calculated based on the assumption that B = 2 anions – Be; ${}^{\ddagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; ${}^{\$}BeO$ was calculated based on assumed 12 total anions; ${}^{ll}CO_2$ was fixed at 2 *apfu* C in synchysite-(Ce); ${}^{\$}H_2O$ contents based on stoichiometry; b.d. = below detection limit; – = not measured.

2.5.2.6 Exo-contact skarns

Exo-contact skarns are associated with dikes Rau 1 and 9. The exo-contact skarns are $\sim 1-3$ cm wide and are composed mostly of calcite and humite group minerals, which are variably altered to talc (Figs. 2.65 and 2.66). The skarns also contain trace amounts of fluoborite and Fe oxide minerals. Humite group minerals consist of norbergite [Mg₃(SiO₄)(F,OH)₂] in the Rau 1 exo-contact skarn and both chondrodite $[(Mg,Fe^{2+})_5(SiO_4)_2(F,OH)_2]$ and norbergite in the Rau 9 exo-contact skarn. Norbergite in the Rau 1 skarn is closer to end-member composition with Mg / (Mg + Fe) = 0.99 - 1.00 (n = 6), whereas norbergite in the Rau 9 skarn contains significantly more Fe²⁺ with up to 2.77 wt.% FeO (0.077 *apfu*) and Mg / (Mg + Fe) = 0.97-0.98 (n = 2) (t stat. = 25.85 > t crit. = 2.45; p-value <.001). Chondrodite contains up to 12.26 wt.% FeO (0.613 *apfu*). Norbergite in the Rau 1 skarn is the most F-rich and contains an average of 17.12 wt.% F (1.820) *apfu*; n = 6), whereas norbergite in the Rau 9 skarn contains an average of 14.14 wt.% F (1.494 *apfu*; n = 2). Chondrodite contains on average of 7.67 wt.% F (1.438 *apfu*; n = 9) (Table 2.34). Minor element contents are low in all humite group minerals, but norbergite tends to have less minor elements than chondrodite. Trace amounts of Mn are present in all analysed specimens, but norbergite in the Rau 9 skarn contains significantly more Mn than norbergite in the Rau 1 skarn, with an average of 0.33 wt.% MnO in Rau 9 (0.009 apfu) and 0.08 wt.% MnO in Rau 1 (0.002 apfu) (t stat. = 5.56 > t crit. = 2.45; p-value .001). Talc, an alteration product of norbergite, contains minor Fe (average 4.62 wt.% FeO; 0.345 apfu; n = 6) and is rich in F, with an average of 2.61 wt.% F (0.735 *apfu*; n = 6) (Table 2.34).

Fluoborite $[Mg_3(BO_3)(F,OH)_3]$ occurs within the exo-contact skarns but only along the contact with the host rock (Fig. 2.65). Fluorine contents ranges from an average of 22.64 wt.% F (2.243 *apfu*; n = 9) in the Rau 9 skarn to 23.80 wt.% F (2.284 *apfu*; n = 4). It is relatively pure with only trace amounts of Fe²⁺ (up to 0.79 wt.% FeO; 0.021 *apfu*), Ca (up to 0.17 wt.% CaO; 0.006 *apfu*), and Mn (up to 0.10 wt.% MnO; 0.003 *apfu*), all in fluoborite in the Rau 9 skarn (Table 2.34). Fluoborite in the Rau 9 exo-contact skarn contains significantly more Fe²⁺ than fluoborite in the Rau 1 exo-contact skarn, with an average of 0.66 wt.% FeO in Rau 9 (0.017 *apfu*; n = 9) and 0.23 wt.% FeO (0.006 *apfu*; n = 4) in Rau 1 (t stat. = 6.90 > t crit. = 2.20; p-value <.001).



Figure 2.65. The exo-contact skarn within a boulder of the dolostone host rock near dike Rau 1.



Figure 2.66. BSE image of the contact between the dolostone host rock and exo-contact skarn. Fluoborite (Flb) occurs within the skarn, near the contact with the host rock. Within the skarn, chondrodite (Chn) has been altered to talc (Tlc).

Sample	R1-J	R1-J	R9b-2a	R9b-2a	R9b-2a	R1-J	R1-J	R9b-2a	R9b-2a	R9b-2a	R9b-2a
Unit	Rau 1	Rau 1	Rau 9	Rau 9	Rau 9	Rau 1	Rau 1	Rau 9	Rau 9	Rau 9	Rau 9
Mineral	*Nrb	Nrb	Nrb	Chn	Chn	Flb	Flb	Flb	Flb	Tlc	Tlc
SiO ₂ (wt.%)	29.06	29.43	29.19	32.89	32.81	b.d.	b.d.	b.d.	b.d.	44.78	44.51
TiO ₂	0.07	0.07	_	-	-	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
B ₂ O ₃	-	-	_	-	-	19.02	19.13	18.43	18.44	_	-
Al ₂ O ₃	0.03	0.03	_	-	-	b.d.	b.d.	b.d.	b.d.	0.25	0.09
Cr_2O_3	b.d.	0.02	_	-	-	b.d.	b.d.	-	-	b.d.	b.d.
FeO _(tot)	0.30	0.31	2.60	9.71	10.02	0.34	0.11	0.59	0.75	5.12	4.33
MgO	59.68	59.91	59.10	50.51	49.94	65.81	66.33	63.55	63.59	38.00	38.65
CaO	0.09	0.10	0.02	0.20	0.13	0.05	0.07	0.12	0.03	0.31	0.41
MnO	0.03	0.03	0.32	1.28	1.39	0.08	b.d.	0.09	b.d.	0.22	0.11
ZnO	0.03	0.02	_	-	-	b.d.	b.d.	-	-	_	-
Na ₂ O	0.03	0.04	_	-	-	b.d.	b.d.	-	-	_	-
K ₂ O	0.03	0.01	-	-	-	b.d.	b.d.	-	-	b.d.	b.d.
F	17.93	17.67	15.06	7.70	7.12	23.50	24.09	24.17	21.60	2.33	2.97
H_2O^{\dagger}	0.36	0.55	1.84	1.43	1.67	3.63	3.43	2.85	4.07	2.28	1.94
-(O=F)	-7.55	-7.44	-6.34	-3.65	-3.38	-9.89	-10.14	-10.18	-9.10	-0.98	-1.25
Total	100.08	100.72	101.78	100.07	99.71	102.54	103.00	99.62	99.39	92.28	91.76
Si ⁴⁺ (<i>apfu</i>)	0.984	0.989	0.975	1.9411	1.950	b.d.	b.d.	b.d.	b.d.	3.974	3.990
Ti ⁴⁺	0.002	0.002	_	-	-	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
B ³⁺	-	-	_	-	-	1.000	1.000	1.000	1.000	_	-
Al ³⁺	0.001	0.001	-	-	-	b.d.	b.d.	b.d.	b.d.	0.026	0.010
Cr ³⁺	b.d.	0.000	_	-	-	b.d.	b.d.	-	-	b.d.	b.d.
Fe(tot)	0.008	0.009	0.073	0.479	0.498	0.009	0.003	0.015	0.020	0.380	0.325
Mg ²⁺	3.012	3.001	2.943	4.444	4.424	2.987	2.995	2.978	2.979	5.027	5.165
Ca ²⁺	0.003	0.004	0.001	0.013	0.009	0.002	0.002	0.004	0.001	0.029	0.040

Table 2.34. Representative chemical compositions and structural formulae of chondrodite, norbergite, fluoborite, and talc in the exo-contact skarns associated with dikes Rau 1 and 9.

Sample	R1-J	R1-J	R9b-2a	R9b-2a	R9b-2a		R1-J	R1-J	R9b-2a	R9b-2a	R9b-2a	R9b-2a
Unit	Rau 1	Rau 1	Rau 9	Rau 9	Rau 9	-	Rau 1	Rau 1	Rau 9	Rau 9	Rau 9	Rau 9
Mineral	*Nrb	Nrb	Nrb	Chn	Chn		Flb	Flb	Flb	Flb	Tlc	Tlc
Mn ²⁺ (<i>apfu</i>)	0.001	0.001	0.009	0.064	0.070		0.002	b.d.	0.003	b.d.	0.016	0.008
Zn ²⁺	0.001	0.000	-	-	-		b.d.	b.d.	-	-	-	-
Na ⁺	0.002	0.002	-	-	-		b.d.	b.d.	-	-	-	-
K+	0.001	0.000	-	-	-		b.d.	b.d.	-	-	b.d.	b.d.
F⁻	1.919	1.878	1.591	1.437	1.338		2.263	2.307	2.403	2.147	0.653	0.841
OH-†	0.081	0.122	0.409	0.563	0.662		0.737	0.693	0.597	0.853	1.347	1.159
O ^{2_}	4.000	4.000	3.975	8.684	8.810		3.000	3.000	3.000	3.000	12.439	12.534

The formulae for norbergite were calculated on the basis of 6 anions, chondrodite on the basis of 10 anions, fluoborite on the basis of 6 anions, and talc on the basis of 4 Si atoms per formula unit.

Phosphorus in humite group minerals, and V and Ba in fluoborite were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); Flb = fluoborite; $^{+}H_2O$ contents based on stoichiometry; b.d. = below detection limit; – = not measured.

2.5.2.7 Host rocks

Samples of the host rock were taken adjacent to dikes Rau 3, 4, 5U, 6, and 9. In the area surrounding dike Rau 3, there was sufficient exposure so that samples could be obtained from close to the pegmatite dike (1.5 m) and farther away (~20 m). Host rock samples adjacent to the other pegmatite dikes could not be obtained due to a lack of outcrop in some parts of the study area. All host rocks are classified as dolostones due to the predominance of dolomite over calcite. The amount of additional minerals other than dolomite and calcite varies from sample to sample, from abundant amphibole supergroup minerals, chlorite group minerals, and titanite in a sample near dike Rau 3, to essentially no accessory minerals in a sample from near dike Rau 9 that also contains an exo-contact skarn (Table 2.35).

Calcite is nearly pure and contains a maximum of 3.83 wt.% MgO (0.092 *apfu* Mg) in host rocks adjacent to the Rau 4 pegmatite dike. The composition of dolomite is similar in all host rocks with an overall average of Ca / (Ca + Mg) = 0.52 (n = 42) (Table 2.36).

All host rocks sampled, except for the sample taken near dike Rau 9, contain accessory mica group minerals. In the host rocks near Rau 3, mica group minerals form small (up to ~1.5 mm, but generally < 200 μ m) grains that have a subhedral tabular to elongated shape (Fig 2.67), whereas grains in the host rocks near dikes Rau 4, 5U, and 6 are usually longer (up to ~400 μ m) and tend to be more elongated with euhedral shapes (Fig. 2.68). Mica group minerals are most abundant in the host rock near dike Rau 3, whereas it occurs in lesser amounts in the host rocks near dikes Rau 4, 5U, and 6.

All analysed mica group minerals in the host rocks near dikes Rau 3 and 6 are phlogopite with Mg / (Mg + Fe) = 0.98-1.00 in all samples (n = 16), whereas the majority of mica group minerals in the host rocks near dikes Rau 4 and 5U are fluorophlogopite with Mg / (Mg + Fe) = 0.98-1.00 (n = 8) in dike Rau 4 and 1.00 (n = 5) in dike Rau 5U (Fig. 2.69). The highest observed F contents in fluorophlogopite occurs in the host rocks near dike Rau 5U with up to 7.27 wt.% F ($1.600 \ apfu$; n = 11). The F contents of the mica group minerals roughly correlate with their distance from a pegmatite dike (Fig. 2.70a).

Minor element contents vary between mica group minerals in different host rocks. Phlogopite in the host rock closest to Rau 3 has the highest contents of Ti, with an average of 0.59 wt.% TiO₂ (0.031 *apfu*; n = 7), followed by phlogopite in the host rock farther away from dike Rau 3, with an average of 0.34 wt.% TiO₂ (0.017 *apfu*; n = 5). These are both significantly higher than the Ti contents of phlogopite in the host rock adjacent to dikes Rau 4 and 6. Titanium contents of phlogopite in dike Rau 4 are not above the detection limit of the EMP. In dike Rau 6, only one specimen of phlogopite contained Ti above the detection limit of the EMP (0.22 wt.% TiO_2 ; 0.012 apfu) (t stat. = 4.03 > t crit. = 2.26; p-value .003 compared to the host rock closer to dike Rau 3; t stat. = 2.74 > t crit. = 2.36; p-value .03 compared to the host rock farther away from dike Rau 3) (Fig. 2.70b). There is a significant difference in the Cl contents of phlogopite in host rocks closer to and farther away from dike Rau 3, with average Cl contents of 0.17 and 0.04 wt.% Cl respectively (0.021 and 0.005 *apfu* respectively; t stat. = 2.69 > t crit. = 2.23; p-value .02) (Fig. 2.70c). Fluorophlogopite and phlogopite in host rocks adjacent to dike Rau 4 have significantly higher contents of Rb (average 1.61 wt.% Rb₂O₃; 0.072 apfu; n = 8) than fluorophlogopite in host rocks adjacent to dike Rau 5U (average 0.27 wt.% Rb₂O₃; 0.012 apfu; n = 5) (t stat. = 3.96 > t crit. = 2.20; p-value .002) (Fig. 2.70d). Barium is present in detectable amounts in all analysed samples of fluorophlogopite (n = 5) in host rocks adjacent to dike Rau 5U, whereas Ba was only above the detection limit of the EMP in one analysis (n = 8) in fluorophlogopite and phlogopite in host rocks adjacent to dike Rau 4 (Fig. 2.70e; Table 2.37).

Amphibole supergroup minerals are only present in host rocks near dike Rau 3, both near the pegmatite dike (~1.5 m) and farther away from it (~20 m). They typically occur as elongated rectangular crystals up to 700 μ m long in areas of the host rock that have a higher abundance of calcite (Fig 2.71). In the sample farther away from the Rau 3 dike, amphibole supergroup minerals form sprays of bladed crystals up to 0.8 cm longer and are again associated with calcite (Fig 2.72). Most analysed grains are part of the calcium amphibole subgroup and the ^W(O,F,Cl)-dominant amphibole group. Specifically, most grains are tremolite, but two analyses of samples of the host rock farther away from dike Rau 3 yielded pargasite (Fig. 2.73). All species are Fepoor with a maximum of 0.53 wt.% Fe₂O₃ (0.054 *apfu*; *n* = 17) in tremolite and 0.12 wt.% Fe₂O₃ (0.012 *apfu*; *n* = 2) in pargasite. Titanium is the only analysed minor element that is elevated in both species of amphibole supergroup minerals. Tremolite in the host rocks closer to dike Rau 3 has an average Ti content of 0.09 wt.% TiO₂ (0.009 *apfu*; *n* = 8), whereas tremolite in the host rocks farther away from dike Rau 3 has a significantly higher average Ti content of 0.34 wt.% TiO₂ (0.035 *apfu*; *n* = 9) (t stat. = 5.22 > t crit. = 2.13; p-value <.001). The highest Ti content of 1.21 wt.% TiO₂ (0.128 *apfu*) occurs in pargasite (Fig. 2.74) (Table 2.38).

Chlorite group minerals occur in the host rocks approximately 20 m from dike Rau 3, and in the host rocks near dikes Rau 4 and 6. The grains are elongated with a micaceous habit. In the host rocks near dike Rau 3, crystals can attain lengths of up to 900 μ m (Fig 2.75), whereas in the host rocks near dikes Rau 4 and 6 they tend to be smaller with a maximum length of ~300 μ m (Fig. 2.76). All analysed grains are clinochlore with Mg / (Mg + Fe) = 0.99–1.00. Clinochlore from the host rock near dike Rau 6 contains on average 1.28 wt.% F (0.361 *apfu*; *n* = 6), which is significantly higher than the average 0.31 wt.% F (0.089 *apfu*; *n* = 6) in clinochlore in host rocks near dike Rau 3 (t stat. =11.80 > t crit. = 2.23; p-value <.001) (Fig. 2.77). Fluorine contents of clinochlore were below the detection limit of the EMP in host rocks near dike Rau 4 (Table 2.39).

Relatively large (up to 400 μ m) crystals of plagioclase occur in the host rock sample closest to dike Rau 3 but are absent in all other host rocks. Grains formed elongated rectangular to rhombohedral shapes and have been altered to clay minerals along the rims (Figs. 2.71 and 2.78). All plagioclase is anorthite and ranges in composition from An₈₃Ab₁₆Or₁ to An₉₆Ab₃Or₁. Trace element contents were negligible in all analyses (Table 2.40).

Titanite and Fe sulphide minerals only occur in the host rocks adjacent to Rau 3. Iron sulphide minerals appear to be slightly more abundant in the host rock farther away from the pegmatite dike than the host rock closer to the dike. Most grains of titanite are highly altered giving them an anhedral shape and some display a poikilitic texture (Fig. 2.67). All titanite is nearly pure end-member composition; however, titanite in the host rock closer to dike Rau 3 contains detectable Sn (up to 0.45 wt.% SnO; 0.007 apfu), whereas all Sn is below the detection limit of the EMP in titanite from the host rock farther away from dike Rau 3. The Al contents of titanite show the opposite trend, with the titanite in the host rock closer to Rau 3 containing less Al, and the host rock farther away from the pegmatite dike containing more Al (t stat. = 5.43 > tcrit. = 2.08; p-value = <.001). Titanite in the host rock closer to the pegmatite dike also has significantly higher Nb contents with an average of 0.32 wt.% Nb₂O₅ (0.004 *apfu*; n = 7 with 3 analyses below the detection limit of the EMP), whereas titanite from the host rock farther away contains an average of 0.12 wt.% Nb₂O₅ (0.001 *apfu*; n = 3 with 10 analyses below the detection limit of the EMP) (t stat. = 2.81 > t crit. = 2.08; p-value .01) (Table 2.41). Iron sulphide minerals were not analysed using the EMP but appear to be pyrrhotite and pyrite based on the ratios of Fe and S.

Unlike the Fe sulphide minerals, Fe oxide minerals occur in more of the host rocks—all except those adjacent to dike Rau 9—although only in trace amounts. Apatite group minerals occur in trace amounts in the host rocks adjacent to the Rau 4, 6, and 9 dikes. The grains are anhedral in shape and extremely small (<10 μ m). Finally, a single grain of allanite-(Ce) was observed in the host rock closest to dike Rau 3 (Fig. 2.71), and a single grain of rutile in the host rock adjacent to dike Rau 6.

A sample of the host rock adjacent to an aplite dike was also collected. Unlike the host rocks adjacent to the pegmatite dikes, it has been extensively altered and is now mainly composed of mica group minerals, calcite, amphibole supergroup minerals, and quartz, with lesser fluorite. Accessory minerals are abundant and include columbite group minerals, beryl, scheelite, ilmenorutile, synchysite, and Fe oxide minerals. All accessory minerals form anhedral to subhedral grains and are associated with coarse-grained, euhedral and subhedral mica, both muscovite and biotite (Fig. 2.79). All specimens of columbite group minerals are columbite-(Fe) with Nb / (Nb + Ta) = 0.93-0.95, Fe_{tot} / (Fe_{tot} + Mn) = 0.86-0.88 (n = 5), and notable amounts of Ti (6.68 wt.% TiO₂; 0.279 *apfu*), Sc (up to 2.54 wt.% Sc₂O₃; 0.123 *apfu*), and W (up to 2.10 wt.% WO₃; 0.303 apfu). Other minor elements include Y (up to 1.00 wt.% Y₂O₃; 0.030 apfu), Bi (up to 0.21 wt.% Bi₂O₃; 0.003 *apfu*), and Sb (up to 0.11 wt.% Sb₂O₃; 0.002 *apfu*) (Table 2.42). Beryl forms anhedral grains associated with muscovite (Fig. 2.80). It is near end-member composition but contains up to 0.16 wt.% Na₂O (0.027 apfu) and up to 0.14 wt.% Rb₂O (0.008 apfu (n = 4) (Table 2.43). Only one specimen of scheelite was analysed by EMP; it contains a substantial amount of Fe^{2+} with 6.83 wt.% FeO (0.253 *apfu*), and a lesser amount of Nb with 1.41 wt.% Nb₂O₅ (0.028 apfu) (Table 2.44). Ilmenorutile contains minor elements similar to columbite-(Fe) with up to 4.72 wt.% Ta₂O₅ (0.019 *apfu*; n = 2), 0.26 wt.% SnO₂ (0.002 *apfu*), 0.23 wt.% Sc₂O₃ (0.002 apfu), 0.08 wt.% Y₂O₃ (0.001 apfu), and 0.11 wt.% Sb₂O₃ (0.001 apfu) (Table 2.44). Only one grain of synchysite was large enough to analyse; it is Ce-dominant with Ce / (Ce + La + Nd) = 56.04 and also contains 3.14 wt.% Pr_2O_3 (0.062 *apfu*), 1.76 wt.% Sm_2O_3 (0.033 apfu), and 1.21 wt.% Y₂O₃ (0.035 apfu) (Table 2.44).

Closest pegmatite dike	Approx. distance (m)	Mica	*Amp	Cln	An	Ttn	Ар	Fe sul	Fe ox	FI	Aln	Rt
Rau 3	1.5	Х	Х	-	Х	Х	-	Т	Т	-	Т	-
Rau 3	20	Х	Х	Х	-	Х	-	Т	Т	-	-	-
Rau 4	1	Х	_	Т	-	-	Т	-	Т	-	-	-
Rau 5U	< 1	Х	_	Т	_	-	Т	-	Т	Т	-	Т
Rau 6	< 1	Х	_	Х	_	-	Т	-	Т	_	-	Т
Rau 9	1	-	_	-	_	-	Т	-	-	_	-	_

Table 2.35. Presence and relative abundance of accessory minerals in each of the host rocks. The host rock samples are ordered based on the closest pegmatite dike and their distance from that dike.

X = accessory mineral; t = trace mineral; – = not observed.

*Abbreviations of mineral names follow Whitney & Evans (2010), Fe sul = Fe sulphide minerals, Fe ox = Fe oxide minerals.

Sample	R3-4a	R3-4a	R3-5a	R3-5a	R4-1	R4-1	R5U-4	R5U-4	R6-2b	R6-2b
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 4	Rau 4	Rau 5U	Rau 5U	Rau 6	Rau 6
Proximity to pegmatite (m)	1.5	1.5	20	20	1	1	0	0	< 1	< 1
Mineral	*Cal	Dol	Cal	Dol	Cal	Dol	Cal	Dol	Cal	Dol
MgO (wt.%)	0.70	20.79	2.43	20.95	1.18	21.24	0.06	21.03	0.64	20.86
FeO	b.d.	0.19	b.d.	0.14	b.d.	0.16	b.d.	0.16	b.d.	b.d.
CaO	56.02	31.40	53.85	31.82	55.78	31.77	56.84	31.73	55.36	31.92
SrO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.09	b.d.
CO_2^\dagger	44.73	47.46	44.92	47.93	45.06	48.22	44.68	47.96	44.18	47.83
Total	101.44	99.84	101.19	100.84	102.01	101.38	101.58	100.87	100.27	100.62
Mg ²⁺ (<i>apfu</i>)	0.017	0.957	0.059	0.954	0.029	0.962	0.001	0.958	0.016	0.953
Fe ²⁺	b.d.	0.005	b.d.	0.003	b.d.	0.004	b.d.	0.004	b.d.	b.d.
Ca ²⁺	0.983	1.038	0.941	1.042	0.971	1.034	0.999	1.038	0.983	1.047
Sr ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	b.d.
C ^{4+†}	1.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000
O ²⁻	3.000	6.000	3.000	6.000	3.000	6.000	3.000	6.000	3.000	6.000

Table 2.36. Representative chemical compositions and structural formulae of calcite and dolomite from the host rocks near the Rau 3, 4, 5U, and 6 pegmatite dikes.

The formulae for calcite were calculated on the basis of 1 cation and dolomite on the basis of 2 cations per formula unit.

Manganese and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]CO₂ was fixed at 1 *apfu* C in calcite and 2 *apfu* C in dolomite; b.d. = below detection limit.



Figure 2.67. BSE image of a sample of the host rock approximately 20 m from the Rau 3 pegmatite dike showing dolomite (Dol), calcite (Cal), phlogopite (Phl), tremolite (Tr), titanite (Ttn), and trace Fe sulphide minerals (Fe sul).



Figure 2.68. BSE image of a sample of the host rock less than 1 m from the Rau 5U pegmatite dike showing dolomite (Dol), calcite (Cal), fluorophlogopite (Fluoro-phl), and fluorite (Fl).



Figure 2.69. Mica group mineral classification diagram (modified from Rieder *et al.*, 1998) showing the composition of mica group minerals in the host rocks.



Figure 2.70. Variation in (a) F, (b) Ti, (c) Cl, (d) Rb, and (e) Ba contents of phlogopite and fluorophlogopite with distance from a pegmatite dike.

Sample	R3-4a	R3-4a	R3-5a	R3-5a	R4-1	R4-1	R4-1	R5U-4	R5U-4	R6-2b	R6-2b
Closest pegmatite	Rau 3	Rau 3	Rau 3	Rau 3	Rau 4	Rau 4	Rau 4	Rau 5U	Rau 5U	Rau 6	Rau 6
dike Proximity to pegmatite (m)	1.5	1.5	20	20	1	1	1	0	0	< 1	< 1
Mineral	*Phl	Phl	Phl	Phl	Phl	Fluoro- Phl	Fluoro- Phl	Fluoro- Phl	Fluoro- Phl	Phl	Phl
SiO ₂ (wt.%)	41.99	43.65	42.46	42.38	39.89	39.64	40.75	43.32	40.76	40.77	40.70
TiO ₂	0.96	0.68	0.54	0.29	0.00	0.00	0.33	0.14	0.00	0.00	0.00
Al ₂ O ₃	15.53	16.82	15.01	14.26	16.79	17.23	16.48	12.11	16.63	16.08	15.62
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	0.68	0.83	0.18	0.00	0.59	0.53	0.17	0.14	0.21	0.25	0.17
MgO	25.54	21.78	26.67	27.01	27.06	25.91	27.59	28.76	27.35	27.35	26.96
CaO	b.d.	2.38	0.14	0.21	0.08	b.d.	0.08	0.09	0.18	0.14	0.08
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	0.21	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	0.14	0.22	b.d.	b.d.	0.83	0.20	0.44	0.80	0.65
Na ₂ O	b.d.	0.61	0.66	0.62	0.34	0.41	0.36	0.26	0.43	0.68	0.79
K ₂ O	10.00	8.67	8.93	8.60	9.19	9.31	10.06	10.14	10.12	9.17	9.38
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	2.39	1.94	0.11	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	0.81	1.06	0.71	1.02	3.71	4.98	4.93	7.27	5.11	2.54	2.82
CI	0.17	0.39	0.03	0.03	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.88	3.76	3.98	3.79	2.53	1.89	2.01	0.86	1.91	3.10	2.93
-(O=F,Cl)	-0.38	-0.53	-0.30	-0.44	-1.56	-2.10	-2.08	-3.06	-2.15	-1.07	-1.19
Total	99.18	100.11	99.12	98.01	101.10	99.96	101.61	100.23	100.99	99.81	98.91
Si ⁴⁺ (apfu)	2.925	3.003	2.943	2.968	2.789	2.796	2.809	3.013	2.818	2.840	2.862
Ti ⁴⁺	0.050	0.035	0.028	0.016	0.000	0.000	0.017	0.007	0.000	0.000	0.000

Table 2.37. Representative chemical compositions and structural formulae of mica group minerals from the host rocks near the Rau 3, 4, 5U, and 6 pegmatite dikes.

Sample	R3-4a	R3-4a	R3-5a	R3-5a	R4-1	R4-1	R4-1	R5U-4	R5U-4	R6-2b	R6-2b
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 4	Rau 4	Rau 4	Rau 5U	Rau 5U	Rau 6	Rau 6
Proximity to pegmatite (m)	1.5	1.5	20	20	1	1	1	0	0	< 1	< 1
Mineral	*Phl	Phl	Phl	Phl	Phl	Fluoro- Phl	Fluoro- Phl	Fluoro- Phl	Fluoro- Phl	Phl	Phl
Al ³⁺ (<i>apfu</i>)	1.275	1.364	1.226	1.177	1.383	1.432	1.339	0.993	1.355	1.320	1.295
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.040	0.048	0.010	0.000	0.034	0.031	0.010	0.008	0.012	0.014	0.010
Mg ²⁺	2.653	2.233	2.756	2.820	2.820	2.724	2.835	2.982	2.819	2.840	2.826
Ca ²⁺	b.d.	0.176	0.010	0.016	0.006	b.d.	0.006	0.007	0.013	0.011	0.006
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.013	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	0.004	0.006	b.d.	b.d.	0.023	0.005	0.012	0.022	0.018
Na⁺	b.d.	0.081	0.088	0.084	0.046	0.056	0.048	0.035	0.058	0.092	0.107
K+	0.889	0.761	0.789	0.768	0.819	0.838	0.884	0.900	0.893	0.814	0.842
Rb⁺	b.d.	b.d.	b.d.	b.d.	0.107	0.088	0.005	b.d.	b.d.	b.d.	b.d.
Cs⁺	b.d.	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	0.178	0.230	0.155	0.226	0.821	1.111	1.074	1.600	1.117	0.560	0.627
CI⁻	0.020	0.046	0.004	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH⁻‡	1.802	1.725	1.841	1.770	1.179	0.889	0.926	0.400	0.883	1.440	1.373
vacancy	0.057	0.317	0.037	0.020	-0.026	0.003	-0.009	-0.003	-0.004	-0.014	0.007
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 per formula unit.

Chromium was also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.71. BSE image of a sample of the host rock approximately 1.5 m from the Rau 3 pegmatite dike showing dolomite (Dol), calcite (Cal), tremolite (Tr), anorthite (An), titanite (Ttn), and trace allanite-(Ce) (Aln) and Fe sulphide minerals (Fe sul).



Figure 2.72. BSE image of a sample of the host rock approximately 20 m from the Rau 3 pegmatite dike showing a large spray of bladed tremolite (Tr) crystals in the dolomite- and calcite-bearing host rock. Between the crystals of tremolite, there is an increased amount of calcite (Cal) over dolomite (Dol). The bright grain is an Fe sulphide mineral (Fe sul).



Figure 2.73. Classification of calcium amphibole subgroup minerals (Hawthorne *et al.*, 2012). Only tremolite is present in the host rocks closer to the Rau 3 pegmatite dike, whereas pargasite also occurs in the host rocks further away from the dike.



Figure 2.74. The difference in the Ti contents of calcium amphibole subgroup minerals with distance from the Rau 3 pegmatite dike. The two analyses with the highest Ti contents are pargasite.

Sample	R3-4a	R3-4a	R3-5a	R3-5a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3					
Proximity to pegmatite (m)	1.5	1.5	20	20	20	20
Mineral	*-	Tr	1	٢r	Р	rg
SiO ₂ (wt.%)	57.66	57.25	55.97	55.67	44.79	43.78
TiO ₂	0.11	b.d.	0.53	0.41	1.17	1.21
Al ₂ O ₃	1.49	1.22	3.46	2.76	15.22	15.71
Cr ₂ O ₃	b.d.	0.08	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}{}^\dagger$	0.49	0.47	0.30	0.53	0.11	0.03
$FeO_{(max)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
MgO	24.06	24.34	23.78	23.90	19.74	19.53
CaO	13.76	13.78	13.56	13.32	13.55	13.44
Na ₂ O	b.d.	b.d.	0.26	0.20	2.15	2.26
K ₂ O	0.14	0.09	0.11	0.10	0.37	0.38
F	0.34	0.38	b.d.	b.d.	b.d.	b.d.
CI	0.04	0.04	b.d.	b.d.	0.04	0.05
H_2O^{\ddagger}	2.04	2.01	2.21	2.19	2.14	2.12
–(O=F,CI)	-0.15	-0.17	0.00	0.00	-0.01	-0.01
Total	99.96	99.48	100.19	99.08	99.27	98.49
Si ⁴⁺ (<i>apfu</i>)	7.829	7.795	7.587	7.623	6.242	6.153
Ti ⁴⁺	0.011	b.d.	0.054	0.043	0.122	0.128
Al ³⁺	0.239	0.196	0.552	0.445	2.500	2.602
Cr ³⁺	b.d.	0.008	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.050	0.049	0.031	0.054	0.012	0.003
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
Mg ²⁺	4.870	4.940	4.806	4.879	4.101	4.091
Ca ²⁺	2.002	2.011	1.970	1.955	2.023	2.024
Na⁺	b.d.	b.d.	0.069	0.053	0.582	0.616
K+	0.025	0.015	0.019	0.018	0.065	0.068
F⁻	0.145	0.165	b.d.	b.d.	b.d.	b.d.
CI⁻	0.009	0.008	b.d.	b.d.	0.010	0.012
OH ^{_‡}	1.845	1.827	2.000	2.000	1.990	1.988
O ^{2_}	21.996	21.929	21.977	21.951	21.944	21.924

Table 2.38. Representative chemical compositions and structural formulae of amphibole supergroup minerals from the host rocks near the Rau 3 pegmatite dike.

The formulae were calculated on the basis of 15 cations per formula unit.

Chromium and Mn were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.75. BSE image of a large crystal of clinochlore (Clc) in host rock approximately 20 m from the Rau 3 pegmatite dike. The host rock is also composed of dolomite (Dol), calcite (Cal), phlogopite (Phl), and titanite (Ttn).



Figure 2.76. BSE image of a sample of the host rock less than 1 m from the Rau 6 pegmatite dike showing dolomite (Dol), calcite (Cal), and elongated grains of clinochlore (Clc).



Figure 2.77. The difference in the F contents of chlorite group minerals with distance from the Rau 3, 4, and 6 pegmatite dikes.

Sample	R3-5a	R3-5a	R4-1	R4-1	R6-2b	R6-2b
Closest pegmatite dike	Rau 3	Rau 3	Rau 4	Rau 4	Rau 6	Rau 6
Proximity to pegmatite (m)	20	20	1	1	< 1	< 1
Mineral	*C	Clc	С	lc	С	lc
SiO ₂ (wt.%)	30.08	29.41	29.09	29.05	29.00	29.10
TiO ₂	0.08	0.06	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	22.29	21.99	22.94	23.30	23.99	23.35
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.28	0.13	0.16	0.18	0.22	0.18
MgO	34.08	33.95	33.75	33.16	33.03	33.24
CaO	b.d.	0.05	0.09	0.10	0.12	0.16
K ₂ O	b.d.	b.d.	0.04	b.d.	b.d.	0.09
F	b.d.	b.d.	1.46	1.27	0.49	0.38
H_2O^{\ddagger}	14.41	14.58	15.08	14.82	15.04	14.96
-(O=F)	0.00	0.00	-0.61	-0.54	-0.21	-0.16
Total	101.23	100.17	101.99	101.35	101.69	101.31
Si ⁴⁺ (<i>apfu</i>)	2.724	2.684	2.624	2.635	2.609	2.628
Ti ⁴⁺	0.005	0.004	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.379	2.365	2.438	2.491	2.543	2.485
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.021	0.010	0.012	0.014	0.017	0.013
Mg ²⁺	4.600	4.620	4.538	4.485	4.429	4.475
Ca ²⁺	b.d.	0.005	0.009	0.010	0.011	0.016
K+	b.d.	b.d.	0.004	b.d.	b.d.	0.010
F⁻	b.d.	b.d.	0.415	0.365	0.139	0.108
OH ^{_‡}	8.704	8.880	9.072	8.967	9.023	9.013
O ²⁻	18.000	18.000	18.000	18.000	18.000	18.000

Table 2.39. Representative chemical compositions and structural formulae of clinochlore from the host rocks near the Rau 3, 4, and 6 pegmatite dikes.

The formulae were calculated on the basis of 7 cations per formula unit.

Chromium, Mn, and Na were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.78. BSE image of rhombohedral grains of anorthite (An) with rims altered to clay minerals. The host rock approximately 1.5 m from the Rau 3 pegmatite dike is composed mainly of dolomite (Dol) and calcite (Cal).

Sample	R3-4a	R3-4a	R3-4a	R3-4a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5
Mineral	*An			
SiO ₂ (wt.%)	44.10	44.17	45.92	46.77
Al ₂ O ₃	36.05	35.72	34.47	33.47
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00
FeO _(max) [†]	b.d.	b.d.	0.20	b.d.
MgO	b.d.	b.d.	0.81	0.58
CaO	19.59	19.57	16.81	16.06
Na ₂ O	0.52	0.38	1.05	1.73
K ₂ O	0.06	0.10	0.11	0.13
Total	100.32	99.94	99.36	98.74
Si ⁴⁺ (<i>apfu</i>)	2.034	2.044	2.120	2.169
Al ³⁺	1.960	1.948	1.876	1.829
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	b.d.	b.d.	0.008	b.d.
Mg ²⁺	b.d.	b.d.	0.055	0.040
Ca ²⁺	0.968	0.970	0.832	0.798
Na ⁺	0.046	0.034	0.094	0.156
K+	0.003	0.006	0.006	0.007
O ^{2_}	8.000	8.000	8.000	8.000

Table 2.40. Representative chemical compositions and structural formulae of anorthite from the host rocks near the Rau 3 pegmatite dike.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Manganese, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010);

 † Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-4a	R3-4a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	20	20
Mineral	*T	tn	T	tn
Nb ₂ O ₅ (wt.%)	0.53	0.52	b.d.	0.15
SiO ₂	29.59	29.95	30.32	29.61
TiO ₂	36.23	37.11	36.67	35.95
Al ₂ O ₃	1.42	1.27	1.81	1.59
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00
FeO _(max) †	0.00	0.00	0.00	0.00
MgO	0.25	b.d.	b.d.	b.d.
CaO	27.67	27.86	28.51	28.05
MnO	b.d.	b.d.	b.d.	b.d.
SnO	0.45	0.27	b.d.	b.d.
Na ₂ O	b.d.	b.d.	b.d.	b.d.
F	b.d.	0.40	0.40	0.52
H_2O^{\ddagger}	0.00	0.38	0.38	0.49
-(O=F)	0.00	-0.17	-0.17	-0.22
Total	96.13	97.60	97.91	96.14
Nb ⁵⁺ (<i>apfu</i>)	1.006	1.004	1.009	1.006
Si ⁴⁺	0.927	0.936	0.918	0.919
Ti ⁴⁺	0.057	0.050	0.071	0.064
Al ³⁺	0.000	0.000	0.000	0.000
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.012	b.d.	b.d.	b.d.
Mg ²⁺	1.009	1.001	1.017	1.021
Ca ²⁺	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	0.007	0.004	b.d.	b.d.
Sn ²⁺	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.008	0.008	b.d.	0.002
F-	b.d.	0.042	0.042	0.055
OH-‡	0.000	0.085	0.084	0.111
O ^{2_}	5.000	4.958	4.958	4.945

Table 2.41. Representative chemical compositions and structural formulae of titanite from the host rocks near the Rau 3 pegmatite dike.

The formulae were calculated on the basis of 5 anions per formula unit. Tantalum was also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.



Figure 2.79. BSE image of extensively altered host rocks near an aplite dike. In this region they are composed of biotite (Bt), amphibole supergroup minerals (Amp), calcite (Cal), quartz (Qz), and fluorite (Fl).



Figure 2.80. BSE image of muscovite (Ms) and biotite (Bt) mica hosting columbite-(Fe) (Col) in the host rocks near an aplite dike. Quartz (Qz) is also a major mineral in these rocks.

Sample	ApIH-4b-1	AplH-4b-1	AplH-4b-1	ApIH-4b-1	ApIH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)
WO ₃ (wt.%)	1.46	1.17	1.43	2.10	1.07
Nb ₂ O ₅	62.35	65.26	64.31	64.23	62.60
Ta ₂ O ₅	7.24	5.85	5.42	6.75	7.69
SiO ₂	0.01	0.05	0.27	0.12	0.10
TiO ₂	6.68	5.48	5.46	6.16	5.63
ZrO ₂	0.49	0.37	0.30	0.17	0.20
SnO ₂	0.04	0.20	b.d.	0.05	b.d.
Al ₂ O ₃	b.d.	b.d.	0.07	0.01	0.15
Sc ₂ O ₃	2.03	2.27	2.54	1.26	1.22
$Fe_2O_{3(min)}^{\dagger}$	4.48	4.87	3.87	3.62	2.68
FeO _(max) †	12.29	12.57	12.04	13.99	12.92
Y ₂ O ₃	0.12	0.02	1.00	0.03	0.49
Sb ₂ O ₃	0.07	0.02	b.d.	0.11	b.d.
Bi ₂ O ₃	0.06	b.d.	b.d.	0.11	0.21
MgO	0.31	0.33	0.32	0.27	0.28
CaO	b.d.	b.d.	b.d.	b.d.	0.55
MnO	2.38	2.26	2.54	2.25	2.16
ZnO	b.d.	b.d.	0.06	0.01	0.03
PbO	0.30	b.d.	b.d.	0.04	0.02
Na ₂ O	b.d.	0.04	0.01	b.d.	b.d.
Th ₂ O	0.13	b.d.	0.13	0.05	0.37
U ₂ O	0.09	0.02	0.21	b.d.	0.26
Total	100.50	100.77	99.98	101.30	98.64
W ⁶⁺ (<i>apfu</i>)	0.021	0.017	0.021	0.030	0.016
Nb ⁵⁺	1.567	1.625	1.614	1.607	1.617
Ta⁵⁺	0.110	0.088	0.082	0.101	0.119
Si ⁴⁺	0.000	0.003	0.015	0.007	0.005
Ti ⁴⁺	0.279	0.227	0.228	0.256	0.242
Zr ⁴⁺	0.013	0.010	0.008	0.004	0.005
Sn ⁴⁺	0.001	0.004	b.d.	0.001	b.d.
Al ³⁺	b.d.	b.d.	0.004	0.001	0.010
Sc ³⁺	0.099	0.109	0.123	0.061	0.061
$Fe^{3+}(min)^{\dagger}$	0.188	0.202	0.162	0.151	0.115
Fe ²⁺ (max) [†]	0.572	0.579	0.559	0.647	0.617
Y ³⁺	0.004	0.001	0.030	0.001	0.015

Table 2.42. Chemical compositions and structural formula of columbite-(Fe) from the host rocks near an aplite dike.

Sample	AplH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)
Sb ³⁺ (<i>apfu</i>)	0.002	0.000	b.d.	0.002	b.d.
Bi ³⁺	0.001	b.d.	b.d.	0.002	0.003
Mg ²⁺	0.025	0.027	0.026	0.022	0.024
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.034
Mn ²⁺	0.112	0.105	0.119	0.105	0.105
Zn ²⁺	b.d.	b.d.	0.002	0.001	0.001
Pb ²⁺	0.004	b.d.	b.d.	0.001	0.000
Na⁺	b.d.	0.004	0.001	b.d.	b.d.
Th⁺	0.002	b.d.	0.002	0.001	0.005
U+	0.001	0.000	0.003	b.d.	0.003
O ²⁻	6.000	6.000	6.000	6.000	6.000

The formulae were calculated on the basis of 6 O atoms per formula unit.

Fluorine was also sought but was below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	AplH-4b-1	AplH-4b-1	AplH-4b-1	AplH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1
Mineral	*Brl	Brl	Brl	Brl
SiO ₂ (wt.%)	67.46	67.70	67.65	67.43
Al ₂ O ₃	18.89	18.83	18.63	18.60
$Fe_2O_{3(min)}^{\dagger}$	b.d.	b.d.	0.00	b.d.
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	0.17	b.d.
BeO [‡]	13.18	12.89	13.28	13.55
MgO	0.09	0.03	0.07	0.06
Na ₂ O	0.16	0.15	0.10	0.12
Rb ₂ O	0.08	0.14	0.04	0.10
Total	99.86	99.75	99.94	99.886
Si ⁴⁺ (<i>apfu</i>)	6.005	6.022	6.024	6.031
Al ³⁺	1.982	1.973	1.955	1.960
Fe^{3+} (min) †	b.d.	b.d.	0.013	b.d.
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	0.013	b.d.
Be ²⁺	3.000	3.000	3.000	3.000
Mg ²⁺	0.012	0.003	0.009	0.008
Na ⁺	0.027	0.025	0.017	0.021
Rb ⁺	0.0004	0.008	0.002	0.006
O ^{2_}	18.012	18.026	18.011	18.026

Table 2.43. Chemical compositions and structural formula of beryl from the host rocks near an aplite dike.

The formulae were calculated on the basis of 8 T and M site cations per formula unit.

Phosphorus, Ti, Cr, Sc, Mn, Zn, Ca, Ba, Cs, K, Cl, and F were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]BeO was calculated based on total wt.% oxide = 100; b.d. = below detection limit.

Sample	ApIH-4b-1	ApIH-4b-1	AplH-4b-1	AplH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1
Mineral	*Sch	llmen	Ilmenorutile	
WO ₃ (wt.%)	70.00	b.d.	0.03	
Nb ₂ O ₅	1.41	21.62	23.01	_
Ta ₂ O ₅	b.d.	4.30	4.72	_
SiO ₂	0.68	0.01	0.11	1.19
TiO ₂	b.d.	65.86	64.49	0.00
ZrO ₂	-	0.02	0.07	b.d.
SnO ₂	-	0.26	0.23	_
Al ₂ O ₃	b.d.	0.13	0.14	0.01
Sc ₂ O ₃	b.d.	0.21	0.23	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	8.63	8.94	0.37
FeO _(max) †	6.83	0.00	0.00	0.00
Y ₂ O ₃	_	b.d.	0.08	1.21
Sb ₂ O ₃	_	0.06	0.11	_
La ₂ O ₃	-	-	-	9.94
Ce ₂ O ₃	_	-	-	24.56
Pr ₂ O ₃	-	_	_	3.14
Nd ₂ O ₃	_	-	-	9.49
Sm ₂ O ₃	-	-	-	1.76
Gd ₂ O ₃	_	-	-	0.67
Tm_2O_3	_	-	-	0.27
Bi ₂ O ₃	-	0.08	b.d.	-
MgO	0.14	0.01	0.01	b.d.
CaO	15.54	b.d.	b.d.	15.44
ZnO	b.d.	0.02	b.d.	-
Na ₂ O	0.08	b.d.	b.d.	b.d.
K ₂ O	-	-	-	0.04
Th₂O	_	b.d.	b.d.	1.63
U ₂ O	-	0.03	b.d.	b.d.
F	b.d.	b.d.	b.d.	5.16
CO_2^{\ddagger}	_	_	_	27.23
H_2O^{\S}	_	_	_	3.13
-(O=F)	_	_	_	-2.17
Total	94.67	101.23	102.15	103.05
W ⁶⁺ (<i>apfu</i>)	0.804	b.d.	0.000	_
Nb ⁵⁺	0.028	0.146	0.155	_

Table 2.44. Chemical compositions and structural formula of scheelite, ilmenorutile, and synchysite-(Ce) from the host rocks near an aplite dike.

Sample	ApIH-4b-1	AplH-4b-1	ApIH-4b-1	AplH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1
Mineral	*Sch	Ilmenorutile		Snc-(Ce)
Ta ⁵⁺ (<i>apfu</i>)	b.d.	0.017	0.019	_
Si ⁴⁺		0.000	0.002	0.064
Ti ⁴⁺	b.d.	0.740	0.725	0.000
Zr ⁴⁺	_	0.000	0.000	0.000
Sn ⁴⁺	_	0.002	0.001	-
Al ³⁺	b.d.	0.002	0.002	0.001
Sc ³⁺	b.d.	0.003	0.003	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.097	0.100	0.015
$Fe^{2+}(max)^{\dagger}$	0.253	0.000	0.000	0.000
Y ³⁺	-	b.d.	0.001	0.015
Sb ³⁺	-	0.000	0.00	-
La ³⁺	-	-	_	0.197
Ce ³⁺	-	_	_	0.484
Pr ³⁺	-	-	_	0.062
Nd ³⁺	_	_	_	0.182
Sm ³⁺	-	-	_	0.033
Gd ³⁺	-	-	_	0.012
Tm ³⁺	_	_	_	0.004
Bi ³⁺	-	0.000	0.000	-
Mg ²⁺	0.009	0.000	0.000	0.000
Ca ²⁺	0.74	b.d.	b.d.	0.890
Zn ²⁺	b.d.	0.000	b.d.	-
Na ⁺	0.006	b.d.	b.d.	b.d.
K+	-	-	_	0.003
Th ⁺	-	b.d.	b.d.	0.020
U ⁺	-	0.000	b.d.	b.d.
F⁻	b.d.	0.000	0.000	0.877
C ^{4+‡}	-	-	-	2.000
OH⁻§	_	-	_	1.123
O ²⁻	3.546	2.046	2.055	6.149

The formula for scheelite was calculated on the basis of 1 2+ cation, ilmenorutile on the basis of 1 Ti + Nb + Fe cation, and synchysite-(Ce) on the basis of 3 cations per formula unit.

Manganese and Pb were sought in all minerals but were below the detection limit of the EMP in all analyses. Molybdenum was also sought in scheelite and P, Eu, Ba, Sr, Tb, Dy, Ho, Er, Yb, and Cl were also sought in synchysite-(Ce).

*Abbreviations of mineral names follow Whitney & Evans (2010); Snc = synchysite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 1 *apfu* C; [§]H₂O contents based on stoichiometry; b.d. = below detection limit; – = not measured.

2.5.3 Cathodoluminescence

Cathodoluminescence imaging was performed on quartz in the Rau 1, 3, 4, 5, 5U, 6, 7, 8, and 10 pegmatite dikes, and in an aplite dike. The purpose of obtaining CL images was to determine individual quartz generations and their origin (primary, secondary, hydrothermal). Secondary and hydrothermal features could provide evidence for a later, melt- or fluid-driven process, such as reaction with late sodic melt, hydrothermal crystallization in pockets, or hydrothermal contamination, that recrystallized the quartz.

A variety of CL textures was observed in coarse-grained quartz in central parts of the pegmatite dikes but the majority of grains are homogeneous (Fig. 2.81) or, more rarely, coarsely zoned with only two different zones. Some of these coarsely zoned grains have differently shaded CL cores and rims, but generally the zones are not distinct (Fig. 2.82). Some secondary alteration is present as secondary precipitation along fractures and secondary overgrowths along the rims of grains (Fig. 2.83). The only oscillatory zoning observed was in quartz from the Rau 5U pegmatite dike (Fig. 2.84). These grains all occur as larger phenocrysts in the finer-grained feldspar and quartz matrix.

Quartz in the endo-contact skarns in dikes Rau 5 and 7 was also imaged. It is very poorly zoned, or displays chaotic CL textures (Fig. 2.85).

Multiple generations of quartz are present in quartz veins within the pegmatite dikes. They have complex oscillatory zoned textures, secondary overgrowths (Fig. 2.86), and show evidence secondary precipitation along fractures (Fig. 2.87). Quartz from pegmatite pockets can show similar textures but tends to be more homogeneous (Fig. 2.88).


Figure 2.81. CL image of homogeneous quartz in the Rau 1 pegmatite dike.



Figure 2.82. CL image of coarsely zoned quartz in the Rau 5U pegmatite dike.



Figure 2.83. CL image of quartz in the Rau 8 pegmatite dike showing secondary precipitation along fractures.



Figure 2.84. CL image of quartz in the Rau 5U pegmatite dike showing oscillatory zoning.



Figure 2.85. CL image of quartz in the endo-contact skarn bordering the Rau 5 pegmatite dike showing chaotic zoning.



Figure 2.86. CL image of quartz in a vein that cuts through the Rau 5U pegmatite dike showing oscillatory zoning and secondary overgrowths.



Figure 2.87. CL image of quartz in a vein that cuts through the Rau 6 pegmatite dike showing secondary precipitation along fractures.



Figure 2.88. CL image of quartz in a pocket in the Rau 7 pegmatite dike showing fairly homogeneous CL textures with slight zoning near the rim of the grain.

2.5.4 Laser ablation inductively coupled plasma mass spectrometry

Laser ablation-inductively coupled plasma-mass spectrometry was used to measure the trace element composition of quartz in the Rau 1, 3, 4, 5, 6, 7, 8, and 10 pegmatite dikes, an aplite dike, and the porphyritic phase of the Rackla pluton (Table 2.45). Although quartz is not generally analysed using LA-ICP-MS because of its extremely low trace element contents (M. Amini, personal communication), recent studies of pegmatitic quartz have shown that their trace element concentrations reflect the geochemical signature of the dikes (e.g., Müller *et al.*, 2013). Because the Rau pegmatite dikes are thought to have a mixed-type geochemical signature, LA-ICP-MS was used to determine whether this was reflected in the trace element contents of quartz. Quartz in an aplite dike and the porphyritic phase of the Rau pluton was also analysed to assess the similarities and/or differences between the chemical composition of quartz in these units and that in the pegmatite dikes.

The majority of trace elements sought proved to occur in too low concentrations to be accurately analysed. However, accurate analyses of Al, Li, B, Ge, and Sc were obtained. The Ge and Sc contents of quartz from all analysed units is quite similar. Germanium ranges from an average of 2 ppm in quartz in dikes Rau 6, 10, and an aplite dike to 8 ppm in Rau 1 (Fig. 2.89a), and Sc ranges from an average of 2 ppm in dikes Rau 3, 4, 6, 7, 10 and an aplite dike to 4 ppm in Rau 8 (Fig. 2.89b).

Although specific NYF- and LCT-type fields based on the Al and Li contents of quartz have not yet been delineated, Müller *et al.* (2013) showed that quartz from NYF-type pegmatites contained between 21 (\pm 7) to 94 (\pm 58) ppm Al and 6 (\pm 4) to 12 (\pm 7) ppm Li, whereas quartz from LCT-type pegmatites had a significantly higher concentration of these elements, with 265(\pm 180) to 766 (\pm 256) ppm Al and 56 (\pm 21) to 98 (\pm 69) ppm Li. The average contents of Al in quartz from the pegmatite dikes ranges from 38 ppm in dike Rau 4 to 268 ppm in dike Rau 3, with an overall average of 159 ppm; however, all analyses of Al in quartz in Rau 7 had poor internal precision. The average contents of Li in quartz from the pegmatite dikes ranges from 2 in Rau 7 to ppm in 18 Rau 1, with an overall average of 8 ppm. When compared to the average concentrations of Al and Li in NYF- and LCT-type pegmatites; however, the Al contents of some dikes, specifically Rau 1 and parts of Rau 3 and 5, are more similar to LCT-type pegmatites. Quartz from the porphyritic phase also has average Al contents more similar to that in LCT-type pegmatites (Fig. 2.90).

Quartz in the Rau 1 pegmatite dike has substantially higher trace element contents than quartz in most of the other pegmatite dikes, an aplite dike, and the porphyritic phase. It contains on average 245 ppm Al (n = 8), which is significantly higher than the Al contents of quartz in dikes Rau 4 (38 ppm; n = 9), Rau 6 (90 ppm; n = 12), Rau 8 (160 ppm; n = 11), Rau 10 (80 ppm; n = 11), and an aplite dike (104 ppm; n = 11). Although quartz from the Rau 1 pegmatite dike does have high Al contents, the Al contents of quartz in the porphyritic phase of the Rackla pluton is still significantly higher with an average of 346 ppm (n = 7) (Fig. 2.89c). The average Li contents of quartz in Rau 1 is 18 ppm (n = 9), which is significantly higher than the contents of Li in quartz from all other analysed units (Figs. 2.89d). Its B contents (average 15 ppm B; n = 8) is significantly higher than the average B contents of quartz in dike Rau 3 (5 ppm; n = 35), Rau 4 (3 ppm; n = 8), Rau 5 (7 ppm; n = 53), Rau 6 (3 ppm; n = 12), Rau 8 (5 ppm; n = 12), Rau 10 (3 ppm; n = 12), and an aplite dike (3 ppm; n = 10) (Fig. 2.89e). All tests of statistical significance can be found in Table 2.46.

The chemistry of quartz from various zones across two of the larger pegmatite dikes (Rau 3 and 5) was analysed. Samples from an inner zone through to an outer zone of Rau 3 were analysed, together with samples from a complete transect across Rau 5. The highest contents of Al, Li, and B in quartz occur in the middle to outer zones of Rau 3. The lowest contents of these elements are all in the outermost zone, although the difference between the Al and Li contents of quartz in the outermost and inner zone is insignificant (Fig. 2.91a). In dike Rau 5, the trace element contents of quartz is more symmetrical with high contents of Al, Li, and B occurring in the inner and middle zones, and the outer zones generally having lower contents of these elements (Fig. 2.91b).

The trace element contents of quartz from an aplite dike are relatively low. It has an average contents of 104 ppm Al (n = 11), 8 ppm Li (n = 11), 3 ppm B (n = 10), 2 ppm Sc (n = 11), and 2 ppm Ge (n = 11). This is similar to some of the pegmatite dikes with lower concentrations of trace elements such as Rau 10 (Figs. 2.89a–c). The trace element contents of quartz in the porphyritic phase of the Rackla pluton also falls within the range of the pegmatite dikes and an aplite dike. Quartz in the porphyritic phase contains an average of 346 ppm Al (n = 7), 7 ppm B (n = 11), 7 ppm Li (n = 11), and 3 ppm Sc (n = 11).

Sample	Unit	Description	Number of analysis points
R2-3	Pegmatite dike	Coarse-grained clear guartz	9
R3-1b	Pegmatite dike	Coarse-grained clear quartz	11
R3-2d	Pegmatite dike	Fe-stained quartz with white feldspars	10
R3-2e	Pegmatite dike	Coarse-grained clear and white quartz	12
R3-3	Pegmatite dike	Coarse-grained clear and white quartz	12
R4-2b	Pegmatite dike	Coarse-grained clear quartz	9
R5-A	Pegmatite dike	Fine-grained smoky quartz and white feldspars	4
R5-B	Pegmatite dike	Coarse-grained clear and white quartz	10
R5-C	Pegmatite dike	Coarse-grained clear quartz	10
R5-D	Pegmatite dike	Coarse-grained clear quartz	12
R5-E1	Pegmatite dike	Coarse-grained clear and white quartz	6
R5-F1	Pegmatite dike	Coarse-grained clear quartz	12
R6-A	Pegmatite dike	Coarse-grained clear quartz	12
R7-A	Pegmatite dike	Fine-grained smoky quartz and white feldspars	3
R8-1b	Pegmatite dike	Coarse-grained clear quartz	12
R10-1a	Pegmatite dike	Coarse-grained clear quartz	12
RApl-3e	Aplite dike	Coarse-grained clear quartz	11
Hrn-1	Porphyritic phase of the Rackla pluton	Coarse-grained clear quartz	11

 Table 2.45. Samples of quartz analysed using LA-ICP-MS.



Figure 2.89. Plots showing the distance of pegmatite dikes, an aplite dike, and the porphyritic phase of the Rackla pluton from the main Rackla pluton versus the contents of (a) Ge, (b) Sc, (c) Al, (d) Li, and (e) B in quartz.



Figure 2.90. Aluminum and Li contents of quartz from the Rau pegmatite dikes, an aplite dike, and porphyritic phase of the Rackla pluton compared to the average Al and Li contents of quartz from NYF- and LCT-type pegmatites (Müller *et al.*, 2013).

Unit A			Unit B				Paired t-test				
Trace element	Sample	Unit	Concentration (ppm)	# of analyses	Sample(s)	Unit	Concentration (ppm)	# of analyses	t stat.	t crit.	p-value
AI	R2-3	Rau 1	245.11	8	R4-2b	Rau 4	37.89	9	18.97	2.13	<.001
AI	R2-3	Rau 1	245.11	8	R6-A	Rau 6	90.34	11	9.67	2.11	<.001
AI	R2-3	Rau 1	245.11	8	R8-1b	Rau 8	160.33	11	4.01	2.11	<.001
AI	R2-3	Rau 1	245.11	8	R10-1a	Rau 10	80.13	11	11.74	2.11	<.001
AI	R2-3	Rau 1	245.11	8	RApl-3e	Aplite	104.38	11	12.05	2.11	<.001
AI	R2-3	Rau 1	245.11	8	Hrn-1	Porphyritic	345.83	7	-7.05	2.16	<.001
Li	R2-3	Rau 1	18.29	9	R3-1b, -2d, -2e	Rau 3	9.66	45	4.91	2.01	<.001
Li	R2-3	Rau 1	18.29	9	R4-2b	Rau 4	3.49	8	8.24	2.13	<.001
Li	R2-3	Rau 1	18.29	9	R5-A, -B, - C, -D, -E1, - F1	Rau 5	7.72	53	9.82	2.00	<.001
Li	R2-3	Rau 1	18.29	9	R6-A	Rau 6	6.88	12	6.58	2.09	<.001
Li	R2-3	Rau 1	18.29	9	R7-A	Rau 7	2.70	3	5.44	2.23	<.001
Li	R2-3	Rau 1	18.29	9	R8-1b	Rau 8	10.91	12	4.19	2.09	<.001
Li	R2-3	Rau 1	18.29	9	R10-1a	Rau 10	5.88	12	8.26	2.09	<.001
Li	R2-3	Rau 1	18.29	9	RApl-3e	Aplite	8.13	11	6.76	2.10	<.001
Li	R2-3	Rau 1	18.29	9	Hrn-1	Porphyritic	6.97	11	6.53	2.10	<.001
В	R2-3	Rau 1	14.94	8	R3-1b, -2d, -2e	Rau 3	5.42	35	4.18	2.02	<.001
В	R2-3	Rau 1	14.94	8	R4-2b	Rau 4	3.03	8	2.63	2.14	.02
В	R2-3	Rau 1	14.94	8	R5-A, -B, - C, -D, -E1, - F1	Rau 5	7.03	53	3.99	2.00	<.001
В	R2-3	Rau 1	14.94	8	R6-A	Rau 6	2.97	12	3.29	2.10	.004
В	R2-3	Rau 1	14.94	8	R8-1b	Rau 8	4.99	12	2.74	2.10	.01

Table 2.46. The difference in trace element contents of quartz in various pegmatite dikes, an aplite dike, and the porphyritic phase of the Rackla pluton. All comparisons in this table are statistically significant (p-value <.05).

Unit A				Unit B				Paired t-test			
Trace element	Sample	Unit	Concentration (ppm)	# of analyses	Sample(s)	Unit	Concentration (ppm)	# of analyses	t stat.	t crit.	p-value
В	R2-3	Rau 1	14.94	8	R10-1a	Rau 10	3.00	12	3.27	2.10	.004
В	R2-3	Rau 1	14.94	8	RApl-3e	Aplite	2.63	10	3.08	2.12	.007



Figure 2.91. Aluminum, Li, B, Sc, and Ge contents of quartz from the (a) inner through to outermost zones of dike Rau 3 and (b) across an entire transect of the Rau 5 pegmatite dike.

2.5.5 Carbon and oxygen stable isotopes

Ratios of stable C and O isotopes were measured in carbonate minerals in the pegmatite dikes, endo-contact skarns, and host rocks. In the pegmatite dikes and endo-contact skarns, only calcite crystals that were large enough to drill out with a tungsten carbide bit affixed to a Dremel[®] rotary drill tool were sampled. This means that all sampled carbonate minerals in these units are from pockets because the carbonate minerals are too small to be drilled out with a Dremel[®] tool. The host rocks, which are a mixture of fine-grained dolomite and lesser calcite, and a calcite-rich portion of an aplite dike were also analysed. The units sampled are listed in Table 2.47.

The carbon and oxygen isotopic signatures of carbonate minerals in the host rocks are distinct from those of the sampled carbonate minerals in the pegmatite and aplite dikes. Their isotopic signatures range from +24.83 to +30.37‰ δ^{18} Ovsmow and -1.58 to +0.35‰ δ^{13} CvPDB (*n* = 9). The carbonate minerals in all of the dikes have similar carbon and oxygen isotopic signatures ranging from +11.23 to +15.42‰ δ^{18} Ovsmow and -8.35 to -3.17‰ δ^{13} CvPDB (n = 15) (Fig. 2.92a). When the occurrence of the carbonate minerals in the pegmatite dikes is taken into account, there is a clear difference between the carbon isotopic signature of the milky white calcite and the calcite with exsolved Fe oxide minerals. The range of the carbon isotopic signatures of milky white calcite is -8.35 to -6.24% δ^{13} C_{VPDB} (n = 9), whereas that of the calcite with exsolved Fe oxide minerals is -5.29 to $-3.17\% \delta^{13}$ C_{VPDB} (n = 7) (Fig. 2.92b) (Table 2.48). The oxygen isotopic signatures of these two types of carbonate minerals are similar. There appears to be no correlation between the isotopic signature of carbonate minerals in the pegmatite and aplite dikes and their distance from the Rackla pluton. Furthermore, there is no correlation between the isotopic signature of carbonate minerals in the host rocks and their distance from a pegmatite or aplite dike. Because the error of the MIA is relatively high $(\sim 0.5\%)$, some differences could be obscured by the resolution of the instrument.

Sample	Unit	Description
R2-2	Pegmatite dike	Calcite with exsolved Fe oxide minerals
R3-1b	Pegmatite dike	Calcite with exsolved Fe oxide minerals
R3-2a	Pegmatite dike	Calcite with exsolved Fe oxide minerals
R4-2d	Pegmatite dike	Calcite with exsolved Fe oxide minerals
R5-F	Pegmatite dike	Milky white calcite
R5U-H	Pegmatite dike	Milky white calcite
R5U-I	Pegmatite dike	Milky white calcite
R6-1c	Pegmatite dike	Milky white calcite
R7-A	Pegmatite dike	Milky white calcite
R7-A	Pegmatite dike	Milky white calcite
Apl-3b	Aplite dike	Milky white calcite
R3-2d	Endo-contact skarn	Calcite with exsolved Fe oxide minerals
R5-3d	Endo-contact skarn	Milky white calcite
R5U-G	Endo-contact skarn	Calcite with exsolved Fe oxide minerals
R6-A	Endo-contact skarn	Milky white calcite
R6-1c	Endo-contact skarn	Calcite with exsolved Fe oxide minerals
R3-4	Rau 3 host rock	~1.5 m from dike Rau 3
R3-5	Rau 3 host rock	~20 m from dike Rau 3
R4-1	Rau 4 host rock	~1 m from dike Rau 4
R5U-4	Rau 5U host rock	~0 m from dike Rau 5U
R6-2	Rau 6 host rock	< 1 m from dike Rau 6
R9b-2a	Rau 9 host rock	~1 m from dike Rau 9
R9b-2a	Rau 9 host rock	~1 m from dike Rau 9
ApIH-4a	Aplite dike host rock	~0 m from an aplite dike
ApIH-4a	Aplite dike host rock	~0 m from an aplite dike

Table 2.47. Samples of carbonate minerals for which stable carbon and oxygen isotopes were measured.



Figure 2.92. $\delta^{18}O_{VSMOW}$ versus $\delta^{13}C_{VPDB}$ of carbonate minerals. (a) When the samples are plotted based on which unit they occur in, the host rocks can be distinguished but all pegmatite and aplite dikes belong to one overlapping field. (b) However, when the samples are plotted based on the occurrence of the carbonate mineral(s) three distinct fields can be defined.

Sample	Unit	Carbonate occurrence	$\delta^{18}O_{VSMOW}$	s.d. δ ¹⁸ Ο	$\delta^{13}C_{\text{VPBD}}$	s.d. δ ¹³ C
R2-2	Pegmatite dike	Cal* with Fe oxide	12.83	0.28	-4.89	0.17
R3-1b	Pegmatite dike	Cal with Fe oxide	12.66	0.42	-3.31	0.16
R3-2a	Pegmatite dike	Cal with Fe oxide	13.08	0.28	-3.43	0.17
R4-2d	Pegmatite dike	Cal with Fe oxide	12.03	0.28	-3.43	0.17
R5-F	Pegmatite dike	Milky white Cal	13.76	0.28	-8.35	0.17
R5U-H	Pegmatite dike	Milky white Cal	13.05	0.28	-7.95	0.17
R5U-I	Pegmatite dike	Milky white Cal	13.62	0.28	-6.47	0.17
R6-1c	Pegmatite dike	Milky white Cal	12.88	0.28	-5.29	0.17
R7-A	Pegmatite dike	Milky white Cal	12.48	0.28	-6.61	0.17
R7-A	Pegmatite dike	Milky white Cal	12.15	0.28	-7.86	0.17
Apl-3b	Aplite dike	Milky white Cal	15.42	0.28	-6.24	0.17
R3-2d	Endo-contact skarn	Cal with Fe oxide	11.23	0.42	-3.85	0.16
R5-3d	Endo-contact skarn	Milky white Cal	12.36	0.28	-7.40	0.17
R5U-G	Endo-contact skarn	Cal with Fe oxide	12.81	0.42	-3.17	0.16
R6-A	Endo-contact skarn	Milky white Cal	13.63	0.28	-7.72	0.17
R6-1c	Endo-contact skarn	Cal with Fe oxide	12.49	0.42	-7.56	0.16
R3-4	Rau 3 host rock	Massive Dol (+Cal)	27.25	0.42	-1.58	0.16
R3-5	Rau 3 host rock	Massive Dol (+Cal)	30.37	0.28	-1.24	0.17
R4-1	Rau 4 host rock	Massive Dol (+Cal)	24.95	0.28	-0.12	0.17
R5U-4	Rau 5U host rock	Massive Dol (+Cal)	24.83	0.28	-0.36	0.17
R6-2	Rau 6 host rock	Massive Dol (+Cal)	26.31	0.28	0.35	0.17
R9b-2a	Rau 9 host rock	Massive Dol (+Cal)	25.44	0.28	-0.73	0.17
R9b-2a	Rau 9 host rock	Massive Dol (+Cal)	25.14	0.28	0.12	0.17
AplH-4a	Aplite dike host rock	Cal - main constituent with mica	28.55	0.28	0.13	0.17
AplH-4b-5	Aplite dike host rock	Cal - main constituent with mica	26.61	0.28	-0.34	0.17

Table 2.48. Carbon and oxygen isotopic ratios of carbonate minerals from the pegmatite dikes, an aplite dike, endo-contact skarns, and host rocks.

*Abbreviations of mineral names follow Whitney & Evans (2010).

2.6 Discussion

2.6.1 Rackla pluton

In the study area, the Rackla pluton is a weakly peraluminous (ASI = 1.08), ferroan, calcalkalic granite. Its ASI is consistent with the weakly peraluminous to metaluminous ASI of the pegmatite dikes and also with previous whole rock data from Thiessen *et al.* (2016) whose analyses of granite, quartz monzonite, and granodiorite portions of the pluton were mostly weakly peraluminous (ASI = 1.02-1.38), with one sample being metaluminous (ASI = 0.92). In terms of *Fe*-number [FeO_{tot} / (FeO_{tot} / MgO); Frost *et al.*, 2001], the ferroan signature of the Rackla pluton is consistent with the pegmatite dikes, the majority of which are classified as ferroan. The deviation of some pegmatite dikes towards a magnesian composition is due to contamination by the Mg-rich dolostone host rocks. Although the Rackla pluton plots within the calc-alkalic field of the modified alkali-lime index (Frost *et al.*, 2001), whereas all pegmatite dikes except for the Rau 10 dike plot in the alkalic field, the alkali contents are similar to those of the pegmatite dikes (Fig. 2.5b). The higher Si content of the Rackla pluton is the variable that causes this different classification. The overall similarity of the geochemical signature of the Rackla pluton to that of the pegmatite dikes, as well as the spatial proximity of the pluton to the pegmatite dikes, supports the view that the Rackla pluton is parental to the Rau pegmatite group.

Thiessen *et al.* (2016) analyzed the major element composition of granite, quartz monzonite, and granodiorite portions of the Rackla pluton in the vicinity of the Tiger zone gold deposit. The composition of these samples is similar to the portion of the Rackla pluton that outcrops near the Rau pegmatite group (Figs. 2.93a, 2.93b, and 2.93c). Of note is that the ASI of the pluton near the Rau pegmatite group is closer to that of the pegmatite dikes, whereas some of the samples analysed by Thiessen *et al.* (2016) deviate towards more peraluminous compositions. Furthermore, the pluton near the Rau pegmatite group is calc-alkalic, while samples near the Tiger deposit are mostly alkali-calcic. The Rackla pluton is dominantly ferroan near the Rau pegmatite group and the Tiger deposit, however one sample near the Tiger deposit has a magnesian composition (Thiessen *et al.*, 2016). Similar to the pegmatite dikes that have a magnesian signature, this is likely due to the influence of the dolostone host rocks.



Figure 2.93. Classification of the Rau 3, 4, 5, 6, 7, 8, 9, and 10 pegmatite dikes, an aplite dike, the porphyritic phase of the Rackla pluton, and the Rackla pluton compared to granite, quartz monzonite, and granodiorite portions of the Rackla pluton in the vicinity of the Tiger zone gold deposit (Thiessen *et al.*, 2016). (a) Classification using the *Fe*-number showing the boundary between ferroan and magnesian granitic rocks (Frost *et al.*, 2001). (b) Classification using the modified alkali-lime index showing the approximate ranges of the alkalic, alkali-calcic, calc-alkalic, and calcic granitic rock series (Frost *et al.*, 2001), as well as ideal compositions of K-feldspar and albite. (c) Classification using Shand's index (Maniar & Piccoli, 1989).

2.6.2 Porphyritic phase of the Rackla pluton

This unit is interpreted to represent the uppermost portion of the Rackla pluton, which formed during its final stages of crystallization. It is rich in secondary REE- and F-bearing carbonate minerals that were produced when late hydrothermal fluids overprinted the magmatic assemblage. These fluids were concentrated as the Rackla pluton crystallized and incompatible elements were excluded from the crystallizing minerals. The trace element composition of the quartz, determined using LA-ICP-MS analysis, confirms that this unit is genetically related to the Rackla pluton and its derived pegmatite and aplite dikes. Additionally, the composition of columbite group minerals shows the relatively unfractionated nature of this unit in comparison to the pegmatite dikes.

The porphyritic phase contains the greatest variety of rare element-bearing minerals of all units sampled in the Rau pegmatite field area. Rare earth element-bearing carbonate minerals in particular are more abundant here than in all other units in the study area. Fluocerite-(Ce) is a unique mineral in this unit, where it is associated with bastnäsite-(Ce) and occurs as a secondary mineral to synchysite-(Ce) and parisite-(Ce) (Figs. 2.12a and 2.12b). Replacement of synchysite-(Ce) and parisite-(Ce) by bastnäsite-(Ce) and fluocerite-(Ce) indicates a relatively higher F and lower Ca contents than the pegmatite dikes. The CO₂ required to form these minerals would have been sourced from the carbonate host rocks.

The quartz phenocrysts in this unit have high Al contents (average 346 ppm): more than the average Al contents of quartz in the highly fractionated Rau 1 (245 ppm), 3 (267 ppm), and 5 (223 ppm) pegmatite dikes, and significantly higher than quartz from less-fractionated pegmatite dikes such as Rau 6 (85 ppm) and 7 (below detection limit). This higher Al contents indicates that the quartz phenocrysts crystallized at higher temperatures than quartz in the pegmatite dikes (Larsen *et al.*, 2004). The contents of B, Li, and Sc in quartz from the porphyritic phase are similar to the contents of those elements in quartz from the other pegmatite dikes and an aplite dike. This provides additional evidence that the pegmatite and aplite dikes are all part of the same pegmatite group, and that their formation is related to the emplacement of the Rackla pluton.

The porphyritic phase of the Rackla pluton is a relatively unfractionated unit. Its whole rock ratios of Zr/Hf and Nb/Ta are low compared to the pegmatite dikes. It is the only unit in the study area in which columbite group minerals rather than pyrochlore supergroup minerals are the

dominant Nb,Ta-bearing oxide minerals. Columbite group minerals in the porphyritic phase are primary, whereas pyrochlore supergroup minerals in the pegmatite dikes are in general secondary. Whole rock geochemical analysis indicates that the source of Nb and Ta is the Rackla pluton and that the host rocks contain very low or undetectable amounts of these elements. The primary nature and relative abundance of columbite group minerals in its porphyritic phase support the interpretation that these elements were sourced from the Rackla pluton. All columbite group minerals in the porphyritic phase of the pluton are columbite-(Fe) [average Nb / (Nb + Ta) = 0.83; n = 5], indicating that there has been little fractionation from the parental granite, whereas more fractionated compositions [columbite-(Mn) and tantalite-(Mn)] are found in the pegmatite dikes. Samarskite-(Y), the only other Nb,Ta-bearing mineral in the porphyritic phase, has a similar Nb / (Nb + Ta) ratio (average = 0.80; n = 8), suggesting a relatively low degree of fractionation in this unit.

2.6.3 Pegmatite dikes

The 10 pegmatite dikes that make up the Rau pegmatite group contain or are associated with unique features such as carbonate pockets and endo- and exo-contact skarns that will be discussed in subsequent sections. All of the pegmatite dikes are independent dikes (i.e., not connected at surface), except for Rau 5 and 5U. The mineralogical similarity of dikes Rau 5 and 5U, as well as their orientation in the field, suggests that Rau 5U is an upper extension of Rau 5, and that the two dikes are connected at depth.

Cathodoluminescence imaging shows that most of the quartz in the pegmatite dikes has homogeneous CL textures, which suggests that the crystallizing medium was a relatively stable system. However, there is also evidence of secondary fluid processes. For example, some of the quartz in the Rau 8 pegmatite dike is associated with secondary albite. The vein texture in the quartz (Fig. 2.83) documents secondary fluid-driven recrystallization that is likely related to albitization. The small bright spots in the CL image are secondary inclusions that are likely accessory minerals that were mobilized during secondary albitization.

The degree of fractionation of pegmatite dikes is expected to increase with distance from their parental pluton (London, 2008). Furthermore, thicker dikes tend to be more fractionated than thinner dikes. To assess the relative fractionation of the Rau pegmatite dikes, numerous EMP analyses of Cs and Rb in K-feldspar and mica were obtained. Cesium was below the detection limit of the EMP in all analyses of K-feldspar and the vast majority of analyses of mica. Rubidium was detected in nearly all analysed grains of mica, but was generally below the detection limit of the EMP in K-feldspar. The average Rb contents of mica does not show much variation from one pegmatite dike to the next, with a range of only 0.135 wt.% RbO₂; however, the lowest average Rb contents do occur in mica from the pegmatite dike closest to the Rackla pluton (Rau 10), whereas the highest average Rb contents occurs in mica from the pegmatite dike farthest away from it (Rau 3). On the basis of overall mineralogy, the Rau 10 pegmatite dike is the most similar in composition to the Rackla pluton, as it is the only pegmatite dike that contains spessartine. Muscovite in this pegmatite dike also has among the lowest average F contents of all mica in the pegmatite dikes. There is also a general increase in the average Rb contents of mica with distance from the Rackla pluton (Fig. 2.94). Due to the small variation in Rb contents, it is difficult to speculate about factors that would cause a deviation from the expected fractionation trend. Of note is that dike Rau 1, which contains minerals normally associated with highly fractionated dikes (amazonite, REE-bearing minerals, etc.; Cempírek & Groat, 2014) has a relatively high average Rb content of 0.22 wt.% RbO₂; this is particularly anomalous given its distance from the pluton. In comparison to other pegmatite groups, the Rb contents of mica is quite low. For example, muscovite in the Li-rich LCT-type Mount Begbie pegmatite dikes contains 0.53–1.52 wt.% RbO₂ (Dixon, 2013).

With increasing fractionation, the amount of incompatible rare elements in a melt increases and the composition of minerals within that melt evolve. Rau 1, 3, 5, and 5U contain substantially more rare element-bearing minerals than any of the other pegmatite dikes in the Rau pegmatite group. Examples of these rare element-bearing minerals include REE-bearing carbonate minerals [bastnäsite-(Ce), synchysite-(Ce), parisite-(Ce)] and REE-, Nb-, and Tabearing minerals [columbite group minerals, pyrochlore supergroup minerals, monazite-(Ce)]. With the exception of Rau 1, these pegmatite dikes are the thickest (Rau 5 and 5U) and farthest away (Rau 3) from the parental Rackla pluton, two factors that are known to influence the degree of fractionation of pegmatite dikes (Černý, 1991b). Rau 1 contains an anomalously evolved and diverse set of accessory minerals, even though it is a relatively thin dike (~0.5 m) and appears to be located closer to the Rackla pluton than other pegmatite dikes in the group. Its higher degree of fractionation does not appear to be related to contamination as the host rocks are not the source of rare elements in this system. The Rau 1 pegmatite dike could have been generated from

a different parental magma that was more fractionated than the Rackla pluton but this seems highly unlikely as the pegmatite is spatially within the Rau pegmatite group and there are no other pegmatite dikes that could be part of this second group. The most plausible reason for its highly evolved mineralogy is that the tectonic conditions at the time of emplacement allowed the pegmatite melt to travel in a different direction than the other pegmatite dikes, resulting in a longer distance between its point of extrusion from the Rackla pluton and its site of crystallization. This could be, for example, a fracture or other plane of weakness within the host rocks that allow the intruding pegmatite melt to alter its direction of propagation. This would allow the melt to travel relatively farther away from the Rackla pluton and increase its degree of fractionation. Furthermore, if the Rau 1 pegmatite dike was emplaced relatively late during the genesis of the Rau pegmatite group, tectonic conditions could have allowed it to propagate farther away from the Rackla pluton than would be expected in the ideal model of pegmatite genesis.

Some of the most pronounced changes in composition with increasing fractionation occur in Nb,Ta-bearing oxide minerals. An increase in Ta over Nb indicates an increasing degree of fractionation. In the pegmatite dikes, the dominant Nb,Ta-bearing oxide minerals are pyrochlore supergroup minerals, whereas columbite group minerals are less abundant. The compositions of pyrochlore supergroup and columbite group minerals provide additional data to evaluate the degree of fractionation of the pegmatite dikes. All analysed pyrochlore supergroup minerals have a similar chemical composition: they are all Ca-dominant at the A site and F-dominant at the Y site. Calcic as opposed to sodic compositions are expected in the Rau pegmatite dikes because of their Ca-rich host rocks. Furthermore, Na present in the original pegmatite melt would have been incorporated into albite. Fluorine enrichment is a common feature in the Rau pegmatite group. The most fractionated microlite compositions, i.e., those with the highest ratio of Ta / (Ta + Nb), occur in the Rau 1, 3, 5U pegmatite dikes. Pyrochlore supergroup minerals from the Rau 5 pegmatite dike were not analysed but due to the mineralogical similarity of Rau 5 and 5U, it is expected that they would also attain high levels of fractionation. In less fractionated pegmatite dikes, such as Rau 6 and 10, all analysed specimens have low ratios of Mn / (Mn + Fe) and Ta / (Ta + Nb) and are columbite-(Fe), whereas more fractionated columbite group minerals, such as columbite-(Mn) and tantalite-(Mn) occur in the Rau 1, 3, and 5 pegmatite dikes. These pegmatite

dikes consistently show features that indicate a high degree of fractionation (e.g., Rb contents of mica, diverse mineral assemblages).

Secondary pyrochlore supergroup minerals in the pegmatite dikes are commonly enriched in Ta compared to primary columbite group minerals. For example, columbite-(Fe) in the Rau 6 pegmatite dike has a Ta / (Ta + Nb) range from 0.15 to 0.19, whereas fluorcalciomicrolite in the same pegmatite has a Ta / (Ta + Nb) range from 0.58 to 0.68. Similarly, in the less fractionated Rau 10 pegmatite dike, Ta / (Ta + Nb) ranges from 0.13 to 0.18 in columbite-(Fe) and increases to 0.33–0.50 in the pyrochlore supergroup minerals. Both stability of the Ta/Nb ratio and are reported in the literature. Whereas acidic or neutral fluids are reported to result in stability of the Ta/Nb ratio due to the equal mobility of Nb and Ta (e.g., Novák *et al.*, 2004), alkaline (Na,Carich) fluids generally cause an enrichment in Ta in secondary minerals due to a preferential partitioning of Ta into the fluid (e.g., Green, 1995; Novák & Černý, 1998) that increases the Ta / (Ta + Nb) ratio in secondary Nb,Ta-bearing minerals. The results of this work supports the preferential mobility of Ta over Nb in secondary hydrothermal fluids and the resulting enrichment of Ta in secondary Nb,Ta-bearing minerals such as pyrochlore supergroup minerals.

The trace element contents of quartz in all of the pegmatite dikes is roughly similar; however, the average Al, Li, and B contents of quartz in the Rau 1 pegmatite dike are significantly higher than in quartz in many of the other pegmatite dikes (Table 2.45). This is consistent with the highly evolved mineralogy of the Rau 1 pegmatite dike (e.g., amazonite, fluor-elbaite, Nb- and Ta-bearing minerals, etc.). Quartz from the Rau 3 and 5 pegmatite dikes has the widest range of Al, Li, and B contents, the higher end of which overlaps with Rau 1 and the lower end of which is more similar to less-fractionated pegmatite dikes. The wide range of trace element contents likely reflects how the Rau 3 and 5 pegmatite dikes were sampled compared to other dikes. Samples were obtained and analysed from transects across Rau 3 and 5, whereas data from the other pegmatite dikes are only based on one sample from each dike. Quartz from the Rau 5 pegmatite, across which a complete transect from outer to inner to outer zones was analysed, has higher contents of Al, Li, and B in the middle and inner zones of the dike. This is consistent with higher levels of fractionation being attained in the inner zones of pegmatites compared to the outer zones (London, 2008).



Figure 2.94. Map showing the Rb contents of mica in the pegmatite and aplite dikes, the porphyritic phase of the Rackla pluton and the Rackla pluton.

2.6.3.1 Carbonate-filled pegmatite pockets

The presence and abundance of carbonate pockets in the pegmatite dikes appears to correlate with both the distance of the dike from the Rackla pluton and its thickness, with greater distance and thickness both resulting in greater abundance of pockets. Distance from the Rackla pluton seems to be the dominant factor as Rau 10 is a thick dike and is closest to the Rackla pluton; it is the only pegmatite dike in which carbonate pockets were not observed. In contrast Rau 3, the pegmatite dike farthest away from the Rackla pluton, contains abundant and large (up to a few centimeters across) pockets of calcite with exsolved Fe oxide minerals and schorl. Large (up to ~8 cm) pockets of calcite with exsolved Fe oxide minerals of magnesio-foitite to dravite occur in the Rau 1 pegmatite (Cempírek & Groat, 2014), a relatively thick dike and the most mineralogically evolved in the field. Rau 5 and 5U are also thick dikes and are located relatively far away from the Rackla pluton, and they contain centimeter-scale pockets of calcite with exsolved Fe oxide minerals and schorl and 1 and 3.

As the pegmatite melts propagated through the host rocks they assimilated carbonate (dolomite + calcite), increasing the concentrations of Ca, Mg, and CO₂ in the melts. As such, the pegmatite dikes farther away from their parental Rackla pluton contain more carbonate pockets. Furthermore, thicker dikes cool more slowly than thinner dikes, which again allows for more interaction with the host rocks and a resulting greater concentration of Ca, Mg, and CO₂ in the pegmatite melt. As pegmatites crystallize, incompatible elements and volatiles are excluded from crystallizing pegmatite minerals and are concentrated in the residual, fluid-rich melt (London, 2008). Any carbonate from the host rocks that was incorporated into the pegmatite dikes would be excluded from crystallizing minerals and concentrated in this residual fluid along with other incompatible elements that were also increasing in concentration as fractionation progressed. As such, some of the carbonate pockets also contain minerals such as beryl, tourmaline, and fluorite that are rich in incompatible elements (Be, B, F, etc.). Cathodoluminescence imaging of quartz crystals in pegmatite pockets confirms that they crystallized from a hydrothermal fluid.

Iron oxide minerals that form exsolution lamellae within the calcite that makes up most of the volume of the carbonate pockets indicate that this residual fluid was also rich in Fe. The textural relationship between the Fe oxide minerals and their host calcite crystals suggests that

they exsolved from the carbonate as the system cooled. Replacement of calcite by Fe oxide minerals seems less likely as the Fe oxide minerals do not follow any fractures or other planes of weakness within the carbonate grains and are essentially evenly dispersed from the cores to the edges.

The isotopic signature of the calcite in these pockets provides additional evidence that they formed later in the genesis of the pegmatite system. Their C and O isotopic compositions are midway between those of primary calcite in the pegmatite dikes and that of the host rocks. By crystallizing later, the carbonate in these pockets would have had more time to interact with the host rocks, modifying their isotopic signature to one closer to that of the host rock.

2.6.4 Aplite dikes

The aplite dikes differ from the pegmatite dikes in grain size and mineralogy. They are genetically related to the pegmatite dikes, as evidenced by their similar geochemical signatures (e.g., A-type, weakly peraluminous, alkali contents), and are derived from the Rackla pluton. Though they have not been dated, they are likely slightly older than the pegmatite dikes because they formed from a melt relatively less rich in fluids and their mineralogy is less evolved than that of the pegmatite dikes. Although the overall fluid content of the aplite dikes is lower than that of the pegmatite dikes, the aplite dikes can still accumulate fluids locally as crystallization progresses. Parts of the aplite dikes contain abundant muscovite and calcite, the product of those local accumulations of fluid. In one of the aplite dikes this zone also contains abundant beryl.

The diversity of Nb,Ta-bearing minerals in the aplite dikes is much less than in the pegmatite dikes and porphyritic phase of the Rackla pluton. Columbite-(Fe) occurs only in trace amounts and no other rare element-bearing oxide minerals were observed. This less diverse mineral assemblage demonstrates the low degree of fractionation of the aplite dikes compared to the pegmatite dikes.

Whole rock geochemical analysis of an aplite dike indicates that it contains the highest F and B contents of all analysed units (4670 and 371 ppm respectively). The abundance of these elements does not indicate high fractionation but rather the occurrence of muscovite- and calcite-rich hydrothermal zones. This is also reflected by the major element composition: the dike is poor in Si (57.10 wt.% SiO₂) and rich in Al and Ca (22.34 wt.% Al₂O₃ and 4.16 wt.% CaO). The Nb/Ta ratio and Rb contents of this aplite dike are lower than those of the pegmatite dikes. These

elements are still elevated compared to the Rackla pluton as the aplite dikes were derived from the pluton and are relatively more fractionated.

The host rock adjacent to one of the aplite dikes is far more altered than any of the host rocks adjacent to the pegmatite dikes. This alteration was caused by the same localized late-stage hydrothermal fluids that formed the muscovite- and calcite-rich zones of the aplite dikes, as the two dominant minerals in the altered host rocks are also muscovite and calcite. Beryl is also present as an accessory mineral in the host rocks.

2.6.5 Endo-contact skarns

All of the endo-contact skarns, both biotite- and amphibole-type, contain elongated mineral grains that have a variable orientation with respect to the margin of the pegmatite dike. This variable orientation, as opposed to an orientation perpendicular to the pegmatite-host rock contact, suggests that these skarns were formed by replacement of the pegmatite dike rather than as a vein that intruded along the contact of the pegmatite dike and the host rock. This replacement reaction was likely initiated when the hot, volatile-rich pegmatite melt was emplaced into the host rocks, creating a reaction zone at their contact, and formation continued as the pegmatites crystallized. The late-stage residual fluid that was exsolved from the pegmatites during their final stages of crystallization would have also reacted with the host rocks and continued to form the endo-contact skarns. This fluid was enriched in F and promoted the crystallization of secondary fluorite (Fig. 2.57). Formation of the endo-contact skarns due to a reaction of the pegmatite dike with the host rocks is supported by the presence of minerals related to both the pegmatite dikes and the host rocks in the endo-contact skarns. The accessory minerals in the endo-contact skarns are similar to accessory minerals in the pegmatite dikes, namely fluorite, pyrochlore supergroup minerals, columbite group minerals, and Fe oxide minerals. Many of the accessory minerals contain a combination of pegmatite- and host rockderived elements, e.g., Al from the pegmatite dikes and Ca from the host rocks in epidote supergroup minerals. Calcite is a major mineral in many of the endo-contact skarns and a major constituent of the host rocks. Furthermore, the main minerals in the endo-contact skarns, biotitephlogopite series mica and calcium amphibole subgroup minerals, require elements from both the pegmatite dikes and host rocks to crystallize. The pegmatite dikes would have provided K,

Si, and Al for the mica, whereas the host rocks would have contributed the Mg in the mica and the Ca in the amphibole supergroup minerals.

Biotite-phlogopite series mica is the dominant mineral in all of the endo-contact skarns except for the skarn associated with the Rau 6 pegmatite dike, which contains a greater proportion of calcium amphibole subgroup minerals such as magnesio- and ferro-hornblende, ferro-edenite, ferro-actinolite, and actinolite. These calcium amphibole subgroup minerals all contain elevated F (up to 1.60 wt.% F in magnesio-hornblende), providing evidence that the endo-contact skarns formed due to reaction with the pegmatite melt, which is the source of F in the system. The other unique feature of the Rau 6 endo-contact skarn is that it is the only endocontact skarn that is separated from the pegmatite dike by a quartz vein. The overall mineralogy of the Rau 6 pegmatite dike is fairly similar to the other pegmatite dikes in the group. It is one of the least evolved dikes and contains only fluorite, columbite group minerals, and pyrochlore supergroup minerals as its accessory minerals. Both biotite-phlogopite series mica and calcium amphibole subgroup minerals require Mg/Fe, Al, and Si to crystallize. The main difference in their compositions is that the biotite-phlogopite series mica contains K, whereas the calcium amphibole subgroup minerals contain Ca. In this system, the source of K is the Rackla pluton and pegmatite dikes, and the source of Ca is the dolostone host rock. It appears that the quartz vein that separates the amphibole-type endo-contact skarn from the Rau 6 pegmatite dike acted as a partial barrier between the two, resulting in more the elements for skarn formation being sourced from the host rock. The other biotite-type endo-contact skarns have a composition much more similar to the pegmatite dikes.

The mineralogy of the endo-contact skarns provides further evidence that some elements partitioned into a late-stage fluid that was excluded from the pegmatite dikes as they crystallized. The endo-contact skarns bordering the Rau 6, 7, and 9 pegmatite dikes contain REE-bearing minerals: minor epidote supergroup minerals, including allanite-(Ce), occur in all three of the skarns. However, REE-bearing minerals were not observed in any of these three pegmatite dikes. This suggests that these minerals crystallized later in the evolution of the pegmatite system because a high enough concentration of REEs was not attained in earlier stages of crystallization. Any REEs that were concentrated as the pegmatite crystallized were excluded from rock-forming minerals and partitioned into the fluid. This partitioning was promoted by the high activity of F in the fluid, which complexes with REEs and enriches them in the melt (Gieré, 1996).

Multiple factors could determine whether or not a pegmatite will be bordered by an endocontact skarn. There seems to be a range of distances from the parental granite where skarn formation can occur: not too close so that the pegmatite melt can accumulate enough volatiles, but not too far away so that the volatile content is not too high, allowing them to diffuse too far away into the host. As the pegmatite dikes fractionate and interact with the host rock their volatile contents will increase, and fractionation increases farther away from the parental granite. This is complicated by dike thickness. For example, the Rau 8 pegmatite dike should have an endo-contact skarn based on its distance from the parental granite alone, but no endo-contact skarn was observed. Mica in Rau 8 also has the lowest Rb contents of all pegmatite dikes except Rau 10, indicating a low degree of fractionation. This low degree of fractionation could indicate that the volatile contents of the Rau 8 pegmatite dike were not high enough to have a significant effect when those volatiles escaped from the parental granite and entered the host rock. The pegmatite dikes that are farthest away from the parental granite, such as Rau 3, would have had higher volatile contents that caused extensive alteration to their adjacent host rocks.

There appears to be a correlation between the presence of an endo-contact skarn bordering a pegmatite dike and the abundance of accessory minerals in the host rock adjacent to the pegmatite dike. However, samples of the host rocks are limited due to the lack of host rock outcrop adjacent to some of the pegmatite dikes, so this possible correlation could not be confirmed. For example, the Rau 3 pegmatite dike is not bordered by an endo-contact skarn, but the host rocks adjacent to it contain the greatest variety and abundance of accessory minerals of all sampled host rocks. In contrast, a biotite-type endo-contact skarn forms a continuous border between the Rau 9 pegmatite dike and its host rock, which is devoid of any accessory minerals. If an endo-contact skarn does form, any volatile-rich fluid that had been concentrated in the residual pegmatite melt appears to react with the host rocks to form the endo-contact skarn, rather than escaping further into the host rocks and altering them.

2.6.6 Exo-contact skarns

The exo-contact skarns formed when a volatile-rich fluid was expelled from the pegmatite dikes during the final phases of crystallization. The formation of this fluid phase is common in pegmatite dikes as volatiles and other incompatible elements are excluded from crystallizing minerals (London, 2014). Exo-contact skarns were only observed in association with the Rau 1

and 9 pegmatite dikes, but exposure of host rock in the field area is very limited and it is likely that there are exo-contact skarns associated with other pegmatite dikes, especially highly fractionated pegmatites such as Rau 3, 5, and 5U because greater fractionation would promote the formation of a late-stage volatile-rich fluid.

The main minerals that form the exo-contact skarns are calcite, humite group minerals, and fluoborite. The major elements required to form these minerals are Ca, Mg, Fe, Si, F, B, and OH. Calcium and Mg are the two main cations that form the dolostone host rock, whereas Si would be sourced from the pegmatite dikes. Fluorine, B, and OH are all volatile elements and compounds that would have been excluded from the pegmatite dikes as they crystallized. There is also evidence that Fe is an element that was enriched in the later stages of pegmatite crystallization. Calcite that occurs in pockets in the pegmatite dikes commonly contains exsolved Fe oxide minerals, and many pegmatite dikes contain trace amounts of Fe oxide and sulphide minerals that appear to have a secondary origin. Chondrodite and Fe oxide minerals in the exo-contact skarns are additional evidence for a late influx of Fe into the system (Section 2.6.8.4).

2.6.7 Behaviour of selected elements

2.6.7.1 Fluorine

The Rackla pluton is the source of the F in the Rau pegmatite dikes and associated units. Although the concentration of F in the Rackla pluton itself is relatively low (252 ppm), its porphyritic phase that was altered by secondary fluids exsolving from the pluton is richer in F (816 ppm) and contains abundant F-bearing accessory minerals including fluocerite-(Ce). Elevated activity of F during pegmatite crystallization is evident from F enrichment in multiple pegmatite minerals such as muscovite, pyrochlore supergroup minerals, REE-bearing carbonate minerals [bastnäsite-(Ce), synchysite-(Ce), and parisite-(Ce)], and epidote supergroup minerals. Because the abundance of these minerals is low compared to feldspars and quartz, F must have been concentrated during crystallization of the pegmatites (Novák *et al.*, 2003). This was facilitated by low contents of B, P, and Li in the pegmatite melt that prevented the crystallization of earlier-crystallizing F-bearing minerals such as elbaite, lepidolite, and F-rich phosphate minerals (Novák *et al.*, 2003).

The habit and mineral associations of fluorite suggest that it formed later during pegmatite crystallization. Fluorite forms anhedral to subhedral crystals, is associated with fine-grained

secondary mica, and can fill fractures between other mineral grains. It also occurs in pockets in the Rau 3 and 7 pegmatite dikes. Pyrochlore supergroup minerals, the other main F-bearing phases in the Rau pegmatite dikes, commonly occur as secondary minerals after columbite group minerals. The late crystallization of these F-bearing minerals is further evidence that F is concentrated in the fluid phase during pegmatite crystallization. This increases the relative concentration of F in the fluid as crystallization progresses, fluid which can later be expelled into the surrounding host rocks.

In nearly all samples of the altered host rocks adjacent to pegmatite dikes, F-bearing phases occur as accessory minerals (e.g., fluorophlogopite in the host rocks near Rau 4 and 5U). These F-bearing minerals crystallized due to F derived from the adjacent pegmatite dikes, and not because F was present in the unaltered host rocks. The host rock adjacent to the Rau 9 pegmatite dike appears to be the least altered sample, and it only contains trace F in fluorapatite. The presence of fluorophlogopite in the host rocks adjacent to pegmatite dikes is evidence of mass transport of fluids from the pegmatite dikes into the host rocks. Many of the elements required to crystallize mica (e.g., K, Al, and Si) are not present in the unaltered dolostone host rock and must have been sourced from the adjacent pegmatite dikes. Fluorine is a volatile element and would be enriched in the late-stage fluid that was exsolved from the pegmatite melt as it reached its final stages of crystallization. This enrichment in F in the exsolving fluids resulted in the mica in the host rocks being more rich in F than the mica in the pegmatite dikes. The compositions of mica samples that were analysed from a complete transect across the Rau 5 and 5U pegmatite dikes demonstrates the behaviour of F as a volatile element in the pegmatite system. Muscovite in the inner zones of both of these dikes has the lowest contents of F, whereas the highest contents of F in muscovite occur in the outer zones of the dikes.

The whole rock geochemistry of the pegmatite dikes does not show a perfect trend of increasing F with distance from the Rackla pluton. The Rau 10 pegmatite dike, a medium-sized dike close to the Rackla pluton that appears to be less fractionated with only trace rare element-bearing minerals, has one of the lowest F contents (223 ppm). In contrast, the Rau 5 pegmatite dike, a large dike distal to the Rackla pluton that appears to be highly fractionated with an abundance of rare element-bearing minerals, has the highest F contents (3698 ppm). These dikes follow the expected trend of increased fractionation with distance from the parental pluton and size of the dike. Deviations from the ideal trend appear to be related to a loss of F from the

pegmatite dikes to the host rocks. The Rau 3 pegmatite is the farthest away from the Rackla pluton and contains abundant rare element-bearing minerals; however, it only contains 236 ppm F. However, the host rocks surrounding this pegmatite are the most altered of all host rocks sampled, evidence that fluids were exsolved from the dike. This pegmatite dike also contains abundant carbonate pockets, indicating a high concentration of the late-stage fluid. In contrast to the Rau 3 pegmatite dike, the Rau 9 pegmatite dike has an anomalously high F contents for its proximity to the Rackla pluton and its thinness (1356 ppm), and the host rocks surrounding this pegmatite exhibit minimal alteration.

2.6.7.2 Titanium

Titanium-bearing minerals were observed in all of the sampled host rocks except those adjacent to the Rau 4 and 9 pegmatite dikes. Titanite is a relatively abundant accessory mineral in the host rocks both closer to (~1.5 m) and farther away from (~20 m) the Rau 3 pegmatite dike, whereas rutile occurs in the host rocks surrounding Rau 5U and 6. Whole rock geochemical analysis indicates that the pegmatite dikes do not contain detectable Ti, and significant Ti contents were not detected in any minerals in the pegmatite dikes during EMP analysis. The solubility of Ti has been shown to strongly increase with the F contents of the melt, meaning that melts with higher F contents favour the enrichment of Ti in the residual melt and crystallize minerals with high Ti contents, such as Ti-bearing oxide minerals (Keppler, 1993). When the F content of the melt is low, Ti will not be enriched. The same pegmatite dikes whose host rocks contain Ti-bearing minerals also contain fluorite as a minor mineral. An aplite dike and its adjacent host rock demonstrate this relationship between Ti and F even more profoundly. Whole rock geochemical analysis indicates that this aplite dike is rich in F, and the adjacent highly altered host rocks contain ilmenorutile and Ti-rich columbite-(Fe) (up to 6.68 wt.% TiO₂), one of the highest contents of Ti detected in columbite group minerals in the study area. The presence of Ti-bearing minerals in the host rocks is evidence that the mineralogical composition of the host rock is influenced by the geochemistry of the associated pegmatite or aplite dike.

2.6.7.3 Rare earth elements

Rare earth element-bearing minerals, which are dominantly REE-bearing carbonate minerals in the Rau pegmatite group, only occur in the Rau 1, 3, 5, and 5U pegmatite dikes. This

is again additional evidence that these pegmatite dikes are the most fractionated in the group, as REEs are progressively concentrated as crystallization progresses (London, 2008). The texture and association of REE-bearing carbonate minerals with fine-grained secondary muscovite suggests that the former are secondary minerals. Their occurrence as secondary minerals indicates that REE-enrichment is occurring later in pegmatite crystallization. The presence of dominantly carbonate REE-bearing minerals rather than other REE-bearing minerals such as oxide and phosphate minerals is due to the incorporation of CO₂ from the host rocks into the pegmatite dikes.

The abundance of REE-bearing minerals correlates with the F content of the pegmatite dikes. The same pegmatite dikes that contain REE-bearing carbonate minerals also contain fluorite as a minor mineral (Table 2.11). This correlation between F enrichment and abundance of REE-bearing minerals is due to the formation of REE–F complexes within the melt (Gieré, 1996). There is also a common association of secondary REE-bearing carbonate minerals with altered monazite-(Ce) (Figs. 2.35a and 2.35b), indicating that some of the REEs were remobilized from previously crystallized magmatic monazite grains.

2.6.7.4 Late-stage iron enrichment

Several features were observed that indicate Fe-enrichment occurs later in the formation of the Rau pegmatite group and its associated units. Many of the pegmatite dikes contain secondary Fe oxide and lesser Fe sulphide minerals. Columbite group minerals in the pegmatite carbonate pockets are in general richer in Fe than those in the pegmatite dikes, and many of the calcite crystals in the pegmatite pockets contain Fe oxide minerals as exsolution lamellae. Iron is also present in major minerals that compose the exo-contact skarns. Additionally, all of the altered host rock samples contain Fe oxide and/or sulphide minerals as trace minerals. Finally, in the Rau 9 endo-contact skarn, muscovite directly borders the pegmatite dike, whereas the mica further away from the dike is annite. Because the endo-contact skarns are a replacement product (Section 2.6.1.6), the muscovite that borders the pegmatite would have crystallized before the annite that borders the host rocks. This indicates that there was an increasing amount of Fe in the system as crystallization progressed.

Late-stage Fe-enrichment in pegmatites has been reported by numerous authors, including Novák and Černý (1998) and Novák and Taylor (2000). Iron-enrichment is commonly attributed

to interaction with the host rocks (e.g., Novák and Černý, 1998); however, the rocks that host the Rau pegmatite group are Mg-rich. There are three hypothesized sources that could be responsible for this influx of late-stage Fe into the system: (1) the argillaceous mudstone horizons (Panton, 2008) or basalt flows (Thiessen et al., 2016) that are intercalated within the Bouvette Formation, (2) mineralizing fluids that are known to have been derived from the Rackla pluton to form the Tiger zone gold deposit (e.g., Thiessen et al., 2016), or (3) minerals within the pegmatite dikes that crystallized earlier but were subsequently broken down during secondary processes. Although intercalated units are noted in the literature, they were not observed in either the 2011 or 2015 field seasons. It should be noted; however, that exposed areas of host rock in the Rau pegmatite field area are very limited and there has been no drilling to determine what units lie at depth. Sourcing of Fe from the mineralizing fluids that formed the Tiger zone gold deposit seems unlikely because these same fluids were responsible for the Au mineralization at the Tiger deposit and Au was not observed in any of the analysed units. The Au mineralization is also associated with minerals such as arsenopyrite and bismuthinite, neither of which were observed in the Rau pegmatite field area. This leaves the hypothesis that the Fe was sourced from the pegmatite dikes themselves. Incompatible elements and volatiles such as H₂O and CO₂ are excluded from crystallizing pegmatite minerals and are concentrated in a residual, fluid-rich melt (London, 2008). This volatile-rich fluid, also known as the boundary layer liquid, can be expelled from the pegmatite dike near the end of crystallization and partially dissolves and replaces existing minerals (London, 2014). Dissolution of primary mica group minerals would liberate Fe into the volatile-rich fluid, making it available for crystallization during the same phase of pegmatite genesis that formed the carbonate pockets. Muscovite in the pegmatite dikes can be enriched in Fe, attaining 7.41 wt.% FeOtot (0.434 apfu Fe) in the Rau 9 pegmatite dike. Muscovite in the Rau 3 pegmatite dike is also rich in Fe, containing on average 3.80 wt.% FeOtot and a maximum of 6.47 wt.% FeOtot. A substantial portion of the muscovite in the pegmatite dikes is secondary, occurring as aggregates of small, needle-shaped crystals, supporting hypothesis that secondary alteration has occurred.

2.6.8 Contamination

The Rau pegmatite dikes were undoubtedly contaminated by their dolostone host rocks. Primary Ca-bearing minerals, such as calcite, fluorite, allanite-(Ce), and fluorcalciomicrolite, as

well as carbonate pockets, are present throughout the pegmatite dikes and are not restricted to the outer zones. This contamination occurred both pre-emplacement, when the pegmatite dikes were propagating through the host rocks, and post-emplacement, once the pegmatite dikes reached their site of crystallization. The C and O isotopic compositions of carbonate minerals show an increase in δ^{13} C and δ^{18} O from primary calcite in the pegmatite dikes, to calcite with exsolved Fe oxide minerals in the pegmatite carbonate pockets, to the host rock carbonate minerals. The signature of the primary calcite in the pegmatite dikes corresponds that of primary magmatic calcite (Sharp, 2017), indicating that pre-emplacement contamination has occurred. The δ^{13} C isotopic composition of the host rocks fall within the δ^{13} C and δ^{18} O signatures of Silurian to middle Devonian seawater delineated by Veizer *et al.* (1999), indicating that the host rocks were not modified by external fluids. The shift in the isotopic signature from that of primary calcite in the pegmatite dikes to that of carbonate minerals in the host rocks corresponds with the mixing of magmatic and sedimentary carbonate. The formation of the endo-contact skarns is evidence that some degree of post-emplacement contamination has occurred.

This carbonate contamination does not appear to have affected the Rackla pluton. Neither Ca- and/or Mg-rich minerals nor carbonate minerals have been observed in the Rackla pluton that outcrops in the Rau pegmatite field area. Thiessen *et al.* (2016) presented evidence that the Rackla pluton was affected by the carbonate host rocks as they observed "carbonate veins with bleached halos" crosscutting the intrusion in their study area. However, their whole rock geochemical data do not suggest that the Rackla pluton assimilated a significant amount of carbonate minerals, as its Ca and Mg contents (average 1.72 wt.% CaO and 0.28 wt.% MgO; *n* = 10) are not elevated and are below that of the average upper continental crust (3.59 wt.% CaO and 2.48 wt.% MgO; Rudnick & Gao, 2003). The Ca and Mg contents of the pegmatite dikes are also relatively low with a maximum of 3.03 wt.% CaO and 1.20 wt.% MgO in the Rau 9 pegmatite dike. This is expected as the pegmatite dikes are mainly composed of feldspars and quartz, and the main effect of carbonate contamination appears to be on the accessory mineral assemblage (Ca-rich minerals including fluorite, Ca-dominant pyrochlore supergroup minerals, and Ca- and REE-bearing carbonate minerals) and the crystallization of calcite in pegmatite pockets.

The trace element contents of minerals in the endo-contact skarns demonstrate the influence of the chemistry of the pegmatite dike on that of its endo-contact skarn. Some of the

highest average F contents in mica were observed in mica in the Rau 7 pegmatite dike (1.50 wt.% F; 0.325 *apfu*; n = 4), whereas mica in the Rau 9 pegmatite dike has some of the lowest average F contents (0.61 wt.% F; 0.134 *apfu*; n = 6). Similarly, mica in the Rau 7 endo-contact skarn has the highest average F contents (3.36 wt.% F; 0.831 *apfu*; n = 6), whereas mica in the Rau 9 endo-contact skarn has the lowest average F contents (1.38 wt.% F; 0.353 *apfu*; n = 3).

The occurrence of the majority of accessory minerals, namely phlogopite, fluorophlogopite, tremolite, pargasite, clinochlore, and anorthite, in the host rocks can be attributed to the pegmatite dikes. The host rocks would have supplied the Ca and Mg necessary to crystallize these minerals but additional elements required are not found in the unaltered host rocks. These additional elements—Si, Al, K, Na, F, Cl, and OH—can all be found in the pegmatite dikes. When the pegmatite dikes were emplaced, they reacted with the host rocks, allowing these elements to be diffused into the host rocks. The influence of the pegmatite dikes on the mineralogy of the host rocks can be far-reaching, as accessory minerals are still relatively abundant in a sample of the host rock ~20 m away from the Rau 3 pegmatite dike. It is evident that the composition of the host rocks influenced the accessory minerals that crystallized in them because in minerals that form solid-solution series, the species present are the Mg-dominant endmembers rather than the Fe-dominant ones (phlogopite versus annite, and clinochlore versus chamosite).

The host rocks near the Rau 3 pegmatite dike appear to have been the most affected by the emplacement of a pegmatite dike. They contain the most abundant and diverse suite of accessory minerals—tremolite, pargasite, titanite, anorthite, Fe sulphide minerals, and allanite-(Ce) all occur in the host rocks near Rau 3 but are not present in any of the other sampled host rocks. This is likely the result of the higher volatile content of the Rau 3 pegmatite dike. Increasing fractionation with distance from the Rackla pluton allows more volatiles to partition into the late-stage fluid that was excluded from the pegmatite dikes as they crystallized. In addition to being the farthest pegmatite dike from the Rackla pluton, Rau 3 is also a relatively thick dike, which would have increased its degree of fractionation and therefore volatile content. A higher volatile content would have allowed for increased diffusion of the late-stage fluid into the surrounding host rocks.

Host rocks were sampled both closer to (~1.5 m) and farther away from (~20 m) the Rau 3 pegmatite dike. These samples are fairly similar in their overall mineralogical composition,
with both samples containing accessory phlogopite, tremolite, and titanite, plus trace Fe oxide and sulphide minerals. When the same accessory mineral occurs in both samples of host rock, their minor element composition can be notably different. In general, the concentration of trace elements in all accessory minerals is higher in the host rocks closer to the pegmatite dike, suggesting that the pegmatite dike is the source of these elements. More specifically, the Sn and Nb contents of titanite is higher in the host rocks closer to Rau 3 compared to the host rocks farther away from that pegmatite dike. The higher concentration of these elements closer to the pegmatite dike is evidence that they were sourced from the pegmatite dikes. Rau 3 is a highly fractionated pegmatite dike and it contains abundant Nb-bearing minerals such as pyrochlore and columbite group minerals. In contrast, the Al contents of titanite is higher in the host rocks farther away from dike Rau 3. The lack of Al in titanite closer to dike Rau 3 could be related to the presence of anorthite in these host rocks. If the Al was being used to crystallize anorthite, less would have been available to be incorporated into titanite. In the host rocks farther away from dike Rau 3, there is no anorthite and any Al present could be incorporated into titanite.

2.6.9 Classification

The presence of minerals typical of both LCT-type (Ta-dominant oxide minerals) and NYF-type [HREE-bearing minerals, REE-bearing (fluoro)carbonates] pegmatites distinguishes the Rau pegmatite group as having a mixed-type geochemical signature. The highly fractionated Rau 1 pegmatite dike best exemplifies this: it contains typical NYF-type minerals such as amazonite and typical LCT-type minerals such as Li-rich muscovite and elbaite. However, this mixed-type signature was not derived from a parental granite that also possessed mixed geochemical characteristics, but is likely the product of contamination of an NYF-type pegmatite melt by a LCT-type crustal signature. This process is similar to that documented at Bližná (Novák *et al.*, 2012), but in the Rau pegmatite group the host rocks are the source of the LCT-type signature rather than the NYF-type signature. The NYF-type signature of the uncontaminated pegmatite melt would have been gradually modified to a mixed-type signature as the pegmatite dikes propagated through the host rocks. Whole rock geochemical analysis shows that the host rocks near the Rau 1 pegmatite dike contain 4.6 ppm Li, whereas the geochemical signature of the Rackla pluton is more similar to the NYF geochemical family, with elevated Nb and Y (128 and 43 ppm respectively; Panton, 2008). Contamination of a LCT-type

pegmatite melt by a NYF-type crustal signature is unlikely because the host rocks do not contain significant quantities of REEs (Section 2.5.2.7).

The trace element contents of quartz from the pegmatite dikes and porphyritic phase of the Rackla pluton provide additional evidence of a mixed-type geochemical signature. The Li contents of the pegmatitic quartz are similar to those of NYF-type pegmatites (Müller *et al.*, 2013), but the Al contents are elevated, especially in quartz from pegmatite dikes that show evidence of greater fractionation (Rau 1, 3, and 5). The Al contents of quartz in the Rau 3 and 5 pegmatite dikes attain the levels of the strongly peraluminous, LCT-type marginal pegmatites of the Podlesí stock (Breiter *et al.*, 2006; Müller *et al.*, 2013).

CHAPTER 3

Meta-Analysis of Pegmatite Literature and Implications for Contamination

3.1 Introduction

The previous chapters showed that the geochemistry and mineralogy of a pegmatite can be dramatically influenced by the composition of its host rocks. The Rau pegmatite dikes contain Ca- and Mg-rich accessory minerals, and secondary REE-bearing carbonate minerals that also crystallized due to contamination of the pegmatite dikes by their dolostone host rocks. Beyond the overall mineralogy of the pegmatite dikes, propagation through these host rocks resulted in the crystallization of carbonate pockets within the pegmatites, and the formation of endo-contact skarns along their borders with the host rocks. These findings suggest that the characteristics of other pegmatites could also be influenced by the composition of their host rocks.

The most accurate way to assess the effects of contamination would be to examine each individual pegmatite occurrence and reinterpret the original results with the new knowledge that contamination by the host rocks may have influenced the minerals that crystallized within the pegmatites. Because the knowledge that contamination could influence the mineralogy of a pegmatite is new, contamination may not have even been considered as a possible mechanism to yield the observed minerals in a pegmatite. Although this method would be most accurate, it is not feasible due to the multitude of pegmatites that have already been studied. A less accurate but more efficient method is to conduct a meta-analysis of the currently available pegmatite literature. A meta-analysis involves synthesizing the data from a large number of studies that have already been completed (Borenstein *et al.*, 2009). Instead of collecting new data, a meta-analysis uses the available data in a different way to draw new conclusions. In this case, the purpose of conducting a meta-analysis is not to definitively determine whether one pegmatite has been contaminated by its host rocks, but to gain insight into whether contamination could have a more widespread influence on pegmatite mineralogy than is currently known.

Currently, an extensive database of pegmatite literature is available. Although it is difficult to generalize thousands of papers, it is clear that the vast majority of papers about pegmatite occurrences do not provide nearly as thorough of a description of the host rocks as they do of the pegmatites. Of course, this is to be expected as these papers focus on the pegmatite occurrence and not on their host rocks. However, evidence presented in this chapter suggests that future studies should include a more thorough description of the host rocks as they may play a crucial role in the resulting mineralogy of the pegmatites.

3.2 Methods

An extensive literature search was conducted, the end result of which was the compilation of nearly 200 pegmatite occurrences worldwide from approximately 100 scientific papers and theses (Table 3.1). The level of detail presented for each occurrence is highly variable, but in each case all available data were collected. Classification and pegmatite genesis papers (e.g., Černý 1991a; 1991b; Černý & Ercit, 2005; Ercit, 2005; Simmons & Webber, 2008), which commonly include lists of pegmatite occurrences as examples, were consulted first and used to create a list of occurrences to explore further using more detailed studies. All available data about pegmatite classification, morphology, zoning, mineralogy, orientation with respect to the host rocks, and contacts with the host rocks, as well as the host rock composition, type, metamorphic grade (if metamorphosed), and presence of bedding or foliation were collected from each examined paper. The amount of data presented in the papers could be highly variable, therefore not all examined pegmatite occurrences are included in every analysis that was performed. For papers that examined large pegmatite groups or fields, the data were subdivided if possible.

All minerals reported for each pegmatite occurrence were recorded, with the exception of common pegmatite minerals such as quartz, feldspars, and common mica group minerals. The detail of the mineralogy was dependent on the amount of detail provided in the paper. All minerals were then categorized based on unique elemental composition. For example, the occurrence of spodumene in a pegmatite indicates that there is some Li present. Spodumene would not be used to indicate the presence of Al, Si, or O because these elements are common constituents of granitic rocks. Likewise, columbite-(Fe) was used to indicate the presence of Nb and Ta in the pegmatite, but not that of Fe, Mn, or O. Exceptions to this categorization system are minerals that are extremely enriched in common elements. For example, the presence of corundum was used to indicate that the pegmatite contains elevated Al, whereas the presence of Fe oxide minerals was used to indicate that the pegmatite contains elevated Fe. The specific

elements that were included in the analyses are Li, Be, B, F, Al, P, Sc, Ti, Mn, Fe, V, Cu, Zn, As, Sr, Nb, Mo, Sn, Sb, Cs, REEs, Ta, W, Pb, Bi, Th, and U. Sulphur was also included, though specifically as sulphide and not sulphate. Although not assigned to a specific element, carbonate minerals were also included as their presence in a pegmatite provides strong evidence that contamination has occurred because they are not typical minerals found in granitic systems.

Once all the data were compiled and categorized, analyses were performed on subsets of the data. This allowed for data from an occurrence to be used even if a complete description of the pegmatites and their host rocks was not available. The subsets of data that were included are the host rock composition, host rock type, pegmatite width, orientation of the pegmatite with respect to host rock foliation, nature of the contact between the pegmatite and host rock, presence of exo-contact features within the host rocks, presence of endo-contact features and/or host rock xenoliths within the pegmatite, and presence of replacement units and/or secondary alteration within the pegmatite. For each of these analyses, the proportion of pegmatite occurrences that contain each element was calculated.

Host rock composition was separated into two groups: felsic and mafic. Felsic rocks are relatively enriched in Si, Al, Na, and K whereas mafic rocks are relatively enriched in Fe and Mg. The mafic group also included ultra mafic rocks, which are composed mostly of mafic minerals, making them extremely enriched in Fe and Mg (e.g., metaperidotite). Pegmatite occurrences that are hosted by both felsic and mafic host rocks were removed from this analysis. Host rock types were grouped into igneous, metamorphic, and sedimentary. Metamorphic host rocks were further subdivided into those with an igneous, sedimentary, and carbonate protolith. Sedimentary host rocks were removed from this analysis because only one of the examined pegmatite occurrences is hosted by an unmetamorphosed sedimentary rock. Pegmatite length was not included in an analysis because the length of all pegmatites within an occurrence was commonly highly variable and generalized in the papers. It is also difficult to determine if pegmatite dikes extend at depth without extremely detailed mapping of the subsurface geology of the study area. There is much less variation in the width of pegmatites within the same occurrence and thus these results were included as an analysis. The widths were grouped together in categories of < 1 m, 1–9.9, 10–19.9, 20–49.9, 50–99.9, and > 100 m. Pegmatite occurrences that contained a range of pegmatite widths were not considered unless the entire range fell into one of these categories. In foliated host rocks, pegmatites were subdivided by

whether they are concordant or discordant to that foliation. The nature of the contact between the pegmatites and their host rocks was subdivided into sharp, gradational, and ductile. Ductile contacts include features such as boudinage structures and shearing along the contact. Exocontact features include all those that suggest fluids from the pegmatites affected the host rocks, such as the presence of exomorphic minerals in the host rocks, metasomatic reaction zones / aureoles in the host rocks, and alteration of minerals within the host rocks. If the presence of an exo-contact reaction zone was not noted in the paper, the occurrence was classified as not having an exo-contact reaction zone. The composition of these exo-contact reaction zones was not considered. Endo-contact reaction zones and xenoliths of the host rocks within the pegmatites were grouped together because they are both features that suggest the pegmatites have been affected by the host rocks. If the presence of an endo-contact reaction zone or host rock xenoliths was not noted in the paper, the occurrence was classified as not possessing these features. Finally, pegmatites that had undergone secondary alteration, such as those that contain replacement zones, were compared to those that are unaltered. Replacement zones include albitization, which is thought to be a secondary process in pegmatite formation (e.g., Jahns, 1982). If the presence of secondary hydrothermal alteration or replacement zones was not noted in the paper, the occurrence was classified as not possessing these features.

Pegmatite zoning was not included in the analysis because the definition of zones appears to be very subjective, with some authors defining multiple versions of the same zone (e.g., intermediate zone 1, intermediate zone 2, etc.), or grouping multiple zones together (e.g., borderwall zone). Replacement units are sometimes also included as separate zones, increasing the number of zones in pegmatites that have undergone secondary alteration. Zoning can also be highly variable from one part of a pegmatite dike to the next.

Other data that were collected from some papers but not included in an analysis were the age of the pegmatite dikes and the metamorphic grade of the host rocks. If the age of the pegmatites had been determined, the accuracy was commonly highly variable from paper to paper. Furthermore, it is highly unlikely that the age of a pegmatite has an impact on contamination compared to other factors such as host rock composition. Metamorphic grade was excluded from the analysis because the vast majority of pegmatite studies did not include at which point during the geologic history of the region the metamorphism occurred, only that the

host rocks were metamorphosed. This information is already contained within the host rock type (igneous, metamorphic, sedimentary) and a separate analysis is not required.

Pegmatites were included in the analyses even if they have not been attributed to a parental granite, as this study seeks to examine the effect of host rock composition on pegmatites, independent from the presence or nature of a parental granite.

If the difference between the percentage of pegmatites containing a certain element in one subset of the data versus another was 10% or higher, the result was considered to be anomalous. For example, if 35% of pegmatites in mafic host rocks contain Be, but only 20% of pegmatites in felsic rocks contain Be, this would be considered an anomalous result as the difference between the two is over 10%.

Pegmatite Occurrence	Source
Christmas Point, Antarctica	Grew et al. (2000)
Larsemann Hills, Antarctica	Grew <i>et al</i> . (1998a)
Mount Pardoe, Antarctica	Grew et al. (2000)
Alta Gracia district, Argentina	Galliski (2009)
Altautina field, Argentina	Galliski & Černý (2006)
Ambato district, Argentina	Galliski (2009)
Ancasti field, Argentina	Galliski & Černý (2006)
Blanca Dora, Argentina	Heimann <i>et al</i> . (2015)
Calchaqui field, Argentina	Galliski (2009)
Centenario district, Argentina	Galliski (2009)
Cerro Blanco field, Argentina	Galliski (2009)
Conlara field, Argentina	Heimann <i>et al</i> . (2015)
Cordoba district, Argentina	Galliski (2009)
El Penon, Argentina	Galliski <i>et al</i> . (2001)
Juan Roman, Argentina	Heimann <i>et al</i> . (2015)
La Elvirita, Argentina	Galliski <i>et al</i> . (2001)
La Juana, Argentina	Galliski & Černý (2006)
La Ona, Argentina	Heimann <i>et al</i> . (2015)
La Viquita, Argentina	Galliski <i>et al</i> . (1999)
Magdalena, Argentina	Heimann <i>et al</i> . (2015)
Quilmes field, Argentina	Galliski (2009)
San Elias, Argentina	Galliski <i>et al</i> . (1999)
Sierra Brava field, Argentina	Galliski (2009)
Sin Nombre, Argentina	Heimann <i>et al</i> . (2015)
Totoral district (Type I), Argentina	Oyarzábal <i>et al</i> . (2009)
Totoral district (Type II), Argentina	Oyarzábal <i>et al.</i> (2009)
Totoral district (Type III), Argentina	Oyarzábal <i>et al.</i> (2009)
Totoral district (Type IV), Argentina	Oyarzábal <i>et al</i> . (2009)
Totoral district (Type V), Argentina	Oyarzábal <i>et al.</i> (2009)
Valle Fertil district, Argentina	Galliski (2009)
Virorco, Argentina	Galliski <i>et al.</i> (2012)
Abydos district, Western Australia	Sweetapple & Collins (2002)
Beryl group, Western Australia	Sweetapple & Collins (2002)
Chinamans Hill group, Western Australia	Sweetapple & Collins (2002)
Coolegong district, Western Australia	Sweetapple & Collins (2002)
Coondina field, Western Australia	Sweetapple & Collins (2002)
Friendly Creek field, Western Australia	Sweetapple & Collins (2002)
Greenbushes pegmatite, Western Australia	Partington <i>et al.</i> (1995)

Table 3.1. All pegmatite occurrences included in the meta-analysis, organized by country.

Pegmatite Occurrence	Source
Haystack Well group, Western Australia	Sweetapple & Collins (2002)
Mills Find group, Western Australia	Sweetapple & Collins (2002)
Moolyella field, Western Australia	Sweetapple & Collins (2002)
Mount Cassiterite group, Western Australia	Sweetapple & Collins (2002)
Mount Francisco district, Western Australia	Sweetapple & Collins (2002)
Mount Hall group, Western Australia	Sweetapple & Collins (2002)
Pilgangoora district, Western Australia	Sweetapple & Collins (2002)
Pinga Creek field, Western Australia	Sweetapple & Collins (2002)
Stannum field, Western Australia	Sweetapple & Collins (2002)
Strelley group, Western Australia	Sweetapple & Collins (2002)
Tabba Tabba group, Western Australia	Sweetapple & Collins (2002)
Tambina group, Western Australia	Sweetapple & Collins (2002)
Tambourah field, Western Australia	Sweetapple & Collins (2002)
Western Wodgina field, Western Australia	Sweetapple & Collins (2002)
White Springs field, Western Australia	Sweetapple & Collins (2002)
Wodgina group, Western Australia	Sweetapple & Collins (2002)
Woodstock group, Western Australia	Sweetapple & Collins (2002)
Beryller, Austria	Přikryl <i>et al</i> . (2014)
Weinebene, Austria	Göd (1989)
Aimorés district, Brazil	Morteani <i>et al</i> . (2000)
Araçuai district, Brazil	Morteani <i>et al</i> . (2000)
Borborema province, Brazil	Beurlen <i>et al</i> . (2013); Soares <i>et al</i> . (2007)
Espera Feliz district, Brazil	Morteani <i>et al</i> . (2000)
Itambé district, Brazil	Morteani <i>et al</i> . (2000)
Nova Era district, Brazil	Morteani <i>et al.</i> (2000)
Safira district, Brazil	Morteani <i>et al.</i> (2000)
Cat Lake-Winnipeg River field, Manitoba, Canada	Černý <i>et al</i> . (1981)
Red Cross Lake suite, Manitoba, Canada	Černý <i>et al</i> . (2012a); Černý <i>et al</i> . (2012b)
Red Sucker Lake, Manitoba, Canada	Chackowsky (1987)
Wekusko Lake field, Manitoba, Canada	Černý <i>et al</i> . (1981)
YITT-B swarm, Manitoba, Canada	Anderson <i>et al.</i> (1998)
Aylmer Lake, Northwest Territories, Canada	Tomascak (1991)
Chantrey Inlet field, Northwest Territories, Canada	Tomascak <i>et al.</i> (1994)
Foxe field, Northwest Territories, Canada	Tomascak <i>et al.</i> (1994)
Kirk Lake, Northwest Territories, Canada	Tomascak (1991)
Little Nahanni group, Northwest Territories, Canada	Groat <i>et al</i> . (2003)
Nebbish Lake, Northwest Territories, Canada	Tomascak (1991)
Reid Lake, Northwest Territories, Canada	Tomascak (1991)
Torp Lake, Northwest Territories, Canada	Tomascak <i>et al</i> . (1994)
Yellowknife field, Northwest Territories, Canada	Meintzer (1987)

Pegmatite Occurrence	Source
Armstrong field, Ontario, Canada	Breaks <i>et al.</i> (2005)
Beryl pit pegmatite, Ontario, Canada	Přikryl <i>et al</i> . (2014)
Gullwing-Tot Lakes group, Ontario, Canada	Breaks <i>et al.</i> (2005)
Mavis Lake group, Ontario, Canada	Breaks & Moore (1992); Breaks <i>et al</i> . (2005)
McCombe pegmatite, Ontario, Canada	Tindle <i>et al</i> . (2005)
Pakeagama Lake, Ontario, Canada	Tindle <i>et al</i> . (2002)
Separation Rapids, Ontario, Canada	Tindle <i>et al</i> . (2002)
Sharbot Lake, Ontario, Canada	Ford (1982)
Swole Lake field, Ontario, Canada	Breaks <i>et al.</i> (2005)
Evans-Lou pegmatite, Québec, Canada	Miles <i>et al</i> . (1971)
Hengshan field, China	Černý (1989)
Koktokay No. 3 pegmatite, China	Zhang <i>et al.</i> (2008)
Bližná pegmatite, Czech Republic	Novák <i>et al</i> . (2012)
Boněnov, Czech Republic	Přikryl <i>et al</i> . (2014)
Dobrá Voda pegmatite, Czech Republic	Černý <i>et al.</i> (1995)
Dolní Bory pegmatite, Czech Republic	Výravský <i>et al</i> . (2017)
Kovářová, Czech Republic	Přikryl <i>et al</i> . (2014)
Kracovice pegmatite, Czech Republic	Novák <i>et al</i> . (2012)
Kutná Hora, Czech Republic	Cempírek & Novák (2006)
Řečice pegmatite, Czech Republic	Novák <i>et al</i> . (1999)
Rožná pegmatite, Czech Republic	Černý <i>et al</i> . (1995)
Scheibengraben pegmatite, Czech Republic	Novák <i>et al</i> . (2003)
Vlastějovice, Czech Republic	Novák <i>et al</i> . (2013)
Bhurpidungri, India	Jagadeesan <i>et al</i> . (2005)
Southern Kerala, India	Soman & Nair (1985)
Alpe Rosso pegmatite, Italy	Guastoni (2012)
Arvogno Albertini pegmatite, Italy	Guastoni (2012)
Arvogno fluorite pegmatite, Italy	Guastoni (2012)
Bodengo pegmatite, Italy	Guastoni (2012)
Elba Island, Italy	Pezzotta (2000)
Emerald Pizzo Marcio pegmatite, Italy	Guastoni (2012)
Garnet Codera valley pegmatite, Italy	Guastoni (2012)
Grignacschi pegmatite, Italy	Guastoni (2012)
Phosphate Codera valley pegmatite, Italy	Guastoni (2012)
Rio Graia pegmatite, Italy	Guastoni (2012)
Summit of Pizzo Marcio pegmatite, Italy	Guastoni (2012)
Anjanabonoina pegmatite, Madagascar	De Vito et al. (2006); Dirlam et al. (2002)
Antandrokomby pegmatite, Madagascar	Simmons et al. (2001)
Antsirabe-Kitsamby district, Madagascar	Bourret (1988)
Antsongombato pegmatite, Madagascar	Laurs <i>et al</i> . (2002)

Pegmatite Occurrence	Source
Cap Andrahomana, Madagascar	Grew <i>et al</i> . (1998b)
Itremo region, Madagascar	Pezzotta (2005)
Sakavalana pegmatite, Madagascar	Laurs <i>et al</i> . (2003)
Namivo pegmatite, Mozambique	Neiva (2013)
Erongo, Namibia	Boudreaux (2014)
Jemaa, Nigeria	Batchelor & Kinnaird (1984)
Tsaobismund pegmatite, Namibia	Fransolet <i>et al.</i> (1986)
Wamba field, Nigeria	Küster (1990)
Almgjotheii, Norway	Grew <i>et al.</i> (1998a; 1998b)
Tørdal, Norway	Bergstøl & Juve (1988)
Drot, Pakistan	Laurs <i>et al.</i> (1998)
Khaltaro, Pakistan	Laurs <i>et al</i> . (1998)
Stak Nala, Pakistan	Laurs <i>et al</i> . (1998)
Michalkowa, Poland	Pieczka <i>et al.</i> (2015)
Pilawa Górna, Poland	Pieczka <i>et al</i> . (2015)
Szklary, Poland	Pieczka <i>et al.</i> (2015)
Lousas pegmatite, Portugal	Novák et al. (2009)
Mount Rovgora, Western Keivy, Russia	Pekov <i>et al.</i> (2009)
Assynt terrane, Scotland	Shaw <i>et al.</i> (2016)
Diabaig, Scotland	Shaw <i>et al.</i> (2016)
Gairloch terrane, Scotland	Shaw <i>et al.</i> (2016)
Langavat Belt, Scotland	Shaw <i>et al</i> . (2016)
Leverburgh Belt, Scotland	Shaw <i>et al</i> . (2016)
Loch Maree group, Scotland	Shaw <i>et al</i> . (2016)
Rhiconich terrane, Scotland	Shaw <i>et al</i> . (2016)
South Harris Igneous Complex, Scotland	Shaw <i>et al</i> . (2016)
Tarbert terrane, Scotland	Shaw <i>et al</i> . (2016)
Uig Hills, Scotland	Shaw <i>et al</i> . (2016)
Cap de Creus field, Spain	Abella <i>et al.</i> (1995)
Franqueira, Iberian Peninsula, Spain and Portugal	Martin-Izard et al. (1995)
Fregeneda-Almendra field, Iberina Peninsula, Spain and Portugal	Roda-Robles et al. (2010)
Homagama pegmatite, Sri Lanka	Grew <i>et al</i> . (1995)
Varuträsk pegmatite, Sweden	Černý <i>et al</i> . (2004)
Ytterby, Sweden	Sjöberg <i>et al</i> . (2014; 2017)
Colonnello Pizzo Paglia pegmatite, Switzerland	Guastoni (2012)
Summit of Pizzo Paglia pegmatite, Switzerland	Guastoni (2012)
Bokan Mountain, Alaska, U.S.A.	Dostal <i>et al.</i> (2014)
Kingman pegmatite, Arizona, U.S.A.	Hanson <i>et al.</i> (2013)
Little Three pegmatite, California, U.S.A.	Morgan & London (1999)

Pegmatite Occurrence	Source
Mesa Grande district, California, U.S.A.	Webber <i>et al.</i> (1999)
Pala district, California, U.S.A.	Webber <i>et al.</i> (1999)
Crystal Mountain field, Larimer County, Colorado, U.S.A.	Hanley <i>et al.</i> (1950); Thurston (1955); Jacobson (1982; 1986a; 1986b) in Jacobson (2016)
Eight Mile Park field, Fremont County, Colorado, U.S.A.	Hanley <i>et al.</i> (1950); Heinrich (1947; 1948) in Jacobson (2016)
Platt (Uranium King) pegmatite, Carbon County, Colorado, U.S.A.	Houston (1961) in Jacobson (2016)
Quartz Creek field, Gunnison County, Colorado, U.S.A.	Hanley <i>et al.</i> (1950); Staatz & Trites (1955) in Jacobson (2016)
St. Peter's dome, El Paso County, Colorado, U.S.A.	Hanley <i>et al.</i> (1950); Staatz & Trites (1955) in Jacobson (2016)
Texas Creek field, Fremont County, Colorado, U.S.A.	Hanley et al. (1950) in Jacobson (2016)
East Selden pegmatite, Connecticut, U.S.A.	Cameron & Shainin (1947)
Fairfield County, Connecticut, U.S.A.	Cameron et al. (1954)
Hartford County, Connecticut, U.S.A.	Cameron <i>et al</i> . (1954)
Litchfield County, Connecticut, U.S.A.	Cameron <i>et al.</i> (1954)
Middlesex County, Connecticut, U.S.A.	Cameron et al. (1954)
New Haven County, Connecticut, U.S.A.	Cameron <i>et al.</i> (1954)
Lord Hill pegmatite, Maine, U.S.A.	Johnson (1998); Wise & Francis (1992) in Heimann <i>et al.</i> (2015)
Topsham district, Maine, U.S.A.	Hanson <i>et al</i> . (1998)
Bennett pegmatite, New Hampshire, U.S.A.	Francis <i>et al.</i> (1993)
Black Mountain pegmatite, New Hampshire, U.S.A.	Francis <i>et al.</i> (1993)
Palermo No. 1 pegmatite, New Hampshire, U.S.A.	Kampf <i>et al.</i> (2012)
Harding pegmatite, New Mexico, U.S.A.	Chakoumakos & Lumpkin (1990)
Custer County, South Dakota, U.S.A.	Staatz et al. (1963)
Fourmile Quadrangle, South Dakota, U.S.A.	Redden (1963)
Pennington County, South Dakota, U.S.A.	Sheridan <i>et al</i> . (1957)
Southern Black Hills, South Dakota, U.S.A.	Norton <i>et al.</i> (1964)
Animikie Red Ace pegmatite, Wisconsin, U.S.A.	Sirbescu <i>et al.</i> (2008)
Bikita pegmatite, Zimbabwe	Černý <i>et al</i> . (2003)

3.3 Results

3.3.1 Host rock composition: felsic versus mafic

Of the 254 pegmatite occurrences included in this analysis, 192 are hosted by felsic rocks and 62 are hosted by mafic rocks. Pegmatites that are hosted by mafic rocks more commonly contain Li, Sn, and Cs than pegmatites hosted by felsic rocks. Pegmatites that are hosted by felsic rocks more commonly contain phosphate minerals than pegmatite hosted by mafic rocks (Fig. 3.1). In general, pegmatites hosted by mafic rocks more commonly contain trace elements (e.g., Be, Ti, Mn, As, Nb, and Th) than those hosted by felsic rocks. This is when all elements are compared instead of just those for which there is a 10% or greater difference between the appearance in pegmatites hosted by felsic versus mafic rocks.

3.3.2 Host rock type: igneous, metamorphic, and sedimentary

A total of 266 pegmatite occurrences were considered in this analysis. Of these occurrences, 19 are hosted by igneous rocks and 247 are hosted by metamorphic rocks. The metamorphic rocks were further subdivided based on their protoliths. A total of 106 of the metamorphic rocks had an igneous protolith, 131 had a sedimentary protolith, and 10 had a carbonate protolith.

Pegmatites that are hosted by igneous rocks more commonly contain Li and F than pegmatites hosted by metamorphic rocks with an igneous protolith. Pegmatites hosted by metamorphic rocks with an igneous protolith more commonly contain Nb, Sn, and Ta than pegmatites hosted by igneous rocks. Pegmatites hosted by igneous rocks more commonly contain F, Ti, Fe, LREEs, HREEs, and Cs than pegmatites hosted by metamorphic rocks with a sedimentary protolith. Pegmatites hosted by metamorphic rocks with a sedimentary protolith more commonly contain P and Sn than pegmatites hosted by igneous rocks. Pegmatites hosted by igneous rocks more commonly contain Zn than pegmatites hosted by metamorphic rocks with a carbonate protolith. Pegmatites hosted by metamorphic rocks with a carbonate protolith more commonly contain Be, B, P, Ti, Mn, Nb, Cs, Ta, W, sulphide, and carbonate minerals than pegmatites hosted by igneous rocks. Pegmatites hosted by metamorphic rocks with an igneous protolith more commonly contain F, Ti, Mn, Nb, Cs, LREEs, HREEs, and Ta than pegmatites hosted by metamorphic rocks with a sedimentary protolith. Pegmatites hosted by metamorphic rocks with a carbonate protolith more commonly contain F, Ti, Mn, Nb, Cs, LREEs, HREEs, and Ta than pegmatites hosted by metamorphic rocks with a sedimentary protolith. Pegmatites hosted by metamorphic rocks with a carbonate protolith more commonly contain F, Ti, Mn, Nb, Cs, LREEs, HREEs, MSEd by metamorphic rocks with a carbonate protolith more commonly contain Li, B, F, Ti, Nb, Cs, W, sulphide, and carbonate minerals than pegmatites hosted by metamorphic rocks with an igneous protolith. Pegmatites hosted by metamorphic rocks with an igneous protolith more commonly contain HREEs than pegmatites hosted by metamorphic rocks with a carbonate protolith. Pegmatites hosted by metamorphic rocks with a carbonate protolith more commonly contain Be, B, F, Ti, Mn, Nb, Cs, LREEs, Ta, sulphide, and carbonate minerals than pegmatites hosted by metamorphic rocks with a sedimentary protolith (Figs. 3.2 and 3.3).

3.3.3 Pegmatite dike width

The dike widths of 129 of the examined pegmatite occurrences were reported. Of these, 14 occurrences are less than 1 m wide, 67 are between 1 and 9.9 m wide, 16 are between 10 and 19.9 m wide, 20 are between 20 and 49.9 m wide, 5 are between 50 and 99.9 m wide, and 7 are greater than 100 m wide. Because so many categories are being compared, it is impractical to list all differences in element content for every range of widths. Of note is that there appears to be a general trend in which the proportion of pegmatites that contain elements such as Li, Be, P, Nb, Sn, Cs, and Ta is higher in wider dikes (Fig. 3.4).

3.3.4 Pegmatite dike orientation: concordant versus discordant

In foliated host rocks, the orientation of the pegmatites within the host rocks was described for 169 occurrences. Seventy-three of these are concordant with their host rocks, whereas 96 are discordant with their host rocks. Pegmatites that are discordant to their host rocks more commonly contain Li, Be, F, Mn, Fe, Nb, Sn, HREEs, and Ta than pegmatites that are concordant to their host rocks (Fig. 3.5).

3.3.5 Contact between pegmatite dike and host rock: ductile, gradational, and sharp

Of the 66 pegmatite occurrences for which the nature of the contact between the pegmatites and their host rocks was described, 53 have sharp contacts, six have gradational contacts, and seven have lobate or folded contacts (evidence of ductile deformation). It should be noted that the sample size of pegmatites with gradational and lobate or folded contacts is too small to yield statistically significant results. Based on the information available it appears that pegmatites with sharp contacts with their host rocks more commonly contain Li, Be, F, P, Ti, Nb, Sn, Cs, LREE, HREE, Ta, and sulphide than pegmatites with both gradational and ductile contacts with their host rocks. Pegmatites with sharp contacts also appear to

more commonly contain U than pegmatite with gradational contacts with their host rocks (Fig. 3.6).

3.3.6 Exo-contact reaction zones

Of the 306 pegmatite occurrences included in this analysis, 84 have an exo-contact reaction zone and 222 do not. This analysis did not discriminate between the size of the reaction zone or its mineral composition. Pegmatites that have exo-contact reaction zones more commonly contain Be, Ti, Nb, Sn, Cs, and Ta than pegmatites that do not have exo-contact reaction zones (Fig. 3.7).

3.3.7 Endo-contact reaction zone or host rock xenoliths

A total of 311 pegmatite occurrences were included in this analysis. Of these, 36 have an endo-contact reaction zone and/or host rock xenoliths, whereas the remaining 275 do not. This analysis did not discriminate between the size of the reaction zone or its mineral composition, nor the type of host rock xenoliths. Pegmatites that have endo-contact reaction zones or that contain xenoliths of their host rocks more commonly contain B and Cs than pegmatites that do not contain these features (Fig. 3.8).

3.3.8 Secondary hydrothermal alteration and/or replacement zones

Of the 316 pegmatite occurrences included in this analysis, 67 contain secondary hydrothermal alteration and/or replacement zones, whereas the remaining 249 do not. This analysis did not discriminate between the abundance of the alteration or size of the replacement zones. Pegmatites that contain secondary hydrothermal alteration or replacement zones more commonly contain Li, Be, P, Nb, Sn, Ta, and U than pegmatites that do not contain these features (Fig. 3.9).



Figure 3.1. The percentage of pegmatite occurrences hosted by felsic and mafic rocks that contain certain elements or minerals.



Figure 3.2. Diagram showing the elements that occur more commonly in pegmatites hosted by various rock types. For example, pegmatites hosted by igneous rocks more commonly contain Li and F than pegmatites hosted by metamorphic rocks with an igneous protolith, whereas pegmatites hosted by metamorphic rocks with an igneous protolith more commonly contain Nb, Sn, and Ta than pegmatites hosted by igneous rocks. All elements that occur in 10% or more of pegmatites hosted by one rock type over another rock type are included. The lengths of the arrows do not reflect the size of the anomaly.



Figure 3.3. The percentage of pegmatite occurrences hosted by igneous rocks, and metamorphic rocks with an igneous, sedimentary, and carbonate protolith, that contain certain elements or minerals.



Figure 3.4. The percentage of pegmatite dikes of varying widths that contain certain elements or minerals.



Figure 3.5. The percentage of pegmatite occurrences in bedded host rocks with varying orientations with respect to bedding that contain certain elements or minerals.



Figure 3.6. The percentage of pegmatite occurrences with varying contacts with their host rocks that contain certain elements or minerals.



Figure 3.7. The percentage of pegmatite occurrences with or without exo-contact reaction zones that contain certain elements or minerals.



Figure 3.8. The percentage of pegmatite occurrences with or without endo-contact reaction zones or host rock xenoliths that contain certain elements or minerals.



Figure 3.9. The percentage of pegmatite occurrences with or without secondary hydrothermal alteration or replacement zones that contain certain elements or minerals.

3.4 Discussion

If the mineralogy of a pegmatite is not influenced by its host rocks, all elements should occur in an equal proportion of pegmatites regardless of external factors. As a specific example, let us consider the overall host rock composition, i.e., whether the host rocks are felsic or mafic. If external factors are not affecting pegmatite composition, any element should occur in pegmatites hosted by felsic rocks equally as commonly as it occurs in pegmatites hosted by mafic rocks. Of course, factors such as the degree of fractionation of the pegmatites affect whether certain elements will be present; however, there should be no reason why pegmatites hosted by felsic rocks are more fractionated than pegmatites hosted by mafic rocks, or vice versa. If there is an apparent difference between the proportion of pegmatites that contain any one element, it suggests that the host rocks have influenced the composition of those pegmatites.

To determine if contamination may be affecting the mineralogy of pegmatites, I examined the difference between the proportion of pegmatites that contain a variety of different elements when characteristics of their host rocks are different. When the composition of the host rock (felsic versus mafic) is considered, there are a few elements that are present in an anomalously larger proportion of pegmatites hosted by mafic rocks than those hosted by felsic rocks. These elements are Cs, Li, and Sn. This is an interesting result because these elements are generally more enriched in felsic rocks (Parker, 1967). If contamination from the felsic host rocks is occurring, one would expect these elements to occur more commonly in pegmatites hosted by felsic rocks. Phosphorus occurs more commonly in pegmatites hosted by felsic rocks than those hosted by mafic rocks. The P contents of the continental crust is low (Rudnick & Gao, 2003), and its abundance in felsic and mafic rocks is very similar (Parker, 1967). This anomaly could instead be due to the abundance of P in metamorphic rocks with a sedimentary protolith, the vast majority of which have a felsic composition. Overall, the elements considered more commonly occur in pegmatites hosted by mafic rocks than those hosted by felsic rocks. The pegmatites included in this analysis are all granitic pegmatites, meaning they all have a felsic composition. When the composition of a pegmatite is similar to its host rock, there will be less of a reaction and exchange of elements between the two when the pegmatite is emplaced than there would be when there is a large difference in composition between the two units. For this reason,

pegmatites hosted by mafic rocks should contain a greater variety and abundance of exotic elements due to their greater difference in composition.

There are many notable differences in the presence of elements in pegmatites hosted by different rock types (igneous or metamorphic). The greatest number of differences occur when comparing metamorphic rocks with a carbonate protolith to other rock types. Many different elements such as B, Cs, and Nb are more commonly present in pegmatites that are hosted by metamorphic rocks with a carbonate protolith than pegmatites that are hosted by igneous rocks, and metamorphic rocks with both an igneous and sedimentary protolith. These pegmatites also more commonly contain carbonate minerals. This demonstrates the highly reactive nature of carbonate rocks and supports the conclusions of the study on the Rau pegmatite group (Chapter 2), namely that the mineralogy of these pegmatites is influenced by their host rocks. In addition to these differences in the composition of pegmatites hosted by metamorphic rocks with a carbonate protolith, there are also differences between pegmatites hosted by other metamorphic and igneous rock types. Fluorine and Cl are more commonly present in pegmatites hosted by igneous rocks than those hosted by metamorphic rocks with an igneous protolith. These are both volatile elements that would be lost from the host rocks during metamorphism, making them relatively more abundant in unmetamorphosed igneous rocks. Another example is the compositional difference between pegmatites hosted by metamorphic rocks with an igneous protolith and metamorphic rocks with a sedimentary protolith. Those hosted by metamorphic rocks with an igneous protolith more commonly contain elements that are more abundant in igneous rocks, such as Nb, REEs, and Ta. All of the above provides evidence that the host rock can influence the mineralogy of a pegmatite and that contamination could play a significant role in determining its final composition.

The width of pegmatites is difficult to use in an analysis such as this because it can vary significantly within one occurrence. To reduce the effect of this variation, this analysis did not include pegmatite occurrences with a large range of widths that were not all contained within one of the defined categories. It should be noted that the results of this analysis could also be skewed by the specific categories that pegmatite widths were subdivided into (e.g., < 1, 1-9.9 m, etc.). Finally, this analysis was conducted under the assumption that all widths reported by authors were from pegmatites that were fully exposed across their width, and not from those could have extended into the subsurface. Due to these confounding factors, these results will not be used to

interpret if there is any correlation between pegmatite width and contamination. Nevertheless, there appears to be an interesting trend between the abundance of certain elements, namely Be, P, Cs, Li, Nb, Sn, and Ta, in pegmatites and their width. The proportion of pegmatites that contain these elements increases with increasing pegmatite width. These elements and minerals are all known to increase in concentration with increasing pegmatite fractionation, and pegmatite fractionation increases with increasing pegmatite size (London, 2008). Therefore, the increase in the proportion of these elements and minerals is likely due to the increasing size of the pegmatites and consequently their increasing degree of fractionation.

Many of the elements considered occur more commonly in pegmatites that are discordant to the foliation/bedding of their host rocks than those that are concordant to the foliation/bedding of their host rocks. These specific elements (e.g., Be, Li, Nb, Ta) are ones that are commonly found in pegmatites, suggesting that these elements were not able to diffuse out of those pegmatites once they were emplaced into the host rocks and that they were instead retained and concentrated within the crystallizing melt. This could be facilitated by a lower temperature environment, such as a post-tectonic regime, which would limit the diffusion of elements between the pegmatites and their host rocks compared to one where the pegmatite melt and host rock were more similar in temperature. Colder host rocks would also favour the discordant emplacement of the pegmatites because under lower temperatures the host rocks would be more brittle and there would be greater opportunity for them to fracture. If fracturing does occur, it creates planes of weakness along which a pegmatite melt can be injected, creating a discordant orientation with the host rocks.

The same reasoning explains the relative abundance of elements (e.g., Be, Li, Nb, Ta) in pegmatites that have sharp contacts with their host rocks compared to those with gradational or ductile contacts. Sharp contacts between the pegmatites and their host rocks indicates that there was a larger temperature difference between the two than if the contacts were gradational or ductile. This would in turn suppress diffusion of elements from the pegmatites to the host rocks, allowing rare elements to remain in the pegmatite melt and concentrate during fractionation.

This effect of the nature of the pegmatite–host rock contact on the mineralogy of the pegmatite dike is demonstrated by the Arvogno fluorite dike and the Arvogno Albertini dike, both located in the Central Alps (Guastoni, 2012). These two pegmatite dikes are both classified as allanite-euxenite-gadolinite type, a new type proposed by Guastoni (2012). They are both

hosted by a medium-grained two-mica orthogneiss and have a simple internal structure consisting of a border-wall zone and a core zone. Although the Arvogno Albertini dike is thicker than the Arvogno fluorite dike (3–4 m versus 1 m respectively), the Arvogno fluorite dike contains a much more diverse set of rare element-bearing minerals, especially in the core of the dike. The main difference between these two pegmatites, other than their mineralogy, is that the Arvogno fluorite dike has sharp contacts with its host rocks, whereas the Arvogno Albertini dike has ductile contacts with its host rocks.

The elements that are present in a greater proportion of pegmatites that have an exo-contact reaction zone than those that do not are all incompatible elements that are concentrated with increasing pegmatite fractionation (e.g., Be, Cs, Ta). Fractionation also increases the concentration of fluxing elements such as H₂O (London, 2008). An increased concentration of fluxing elements would allow for the formation of exo-contact reaction zones because these elements are volatile and would be expelled from the pegmatite into the host rocks during its final stages of crystallization. Overall, almost all of the elements that were examined are present more commonly in pegmatites with exo-contact reaction zones than those without, demonstrating a correlation with increasing fractionation. Notably, the proportion of pegmatites with and without an exo-contact reaction zone that contain B is essentially equal. This is because B that is concentrated in pegmatites during fractionation is commonly released into the host rocks during the final stages of crystallization instead of crystallizing within the pegmatites (London, 2008).

Endo-contact reaction zones and host rock xenoliths both indicate that the pegmatites have been affected by the host rocks. Two elements show an anomalous difference (> 10%) between their presence in pegmatites that have an endo-contact reaction zone or host rock xenoliths and those that do not: B and Cs. The concentration of both B and Cs would increase with fractionation, with higher concentrations being attained in highly fractionated, volatile-rich pegmatite melts. A volatile-rich melt would promote reaction between the pegmatites and the host rocks, forming endo-contact reaction zones.

A number of different elements are present in a greater proportion of pegmatites that contain secondary hydrothermal alteration or replacement zones than those that do not. This difference is likely related to fractionation instead of contamination. Pegmatite-forming melts that are more fractionated are also less viscous because they contain a larger amount of fluxing and volatile elements (London, 2014). Fluxing and volatile elements are incompatible in the bulk

pegmatite melt and are concentrated at the crystallization front, in what is termed the boundary layer liquid. Once this liquid reaches saturation, an aqueous fluid is exsolved that can react with earlier-formed pegmatite assemblages and form replacement bodies (London, 2014). This boundary layer liquid is more likely to reach saturation and be exsolved from the pegmatite in a more fractionated melt.

3.4.1 Limitations

There are a number of limitations to this study that must be acknowledged. Many of these limitations are inevitable due to the current pegmatite literature available. The first of these is that far more rare-element pegmatites than barren pegmatites are included in this study, even though barren pegmatites are more abundant in nature. This is because barren pegmatite occurrences are generally not reported in the literature, likely due to the fact that they are generally not geochemically interesting or unique enough to warrant further study.

Language has also constrained which pegmatite occurrences could be included in this study. Because I am only proficient in English, any papers that were written in other languages could not be included. This has in part also limited the scope of the study geographically as publications in journals from non-English-speaking countries are underrepresented (e.g., Russia, China).

One of the limitations of this study is that much of the data included are for entire pegmatite occurrences rather than single pegmatite dikes. This is due to the coarseness of data available in the pegmatite literature. Many studies, especially earlier ones, provide generalizations of an entire pegmatite group or field, and only examine some, if any, of the pegmatite dikes in greater detail individually. Generally, the only studies that provide great detail for single pegmatite dikes are those that were conducted on a particularly unique occurrence, such as the Kracovice and Bližná pegmatites (Novák *et al.*, 2012), or those that are investigating the occurrence of a unique mineral, such as londonite in the Antandrokomby pegmatite (Simmons *et al.*, 2001). For studies that have made generalized conclusions about larger pegmatite occurrences, I assumed that the authors sampled a representative portion of the occurrence, and that the data presented are not biased towards a subset of the pegmatites, such as those that are more mineralogically interesting. This assumption should be valid as a

representative description and accurate generalizations should be required for publication in any peer-reviewed journal.

This limitation has affected the way this meta-analysis was conducted. In a traditional meta-analysis each pegmatite occurrence would be weighted so that an occurrence that contains more pegmatite dikes would have more of an impact on the results of the analysis than an occurrence that contains fewer dikes. Unfortunately, due to the data available in the pegmatite literature, weighting the data is not possible in this case. The number of individual dikes present within a pegmatite field is commonly not provided. These data could be absent from the literature because many pegmatite occurrences contain hundreds of dikes, and counting each individual dike is impractical, especially when many of them have similar characteristics. Furthermore, especially for remote pegmatite occurrences or ones that are difficult to access, the complete extent of the occurrence may be unknown. As an example, only six of the nine total pegmatite dikes that have been discovered thus far in the Rau pegmatite group were first noted during initial exploration in 2011. Due to dense forest cover in the area, it is entirely possible that there are still pegmatite dikes within the Rau pegmatite group that have not yet been discovered.

I believe that focusing on pegmatite occurrences rather than individual dikes is sufficient for this particular study because its purpose was not to determine if specific pegmatites are contaminated or not, but rather to assess if there is evidence that contamination may be a process affecting more pegmatites than previously thought.

In theory this study could be expanded until it includes all pegmatite occurrences that have ever been published or studied and documented in some form. However, continued expansion of the study is unlikely to provide different or new results because the current data set has a large sample size (n = 66-316 depending on the specific analysis) and includes pegmatites from all five pegmatite classes (abyssal, muscovite, muscovite–rare-element, rare-element, and miarolitic; Černý and Ercit, 2005) and all three petrogenetic families (NYF, LCT, and mixed NYF + LCT; Černý 1991a), plus barren pegmatites. Each class and family is not equally represented, but this is a product of the pegmatite literature available. The majority of pegmatites included in this study belong to the rare-element class, which is consistent with the abundance of studies on rare-element class pegmatites available in the literature. Pegmatites in the less evolved classes such as abyssal and muscovite, as well as barren pegmatites, are poorly represented, and are much less common in the pegmatite literature. Mixed-type pegmatites are also poorly represented

compared to NYF-type and especially LCT-type. This is because only a limited number of scientific studies of mixed-type pegmatites have been completed (e.g., Ercit *et al.*, 2003; De Vito *et al.* 2006; Novák *et al.*, 2012). Therefore, the included data are representative of the currently available literature.

3.4.2 Recommendations

By conducting this meta-analysis of the pegmatite literature it has become evident that the studies conducted on pegmatite occurrences are highly variable in their scope and depth. Very few studies provide a thorough description of the host rocks, and even fewer consider the potential impact that those host rocks could have on the mineralogy of the pegmatites. If the influence of the host rocks on the mineralogy of the pegmatites is considered, it is usually in cases where the mineralogy of the host rocks are carbonate rocks (e.g., Novák *et al.*, 2012) or Febearing skarns (Novák *et al.*, 2013). As such, it is clear that future studies of pegmatites should conduct more thorough investigations of the host rocks, including detailed descriptions of their mineralogy. Studies should also note any possible reaction products, both within the pegmatites and within the host rocks. Their presence could not only suggest that some contamination has occurred, but also help to determine which elements have been involved in the chemical exchange between the pegmatites and the host rocks.

If making conclusions about the formation of the pegmatites, it is important to consider that the chemical composition of the host rocks could have an impact on the mineralogy and overall geochemical signature of the pegmatites. This potential contamination could also influence how pegmatites are classified. The current petrogenetic classification scheme ties the geochemical signature of a pegmatite to its formation (Černý, 1991a). The mixed NYF + LCT type family can have diverse origins, but one possible mechanism of formation is the contamination of an NYF-type magma by LCT-type lithologies, or vice versa. If contamination does change the geochemical signature of more pegmatites than previously recognized, it could point to a greater flaw in this classification scheme as currently contamination is only attributed to the formation of the mixed-type signature.

Due to the number of limitations in this study, I hesitate to provide any concrete conclusions. However, it can be confidently stated that there are anomalies in the occurrence of

elements within pegmatites related to factors such as host rock type and composition. It seems reasonable, especially in light of the findings presented for the Rau pegmatite group (Chapter 2), to conclude that pegmatite contamination is a much more common mechanism that can cause the modification of the mineralogy of a pegmatite than is currently recognized.

CHAPTER 4

Recommendations for a New Pegmatite Classification Scheme

4.1 **Pegmatite Classes**

A fundamental problem with the class system (Černý & Ercit, 2005) is highlighted by the Rau pegmatite group. To the naked eye, the Rau pegmatite dikes appear to be composed of mainly only quartz, feldspar, micas, and fluorite, with the rare element-bearing minerals being too small to see. However, examination with a scanning electron microscope reveals that some of the pegmatites contain thousands of microscopic grains of Nb, Ta-bearing minerals, mainly members of the pyrochlore supergroup. Based on the presence of pyrochlore supergroup minerals, and their likely secondary origin after primary columbite group minerals, one could argue that the Rau pegmatite group should be classified as part of the beryl-columbite subtype of the rare-element class. Both classification as part of the muscovite class, or as a barren pegmatite, does not seem appropriate based on the large number of pyrochlore supergroup minerals grains in many of the pegmatite dikes and the diverse assemblages of other rare element-bearing minerals such as euxenite-(Y), monazite-(Ce), and REE-bearing carbonate minerals. However, the name "beryl-columbite" subtype implies that the Rau pegmatite dikes should also contain beryl, which they do not except as a trace secondary mineral in the Rau 1 and 3 pegmatite dikes. This highlights three problems: (1) the modal abundance of a mineral required for a pegmatite to be considered part of a subtype, (2) the modal abundance of rare elementbearing minerals required for a pegmatite to be considered part of the rare-element class, and (3) the classification of a pegmatite as part of a subtype if it does not contain one or more of the minerals that define that subtype.

I echo the suggestion of Müller *et al.* (2018) that modal abundance should be an integral part of a new classification scheme. In order for a classification scheme to be consistently used, more specific guidelines are needed that outline the percentage of a mineral that is required for it to be considered part of a pegmatite class, subclass, type, or subtype. If that percentage is not attained, it should also be clear how the pegmatite would then be classified. This process is well-known from mineral supergroup nomenclature (e.g., Atencio *et al.*, 2010). I would suggest a simple solution such as a flow chart scheme in which the user would consider each criterion

separately and be directed to the final classification, with the result of not satisfying any of the criteria being that the pegmatite is classified as barren. Other potential solutions would include name modifiers, such as barren-beryl-columbite, but these would introduce further complexity. If a new classification scheme is to include subtypes, there also must be guidelines on whether or not all minerals within a subtype name are required for classification, and details on the protocol if one or more of the minerals within a subtype are not present.

Without guidelines on the modal abundance of a mineral required for classification, the decision on whether to classify a pegmatite within a less or more rare element-enriched type or subtype is left to the individual(s) studying the pegmatite. This could lead to a bias in the literature towards pegmatites that have been oversold, meaning that they were classified as a more evolved class or type because these tend to be of more interest to the pegmatite community. Based on an extensive examination of the pegmatite literature (Chapter 3), I can confidently state that pegmatites of the rare-element class are far more abundant in the pegmatite literature than pegmatites of the muscovite class or barren pegmatites. One could question whether that is at least partially influenced by the flexibility of the currently accepted classification scheme.

The geochemical signature of the Rau pegmatite group was altered due to contamination, specifically by crystallizing Ca-bearing minerals such as calcite, fluorite, allanite-(Ce), and fluorcalciomicrolite. Although in this case the presence of these minerals did not affect how the pegmatite was classified using the class system (Černý & Ercit, 2005), contamination does have the potential to affect the classification of a pegmatite depending on how it changes its geochemical signature. Because the currently accepted classification scheme has genetic implications, extreme contamination could theoretically change the genetic interpretation imposed by the classification scheme.

4.2 Mixed NYF + LCT Pegmatites

Černý (1991a) defined pegmatites of the mixed NYF + LCT family as simply "cross-bred" LCT- and NYF-type pegmatites. However, Černý and Ercit (2005) emphasized that both the LCT and NYF family can contain elements that are characteristic of the other family. For example, highly evolved members of the NYF family can contain some minerals that are typical of the LCT family (Černý & Ercit, 2005). If an LCT-type pegmatite can contain some elements characteristic of the NYF family, and an NYF-type pegmatite can contain some elements

characteristic of the LCT family, the point at which a pegmatite is considered a member of the mixed NYF + LCT family becomes even more unclear. If the mixed-type family is maintained in a new classification scheme, the modal abundance of LCT- and NYF-type minerals required for classification as a LCT-, NYF-, or mixed-type pegmatite must be clearly defined.

The Rau pegmatite group is another example of a mixed-type pegmatite whose geochemical signature was generated due to contamination of a NYF-type pegmatite melt by a LCT-type crustal signature. This is considered to be the most common mechanism for the formation of a mixed NYF + LCT signature (Černý & Ercit, 2005). Notable exceptions are the external pegmatites of the O'Grady Batholith (Ercit *et al.*, 2003) that were derived from a batholith with mixed characteristics, and the Bližná pegmatite, an originally LCT-type pegmatite that was subjected to pre-emplacement contamination by NYF-type carbonatite-like marbles (Novák *et al.*, 2012). Whalen *et al.* (1987) also stated that mixed-type pegmatites could be derived from a partially depleted crustal protolith, or by anatexis of a mixed range of depleted and undepleted protoliths, both of which are still considered to be relevant hypotheses (e.g., Černý & Ercit, 2005). The fact that pegmatites that were generated by vastly different processes can be grouped into the same geochemical family points to a flaw in the current classification scheme. As more pegmatites continue to be described and more are being classified as this ambiguous mixed-type, the need for a classification scheme that integrates mixed-type pegmatites into it, rather than forcing them into a poorly defined "other" category, is highlighted.

CHAPTER 5

From Pegmatites to Pedagogy

To this point this dissertation has focused on providing the first comprehensive investigation of the previously unstudied mixed NYF + LCT Rau pegmatite group. Innovative methods, such as measuring the trace element contents of quartz and the C and O isotopic signature of carbonate minerals, were employed to reveal the timing of contamination and its effect on the mineralogy of the pegmatites. The results presented provide new data on mixedtype pegmatites and were used to comment on the validity of the mixed NYF + LCT family, as well as the state of pegmatite classification in general. In order to assess the potential impact of the host rocks on pegmatite mineralogy, this dissertation also presented an extensive metaanalysis of the pegmatite literature that demonstrated that contamination is probably a more prevalent phenomenon than previously recognized.

The fundamental knowledge required to conduct a study of this nature was gained during my undergraduate degree. An introductory mineralogy course taken during my second year of study formed the basis of my understanding of mineralogy. I solidified and expanded upon my knowledge as I progressed through my undergraduate degree and into the graduate program at UBC. Without the solid foundation that was created by my introductory mineralogy course, completing a graduate-level research project in mineralogy would not have been possible. Even if a graduate degree is not pursued, mineralogy forms the basis for the understanding of many earth processes and is integral to careers in all subdisciplines of the geosciences (Dyar *et al.*, 2004). It is thus of utmost importance that undergraduate students learn key mineralogy concepts in their introductory mineralogy course.

The following chapter presents a concept inventory that can reliably evaluate learning in undergraduate mineralogy courses. This statistically validated multiple choice assessment can be deployed as a pre- and post-assessment to evaluate students' prior knowledge of mineralogy concepts and how much they have learned after completing an introductory mineralogy course. Instructors can use this concept inventory to evaluate the effectiveness of their instruction, compare the effectiveness of different pedagogies, and identify areas of their curriculum that require reform, all of which will help to ensure that their students have the pre-requisite skills
required for future courses and graduate studies (Libarkin & Anderson, 2005). The concept inventory has been developed through consultation with experts who teach post-secondary introductory mineralogy courses and can be implemented in any introductory level mineralogy course to measure learning gains.

I also present additional evidence that employing a student-centred pedagogy may increase learning gains more than an instructor-centred pedagogy. This was ascertained by deploying the concept inventory in two undergraduate mineralogy courses that have similar course content but employ different pedagogies—student-centred and instructor-centred—and comparing the learning gains between the two courses.

CHAPTER 6

The Mineralogy Concept Inventory (MCI): A Statistically Validated Assessment to Measure Learning Gains and Compare Pedagogies

Mineralogy is a foundational course in all undergraduate geological sciences programs and is commonly the first geological sciences course that students are required to take above the 100-level. Students need to have a basic knowledge of the materials that make up the Earth in order to explore other geoscience disciplines (Dyar *et al.*, 2004). The understanding of mineralogy concepts is fundamental to the geological sciences as these concepts form the foundation for key concepts in subsequent courses such as petrology, economic geology, geochemistry, and structural geology. As such, it is important for instructors to be able to accurately assess student learning of key mineralogy concepts.

Concept inventories are an appropriate tool to assess student learning and compare the impact of different pedagogical practices because they can accurately evaluate whether students understand concepts rather than if they can recall facts (Adams & Wieman, 2011). They are statistically validated multiple-choice assessments (Libarkin, 2008). Although concept inventories have been developed for other sub-disciplines within the geosciences (e.g., Arthurs *et al.*, 2015; Libarkin & Anderson, 2005), to our knowledge there does not exist a concept inventory for introductory mineralogy. A concept inventory for introductory mineralogy courses would provide instructors with critical information about how well their students are learning.

A variety of pedagogical approaches, across a spectrum from instructor- to student-centred, are employed to teach mineralogy. Some literature has described how to structure mineralogy courses and incorporate active learning techniques into the classroom (e.g., Dyar *et al.*, 2004; Mogk, 2007) but, to the best of our knowledge, the impact of these techniques on student learning of mineralogy concepts has not been evaluated with a validated assessment tool.

I developed the Mineralogy Concept Inventory (MCI) with two goals: (1) to create a statistically validated assessment that can be implemented in any introductory mineralogy course to measure learning gains, and (2) to assess the impact of pedagogical methods on student learning of mineralogy concepts. This was pursued through a two-year iterative development process involving deployment in two second-year introductory mineralogy courses at two

different research-intensive Canadian universities, statistical analysis of both the first draft and revised version of the concept inventory, and confirmation of key concepts with experts at 77 post-secondary institutions around the world. To assess the impact of pedagogical methods, the MCI was implemented both in a course that uses a student-centred pedagogy and in one that has similar course content but uses instructor-centred teaching methods.

6.1 Background

6.1.1 Concept inventories

Faculty in the geosciences recognize the importance of teaching students to understand and apply concepts (Libarkin *et al.*, 2014). With this recognition comes the need for assessment tools that can accurately measure students' abilities (Adams & Wieman, 2011).

Unlike traditional assessments, the development of validated concept inventories commonly involves expert consultation, student interviews, integration of student language into the assessment questions, and statistical validation. These steps are to ensure that the set of questions targets concepts that experts have determined are fundamental to that sub-discipline, that the test questions are worded in a way that students will understand, and that questions have been evaluated for validity and reliability. Useful concept inventories are aligned with the student population and will provide an accurate measurement of conceptual understanding (Libarkin, 2008).

Results from concept inventories can help evaluate changes in conceptual understanding related to instruction, compare the impacts of different pedagogies, identify areas of the curriculum that require reform, and ensure that students have the pre-requisite skills required for future courses and graduate studies (Libarkin & Anderson, 2005; Libarkin, 2008).

The Force Concept Inventory (FCI; Hestenes *et al.*, 1992), developed for use in collegelevel physics courses in the early 1990s, is commonly regarded as the first concept inventory to be produced for a scientific discipline (Libarkin, 2008). This instrument had a dramatic impact on physics education, leading to significant changes in physics instruction (González-Espada, 2003). The success of the FCI led to the proliferation of concept inventory development into other fields such as biology (e.g., Anderson *et al.*, 2002; Klymkowsky *et al.*, 2010), astronomy (e.g., Hufnagel, 2002; Lindell & Olsen, 2002), and the geosciences (e.g., Libarkin & Anderson, 2005; Libarkin *et al.*, 2018).

6.1.2 Earth science concept inventories

The Geoscience Concept Inventory (GCI; Libarkin & Anderson, 2005) was the first concept inventory that was developed for the geosciences. The GCI is unique because it can be used in a wide range of introductory geoscience courses, rather than being targeted to one specific sub-discipline as most concept inventories are. Users can easily generate course-specific sub-tests from a bank of 73 questions (Libarkin *et al.*, 2011). As of 2011, over 200 faculty and researchers across the United States reported using the GCI (Libarkin *et al.*, 2011).

Although the GCI is an innovative instrument that is extremely useful for measuring the understanding of key geoscience concepts by non-science majors, it does not contain any questions that are appropriate for an introductory mineralogy course. To our knowledge, the only other published concept inventories that target geoscience concepts are the Landscape Identification and Formation Test (LIFT; Jolley *et al.*, 2013) and the Oceanography Concept Inventory (Arthurs *et al.*, 2015), both of which do not contain any questions about key mineralogy concepts. For this reason, the development of a concept inventory specifically for introductory mineralogy courses is warranted.

6.1.3 Content of mineralogy courses

Mineralogy course content is influenced by instructor and department choices, which in turn may be influenced by mineralogy textbooks and other available teaching material, as well as professional organizations. For example, Geoscientists Canada, the organization that governs Canada's professional geoscientists and geoscientists-in-training, has knowledge and experience requirements for professional registration in Canada. It separates mineralogy into two categories: (1) mineralogy and petrology, and (2) optical mineralogy. Mineralogy and petrology includes systematic mineralogy (e.g., identification, classification, and description), physical and chemical properties of minerals, crystallography and crystal systems (e.g., symmetry and crystal structure), descriptions of rocks in hand samples, and applicable techniques in mineral and rock identification (e.g., optical, electrical, and magnetic). Optical mineralogy includes properties of light and its interaction with mineral grains (e.g., reflection, refraction, polarization, interference phenomena, extinction, colour, and pleochroism), refractometry, interpretation of interference figures, and isotropic, uniaxial, and biaxial optics (Geoscientists Canada, 2019).

Beyond guidelines from professional organizations, literature is available that suggests topics and frameworks for mineralogy courses. Typical topics taught in an introductory mineralogy course fall into the broad categories of crystallography, crystal chemistry, and systematic mineralogy, which is generally linked to petrologic environments and how minerals can be used to interpret Earth's processes (Dutrow, 2004). Swope & Gieré (2004) describe a course structure starting with crystal chemistry (including Pauling's rules, coordination number, substitution), then crystallography (including symmetry, Miller indices, crystal forms), descriptive mineralogy (silicates), mineral identification (hand specimen and thin section), and analytical methods (X-ray diffraction and electron microprobe analysis) (Swope & Gieré, 2004). Dutrow (2004) presents an alternative course organization in which Earth is used as a reference framework and concepts are integrated into a discussion of earth materials and geologic processes of formation. Specific concepts included in this core to crust model are physical properties of minerals, crystallography (including bonding, polyhedra, Pauling's rules), crystal symmetry, mineral classification, systematic mineralogy (including polymorphs, solid solution, etc. when applicable), and the chemical makeup of the Earth (Dutrow, 2004). Framing and specific content vary, but there is considerable overlap in mineralogy concepts highlighted by professional organizations and the geoscience education literature.

6.1.4 Participating universities

The MCI was developed and deployed in two second-year introductory mineralogy courses at two different Canadian universities, hereafter referred to as "UX" and "UY". The mineralogy courses at these two universities have similar course content but are taught using different teaching methods. For over a decade, there has been a well-funded initiative at UX to improve science education, resulting in a shift towards more student-centred pedagogies that incorporate active learning techniques in undergraduate courses, including introductory mineralogy. The introductory mineralogy course at UX was transformed between 2008 and 2010 and has undergone continuous iteration since. Changes included the addition of learning objectives to each lesson with associated review questions, and the development of several new in-class activities. The labs were also redesigned as part of this course transformation. In contrast, no such initiative has been available at UY and the course is taught using mainly instructor-centred teaching methods.

There are other key differences between the mineralogy courses and structure of the undergraduate degree programs at UX and UY that could impact student learning (Table 6.1). For example, students at UY likely have more content knowledge due to the prerequisite courses they are required to take.

	UX	UY
Pedagogical approach	Student-centred	Instructor-centred
Number and length of classes	~25, 50-minute classes	~35, 50-minute classes
Number and length of labs	10, 3-hour labs	10, 3-hour labs
Average number of students per term	86 students	64 students
Instructor(s)	Co-instructed by one senior and one new faculty member, neither of whom were involved in the 2008–2010 course transformation	Instructed by one senior faculty member who has been teaching the course for 35 years
Prerequisite courses for the mineralogy course	Introductory Chemistry	Introductory Chemistry, Introductory Geology

Table 6.1. Differences between the mineralogy courses and the structure of undergraduate geoscience degree programs at UX and UY.

6.2 Development of the MCI

The development of the MCI occurred over two years and included two iterations of test development and deployment. This included establishing key concepts, validating these key concepts and relative importance with experts, writing open-ended questions, generating forced-answer questions through student interviews, piloting the test with students, and performing Rasch analysis to examine the validity and reliability of the test. The portion of the process from identifying key concepts to creating questions is considered blueprinting, an approach used to validate assessment content, ensuring that it aligns with content that instructors view as important (Coderre *et al.*, 2009). During development, a total of eight student interviews were conducted. 314 students at two different Canadian universities took either version 1 or version 2 of the MCI as a pre- and post-assessment (299 paired pre- and post-assessments). Detailed material from the three mineralogy instructors at these two universities was consulted (at one of these universities, mineralogy is co-taught). Experts from an additional 77 post-secondary institutions who have taught introductory mineralogy within the past five years provided

feedback on the key concepts and questions included on the MCI. All activity was approved by ethics review boards at both universities.

6.2.1 Identification of key concepts

The first step was to examine all course content, assignments, labs, and assessments from both of the mineralogy courses. For each course, a complete list of all the concepts included in this material was created. The concepts on these lists were then grouped into broader concept areas, or "key concepts" (e.g., "birefringence" and "interference figures" were both grouped into the key concept "optical mineralogy"). Eight of the key concepts that emerged are common to the course content in both courses. Four of these key concepts (deep Earth mineralogy, forensic mineralogy, mineral evolution, and plane groups) are represented in only one of the two courses (Table 6.2). These key concepts comprise the vast majority of the content of these two mineralogy courses.

The three instructors who were piloting the MCI in their courses were asked to indicate the relative weighting of each key concept by qualitatively ranking them as having high, medium, or low importance. Furthermore, they were asked to indicate if any of the included concepts were not important in the course and should be removed from the list (Table 6.2). Through this process, "plane groups" was removed from the list of key concepts. (Four other key concepts were later removed from the MCI on the basis of low importance ratings, student interviews, or Rasch analysis, leaving seven).

To determine whether the seven key concepts included in the MCI are common in introductory mineralogy courses, and not just at the two institutions included in the pilot study, experts who recently (in the past 5 years) taught an introductory mineralogy course were surveyed. Participants were solicited using the Mineralogical Society of America electronic mailing list. 77 responses from instructors of introductory mineralogy courses at post-secondary institutions in 11 countries met the criteria for recency and course topic (Appendix B). The experts were asked to indicate what percentage of their course content was included in the key concepts targeted by the MCI (distribution in Fig. 6.1; average = 87%; n = 75 respondents), and were also asked to rank the importance of each of the key concepts in their introductory mineralogy course. Five of the key concepts are covered by virtually all respondents. The other

two (optical mineralogy and composition of Earth's layers) were covered by approximately 80% of respondents (Fig. 6.2; Table 6.3).

Key concepts at UX	UX instructor ranking	Key concepts at UY	UY instructor ranking	Number of open-ended questions generated*	Number of questions included on version 1 [†]	Number of questions included on version 2 [‡]	Question number on the final MCI
Optical mineralogy	Low	Optical mineralogy	High	5	2	3	9, 14, 15
Crystal structure	Medium	Crystal structure	Medium	4	2	2	2, 10
Mineral chemistry Physical	High	Mineral chemistry Physical	High	7	5	5	1, 3, 5, 13, 16
properties of minerals	Medium	properties of minerals	High	2	1	1	12
Mineral classes and classification	High	Mineral classes	High	6	2	4 [§]	8, 17, 18
Crystal symmetry	Medium	Crystal symmetry	High	4	2	2	6, 7
Miller indices	High	Miller indices	Low	2	1	0	
Analytical methods	Low	Analytical methods	Medium	2	0	0	
Composition of Earth's layers	Medium	-	-	2	1	2	4, 11
Forensic mineralogy	Low	-	-	0	0	0	
Mineral evolution	Low	-	-	2	1	0	
_	_	Plane groups	Not a key concept	0	0	0	

Table 6.2. The key concepts taught at UX and UY, their rankings by the respective instructors, the number of open-ended questions that were generated for think-aloud student interviews, the number of questions included on both versions 1 and 2 of the MCI, and the corresponding questions numbers on the final MCI.

*Two questions that were piloted during think-aloud interviews could not be directly assigned to a key concept.

[†]One question about 3-dimensional thinking was included on version 1 of the MCI. It was completely rewritten for version 2 of the MCI because it showed bias.

[‡]Two questions about 3-dimensional thinking were included on version 2 of the MCI. Both of these questions were removed from the final MCI. One was removed because, due to the way it was structured, it could not be compared to the other questions. The second question that was removed had OUTFIT and INFIT statistics greater than 2.

[§]One question about mineral classes and classification was removed from the final MCI because its OUTFIT and INFIT statistics were greater than 2.



Figure 6.1. Distribution of expert answers to "What percentage of your total course content is included in the seven [key concepts targeted by the MCI]? (n = 75).



Figure 6.2. Distribution of expert answers to "Rank the importance of each of the ... seven topic categories in your introductory mineralogy course." (n = 76 for physical properties of minerals; n = 77 otherwise). Answer options are in the legend.

Table 6.3. Results of a survey of experts who have taught an introductory mineralogy course at a post-secondary institution in the past 5 years. For each key concept on the MCI, the number of respondents and the percentage of those who ranked the concept as having high, medium, and low importance, or as not being covered in their course, is shown.

Key concept*	Number of respondents	High importance	Medium importance	Low importance	Not covered
Optical mineralogy	77	52%	25%	5%	18%
Crystal structure	77	60%	35%	5%	0%
Mineral chemistry	77	77%	23%	0%	0%
Physical properties of minerals	76	58%	34%	8%	0%
Mineral classes and classification	77	47%	36%	17%	0%
Crystal symmetry	77	38%	48%	13%	1%
Composition of Earth's layers	77	26%	29%	26%	19%

*Miller indices, analytical methods, forensic mineralogy, and mineral evolution were not included in the list of key concepts on this survey because they had already been removed from the MCI during think-aloud student interviews.

6.2.2 Creation of open-ended questions

Open-ended questions targeting the key concepts were written for use in think-aloud student interviews. Two to seven open-ended questions were written per concept, and in general more questions were written for concepts of high importance to instructors. These questions were revised by myself and Dr. Harris until a total of 38 questions, covering 10 key concepts were selected to be piloted during validation interviews (Table 6.2). The majority of these questions were open-ended but eight forced-answer questions (seven multiple-choice and one matching) were also included. These forced-answer questions included diagrams as answer choices, and students were asked to explain why they did or did not choose each diagram.

6.2.3 Think-aloud student interviews

Student interviews using open-ended questions are a crucial part of assessment development. The answers that students provide to open-ended questions can be used as response options, providing the greatest chance that students will understand the questions as intended (Adams & Wieman, 2011). Furthermore, think-aloud interviews elucidate a student's thought process as they are answering a question. For the questions that were piloted as forced-answer questions with diagrams as response options, think-aloud interviews were essential in determining why students did or did not choose a response option, which guided subsequent changes to the diagrams.

Eight student interviews were conducted over the two cycles of test development, four in developing version 1 of the MCI and four in revising for version 2 of the MCI. Participants were offered a small amount of monetary compensation for their time. All of the interviews were with students who had not taken mineralogy. All but one student had taken an introductory geoscience course. Three of the students self-identified as female; five self-identified as male.

The 'think-aloud' protocol was employed during interviews (Ericsson & Simon, 1998) and the interviews were audio-recorded. The first question was a practice think-aloud question in which participants were asked to describe how to make their favorite breakfast food. This was followed by the questions about key concepts in mineralogy. Participants were asked to explain their reasoning after answering each question, providing insight into their thinking and aiding in question revision. The interviews lasted 20–90 minutes depending on how quickly participants progressed through the questions.

Because clear feedback emerged from each interview, the open-ended questions were revised after every interview instead of following the procedure in which questions are revised at the end of all interviews. These revisions involved adjusting the wording (e.g., specifying that polarized rays of light enter the same side of the crystal in question 14), removing information that was not required to answer a question (e.g., mineral names were removed from question 5), or making changes to diagrams (e.g., relative side lengths were added to the diagrams in question 14). Based on the first three interviews, questions were removed due to a lack of clarity or a lack of clear alignment with a key concept. For example, a question about X-ray diffraction was removed because all interviewees interpreted the question differently. A question that asked students to determine the percentage of a field of view that was taken up by black shapes was removed because it was not clearly aligned with a key concept. Others were removed because the correct answer could be determined without knowledge of the concept. For example, the answer to a question about optical mineralogy could be determined by matching the relative distance between arrows, which represented optic axes, and isogyres in an interference figure. Regarding this question, an interviewee stated, "I'm going to do through process of elimination and not through knowledge.". Wording for version 1 of the MCI was based on student responses during these first four interviews.

Four additional think-aloud interviews were conducted between the deployment of version 1 and version 2 of the MCI. Interviews, plus information from student performance on version 1 of the MCI, contributed to modifying the questions for inclusion on version 2. These interviews served to check student understanding of question wording, and search for new distractors (i.e., incorrect answer options). Two new questions were also included in these interviews.

This second round of interviews validated the new and revised questions by providing additional evidence that students were interpreting the questions as intended. Unlike the first round of interviews, which resulted in major changes to the wording and structure of questions and generated many question distractors, this second round of interviews only resulted in the generation of one new distractor (question 8). This new distractor replaced one chosen by very few students on version 1 of the MCI (4% and 3% of students on the pre- and post-assessment respectively). The responses that interviewees provided to the other open-ended questions were

similar or identical to the distractors and answers that were already being used. Although the number of interviews conducted during the development of the MCI is small, the fact that only one new distractor was generated in the second round of interviews provides evidence that the number was reasonable and saturation was reached.

6.2.4 Creation of forced-answer questions

After each round of interviews, open-ended questions were converted to forced-answer questions with response options written using student language. For one question (question 3), only two distractors were obtained from interviews. In this case a third distractor was generated by one of the instructors who was piloting the MCI. This instructor reported that students commonly said in class that colour is "due to small inclusions of other minerals within the main mineral", suggesting that this is a student misconception. The results of the implementation of the MCI support that this is a misconception: this distractor was the most popular answer choice on both the pre- and post-assessment of version 2 of the MCI. Furthermore, in a think-aloud interview after version 1 of the MCI, a student stated that different colours "have to do with…what minerals are inside of it".

Standard practices for writing multiple-choice questions were employed (Haladyna *et al.*, 2002; Frey *et al.*, 2005). Each forced-answer question contained one correct answer, two to four (generally three) incorrect distractors, and an "I do not know" option. The "I do not know" option was included to discourage students from guessing. It was treated as an incorrect answer during statistical validation. To ensure that the lengths and structures of the response options were similar, some of the actual student responses were slightly modified but, as much as possible, the original student wording was maintained.

6.2.5 Deployment

The MCI was piloted at UX and UY as both a pre- and post-assessment. In year one, with version 1 of the MCI, 85 students completed the pre-assessment and 80 students completed the post-assessment at UX, whereas 69 students completed the pre-assessment and 64 students completed the post-assessment at UY. This resulted in 144 paired pre- and post-assessments. In year two, with version 2 of the MCI, 96 students completed the pre-assessment and 92 students completed the post-assessment at UX, whereas 64 students completed the pre-assessment and 63

students completed the post-assessment at UY (155 paired pre- and post-assessments). All students who completed the pre-assessment were asked to provide demographic information (e.g., gender, age, ethnicity).

Administration of the pre-assessment at the two universities was slightly different due to time restrictions and instructor preference. At UX, I administered the pre-assessment during the first class. At UY, instructions for administering the assessment and a study information statement to be read to students were sent to the course teaching assistants. The teaching assistant for each of the three lab sections administered the assessment during the first lab, which is held during the second week of classes. In both cases, students were given 20 minutes to complete the assessment. The post-assessment was included as part of the final exam at both universities.

6.3 Validity and Reliability of the MCI

Throughout the development process, the validity and reliability of the MCI was evaluated using Rasch analysis to ensure that the assessment can distinguish between low- and high-performing students. and that the questions are not biased towards or against any subset of the population. Rasch analysis is a form of item response modeling and addresses the fact that a raw test score (number of correct answers) cannot accurately measure the degree to which a student possesses the ability being measured, which in this case is the understanding of mineralogy concepts (Bond & Fox, 2015). Compared to classical test theory, which is based on overall scores on a test, the Rasch model examines how well each question performs based on which responses were chosen by each student. Students with higher abilities in mineralogy, who can answer more questions correctly, should also have a higher probability of correctly answering hard questions than students with lower abilities. Questions without these characteristics are flagged for removal from the test. In addition, each question is evaluated to see if particular demographic groups are favored, and these items are also flagged.

Following Libarkin *et al.* (2018), the Rasch model in Winsteps (Linacre, 2017) was used to analyse both the version 1 and version 2 of the MCI. One question was removed prior to Rasch analysis because it was the only open-ended question on version 1 of the MCI and could not be compared to the other questions on the assessment. Based on Rasch analysis of version 1, three questions were removed because they showed gender or ethnicity bias and three others were completely rewritten for version 2.

The remainder of this section details Rasch analysis of version 2 of the MCI, and the resultant test statistics of the final MCI. These are based on the 155 paired student responses on version 2. This sample size is large enough to yield high confidence in our estimates of question difficulty and student ability (Linacre, 2019). A typical minimum sample size cited for Rasch analysis is 30 (Bond & Fox, 2015).

Principal components analysis of residuals was used to evaluate unidimensionality, meaning whether correct MCI responses depend only on knowledge of mineralogy concepts, a requirement for Rasch analysis. The eigenvalue of the first contrast was 2.11, well below the maximum of 3.0 expected for unidimensional scales (Linacre, 2019). The residual variance was 8.7%, approximately the same as the 10.6% variance that was expected by chance. These results suggest that the assessment is unidimensional and that Rasch analysis is an appropriate method to evaluate item functioning.

INFIT and OUTFIT mean-square statistics were used to assess item functioning. These standard Rasch fit statistics describe how well data fit the Rasch model, and will have a value of 1 if the data perfectly fits the model. INFIT statistics are sensitive to inliers, meaning data that lie within a statistical distribution but are in fact errors. OUTFIT statistics are sensitive to outliers, meaning data that is separate from the main group of data. Two questions exhibited INFIT and OUTFIT greater than 2, potentially indicating an inaccurate measurement (Linacre, 2019). These questions were removed from further analysis, leaving 18 questions with acceptable INFIT and OUTFIT statistics (Table 6.4). Removal of these questions also decreased the standardized residual values by lowering the eigenvalue of the first contrast to 2.0 and the residual variance to 9.1% (11.3% expected by chance).

Reliability measures are used to ensure that the questions range from high to low difficulty, and that the test is sensitive enough to distinguish between low and high performers (Linacre, 2019). Item separation was 4.07 (reliability = 0.94), indicating that the sample size is large enough to accurately establish the scaled difficulty of each question. Person separation was 1.05 (reliability = 0.53).

Differential item functioning (DIF) was used to investigate questions bias for gender (female, male), ethnicity (Caucasian, non-Caucasian), age (18–19, > 20), years lived in Canada (> 10 years, < 10 years), and first language (English, other). All 18 questions exhibited negligible DIF in all of the above categories.

ltem	Measure	Standard Error	% correct	INFIT mean- square	INFIT standardized	OUTFIT mean- square	OUTFIT standardized
Q1	-1.18	0.26	92	0.65	-2.2	0.49	-2.0
Q2	-0.20	0.20	61	1.44	+3.8	1.60	+3.1
Q3	-0.90	0.24	80	1.21	+1.4	1.10	+0.5
Q4	+0.10	0.19	69	0.95	-0.6	0.87	-1.0
Q5	-1.04	0.25	90	0.70	-2.0	0.51	-2.1
Q6	-0.81	0.23	79	1.23	+1.5	1.42	+1.6
Q7	-0.84	0.24	79	1.39	+2.4	1.42	+1.6
Q8	-0.70	0.23	88	0.93	-0.4	1.03	+0.2
Q9	+0.60	0.18	63	1.08	+1.1	1.12	+1.1
Q10	+1.37	0.18	39	1.02	+0.4	1.10	+1.1
Q11	+1.31	0.18	50	1.04	+0.7	1.07	+0.8
Q12	+0.39	0.18	57	1.14	+1.8	1.15	+1.3
Q13	-0.76	0.23	78	1.24	+1.6	1.29	+1.2
Q14	+0.88	0.18	87	1.01	+0.2	1.00	+0.0
Q15	+1.77	0.18	43	1.15	+2.0	1.14	+1.2
Q16	+1.06	0.18	55	1.02	+0.4	1.07	+0.8
Q17	-0.93	0.24	85	0.97	-0.1	0.85	-0.5
Q18	-0.11	0.20	74	0.95	-0.5	0.93	-0.4

Table 6.4. Post-assessment data (n = 155) including difficulty estimates, standard errors, percentage of students who answered the question correctly, and Rasch modeling fit statistics for the final MCI items.

6.3.1 Alignment of items and students

A concept inventory should contain questions with a range of difficulties that align with the range of abilities of students. The use of Rasch analysis allows scaled assessment scores to be calculated based on the difficulty of the questions, and provides a visual representation of question difficulty and student ability that can be used to ensure this alignment. These scaled scores provide a more meaningful measure of student ability because a students' overall scores are based not only on how many questions they answered correctly, but also on how difficult those questions were (Bond & Fox, 2015). These scaled scores can be represented as "measures" and are used to describe both the difficulty of questions and the ability of students. In the case of this study, the ability is the understanding of mineralogy concepts. In the case of question difficulty, higher measures indicate a question is more difficult. For students, higher measures higher ability levels. The use of scaled scores (measures) allows for a more meaningful evaluation of student ability and allows different administrations of the test to be compared (Bond & Fox, 2015).

A useful way to visualize question difficulty versus student ability is to use a Wright map. In this map, the questions are plotted based on their difficulty measures, whereas the students are plotted based on their ability measures. This allows the distribution of question difficulties and their alignment with the ability of the student population to be assessed (Fig. 6.3).

Overall, most of the questions on the pre-assessment are within the range of ability measures of all students (measures -2.5 to +1.2; mean ability measure = -0.68; Fig. 6.3a). The questions are spread over a wide range of difficulties, from measure -1.2 (question 1) to measure +1.8 (question 15), with a small cluster around measures -0.9 to -0.8. Six questions have a higher difficulty than the ability measures of all except one outlying student (ability measure = +1.13). If the outlying student is considered, only three questions (questions 10, 11, and 15) on the pre-assessment are more difficult than the ability level of all students. Two of these questions target common misconceptions (ionic radius and coordination, and crustal composition), whereas the other uses a two-component phase diagram that is generally a difficult concept for students to grasp.

There are no questions that are the same difficulty as students at the lowest ability measures on the pre-assessment (≤ -1.2). Considering that the question with the lowest difficulty measure (i.e., the easiest question; question 1) is tied to introductory chemistry and is not entirely learned in a mineralogy course, questions that would align with these lower ability students may well target concepts learned prior to a mineralogy course rather than mineralogy concepts. Although very low difficulty questions for mineralogy concepts could likely be written, results from the post-assessment (Fig. 3b) indicate that most students' abilities rose above the difficulty level of question 1, and an additional very easy question or two may not be needed.

The Wright map for the post-assessment shows that the difficulty of test questions is wellaligned with the student population, in that no questions are more difficult than the student with the highest ability measure on the post-assessment (Fig. 6.3b). There are several students that had a higher ability measure than all questions on the test, but only three students answered all questions correctly, suggesting that the post-assessment was at an appropriate level for the majority of students. Because the post-assessment measures were anchored to the pre-assessment measures, they span the same range of difficulty measures (-1.2 to +1.8).



Figure 6.3. Wright maps for the (a) pre-assessment and (b) post-assessment (Linacre, 2017). The students are plotted on the left side of each map, whereas the questions are plotted on the right side. Each "#" represents 2 students, whereas each "." represents 1 student.

6.3.2 Construct, content, and criterion validity

In addition to Rasch analysis, several steps were taken during the development of the MCI to address construct, content, and criterion validity. These are three aspects of validity that are typically discussed in concept inventory development (e.g., Libarkin *et al.*, 2018).

Construct validity is whether the assessment is in fact measuring the ability that it was designed to measure (Brown, 1996), in this case the understanding of mineralogy concepts. Principal components analysis of residuals indicates that the assessment is only measuring one concept. Experts at the two universities at which the MCI was developed approved the list of concepts that were included on the instrument and indicated their importance in their mineralogy courses. Furthermore, a survey of 77 experts from around the world who teach introductory mineralogy courses at post-secondary institutions indicated that a high percentage of their course content is included in the concepts covered by the MCI (average 87%; n = 75). Content validity is whether the assessment reasonably represents the discipline (Cronbach & Meehl, 1955). This was achieved by using blueprinting (e.g., Coderre *et al.*, 2009) to ensure that the assessment content is aligned with expert views of key concepts in mineralogy. Furthermore, using standard practices for writing multiple-choice questions (Haladyna *et al.*, 2002; Frey *et al.*, 2005) ensures the questions conform with research-based best practices. Criterion validity is whether the questions and response options are interpreted as intended (Cronbach & Meehl, 1955). It was addressed by conducting think-aloud interviews with students.

6.4 Insights from the Application of the MCI

The MCI was implemented in two undergraduate mineralogy courses that employ different pedagogies: student-centred and instructor-centred. These contrasting courses were selected to assess the impact of pedagogical methods on student learning of mineralogy concepts. Data from implementation of version 1 of the MCI allowed the questions to be refined so that the final implementation would provide as accurate an assessment of student learning as possible. Implementing the MCI as a pre- and post-assessment provided insight into the prior knowledge of students from both universities and the learning gains that each group had attained by the end of the course.

6.4.1 Participants

Participants who completed the pre-assessment were asked to provide demographic information (Table 6.5). The age of participants was similar at both universities with the majority of respondents being between 18 and 19 years old. Other demographics were notably different. At UX, the majority of respondents identified as male, whereas at UY the majority identified as female. A greater proportion of students at UX identify with ethnicities other than Caucasian, had spent less than a decade of their life in Canada, and spoke languages other than English as their first language.

	Gen	lder	Ethn	icity	Aç	ge	Years Car	lived in ada	First La	nguage
	Female	Male	Cauca- sian	Other	18–19	> 20	> 10	< 10	English	Other
	40%	60%	57%	43%	57%	43%	51%	49%	64%	34%
υx	(<i>n</i> =27)	(<i>n</i> =40)	(<i>n</i> =36)	(<i>n</i> =27)	(<i>n</i> =38)	(<i>n</i> =29)	(<i>n</i> =32)	(<i>n</i> =31)	(<i>n</i> =38)	(<i>n</i> =21)
	71%	29%	81%	19%	61%	39%	84%	16%	86%	14%
UT	(<i>n</i> =40)	(<i>n</i> =16)	(<i>n</i> =46)	(<i>n</i> =11)	(<i>n</i> =35)	(<i>n</i> =22)	(<i>n</i> =48)	(<i>n</i> =9)	(<i>n</i> =49)	(<i>n</i> =8)

Table 6.5. Participant demographics at both UX and UY. Note that not all participants provided all requested demographic information.

6.4.2 Key concepts

The key concepts covered in both courses are quite similar, but there are a few notable differences between the importance that instructors at each university place on these key concepts (Table 6.2). The biggest discrepancy relates to optical mineralogy. This concept has high importance at UY, with seven lectures and five of the ten labs focusing it, whereas it is ranked as having low importance at UX and only one lecture is devoted to the subject. Because it is such a large part of the UY course content and included in many introductory mineralogy courses, three questions are included on the final MCI, with the understanding that this concept may not be as important in all mineralogy courses.

The second discrepancy relates to Miller indices. Interestingly, the instructor at UY ranks this concept as having low importance even though it is included in five lectures and three of the ten labs. I suggest that this is because Miller indices are intimately tied to crystal systems, which were ranked as having high importance. It could be that the instructor sees this concept as being a less important aspect of crystal systems, and not deserving of a high ranking on its own. The key concepts that are only present in UX course content, specifically forensic mineralogy, mineral evolution, and deep Earth mineralogy, were all ranked as having low or medium importance. Neither forensic mineralogy nor mineral evolution are included in the final MCI, but one question on deep Earth mineralogy is included because it was ranked as being of relatively higher importance. This question on deep Earth mineralogy could be answered using knowledge of mineral classes and is therefore still an appropriate question for inclusion on the MCI.

6.4.3 Pre- and post-assessment scores

The average pre-assessment score was approximately the same at UX and UY, with average scaled scores of 24% and 27% respectively. Specific concepts that a significantly greater proportion of students at UY answered correctly in the pre-assessment were tetragonal crystal symmetry (question 6; t stat. = 4.64 > t crit. = 1.98; p-value < .001) and classification of sulfide versus sulfate minerals (question 17; t stat. = 3.12 > t crit. = 1.98; p-value < .001) (Fig. 6.4a). Students at UY likely performed better on these questions because they are required to take an introductory geology course as a prerequisite to mineralogy, in which mineral classification is included. A significantly greater proportion of students at UX correctly answered questions about the composition of the Earth's crust (question 11; t stat. = 2.27 > t crit. = 1.98; p-value .02) and optical mineralogy (question 15; t stat. = 2.24 > t crit. = 1.98; p-value .03). Because the percentage of students that answered these questions correctly is very low at both universities, this difference likely does not signify a greater understanding of the concept by students at UX.

The average scaled score on the post-assessment was 57% at UX and 44% at UY, with normalized learning gains (Hake, 1998) of +0.44 and +0.24 respectively (effect size of 2.80 and 1.43 respectively; Fig. 6.5). The average ability measure on the post-assessment for students at UX was +1.53, whereas the average ability measure of students at UY was +0.65. Although the average pre-assessment scores were similar at both universities, the average post-assessment score of UX was significantly higher than that of UY (t stat. = 5.53 > t crit. = 1.98; p-value < .001) and as such their learning gains were also significantly higher (t stat. = 6.41 > t crit. = 1.98; p-value < .001). Half of the questions on the post-assessment were answered correctly by a significantly greater proportion of students at UX than at UY (p-value < .05; Fig 6.3b). These results suggest that although students at UX and UY begin their mineralogy course with similar

content knowledge, students at UX learn more during their mineralogy course and have more content knowledge than students at UY upon completion.



Figure 6.4. The percentage of students who answered each question correctly at UX and UY on both the (a) pre-assessment and (b) post-assessment. The questions are ordered by difficulty, as calculated by Rasch analysis. The stars indicate when there is a statistically significant difference between the percentage of students who answered the question correctly at UX and UY.



Figure 6.5. The distribution of matched scaled pre- and post-assessment scores at (a) UX and (b) UY. These scaled scores include the 88 students at UX and 63 students at UY that completed both the pre- and post-assessment

6.4.4 Comparing pedagogies

The pedagogical approaches applied at UX and UY are notably different. As part of an initiative to improve science education at UX, the introductory mineralogy course underwent a course transformation that included a shift towards a more student-centred pedagogy. All classes now include learning objectives and related review questions are provided at the end of each class. Arguably the most significant change is that now the majority of the classes incorporate one or two in-class activities related to key course concepts. There is no such initiative to change pedagogy at UY. During most classes, the instructor lectures, incorporates demonstrations and real-world examples, and asks questions of the full class. The courses at both universities have a weekly lab.

The higher learning gains and post-assessment scores of students at UX on the MCI suggest that they learned more in their mineralogy course than students at UY. Although these higher learning gains could also be due to factors such as class composition, class size, number of weeks of class, etc., they are likely strongly influenced by pedagogical approach. It is well-documented that classes taught using active learning result in higher average examination scores and normalized learning gains in a wide variety of disciplines, including the sciences (e.g., Freeman *et al.*, 2014; Hake, 1998). Furthermore, there is evidence that the instructor and their pedagogical choices has the largest effect on learning gains, whereas factors such as class composition and size have comparatively little influence (Wright *et al.*, 1997). As the chosen pedagogical methods of the instructors is the main difference between these two courses, it seems reasonable that the use of a student-centred pedagogy that incorporates active learning techniques has resulted in higher learning gains at UX.

6.5 Implications for Mineralogy Educators

Results of a survey of experts who currently teach or recently (in the past 5 years) taught an introductory mineralogy course support that the MCI can be implemented in any introductory mineralogy course. These experts indicated that on average 87% (n = 75) of their total course content is included in the seven key concepts targeted by the MCI (Fig. 6.1). The percentage of total course content ranged from 50–100%. When experts were asked to rank the importance of the key concepts in their courses, optical mineralogy, crystal structure, mineral chemistry, and physical properties of minerals were all ranked as having high importance by the majority of respondents (Table 6.3; Fig. 6.2). Notably, 18% of respondents (n = 14) stated that optical mineralogy is not covered in their courses. Many of these respondents left comments in the survey that optical mineralogy was part of another course at their institution. Crystal symmetry was ranked as having medium importance by 48% of respondents (n = 37), closely followed by high importance (38%; n = 29). The key concept "composition of the Earth's layers" was ranked as high, medium, and low importance by an approximately equal number of respondents (26%, 29%, and 26% respectively; n = 20, 22, and 20), whereas 19% of respondents (n = 15) stated that this concept was not covered in their course.

Experts were also asked to indicate whether they would expect their students to be able to answer each of the 18 questions on the MCI correctly following completion of their introductory mineralogy course, assuming the students had achieved their learning objectives. Between 65 and 74 experts responded to each of these questions (Table 6.6). For most of the questions a high percentage ($\geq 78\%$) of experts thought that their students should be able to answer each question correctly. The questions that received lower agreement were questions 8, 9, 14, 15, and 16. Questions 9, 14, and 15 all target optical mineralogy which is not covered by 18% of respondents (Table 6.3). Question 8 targets mineral classes and classification but refers to a specific mineral formed in a marine environment. Some of the comments left by experts who would not expect their students to be able to correctly answer this question included "We don't cover depositional environments in any detail", "Although I cover many mineral occurrences, this aspect of aragonite isn't covered", and "This mineral group is covered in sedimentary geology". Question 16 targets phase diagrams, an aspect of mineral chemistry. Some of the comments left by experts who would not expect their students to be able to correctly answer this question included "We do not cover phase diagrams like this. We cover simple phase boundaries such as aluminosilicates" and "Cover only the C and Al₂SiO₅ diagram in Mineralogy".

Although there is some diversity of content in mineralogy courses (Table 6.3), the survey respondents generally have high expectations of their students' abilities to answer the 18 questions on the final MCI, if the students achieved their course's objectives (Table 6.6). Given that the average scaled score on the post-assessment with actual students was 52%, there is clearly room for additional student learning of mineralogy, and the MCI could be used to track that learning.

ltem	Number of respondents	Instructors who would expect their students				
		to be able to answer question correctly				
Q1	74	93%				
Q2	71	89%				
Q3	72	83%				
Q4	68	82%				
Q5	73	89%				
Q6	72	92%				
Q7	72	89%				
Q8	73	71%				
Q9	70	69%				
Q10	74	88%				
Q11	74	95%				
Q12	70	90%				
Q13	72	92%				
Q14	72	71%				
Q15	65	52%				
Q16	73	66%				
Q17	74	78%				
Q18	70	84%				
Average	68	78%				

Table 6.6. Results of a survey of experts who are currently teaching or have recently taught an introductory mineralogy course at a post-secondary institution. For each question on the MCI, the number of respondents and the percentage of those who would expect their students to be able to correctly answer each question is shown.

CHAPTER 7

Conclusions

7.1 Summary

The Rau pegmatite dikes were derived from the ~63 Ma Rackla pluton, a weakly peraluminous, ferroan, and calc-alkalic biotite-muscovite granite. The similarity of the geochemical signatures of the pluton and pegmatite dikes, especially those of the less fractionated pegmatite dikes, confirm that the Rackla pluton is parental to the Rau pegmatite group. During the final stages of crystallization of the pluton, late hydrothermal fluids overprinted its uppermost portion and formed a Ca-, REE-, F-, and CO₂-rich, but relatively unfractionated, porphyritic phase.

The degree of fractionation of the pegmatite dikes increases with distance from the Rackla pluton and with increasing thickness of the dikes. Rare element-bearing minerals are substantially more abundant and diverse in the Rau 1, 3, 5, and 5U pegmatite dikes. The Rau 3 pegmatite dike is the farthest from the Rackla pluton, whereas the Rau 5 and 5U pegmatite dikes are the thickest. The anomalously evolved nature of the Rau 1 pegmatite dike is hypothesized to be due to tectonic conditions at the time of emplacement, causing it to travel a farther distance from the Rackla pluton to its site of emplacement. Higher fractionation of these pegmatites has resulted in higher ratios of Ta / (Ta + Nb) in columbite group and pyrochlore supergroup minerals, the presence of rare earth element-bearing minerals, and higher contents of trace elements in quartz.

Aplite dikes were formed slightly later than the pegmatite dikes, when the melt was relatively less rich in fluids. Local fluid accumulation produced zones of abundant muscovite and calcite (\pm beryl) and altered the adjacent host rocks. The aplite dikes are much less evolved than the pegmatite dikes, demonstrated by their lower Nb/Ta ratio and the Rb contents of muscovite.

The endo-contact skarns were formed due to the reaction of the pegmatite melt and its latestage fluid with the host rocks. Their formation was controlled by multiple factors, including the distance of the pegmatite dike from the Rackla pluton, its degree of fractionation, and dike thickness, which all affect the volatile contents of the pegmatite. These endo-contact skarns are composed of both pegmatite- and host rock-derived elements such as Al from the pegmatite dikes and Ca from the host rocks. The presence of REE-bearing minerals in endo-contact skarns that border relatively barren pegmatites is evidence that the late-stage fluid that exsolved from the pegmatites during their final stages of crystallization was responsible at least in part for the formation these skarns as REEs would have been excluded from the crystallizing melt and concentrated in this fluid.

Exo-contact skarns were formed within the host rocks when the late-stage, volatile-rich fluid was expelled from the pegmatites during their final stage of crystallization. They are composed of minerals that require elements sourced from both the pegmatite dikes and the host rocks such as Ca, Si, F, and B.

Late-stage enrichment of Fe in the system is demonstrated by a number of features, including exsolved Fe oxide minerals within the carbonate pockets and Fe oxide and sulphide minerals in the altered host rocks. The most likely mechanism for Fe enrichment is the dissolution of primary mica group minerals by a volatile-rich pegmatite-forming fluid, making it available during the later stages of crystallization.

The composition of the Rau pegmatite dikes was affected by contamination by the dolostone host rocks. Primary calcite and Ca- and Mg-rich accessory minerals occur within the pegmatite dikes, and REE-bearing carbonate minerals are a common secondary mineral. The primary calcite has a magmatic C and O isotopic signature, indicating that pre-emplacement contamination has occurred. Late-stage, carbonate-filled pockets are also present within the pegmatite dikes. Calcite in the pockets has a C and O isotopic composition midway between that of the host rocks and the primary calcite, indicating that after carbonate was assimilated into the pegmatite dikes it had some time to homogenize as it was concentrated in the residual, fluid-rich pegmatite melt. The pegmatite dikes have also been subjected to post-emplacement contamination that resulted in the formation of endo-contact skarns along the border of some pegmatite dikes.

Contamination has also affected the composition of the host rocks. The host rocks adjacent to some of the pegmatite dikes are altered and contain minerals such as tremolite, pargasite, clinochlore, and fluorophlogopite. Although the host rocks would have supplied the Ca and Mg necessary to crystallize these minerals, the additional elements required were sourced from the pegmatite dikes. Host rocks adjacent to pegmatites farther away from the Rackla pluton are more

altered due to the higher volatile content of these dikes. The presence of fluorophlogopite in the host rocks is due to the F-rich nature of the Rau pegmatite dikes and their associated units. Fluorine was sourced from the Rackla pluton and concentrated during pegmatite crystallization due to the absence of earlier-crystallizing F-bearing minerals. As crystallization progressed, the relative concentration of F in the remaining pegmatite-forming melt increased and late F-bearing minerals (pyrochlore supergroup minerals, REE-bearing carbonate minerals) crystallized. Because F is a volatile element, its concentration also increased in the late-stage fluid that was later expelled into the surrounding host rocks, altering them and crystallizing F-rich minerals such as fluorophlogopite.

Mineralogical and geochemical features of the Rau pegmatite group and its host rocks provide clear evidence that contamination has occurred. In fact, this was hypothesized when this pegmatite group was first discovered because the dolostone host rocks are geochemically distinct from the pegmatite dikes and they are also highly reactive. However, contamination is likely a much more common mechanism that can cause the modification of the mineralogy and geochemistry of a pegmatite even when there is not such a stark difference between the composition of the pegmatite and its host rocks. The results of an extensive analysis of the pegmatite literature indicate that there are numerous anomalies in the occurrence of elements within pegmatites related to factors such as host rock type and composition. Very few published studies of pegmatites provide a thorough description of the host rocks, and even less consider the impact that those host rocks could have on the mineralogy of the pegmatites. As such, I recommend that future studies of pegmatites include detailed descriptions of the host rocks, including their mineralogy, and consider the effect that propagation through and crystallization within these host rocks could have on the pegmatites.

Investigation of the Rau pegmatite group has also highlighted issues with the currently accepted pegmatite classification scheme of Černý and Ercit (2005). Most pronounced is the issue with the modal abundance of a mineral required for the pegmatite to be classified within a class, subclass, type, or subtype. Upon initial examination, the Rau pegmatite group appears to be devoid of rare element-bearing minerals. However, when the pegmatite is examined microscopically, thousands of grains of Nb,Ta-bearing minerals become apparent. It is currently unclear whether the Rau pegmatite group should be classified as a beryl-columbite subtype

pegmatite, or as a barren pegmatite. Furthermore, the pegmatites only contain trace beryl, but the classification scheme does not include a subtype or type modification to account for this.

All of the above represents the results of advanced research in mineralogy conducted during a doctoral degree. Its completion required extensive knowledge of mineralogy concepts. To ensure future students can conduct this level of research in mineralogy, I developed a concept inventory for introductory mineralogy courses. The MCI is a statistically validated concept inventory that, when implemented as a pre- and post-assessment, can be used to measure learning gains. The 18 questions on the final version of the MCI (Appendix B) were created through an iterative development process that included consultation with experts from > 75 post-secondary institutions, think-aloud interviews with students, and Rasch analysis. Rasch analysis indicates that the difficulty of items on the MCI is well aligned with the ability of students, both as a pre- and post-assessment. Examination for DIF indicates that no questions display item bias for gender, ethnicity, age, years lived in Canada, and first language. A survey of 77 mineralogy instructors indicates that the MCI targets key concepts that are part of the course content in introductory mineralogy courses in 11 countries and suggests that the MCI could be implemented in nearly any introductory mineralogy course to assess learning gains.

Although the average pre-assessment score was similar at UX and UY, the average postassessment score and consequentially the normalized learning gains were significantly higher at UX. These two courses have very similar course content, with the main difference between them being that the instructors at UX employ active learning techniques in a student-centred learning environment, whereas the instructor at UY uses an instructor-centred approach. The results of this implementation of the MCI suggest that the use of a student-centred pedagogy that utilizes active learning techniques can significantly improve learning gains of mineralogy concepts.

7.2 Key Findings

This dissertation has provided the first characterization and investigation of the Rau pegmatite group, and one of only a few investigations of pegmatites hosted by carbonate rocks. It has determined the genesis of the system, from emplacement of the Rackla pluton to formation of exo-contact skarns and host rocks alteration, as well as deciphered notable features such as late-stage Fe enrichment and the behaviour of F, Ti, and REEs. This study has also successfully addressed several research questions: (1) What was the effect of host rock contamination on the

mineralogy of the Rau pegmatite dikes? (2) What was the effect of the intrusion of the Rau pegmatite melts on the composition of the dolostone host rocks? (3) What was the timing of fluid exchange between the pegmatite dikes and their host rocks? and (4) What was the source of the CO₂-bearing fluids that crystallized the carbonate minerals in the Rau pegmatite dikes?

Unique and innovative approaches were employed when conducting this investigation of the Rau pegmatite group, namely the analysis of the C and O isotopic signature of carbonate minerals to assess the timing of contamination and the measurement of the trace element signature of quartz to determine the geochemical signature. The isotopic signature of primary carbonate minerals and late-stage carbonate-filled pockets within the pegmatites, as well as carbonate minerals in the host rocks, were measured using the MIA. This method is a fast and cost-effective way of measuring the C and O isotopic signatures of carbonate minerals. To the best of my knowledge, the MIA has never been used before to assess the timing of contamination of pegmatites. With data collected using the MIA I was able to determine that the Rau pegmatite group was subjected to pre-emplacement contamination, which modified the isotopic signature from primary magmatic to one closer to the signature of the host rocks. The success of this method suggests that stable isotope signatures could be used in future studies of pegmatites to determine if contamination has occurred and potentially expanded, using other methods of isotopic analysis, to other stable isotopes.

Trace elements have only recently begun to be measured in quartz (e.g., Müller *et al.*, 2013) and this dissertation represents the first study that has used the trace element signature of quartz to, in part, determine the geochemical signature of and classify a pegmatite. Because the trace element composition of quartz is a value that can be measured, it provides a more accurate way to characterize pegmatites than, for example, estimating a pegmatite's overall mineralogy. The trace element signature of quartz could be used as a criterion in a new pegmatite classification scheme because quartz is a major mineral in all pegmatites.

One of the biggest contributions of this dissertation is that it provides strong evidence that pegmatite dikes and their host rocks have an influence on one another's chemical signature, and suggests that this influence should be considered when making interpretations about the chemical signature and subsequent classification of pegmatite dikes. Currently, the vast majority of studies about pegmatites regard the pegmatites and their host rocks separately but evidence presented in this dissertation emphasizes the need for more comprehensive studies that integrate the

interpretation of pegmatite and host rock data. Finally, examination of the Rau pegmatite group has highlighted problems with the currently accepted pegmatite classification scheme.

Another significant contribution of this dissertation is the creation of the MCI: the first statistically validated assessment that can be used in any introductory mineralogy course to accurately measure learning gains. Using a statistically validated instrument is essential because it provides an accurate measure of students' abilities and ensures that the assessment is not biased towards or against any subset of the student population. By developing this concept inventory using two introductory mineralogy courses that employ different pedagogies, I was also able to assess the impact of different pedagogical methods on learning gains. This provides clear evidence that an instructor-centred pedagogy increases students' learning of mineralogy course, the results can be used to improve student learning of mineralogy concepts, which are foundational concepts in a geosciences degree.

In summary this dissertation has demonstrated that the mineralogy and geochemistry of the Rau pegmatite dikes and their host rocks have been influenced by one another, and has provided a detailed account of the impact of this contamination. It has also provided strong evidence that the mineralogy of pegmatite dikes and their host rocks can be influenced by contamination, providing a call to the community to conduct more thorough investigations of pegmatite host rocks. Finally, this dissertation has presented the first statistically validated assessment for introductory mineralogy courses and provided evidence that active learning techniques can significantly improve learning gains of mineralogy concepts.

7.3 Suggestions for Future Research

Although the accuracy of the MIA was such that the timing of contamination could be discerned, a more advanced method such as mass spectrometry could allow for the isotopic signature of each pegmatite dike to be distinguished. The C and O isotopic signature of pegmatite dikes should move closer to that of the host rocks with increasing distance from the Rackla pluton, but this would also be complicated by dike thickness. This method was not employed for this dissertation due to cost restrictions and the decision to maximize the number of samples that could be analysed.

The meta-analysis of the pegmatite literature highlights the need for more comprehensive studies of pegmatite occurrences that include detailed characterizations of the host rocks. Researchers should bear in mind the potential impact of contamination when interpreting results and, if contamination is suspected, conduct specific analyses such as measurement of stable isotopes to assess the timing and degree of contamination.

A new pegmatite classification scheme is essential as the scientific community develops a deeper understanding of pegmatite formation and continues to uncover and recognize the shortcomings of the currently accepted classification scheme. This new scheme should ideally use mineral modal abundance as a key criterion and integrate the knowledge of the impact that contamination can have on the geochemical signature of a pegmatite.

Concept inventories are an important tool that can provide an accurate measurement of student ability. However, the development of concept inventories has been quite limited, with the MCI being only the fourth concept inventory to be developed for the geosciences, and the second intended for a course above 100-level. In particular, concept inventories should be developed for other core geoscience courses such as igneous and metamorphic petrology, sedimentology, and structural geology because these courses are generally required as part of a geosciences degree and understanding of these concepts is essential for upper-level courses and geoscience careers (Geoscientists Canada, 2019).
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APPENDIX A

Complete Electron Microprobe Dataset

Sample	Gra-1a	Gra-1a	Gra-1a	Gra-1a	Gra-1a	Gra-1a	Gra-2c	Gra-2c	Gra-2c	Gra-2c	Gra-2c
Unit	Rackla Pluton										
Notes	-	-	-	-	Perthitic	Perthitic	-	-	-	-	-
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	65.72	65.53	65.50	65.42	64.89	65.25	64.55	64.99	63.67	64.63	64.53
Al ₂ O ₃	18.40	18.33	18.35	18.29	18.12	18.29	18.42	18.30	18.39	18.18	18.08
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.07	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	0.00	0.00	b.d.	0.00	b.d.	b.d.	0.00	0.00	b.d.	b.d.
CaO	b.d.	0.04	b.d.								
Na ₂ O	1.26	1.26	1.08	0.97	0.75	1.04	1.08	1.18	0.38	0.67	0.46
K ₂ O	15.45	15.43	15.96	15.88	16.11	15.88	15.52	15.37	16.46	15.95	16.52
Total	100.83	100.62	100.98	100.57	99.87	100.46	99.57	99.84	98.90	99.48	99.59
Si ⁴⁺ (<i>apfu</i>)	3.004	3.003	2.999	3.004	3.004	3.001	2.992	3.001	2.984	3.001	3.001
Al ³⁺	0.991	0.990	0.990	0.990	0.989	0.991	1.006	0.996	1.015	0.995	0.991
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	0.002	0.003	b.d.	0.000	b.d.	b.d.	0.000	0.000	b.d.	b.d.
Ca ²⁺	b.d.										
Na ⁺	0.112	0.112	0.096	0.086	0.067	0.092	0.097	0.106	0.035	0.060	0.042
K ⁺	0.901	0.902	0.932	0.930	0.951	0.932	0.918	0.905	0.984	0.945	0.980
O ^{2_}	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.1. Chemical compositions and structural formulae of K-feldspar in the Rackla Pluton.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Magnesium, Mn, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	Gra-1a	Gra-1a	Gra-2c	Gra-2c	Gra-2c	Gra-2c
Unit	Rackla Pluton	Rackla Pluton	Rackla Pluton	Rackla Pluton	Rackla Pluton	Rackla Pluton
Notes	Perthitic exsolution	Perthitic exsolution				
Mineral	*Ab	Ab	Ab	Ab	Ab	Ab
SiO ₂ (wt.%)	69.00	68.86	61.03	68.24	68.03	66.80
Al ₂ O ₃	19.41	19.61	20.01	19.93	20.12	20.78
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.10	0.07	0.08	0.00
FeO _(max) †	b.d.	b.d.	0.00	0.00	0.00	b.d.
MgO	b.d.	b.d.	0.10	b.d.	b.d.	b.d.
CaO	0.18	0.06	0.57	0.72	0.91	1.44
Na ₂ O	11.69	11.46	9.89	10.93	10.65	10.52
K ₂ O	0.21	0.11	0.17	0.17	0.14	0.26
Total	100.48	100.11	91.88	100.05	99.93	99.79
Si ⁴⁺ (<i>apfu</i>)	3.000	3.000	2.907	2.979	2.973	2.932
Al ³⁺	0.995	1.007	1.123	1.026	1.036	1.075
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.004	0.002	0.003	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	0.000	0.000	0.000	b.d.
Mg ²⁺	b.d.	b.d.	0.007	b.d.	b.d.	b.d.
Ca ²⁺	0.008	0.003	0.029	0.034	0.043	0.068
Na⁺	0.985	0.968	0.913	0.925	0.902	0.895
K⁺	0.011	0.006	0.011	0.009	0.008	0.014
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000

Table A.2. Chemical compositions and structural formulae of albite in the Rackla Pluton.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Manganese, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	Gra-1a									
Unit	Rackla Pluton									
Mineral	*Ann	Ann	Ms	Ms						
SiO ₂ (wt.%)	34.72	34.71	34.34	34.23	34.34	34.05	34.85	34.98	45.10	45.52
TiO ₂	0.42	0.36	0.38	0.53	0.33	0.43	0.53	0.23	0.27	0.43
Al ₂ O ₃	19.45	19.20	19.04	19.00	19.35	19.55	19.25	19.28	31.25	30.38
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	28.59	29.66	29.65	28.86	28.56	28.03	29.58	28.40	4.50	5.80
MgO	0.05	0.05	b.d.	0.05	0.06	b.d.	0.06	0.07	0.08	b.d.
MnO	1.66	1.56	1.69	1.73	1.55	1.66	1.34	1.33	b.d.	b.d.
Na ₂ O	0.12	0.10	0.18	0.11	0.13	0.09	b.d.	b.d.	0.14	0.14
K ₂ O	9.25	9.44	9.08	9.29	9.47	9.29	9.43	9.26	11.27	11.13
Rb ₂ O	0.74	0.78	0.79	0.74	0.73	0.73	0.72	0.73	0.06	0.32
Cs ₂ O	0.00	0.16	b.d.	b.d.	b.d.	b.d.	0.09	0.11	b.d.	b.d.
F	2.52	2.52	2.28	2.01	2.55	2.21	2.21	1.88	0.49	0.54
CI	0.08	0.16	0.07	0.08	0.04	0.05	0.21	0.14	0.03	b.d.
H_2O^{\ddagger}	2.49	2.49	2.59	2.70	2.46	2.60	2.63	2.77	4.04	4.04
–(O=F,CI)	-1.06	-1.06	-0.96	-0.85	-1.07	-0.93	-0.93	-0.79	-0.21	-0.23
Total	99.03	100.13	99.12	98.48	98.51	97.76	99.96	98.39	97.03	98.07
Si ⁴⁺ (<i>apfu</i>)	2.806	2.797	2.791	2.793	2.796	2.787	2.803	2.839	3.158	3.178
Ti ⁴⁺	0.025	0.022	0.023	0.033	0.020	0.026	0.032	0.014	0.014	0.022
Al ³⁺	1.853	1.823	1.823	1.828	1.857	1.886	1.825	1.844	2.579	2.499
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.933	1.999	2.016	1.970	1.945	1.919	1.989	1.927	0.264	0.338
Mg ²⁺	0.006	0.006	b.d.	0.006	0.007	b.d.	0.008	0.008	0.008	0.000
Mn ²⁺	0.114	0.106	0.116	0.119	0.107	0.115	0.091	0.092	0.000	0.000
Na ⁺	0.018	0.015	0.029	0.017	0.021	0.015	0.000	0.000	0.019	0.019

Table A.3. Chemical compositions and structural formulae of mica group minerals in the Rackla Pluton.

Sample	Gra-1a									
Unit	Rackla Pluton									
Mineral	*Ann	Ann	Ms	Ms						
K ⁺ (apfu)	0.954	0.970	0.941	0.967	0.984	0.970	0.967	0.958	1.007	0.991
Rb⁺	0.039	0.041	0.041	0.039	0.038	0.039	0.037	0.038	0.003	0.014
Cs⁺	0.000	0.006	b.d.	b.d.	b.d.	b.d.	0.003	0.004	b.d.	b.d.
F⁻	0.645	0.641	0.587	0.519	0.656	0.573	0.561	0.482	0.109	0.118
CI⁻	0.011	0.021	0.009	0.011	0.005	0.007	0.029	0.019	0.003	b.d.
OH⁻‡	1.344	1.337	1.404	1.470	1.339	1.420	1.409	1.499	1.888	1.882
vac.	0.263	0.246	0.231	0.251	0.267	0.268	0.252	0.275	0.976	0.962
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + CI + OH) = 2 formula unit.

Chromium, Ca, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Table A.4. Chemical compositions and structural formulae of muscovite in the porphyritic phase of the Rackla Pluton.

Sample	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic
Mineral	*Ms	Ms
SiO ₂ (wt.%)	46.53	45.96
TiO ₂	b.d.	0.06
Al ₂ O ₃	33.23	33.21
Sc ₂ O ₃	0.07	0.07
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00
FeO _(max) [†]	2.54	2.60
MnO	0.04	0.03
Na ₂ O	0.14	0.11
K ₂ O	11.00	10.91
F	0.73	0.65
H ₂ O [‡]	4.05	4.05
−(O=F,CI)	-0.31	-0.27
Total	98.02	97.38
Si ⁴⁺ (<i>apfu</i>)	3.175	3.159
Ti ⁴⁺	b.d.	0.003
Al ³⁺	2.672	2.690
Sc ³⁺	0.000	0.000
$Fe^{3+}(min)^{\dagger}$	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.145	0.150
Mn ²⁺	0.00	0.00
Na⁺	0.02	0.014
K+	0.957	0.957
F⁻	0.158	0.142
OH⁻	1.842	1.858
vac.	1.001	0.994
O ²⁻	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + OH) = 2 per formula unit. Phosphorus, Cr, Mg, Zn, Ca, Ba, Cs, Rb, and Cl were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	Hrn-1						
Unit	Porphyritic						
Mineral	*Prs-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Bst-(Ce)	Bst-(Ce)	Bst-(Ce)
SiO ₂ (wt.%)	0.43	0.96	1.43	0.28	b.d.	b.d.	b.d.
ThO ₂	0.55	0.25	0.23	0.00	0.16	0.23	0.11
Al ₂ O ₃	0.09	0.44	0.57	b.d.	b.d.	b.d.	0.12
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.65	0.00	0.00	0.00	0.00	0.20
$FeO_{(max)}^{\dagger}$	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	0.18
Y_2O_3	0.65	2.50	3.38	2.59	0.58	0.50	0.20
La ₂ O ₃	8.90	5.80	6.67	7.22	16.98	17.03	23.06
Ce ₂ O ₃	29.37	23.50	22.87	22.51	39.41	39.59	38.69
Pr ₂ O ₃	3.51	3.69	3.31	3.22	3.99	3.68	3.13
Nd ₂ O ₃	10.70	12.50	11.35	11.30	11.22	10.93	8.12
Sm ₂ O ₃	1.88	2.74	2.94	3.19	1.30	1.19	0.44
Gd_2O_3	0.57	0.86	1.31	1.39	0.49	0.48	b.d.
Dy ₂ O ₃	b.d.	b.d.	b.d.	0.36	b.d.	b.d.	b.d.
Tm ₂ O ₃	0.24	0.39	0.40	0.52	b.d.	b.d.	b.d.
CaO	11.05	15.91	15.77	17.05	0.37	0.55	0.28
K ₂ O	b.d.	0.21	0.26	b.d.	b.d.	b.d.	0.01
F	4.64	4.69	4.49	4.49	7.39	7.13	7.31
CO_2^{\dagger}	24.09	28.24	28.46	27.74	19.83	19.67	20.21
H_2O^{\ddagger}	1.09	3.56	3.69	3.55	0.55	0.64	0.67
-(O=F)	-1.95	-1.98	-1.89	-1.89	-3.11	-3.00	-3.08
Total	95.81	104.90	105.27	103.51	99.16	98.62	99.64
Si ⁴⁺ (apfu)	0.039	0.050	0.074	0.015	b.d.	b.d.	b.d.
Th ⁴⁺	0.011	0.003	0.003	0.000	0.001	0.002	0.001
Al ³⁺	0.010	0.027	0.035	b.d.	b.d.	b.d.	0.005

Table A.5. Chemical compositions and structural formulae of parisite-(Ce), synchysite-(Ce) and bastnäsite-(Ce) in the porphyritic phase of the Rackla Pluton.

Sample	Hrn-1						
Unit	Porphyritic						
Mineral	*Prs-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Bst-(Ce)	Bst-(Ce)	Bst-(Ce)
Fe ³⁺ (min) [†] (<i>apfu</i>)	0.000	0.025	0.000	0.00			0.005
Fe ²⁺ (max) [†]	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	0.000
Y ³⁺	0.032	0.069	0.093	0.073	0.011	0.010	0.004
La ³⁺	0.299	0.111	0.127	0.141	0.228	0.228	0.308
Ce ³⁺	0.981	0.446	0.431	0.435	0.525	0.527	0.513
Pr ³⁺	0.117	0.070	0.062	0.062	0.053	0.049	0.041
Nd ³⁺	0.348	0.232	0.209	0.213	0.146	0.142	0.105
Sm ³⁺	0.059	0.049	0.052	0.058	0.016	0.015	0.006
Gd ³⁺	0.017	0.015	0.022	0.024	0.006	0.006	b.d.
Dy ³⁺	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.
Tm ³⁺	0.007	0.006	0.006	0.009	b.d.	b.d.	b.d.
Ca ²⁺	1.079	0.884	0.870	0.965	0.014	0.021	0.011
K+	b.d.	0.014	0.017	b.d.	b.d.	b.d.	0.000
F⁻	1.339	0.770	0.731	0.749	0.850	0.820	0.837
C ^{4+†}	3.000	2.000	2.000	2.000	1.000	1.000	1.000
OH⁻	0.661	1.230	1.269	1.251	0.150	0.180	0.163
O ^{2_}	9.316	6.173	6.220	6.150	3.143	3.170	3.155

The formulae for parisite-(Ce) were calculated on the basis of 3 *A* and *B* site cations, synchysite-(Ce) on the basis of 2 *A* and *B* site cations, and bastnäsite-(Ce) on the basis of 1 *A* and *B* site cations per formula unit.

Phosphorus, Ti, Zr, U, Eu, Er, Mg, Pb, Ba, Sr, and Na in parisite-(Ce), synchysite-(Ce), and bastnäsite-(Ce), and Mn in bastnäsite-(Ce) were also sought but were below the detection limit of the EMP in all analyses.

*Prs = parisite, Snc = synchysite, Bst = bastnäsite; $^{\dagger}CO_2$ was fixed at 3 *apfu* C in parisite-(Ce), 2 *apfu* C in synchysite-(Ce), and 1 *apfu* C in bastnäsite-(Ce); $^{\ddagger}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic
Mineral	*Flc-(Ce)	Flc-(Ce)	Flc-(Ce)
ThO ₂ (wt.%)	0.10	0.11	0.69
Y ₂ O ₃	0.69	0.69	0.54
La ₂ O ₃	30.12	29.44	22.39
Ce ₂ O ₃	47.31	46.62	49.64
Pr ₂ O ₃	3.93	3.80	4.56
Nd ₂ O ₃	10.72	10.95	13.59
Sm ₂ O ₃	0.86	1.02	1.57
Gd ₂ O ₃	0.43	0.39	0.47
CaO	0.22	0.22	0.50
F	33.61	34.42	34.32
-(O=F)	-14.15	-14.50	-14.45
Total	113.83	113.16	113.83
Th ⁴⁺ (<i>apfu</i>)	0.001	0.001	0.004
Y ³⁺	0.010	0.010	0.008
La ³⁺	0.314	0.299	0.228
Ce ³⁺	0.489	0.470	0.502
Pr ³⁺	0.040	0.038	0.046
Nd ³⁺	0.108	0.108	0.134
Sm ³⁺	0.008	0.010	0.015
Gd ³⁺	0.004	0.004	0.004
Ca ²⁺	0.007	0.006	0.015
F-	3.000	3.000	3.000

Table A.6. Chemical compositions and structural formulae of fluocerite-(Ce) in the porphyritic phase of the Rackla Pluton.

The formulae were calculated on the basis of 3 anions per formula unit.

Phosphorus, Ti, Zr, U, Al, Sc, Fe, Tb, Dy, Ho, Er, Tm, Yb, Mg, Mn, Pb, Eu, and Na were also sought but were below the detection limit of the EMP in all analyses.

*FIc = fluocerite; b.d. = below detection limit.

Sample	Hrn-1								
Unit	Porphyritic								
Mineral	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Mnz-(Ce)	Mnz-(Ce)	Mnz-(Ce)	Sch
WO ₃ (wt.%)	8.17	7.85	0.44	0.06	2.43	_	_	_	78.04
P_2O_5	_	-	-	-	_	19.11	21.80	30.50	_
Nb ₂ O ₅	55.90	56.24	59.68	55.34	58.30	_	-	-	0.21
Ta ₂ O ₅	15.45	15.08	21.09	24.46	19.34	_	-	_	b.d.
SiO ₂	0.10	0.06	0.08	0.04	0.06	4.86	6.26	0.52	b.d.
TiO ₂	0.22	0.37	0.51	0.73	0.04	b.d.	b.d.	0.00	b.d.
ZrO ₂	b.d.	0.01	b.d.	0.08	b.d.	0.34	0.27	0.45	_
SnO ₂	0.01	0.07	b.d.	0.08	b.d.	_	-	-	_
ThO ₂	0.01	b.d.	b.d.	b.d.	0.02	25.67	15.50	1.82	_
UO ₂	0.06	b.d.	b.d.	b.d.	b.d.	0.30	0.25	b.d.	_
Al ₂ O ₃	0.01	0.01	b.d.	0.00	0.01	_	-	_	b.d.
$Fe_2O_{3(min)}^{\dagger}$	2.47	3.61	2.54	2.39	2.42	0.30	1.20	0.00	0.00
FeO _(max) †	17.75	16.99	11.26	10.97	16.89	0.00	0.00	0.00	0.10
Sc ₂ O ₃	0.05	0.03	0.26	0.63	0.05	b.d.	b.d.	0.00	b.d.
As ₂ O ₃	-	-	-	-	-	b.d.	0.05	0.08	_
Y ₂ O ₃	b.d.	b.d.	0.04	0.03	b.d.	0.86	0.44	0.38	_
La ₂ O ₃	_	-	-	-	_	6.29	6.70	11.95	_
Ce ₂ O ₃	-	-	-	-	_	19.42	24.15	33.65	_
Pr ₂ O ₃	_	-	-	-	_	2.98	3.65	4.72	_
Nd ₂ O ₃	-	-	-	-	_	9.59	11.86	15.13	_
Sm ₂ O ₃	-	-	-	-	_	1.69	2.05	2.22	_
Gd_2O_3	_	_	_	_	-	0.67	0.57	0.37	_
Dy ₂ O ₃	-	-	-	-	-	0.17	b.d.	b.d.	_
Er ₂ O ₃	_	-	-	-	-	0.12	b.d.	b.d.	_

Table A.7. Chemical compositions and structural formulae of columbite-(Fe), monazite-(Ce), and scheelite in the porphyritic phase of the Rackla Pluton.

Sample	Hrn-1								
Unit	Porphyritic								
Mineral	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Mnz-(Ce)	Mnz-(Ce)	Mnz-(Ce)	Sch
Bi ₂ O ₃ (wt.%)	0.24	0.23	b.d.	b.d.	0.14	-	-	_	_
MgO	0.02	0.02	0.09	0.16	0.01	-	-	-	b.d.
CaO	b.d.	0.20	b.d.	b.d.	0.07	3.31	0.43	0.22	19.36
MnO	1.13	1.00	6.72	6.20	1.44	-	-	-	b.d.
ZnO	b.d.	0.01	0.04	b.d.	b.d.	-	-	-	-
PbO	0.06	b.d.	0.06	b.d.	b.d.	0.07	0.07	0.00	b.d.
Na ₂ O	0.01	0.03	0.04	b.d.	0.02	b.d.	b.d.	0.00	b.d.
Total	101.65	101.80	102.83	101.19	101.24	95.73	95.24	102.01	97.71
W ⁶⁺ (<i>apfu</i>)	0.128	0.122	0.007	0.001	0.038	_	-	_	0.971
P ⁵⁺	-	-	-	-	_	0.701	0.771	0.990	-
Nb ⁵⁺	1.525	1.523	1.593	1.520	1.590	_	-	-	0.004
Ta⁵⁺	0.254	0.246	0.339	0.404	0.317	_	-	-	b.d.
Si ⁴⁺	0.006	0.003	0.005	0.003	0.004	0.210	0.262	0.020	b.d.
Ti ⁴⁺	0.010	0.016	0.023	0.033	0.002	b.d.	b.d.	0.000	b.d.
Zr ⁴⁺	b.d.	0.000	b.d.	0.002	b.d.	0.007	0.006	0.008	-
Sn ⁴⁺	0.000	0.002	b.d.	0.002	b.d.	_	-	-	-
Th ⁴⁺	0.000	b.d.	b.d.	b.d.	0.000	0.253	0.147	0.016	-
U ⁴⁺	0.001	b.d.	b.d.	b.d.	b.d.	0.003	0.002	b.d.	-
Al ³⁺	0.001	0.001	b.d.	0.000	0.001	_	_	-	b.d.
Fe ³⁺ (min) [†]	0.112	0.163	0.113	0.109	0.110	0.01	0.04	0.00	0.000
$Fe^{2+}(max)^{\dagger}$	0.896	0.851	0.556	0.557	0.853	0.00	0.00	0.00	0.004
Sc ³⁺	0.003	0.001	0.013	0.033	0.002	b.d.	b.d.	0.00	b.d.
As ³⁺	-	_	_	-	_	b.d.	0.00	0.00	-
Y ³⁺	0.000	0.000	0.001	0.001	b.d.	-	-	_	-
La ³⁺	_	_	_	_	_	0.100	0.103	0.169	_
Ce ³⁺	-	_	-	_	_	0.308	0.370	0.472	_

Sample	Hrn-1								
Unit	Porphyritic								
Mineral	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Mnz-(Ce)	Mnz-(Ce)	Mnz-(Ce)	Sch
Pr ³⁺ (<i>apfu</i>)	-	-	-	-	_	0.047	0.056	0.066	-
Nd ³⁺	-	-	-	-	-	0.148	0.177	0.207	-
Sm ³⁺	-	-	-	-	_	0.025	0.030	0.029	-
Gd ³⁺	-	-	-	-	_	0.010	0.008	0.005	-
Dy ³⁺	-	-	-	-	_	0.00	b.d.	b.d.	-
Er ³⁺	-	-	-	-	_	0.00	b.d.	b.d.	-
Bi ³⁺	0.004	0.004	0.000	b.d.	0.002	-	-	_	-
Mg ²⁺	0.002	0.002	0.007	0.015	0.001	_	-	_	b.d.
Ca ²⁺	b.d.	0.013	0.000	b.d.	0.005	0.154	0.019	0.009	0.996
Mn ²⁺	0.058	0.051	0.336	0.319	0.074	_	-	_	b.d.
Zn ²⁺	b.d.	0.000	0.002	b.d.	b.d.	_	-	_	
Pb ²⁺	0.001	b.d.	0.001	b.d.	b.d.	0.001	0.001	0.000	b.d.
Na⁺	0.001	0.003	0.005	b.d.	0.002	b.d.	b.d.	0.000	b.d.
O ^{2_}	6.000	6.000	6.000	6.000	6.000	3.846	3.960	3.992	3.923

The formulae for columbite-(Fe) were calculated on the basis of 3 cations, monazite-(Ce) on the basis of 2 cations, and scheelite on the basis of 1 Ca per formula unit.

Zinc Sb, and F in columbite-(Fe), Sr and S in monazite-(Ce), and Zn, Mo, and F in scheelite were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	Hrn-1							
Unit	Porphyritic							
Zone	_	-	-	Core	Core	Core	Rim	Rim
Mineral	*Smk-(Y)	Smk-(Y)						
WO₃ (wt.%)	1.93	0.59	1.24	0.51	0.68	0.71	2.03	1.78
P_2O_5	0.06	0.06	0.07	b.d.	0.05	b.d.	0.05	0.08
Nb ₂ O ₅	30.91	35.83	37.18	35.91	35.74	35.76	41.37	38.24
Ta₂O₅	21.79	16.52	15.41	16.24	16.03	16.41	9.89	9.23
SiO ₂	0.25	0.34	0.23	0.19	0.16	0.17	0.17	4.79
TiO ₂	0.22	0.05	0.17	0.15	0.20	0.14	0.04	0.01
ThO ₂	0.26	3.44	1.21	3.16	3.90	3.31	5.61	3.74
UO ₂	0.10	1.29	0.16	0.52	0.75	0.58	0.87	1.57
Al ₂ O ₃	b.d.	1.02						
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.50
$FeO_{(max)}^{\dagger}$	b.d.	0.00						
Sc ₂ O ₃	b.d.							
As_2O_3	0.00	0.03	b.d.	0.01	0.02	0.05	0.01	b.d.
Y ₂ O ₃	31.22	28.07	30.46	28.13	27.13	27.47	27.16	18.10
La ₂ O ₃	b.d.	b.d.	0.00	0.22	b.d.	0.17	b.d.	b.d.
Ce ₂ O ₃	0.57	0.64	0.39	1.65	1.37	1.67	0.45	0.67
Pr_2O_3	0.31	b.d.	0.38	0.78	0.61	0.59	0.34	b.d.
Nd ₂ O ₃	1.99	2.23	2.14	4.32	4.11	4.19	1.79	1.63
Sm ₂ O ₃	2.44	2.28	3.22	2.67	2.45	2.79	1.74	1.80
Gd ₂ O ₃	3.01	2.36	4.16	2.35	2.46	2.55	1.96	1.97
Tb ₂ O ₃	0.39	0.28	0.53	0.23	0.28	0.26	0.24	0.18
Dy ₂ O ₃	1.96	0.92	2.28	0.81	0.98	0.93	1.32	1.17
Ho ₂ O ₃	0.25	b.d.						
Er ₂ O ₃	0.72	0.30	0.77	0.31	0.45	0.38	0.86	0.61

Table A.8. Chemical compositions and structural formulae of samarskite-(Y) in the porphyritic phase of the Rackla Pluton.

Sample	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1	Hrn-1
Unit	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic	Porphyritic
Zone	-	-	-	Core	Core	Core	Rim	Rim
Mineral	*Smk-(Y)	Smk-(Y)	Smk-(Y)	Smk-(Y)	Smk-(Y)	Smk-(Y)	Smk-(Y)	Smk-(Y)
Tm ₂ O ₃ (wt.%)	0.71	0.47	0.66	0.53	0.57	0.61	0.50	0.43
Lu ₂ O ₃	0.30	0.23	0.27	0.22	0.23	0.27	0.42	0.27
Yb ₂ O ₃	0.95	0.34	0.86	0.42	0.53	0.66	1.81	1.23
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.26
CaO	0.12	1.14	0.15	0.15 0.56 0.80 0.67		0.67	1.54	1.85
Na ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08
F	0.29	0.34	0.25	0.27	0.27	0.28	0.25	0.08
-(O=F)	-0.12	-0.14	-0.11	-0.11	-0.11	-0.12	-0.11	-0.03
Total	100.60	97.58	102.07	100.05	99.66	100.49	100.33	92.26
W ⁶⁺ (<i>apfu</i>)	0.047	0.015	0.029	0.013	0.017	0.017	0.048	0.042
P ⁵⁺	0.005	0.004	0.005	b.d.	0.004	b.d.	0.004	0.006
Nb ⁵⁺	1.328	1.543	1.541	1.530	1.531	1.524	1.709	1.574
Ta⁵+	0.563	0.428	0.384	0.416	0.413	0.421	0.246	0.229
Si ⁴⁺	-	-	0.021	0.018	0.015	0.016	-	0.436
Ti ⁴⁺	0.015	0.004	0.012	0.011	0.014	0.010	0.003	0.001
Zr ⁴⁺	0.000	0.000	b.d.	b.d.	b.d.	b.d.	0.000	b.d.
Th ⁴⁺	0.006	0.074	0.025	0.068	0.084	0.071	0.117	0.077
U ⁴⁺	0.002	0.027	0.003	0.011	0.016	0.012	0.018	0.032
Al ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.110
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.103
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000
Sc ³⁺	-	-	b.d.	b.d.	b.d.	b.d.	-	b.d.
As ³⁺	0.000	0.002	b.d.	0.001	0.001	0.003	0.00	b.d.
Y ³⁺	1.578	1.423	1.486	1.411	1.368	1.378	1.321	0.877
La ³⁺	b.d.	b.d.	0.000	0.008	b.d.	0.006	b.d.	b.d.

Sample	Hrn-1							
Unit	Porphyritic							
Zone	-	-	-	Core	Core	Core	Rim	Rim
Mineral	*Smk-(Y)	Smk-(Y)						
Ce ³⁺ (<i>apfu</i>)	0.020	0.022	0.013	0.057	0.048	0.058	0.015	0.022
Pr ³⁺	0.011	0.00	0.013	0.027	0.021	0.020	0.011	b.d.
Nd ³⁺	0.068	0.076	0.070	0.145	0.139	0.141	0.059	0.053
Sm ³⁺	0.080	0.075	0.102	0.087	0.080	0.091	0.055	0.057
Gd ³⁺	0.095	0.074	0.126	0.073	0.077	0.080	0.059	0.059
Tb ³⁺	0.012	0.009	0.016	0.007	0.009	0.008	0.007	0.005
Dy ³⁺	0.06	0.03	0.067	0.025	0.030	0.028	0.039	0.034
Ho ³⁺	0.01	0.00	b.d.	b.d.	b.d.	b.d.	0.00	b.d.
Er ³⁺	0.02	0.01	0.022	0.009	0.013	0.011	0.025	0.017
Tm ³⁺	0.02	0.01	0.019	0.016	0.017	0.018	0.014	0.012
Lu ³⁺	0.01	0.01	0.007	0.006	0.006	0.008	0.012	0.007
Yb ³⁺	0.03	0.01	0.024	0.012	0.015	0.019	0.050	0.034
Mg ²⁺	b.d.	0.035						
Ca ²⁺	0.012	0.117	0.015	0.057	0.081	0.067	0.151	0.181
Na⁺	b.d.	0.014						
F⁻	0.088	0.103	0.073	0.081	0.081	0.084	0.073	0.023
O ²⁻	7.956	7.948	7.963	7.960	7.959	7.958	7.963	8.040

The formulae were calculated on the basis of 8 O anions per formula unit.

Zirconium, Eu, Bi, Mn, K, and Pb were also sought but were below the detection limit of the EMP in all analyses. *Smk = samarskite; $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R2-3	R2-3	R2-3	R2-3	R2-3	R2-3	R2-3	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1
Mineral	*Kfs	Kfs	Kfs	Kfs							
SiO ₂ (wt.%)	64.05	63.67	63.74	64.82	64.93	63.27	64.30	65.02	65.22	65.22	65.13
Al ₂ O ₃	18.46	18.45	18.26	18.21	18.27	18.17	18.14	18.05	18.00	18.36	18.11
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.16	b.d.
BaO	0.45	0.65	b.d.	b.d.	b.d.						
Na ₂ O	0.29	0.30	1.05	0.90	1.00	0.86	0.70	0.73	0.62	0.65	0.68
K ₂ O	16.78	16.53	15.10	15.72	15.74	15.40	16.13	15.38	15.55	15.81	15.42
Rb ₂ O	b.d.	b.d.	0.08	0.03	b.d.	0.04	b.d.	0.70	0.71	0.77	0.74
Total	100.03	99.60	98.22	99.68	99.94	97.74	99.31	99.87	100.09	100.97	100.08
Si ⁴⁺ (<i>apfu</i>)	2.981	2.978	2.992	3.002	3.000	2.989	2.996	3.012	3.016	2.998	3.012
Al ³⁺	1.012	1.017	1.010	0.994	0.995	1.011	0.996	0.985	0.981	0.995	0.987
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.008	b.d.
Ba ²⁺	0.008	0.012	b.d.	b.d.	b.d.						
Na⁺	0.026	0.027	0.095	0.081	0.089	0.079	0.063	0.065	0.055	0.058	0.061
K+	0.996	0.986	0.904	0.929	0.928	0.928	0.959	0.909	0.917	0.927	0.910
Rb⁺	b.d.	b.d.	0.002	0.001	b.d.	0.001	b.d.	0.021	0.021	0.023	0.022
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.9. Chemical compositions and structural formulae of K-feldspar in the Rau 1 pegmatite dike.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Iron, Mn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit; - = not analyzed.
Sample	R1-J	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1				
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.54	65.73	65.64	65.64	65.77
Al ₂ O ₃	18.21	18.11	18.33	18.22	18.18
MgO	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	1.11	1.10	1.16	0.93	0.98
K ₂ O	14.96	14.64	14.69	14.98	14.92
Rb ₂ O	0.68	0.62	0.64	0.64	0.67
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.50	100.19	100.46	100.42	100.52
Si ⁴⁺ (<i>apfu</i>)	3.011	3.021	3.011	3.015	3.018
Al ³⁺	0.986	0.981	0.991	0.987	0.983
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.099	0.098	0.104	0.083	0.087
K+	0.877	0.858	0.860	0.878	0.873
Rb⁺	0.020	0.018	0.019	0.019	0.020
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.
O ^{2_}	8.000	8.000	8.000	8.000	8.000

Table A.9. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 1 pegmatite dike.

Iron, Mn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit; - = not analyzed.

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.21	64.57	64.87	64.62	64.78	64.53	64.38	64.81	64.49	64.56	64.69
Al ₂ O ₃	18.39	18.52	18.41	18.27	18.37	18.44	18.49	18.43	18.20	18.32	18.30
$Fe_2O_{3(\text{min})}^\dagger$	0.07	0.09	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.07
$FeO_{(max)}^{\dagger}$	0.00	0.00	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	0.00
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	-	-	-	-	-	-	-	-	-	-	-
Na ₂ O	0.37	0.34	0.35	0.29	0.35	0.25	0.24	0.25	0.22	0.29	0.22
K ₂ O	16.71	17.04	16.79	16.80	16.84	16.85	16.86	16.89	17.04	16.84	16.95
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.79	100.55	100.41	99.97	100.34	100.15	99.97	100.38	99.95	100.02	100.24
Si ⁴⁺ (<i>apfu</i>)	2.997	2.984	2.994	2.996	2.994	2.989	2.987	2.993	2.995	2.993	2.995
Al ³⁺	0.996	1.008	1.002	0.998	1.000	1.007	1.011	1.003	0.996	1.001	0.998
Fe^{3+} (min) †	0.002	0.003	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.003
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	0.000
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na⁺	0.033	0.030	0.031	0.026	0.031	0.022	0.021	0.023	0.020	0.026	0.020
K+	0.980	1.004	0.988	0.994	0.993	0.996	0.998	0.995	1.010	0.996	1.001
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.001	8.002	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.001
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Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.53	64.25	64.51	64.30	64.90	64.52	64.56	64.98	65.70	64.86	64.77
Al ₂ O ₃	18.32	18.37	18.27	18.35	18.32	18.28	18.23	18.43	18.45	18.43	18.39
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	_	-	-	-	-	-	-	-	-	-	_
Na ₂ O	0.35	0.27	0.31	0.24	0.26	0.28	0.32	0.49	0.49	1.02	0.31
K ₂ O	16.78	16.83	17.13	16.92	16.77	17.01	16.95	16.60	16.67	15.95	16.91
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	99.98	99.72	100.22	99.81	100.36	100.09	100.05	100.49	101.32	100.29	100.39
Si ⁴⁺ (<i>apfu</i>)	2.993	2.989	2.991	2.990	2.997	2.993	2.995	2.994	3.001	2.991	2.993
Al ³⁺	1.002	1.007	0.998	1.006	0.997	0.999	0.997	1.001	0.993	1.001	1.002
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na⁺	0.032	0.024	0.028	0.021	0.023	0.025	0.029	0.043	0.044	0.091	0.028
K+	0.993	0.999	1.013	1.004	0.988	1.006	1.003	0.976	0.972	0.938	0.997
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.002	8.000	8.000	8.000	8.000	8.000	8.000
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Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3				
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.99	64.78	64.90	64.93	64.69	64.66	64.31	64.28	64.32	65.05	64.67
Al ₂ O ₃	18.34	18.39	18.44	18.38	18.55	18.32	18.24	18.27	18.28	18.26	18.33
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	-	-	-	-	-	-	-	-	-	-	-
Na ₂ O	0.33	0.36	0.31	0.27	0.30	0.66	1.03	0.58	0.93	1.38	0.99
K ₂ O	16.82	16.80	16.81	16.66	16.83	16.17	15.03	16.26	15.46	14.66	15.02
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.59	b.d.	0.67	0.57	0.89
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.48	100.32	100.46	100.24	100.38	99.80	99.20	99.39	99.65	99.93	99.91
Si ⁴⁺ (<i>apfu</i>)	2.997	2.993	2.994	2.998	2.988	2.996	2.997	2.993	2.993	3.004	2.998
Al ³⁺	0.997	1.001	1.003	1.000	1.010	1.000	1.002	1.003	1.003	0.994	1.002
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na ⁺	0.029	0.032	0.027	0.024	0.027	0.059	0.093	0.053	0.084	0.123	0.089
K+	0.990	0.991	0.989	0.981	0.992	0.956	0.894	0.966	0.918	0.864	0.888
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.018	b.d.	0.020	0.017	0.027
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
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Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.24	64.29	65.28	65.55	65.10	64.80	65.34	65.12	64.79	64.88	64.73
Al ₂ O ₃	18.29	18.28	18.46	18.32	18.37	18.36	18.39	18.46	18.29	18.25	18.41
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	_	-	-	-	-	-	-	-	-	-	-
Na ₂ O	1.02	1.34	1.02	0.67	0.89	0.99	0.95	0.85	1.08	0.95	1.16
K ₂ O	14.88	14.53	15.50	16.37	15.74	15.83	15.69	16.34	15.33	15.58	15.36
Rb ₂ O	0.93	0.70	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	99.36	99.14	100.30	100.90	100.15	99.97	100.38	100.76	99.49	99.66	99.67
Si ⁴⁺ (<i>apfu</i>)	2.995	2.996	3.000	3.004	2.999	2.995	3.002	2.992	3.000	3.002	2.994
Al ³⁺	1.005	1.004	1.000	0.989	0.998	1.000	0.996	0.999	0.998	0.995	1.004
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na⁺	0.092	0.121	0.091	0.059	0.080	0.089	0.085	0.076	0.097	0.085	0.104
K+	0.885	0.864	0.909	0.957	0.925	0.933	0.920	0.958	0.906	0.920	0.907
Rb⁺	0.028	0.021	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
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Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.63	64.89	64.62	65.64	65.22	64.91	65.54	64.74	64.44	64.76	65.48
Al ₂ O ₃	18.41	18.39	18.36	18.60	18.32	18.44	18.54	18.73	18.41	18.55	18.48
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	0.04	0.04	b.d.	b.d.	b.d.	b.d.	0.03	b.d.
MnO	b.d.	b.d.	b.d.	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	_	-	-	-	-	-	-	-	-	-	-
Na ₂ O	1.24	1.23	1.10	1.19	0.92	0.62	1.25	0.81	0.31	1.18	1.07
K ₂ O	15.49	15.63	15.72	15.40	15.62	16.32	15.29	16.16	16.94	15.31	16.02
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	99.77	100.15	99.80	100.94	100.12	100.30	100.63	100.44	100.10	99.82	101.05
Si ⁴⁺ (<i>apfu</i>)	2.990	2.993	2.992	2.997	3.003	2.994	2.999	2.982	2.988	2.990	2.995
Al ³⁺	1.004	1.000	1.002	1.001	0.994	1.003	1.000	1.017	1.006	1.009	0.996
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	0.002	0.002	b.d.	b.d.	b.d.	b.d.	0.001	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na⁺	0.111	0.110	0.099	0.105	0.082	0.055	0.111	0.073	0.028	0.105	0.095
K ⁺	0.914	0.920	0.928	0.897	0.918	0.960	0.893	0.950	1.002	0.902	0.935
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
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Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3				
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.55	65.85	65.57	65.37	64.90	64.51	64.96	64.72	64.47	64.66	65.11
Al ₂ O ₃	18.54	18.50	18.42	18.58	18.44	18.42	18.43	18.39	18.35	18.48	17.86
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.00
MgO	b.d.	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.04	0.03	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	-	-	-	-	-	-	-	-	-	-	-
Na ₂ O	1.36	1.39	1.29	1.14	0.33	0.37	0.33	0.30	0.49	0.39	0.52
K ₂ O	15.37	15.22	15.48	15.63	16.81	16.59	16.90	16.89	16.58	16.70	16.23
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.32
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.06	b.d.	b.d.	b.d.	b.d.
Total	100.86	100.99	100.76	100.72	100.49	99.89	100.67	100.30	99.89	100.23	100.12
Si ⁴⁺ (<i>apfu</i>)	2.996	3.002	3.000	2.994	2.993	2.991	2.993	2.993	2.991	2.990	3.014
Al ³⁺	0.999	0.994	0.994	1.003	1.002	1.007	1.001	1.002	1.003	1.007	0.975
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.002	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	-	-	-	-	-	-	-	-	-	-	-
Na⁺	0.120	0.123	0.114	0.101	0.029	0.033	0.029	0.027	0.044	0.035	0.047
K+	0.896	0.885	0.904	0.913	0.989	0.982	0.993	0.997	0.981	0.985	0.959
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.010
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.001
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Sample	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.10	65.60	65.79	64.66	64.91	65.10	65.04	64.66	65.48	65.99	65.09
Al ₂ O ₃	18.45	18.30	18.54	18.27	18.45	18.42	18.29	18.36	18.45	18.67	18.43
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.08
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	0.00
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.05	b.d.	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	0.06
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.05	b.d.
BaO	-	-	-	-	-	-	-	-	-	-	-
Na ₂ O	0.94	1.19	1.35	0.71	1.24	1.11	1.09	1.22	1.03	1.08	0.76
K ₂ O	15.84	15.54	15.40	15.65	14.95	15.35	15.19	15.11	15.86	15.64	16.17
Rb ₂ O	b.d.	b.d.	b.d.	0.39	0.46	0.15	0.13	0.31	b.d.	b.d.	b.d.
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.39	100.62	101.14	99.69	100.02	100.12	99.75	99.67	100.89	101.47	100.59
Si ⁴⁺ (<i>apfu</i>)	2.995	3.005	2.998	3.000	2.996	2.999	3.004	2.995	2.998	2.998	2.994
Al ³⁺	1.000	0.988	0.996	0.999	1.003	1.000	0.996	1.002	0.996	1.000	0.999
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.003
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	0.000
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.003	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	0.003
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.
Ba ²⁺	_	-	-	-	-	-	-	_	_	-	_
Na⁺	0.084	0.106	0.119	0.064	0.111	0.099	0.098	0.110	0.091	0.095	0.068
K+	0.930	0.908	0.895	0.926	0.880	0.902	0.895	0.893	0.926	0.907	0.949
Rb⁺	b.d.	b.d.	b.d.	0.012	0.014	0.004	0.004	0.009	b.d.	b.d.	b.d.
Cs+	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.001	8.000	8.001
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Sample	R3-2d	R3-2d	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e	R3-2e	R3-2e	R3-3
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3				
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.07	65.05	65.12	65.10	65.01	64.06	62.56	64.84	64.64	65.34	65.25
Al ₂ O ₃	18.46	18.39	18.65	17.85	18.68	18.22	17.66	18.37	18.39	18.47	18.23
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.05	0.08	0.00	0.11	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	0.00	0.00	b.d.	0.00	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.04	0.07	0.03	b.d.	b.d.	b.d.	0.77	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	-	-	-	-	-	-	-	-	-	-	b.d.
Na ₂ O	1.03	1.09	0.90	0.28	0.90	0.25	0.28	0.66	0.25	0.99	0.98
K ₂ O	15.67	15.91	15.80	16.52	15.92	17.24	16.14	16.41	16.68	15.42	15.14
Rb ₂ O	b.d.	b.d.	b.d.	0.34	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.52
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07
Total	100.27	100.51	100.50	100.15	100.61	99.77	97.52	100.28	99.96	100.23	100.20
Si ⁴⁺ (<i>apfu</i>)	2.995	2.993	2.991	3.015	2.986	2.987	2.982	2.994	2.995	3.002	3.008
Al ³⁺	1.001	0.997	1.010	0.975	1.011	1.001	0.992	0.999	1.004	1.000	0.990
Fe^{3+} (min) †	0.000	0.000	0.000	0.002	0.003	0.000	0.004	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	0.000	0.000	b.d.	0.000	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.002	0.003	0.002	b.d.	b.d.	b.d.	0.039	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	_	-	-	-	-	-	-	-	-	-	b.d.
Na⁺	0.092	0.097	0.080	0.026	0.080	0.023	0.026	0.059	0.023	0.088	0.088
K ⁺	0.920	0.934	0.926	0.976	0.933	1.025	0.982	0.967	0.986	0.904	0.890
Rb⁺	b.d.	b.d.	b.d.	0.010	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.016
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.001	8.001	8.000	8.002	8.000	8.000	8.000	8.000
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Sample	R3-3	R3-3	R3-3	R3-3	R3-3	R3-3
Unit	Rau 3					
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.43	65.22	65.54	65.23	65.22	65.21
Al ₂ O ₃	18.48	18.48	18.20	18.33	18.45	18.34
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.06	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.00	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	0.04	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	0.16	0.10
Na ₂ O	1.19	1.23	0.70	1.29	0.98	0.80
K ₂ O	15.18	15.42	16.02	15.24	15.78	16.08
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs ₂ O	0.06	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.34	100.39	100.47	100.09	100.64	100.54
Si ⁴⁺ (<i>apfu</i>)	3.002	2.995	3.010	3.002	2.996	3.000
Al ³⁺	0.999	1.001	0.986	0.994	0.999	0.994
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.002	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	b.d.	b.d.	b.d.	0.000	b.d.
Mg ²⁺	0.000	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.000	0.002	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	0.000	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	0.003	0.002
Na⁺	0.106	0.110	0.063	0.115	0.087	0.072
K+	0.889	0.904	0.939	0.895	0.925	0.944
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Cs⁺	0.001	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.10. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 3 pegmatite dike.

O²- (apfu)	8.000	8.000	8.000	8.000	8.001	8.000
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The formulae were calculated on the basis of 8 O atoms per formula unit. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R4-A	R4-A	R4-A	R4-A	R4-A	R4-A	R4-A	R4-2d	R4-2d	R4-2d	R4-2d	R4-2d
Unit	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.03	63.66	63.53	65.12	65.02	64.60	64.99	64.52	65.02	65.10	64.00	63.68
Al ₂ O ₃	18.47	18.36	18.40	18.44	18.28	18.41	18.37	18.47	18.61	18.65	18.40	18.35
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.02	b.d.	b.d.
BaO	0.10	0.19	0.10	0.11	b.d.	0.12	b.d.	-	-	-	-	-
Na ₂ O	0.64	0.31	0.30	0.38	0.85	0.47	0.81	0.31	0.52	0.54	0.51	0.30
K ₂ O	15.64	16.69	16.92	16.84	15.95	16.39	16.16	16.49	16.74	16.33	16.55	16.52
Total	99.89	99.20	99.25	100.90	100.10	99.99	100.33	99.79	100.89	100.64	99.46	98.84
Si ⁴⁺ (<i>apfu</i>)	3.001	2.982	2.977	2.994	3.001	2.992	2.996	2.992	2.987	2.991	2.984	2.986
Al ³⁺	1.005	1.014	1.016	0.999	0.994	1.005	0.998	1.009	1.008	1.010	1.011	1.014
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	b.d.	b.d.
Ba ²⁺	0.002	0.003	0.002	0.002	b.d.	0.002	b.d.	-	-	-	-	-
Na⁺	0.057	0.028	0.027	0.034	0.076	0.042	0.073	0.027	0.046	0.048	0.046	0.027
K+	0.921	0.998	1.012	0.988	0.939	0.968	0.950	0.976	0.981	0.957	0.984	0.988
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.11. Chemical compositions and structural formulae of K-feldspar in the Rau 4 pegmatite dike.

Iron, Ca, Mn, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit; - = not analyzed.

Sample	R5-A	R5-A	R5-A	R5-A	R5-A	R5-A	R5-A	R5-A	R5-A	R5-B1	R5-B1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.10	65.13	64.58	66.03	65.98	64.91	65.23	64.39	65.10	64.25	64.75
Al ₂ O ₃	18.29	18.34	18.41	18.64	18.46	18.52	18.50	18.41	18.57	18.72	18.49
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.05	b.d.	b.d.	0.09	b.d.	0.06	b.d.	b.d.	0.06	b.d.	b.d.
BaO	0.17	b.d.	0.17	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.24	0.16
Na ₂ O	0.40	0.79	0.30	1.13	0.80	0.85	0.91	0.37	0.64	0.27	0.21
K ₂ O	16.42	16.07	16.98	15.62	16.41	16.08	15.86	16.72	16.16	16.68	16.73
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	99.43	100.33	100.45	101.55	101.71	100.41	100.50	99.90	100.53	100.16	100.34
Si ⁴⁺ (<i>apfu</i>)	2.990	3.000	2.988	2.998	3.001	2.990	2.996	2.989	2.993	2.978	2.992
Al ³⁺	1.006	0.996	1.004	0.998	0.990	1.005	1.001	1.007	1.006	1.023	1.007
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.003	b.d.	b.d.	0.005	b.d.	0.003	b.d.	b.d.	0.003	b.d.	b.d.
Ba ²⁺	0.003	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	0.003
Na⁺	0.036	0.070	0.027	0.100	0.070	0.076	0.081	0.034	0.057	0.025	0.019
K+	0.977	0.944	1.002	0.905	0.952	0.945	0.930	0.990	0.948	0.986	0.986
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.000	8.000

Table A.12. Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-C	R5-C	R5-C	R5-C
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5					
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.42	63.84	64.22	63.82	64.59	64.58	64.59	64.71	64.91	65.35	65.75
Al ₂ O ₃	18.71	18.57	18.29	18.33	18.27	18.52	18.51	18.37	18.35	18.44	18.32
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	0.00	0.00	0.17	0.27	b.d.	0.11	0.16	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.92	0.27	0.30	0.32	1.13	0.26	0.33	0.97	1.01	1.07	0.87
K ₂ O	15.21	16.44	16.78	16.58	15.12	16.82	16.81	15.81	14.96	15.41	15.81
Rb ₂ O	0.37	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.23	b.d.	b.d.
Total	99.62	99.12	99.76	99.30	99.14	100.29	100.40	99.86	99.46	100.27	100.75
Si ⁴⁺ (<i>apfu</i>)	2.985	2.982	2.990	2.985	3.000	2.988	2.987	2.994	3.004	3.002	3.009
Al ³⁺	1.022	1.022	1.004	1.010	1.000	1.010	1.009	1.001	1.001	0.998	0.988
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	0.000	0.000	0.003	0.005	b.d.	0.002	0.003	b.d.	b.d.	b.d.	b.d.
Na⁺	0.082	0.025	0.027	0.029	0.102	0.024	0.030	0.087	0.091	0.095	0.077
K ⁺	0.899	0.979	0.997	0.989	0.896	0.993	0.992	0.933	0.883	0.903	0.923
Rb⁺	0.011	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.12. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	65.00	65.10	64.84	64.33	65.35	65.30	64.80	64.50	64.33	64.77	65.14
Al ₂ O ₃	18.34	18.26	18.21	18.45	18.48	18.34	18.51	18.53	18.23	18.26	18.28
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.10	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	0.00	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	0.04	b.d.	0.04	0.04	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.59	1.08	0.24	0.26	0.78	0.88	0.79	0.68	0.34	0.23	0.27
K ₂ O	16.24	15.21	16.87	16.78	16.04	15.72	15.97	16.18	16.89	16.99	16.79
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.17	99.65	100.19	99.82	100.85	100.29	100.07	99.89	99.79	100.35	100.48
Si ⁴⁺ (<i>apfu</i>)	3.000	3.006	3.000	2.988	2.996	3.003	2.992	2.987	2.992	2.996	3.002
Al ³⁺	0.998	0.994	0.993	1.010	0.998	0.994	1.007	1.011	1.000	0.995	0.993
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.004	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	0.000	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	0.002	b.d.	0.002	0.002	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.053	0.096	0.021	0.024	0.069	0.079	0.071	0.061	0.030	0.021	0.024
K ⁺	0.956	0.896	0.996	0.994	0.938	0.923	0.940	0.956	1.002	1.003	0.987
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.002	8.000

Table A.12. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5-D1	R5-D1	R5-D1	R5-E1							
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	64.77	64.77	64.53	64.47	63.98	63.52	63.95	63.44	64.13	64.61	63.78
Al ₂ O ₃	18.30	18.19	17.99	18.23	18.43	18.30	18.29	18.18	18.19	18.36	18.08
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.12	0.00	0.00	0.13
Na ₂ O	0.27	0.34	0.36	0.35	0.35	0.46	1.29	0.39	0.84	1.09	0.38
K ₂ O	16.91	16.66	16.74	16.81	16.72	16.59	15.50	16.39	15.85	15.24	16.24
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.26	99.97	99.62	99.86	99.50	98.92	99.11	98.52	99.01	99.30	98.61
Si ⁴⁺ (<i>apfu</i>)	2.996	3.001	3.003	2.995	2.983	2.981	2.984	2.987	2.994	2.997	2.996
Al ³⁺	0.998	0.994	0.987	0.998	1.013	1.012	1.006	1.009	1.001	1.004	1.001
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	0.000	0.000	0.002
Na⁺	0.024	0.031	0.032	0.031	0.031	0.042	0.117	0.035	0.076	0.098	0.034
K+	0.998	0.985	0.994	0.996	0.994	0.993	0.923	0.984	0.944	0.902	0.973
Rb⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.000

Table A.12. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5-E1	R5-E2									
Unit	Rau 5										
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	64.40	63.79	63.86	63.83	63.96	63.54	64.10	63.78	64.63	63.74	63.86
Al ₂ O ₃	18.20	18.14	18.33	18.29	18.31	18.18	18.23	18.33	18.45	18.37	18.44
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.										
MgO	b.d.										
CaO	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.16	b.d.
BaO	b.d.	b.d.	0.24	0.09	b.d.						
Na ₂ O	1.19	1.03	0.73	0.26	0.72	0.40	0.43	0.94	0.96	1.12	1.06
K ₂ O	15.11	15.53	16.01	16.82	15.83	16.59	16.49	15.86	15.45	15.36	15.64
Rb ₂ O	b.d.										
Total	98.90	98.49	99.21	99.29	98.82	98.72	99.24	98.92	99.50	98.76	98.99
Si ⁴⁺ (<i>apfu</i>)	2.999	2.992	2.985	2.986	2.991	2.987	2.993	2.984	2.994	2.982	2.982
Al ³⁺	0.999	1.003	1.010	1.008	1.009	1.007	1.003	1.011	1.008	1.013	1.015
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.										
Mg ²⁺	b.d.										
Ca ²⁺	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.008	b.d.
Ba ²⁺	b.d.	b.d.	0.004	0.002	b.d.						
Na⁺	0.108	0.094	0.066	0.023	0.065	0.037	0.039	0.085	0.086	0.102	0.096
K ⁺	0.898	0.929	0.955	1.004	0.944	0.995	0.982	0.947	0.913	0.917	0.932
Rb⁺	b.d.										
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.12. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5-F1	R5-F1	R5-F1	R5-F1	R5-F1	R5-F1	R5-F1	R5-F1	R5F-A3	R5F-A3
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.72	64.61	64.30	63.65	63.82	64.19	64.87	64.37	64.97	65.13
Al ₂ O ₃	18.46	18.31	18.49	18.32	18.44	18.51	18.55	18.44	18.73	18.71
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	0.26	0.25	0.39	0.38	0.27	0.32	0.23	0.40	0.29	0.17
Na ₂ O	0.36	0.24	0.30	0.27	0.24	0.27	0.30	0.27	0.32	0.26
K ₂ O	16.70	16.95	16.66	16.81	16.61	16.90	16.66	16.82	16.72	16.54
Rb ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Total	100.50	100.36	100.14	99.43	99.38	100.19	100.67	100.30	101.03	100.80
Si ⁴⁺ (<i>apfu</i>)	2.990	2.992	2.985	2.981	2.983	2.981	2.990	2.986	2.985	2.991
Al ³⁺	1.005	0.999	1.011	1.011	1.016	1.013	1.008	1.008	1.014	1.013
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	0.005	0.005	0.007	0.007	0.005	0.006	0.004	0.007	0.005	0.003
Na⁺	0.032	0.022	0.027	0.024	0.022	0.024	0.027	0.024	0.029	0.023
K+	0.984	1.001	0.986	1.004	0.990	1.001	0.979	0.995	0.980	0.969
Rb ⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.001	8.000	8.000	8.000

Table A.12. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5 pegmatite dike.

Sample	R5U-A	R5U-F	R5U-B	R5U-B							
Unit	Rau 5U										
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	65.08	64.34	65.16	64.42	64.89	64.45	64.89	64.30	64.40	64.21	65.17
Al ₂ O ₃	18.22	18.36	18.43	18.41	18.47	18.47	18.70	18.36	18.03	18.37	18.22
$Fe_2O_{3(\text{min})}^\dagger$	0.06	0.07	0.00	0.00	0.00	0.00	0.00	0.17	0.04	0.00	0.09
$FeO_{(max)}^{\dagger}$	0.00	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	0.00	b.d.	0.00
MgO	b.d.	0.05	b.d.	b.d.	b.d.						
CaO	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	0.04	b.d.	b.d.
BaO	0.14	0.26	b.d.	b.d.	0.12	0.10	0.34	0.29	b.d.	0.34	0.10
Na ₂ O	0.26	0.22	1.14	0.32	0.73	0.31	0.80	0.24	0.22	0.32	0.55
K ₂ O	16.65	16.74	15.68	16.77	15.92	16.71	15.94	16.63	16.77	16.58	16.37
Rb ₂ O	b.d.	0.18	b.d.	b.d.							
Total	100.41	99.98	100.41	99.93	100.16	100.06	100.66	100.04	99.68	99.82	100.50
Si ⁴⁺ (<i>apfu</i>)	3.003	2.989	2.996	2.989	2.994	2.988	2.985	2.987	3.000	2.988	3.003
Al ³⁺	0.991	1.005	0.999	1.007	1.005	1.009	1.014	1.005	0.990	1.008	0.989
${\sf Fe}^{3+}{}_{({\sf min})}^{\dagger}$	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.006	0.002	0.000	0.003
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	0.000	b.d.	0.000
Mg ²⁺	b.d.	0.003	b.d.	b.d.	b.d.						
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	0.002	b.d.	b.d.
Ba ²⁺	0.002	0.005	b.d.	b.d.	0.002	0.002	0.006	0.005	b.d.	0.006	0.002
Na ⁺	0.023	0.019	0.102	0.029	0.065	0.028	0.071	0.022	0.020	0.029	0.049
K⁺	0.981	0.992	0.919	0.993	0.937	0.988	0.935	0.985	0.997	0.984	0.962
Rb⁺	b.d.	0.005	b.d.	b.d.							
O ²⁻	8.001	8.001	8.000	8.000	8.000	8.000	8.000	8.003	8.001	8.000	8.002

Table A.13. Chemical compositions and structural formulae of K-feldspar in the Rau 5U pegmatite dike.

Sample	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D
Unit	Rau 5U										
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	64.93	65.14	64.71	64.43	64.92	64.72	64.31	64.93	64.51	64.34	64.88
Al ₂ O ₃	18.35	18.57	17.96	18.15	18.20	18.17	18.46	18.71	18.27	18.40	18.52
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.										
MgO	b.d.	b.d.	b.d.	0.02	b.d.						
CaO	b.d.	b.d.	0.03	b.d.							
BaO	b.d.	0.12	b.d.	0.14	b.d.	b.d.	0.12	b.d.	b.d.	0.09	b.d.
Na₂O	0.59	0.65	0.55	0.33	0.35	0.51	0.36	0.70	0.35	0.46	0.24
K ₂ O	16.14	16.02	16.03	16.44	16.63	16.28	16.36	16.13	16.62	15.88	16.71
Rb ₂ O	b.d.										
Total	100.00	100.50	99.29	99.50	100.11	99.68	99.59	100.47	99.74	99.18	100.35
Si ⁴⁺ (<i>apfu</i>)	3.000	2.995	3.010	3.000	3.003	3.002	2.990	2.987	2.996	2.996	2.993
Al ³⁺	0.999	1.006	0.985	0.996	0.992	0.994	1.011	1.014	1.000	1.010	1.007
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.										
Mg ²⁺	b.d.	b.d.	b.d.	0.001	b.d.						
Ca ²⁺	b.d.	b.d.	0.001	b.d.							
Ba ²⁺	b.d.	0.002	b.d.	0.002	b.d.	b.d.	0.002	b.d.	b.d.	0.002	b.d.
Na⁺	0.052	0.058	0.050	0.029	0.031	0.046	0.032	0.062	0.032	0.042	0.021
K+	0.951	0.940	0.951	0.976	0.981	0.963	0.970	0.947	0.985	0.943	0.983
Rb⁺	b.d.										
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.13. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5U pegmatite dike.

Sample	R5U-D	R5U-D	R5U-C								
Unit	Rau 5U										
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	65.02	64.76	65.12	65.17	64.75	64.52	65.05	64.94	64.26	65.26	65.20
Al ₂ O ₃	17.99	18.39	18.63	18.44	18.45	18.14	18.34	18.36	18.56	18.32	18.27
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	0.00	b.d.							
MgO	b.d.	b.d.	b.d.	0.02	b.d.						
CaO	b.d.	b.d.	b.d.	0.04	b.d.						
BaO	b.d.	0.16	0.18	0.10	0.22	0.11	0.10	0.12	0.20	b.d.	0.11
Na₂O	0.47	0.29	0.34	0.87	0.50	0.56	0.60	0.33	0.23	0.72	0.84
K ₂ O	16.32	16.60	16.54	15.90	16.54	16.36	16.28	16.65	16.76	16.11	15.92
Rb ₂ O	b.d.										
Total	99.81	100.21	100.94	100.53	100.46	99.68	100.38	100.40	100.00	100.41	100.34
Si ⁴⁺ (<i>apfu</i>)	3.012	2.995	2.990	2.996	2.990	2.999	2.999	2.997	2.983	3.002	3.003
Al ³⁺	0.982	1.003	1.008	0.999	1.004	0.993	0.997	0.999	1.015	0.994	0.992
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	0.000	b.d.							
Mg ²⁺	b.d.	b.d.	b.d.	0.001	b.d.						
Ca ²⁺	b.d.	b.d.	b.d.	0.002	b.d.						
Ba ²⁺	b.d.	0.003	0.003	0.002	0.004	0.002	0.002	0.002	0.004	b.d.	0.002
Na ⁺	0.043	0.026	0.030	0.078	0.045	0.050	0.054	0.030	0.021	0.064	0.075
K⁺	0.964	0.979	0.969	0.932	0.975	0.970	0.957	0.980	0.993	0.945	0.935
Rb⁺	b.d.										
O ²⁻	8.000	8.000	8.002	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.13. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5U pegmatite dike.

Sample	R5U-E	R5U-F	R5U-F									
Unit	Rau 5U											
Mineral	*Kfs	Kfs										
SiO ₂ (wt.%)	63.98	64.13	64.63	64.61	65.06	65.32	65.27	64.97	64.76	64.39	65.32	64.65
Al ₂ O ₃	18.52	18.59	18.31	18.28	18.47	18.60	18.64	18.36	18.49	18.40	18.36	18.30
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.08	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	b.d.	0.00	b.d.	b.d.	0.00	b.d.						
MgO	b.d.											
CaO	b.d.	0.03	b.d.	b.d.								
BaO	0.42	0.20	0.14	0.11	0.10	0.00	0.17	b.d.	0.10	0.23	b.d.	b.d.
Na ₂ O	0.31	0.32	0.20	0.31	0.79	0.80	0.54	0.44	0.28	0.28	1.09	0.27
K ₂ O	16.35	16.36	16.77	16.77	16.02	15.81	16.21	16.55	16.56	16.62	15.76	16.70
Rb ₂ O	b.d.											
Total	99.59	99.67	100.05	100.08	100.52	100.53	100.83	100.32	100.19	99.93	100.53	99.93
Si ⁴⁺ (<i>apfu</i>)	2.983	2.983	2.996	2.995	2.994	2.997	2.994	2.998	2.993	2.990	3.000	2.997
Al ³⁺	1.018	1.019	1.000	0.999	1.002	1.005	1.008	0.998	1.007	1.007	0.994	1.000
Fe^{3+} (min) †	0.000	0.003	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	0.000	b.d.	b.d.	0.000	b.d.						
Mg ²⁺	b.d.											
Ca ²⁺	b.d.	0.001	b.d.	b.d.								
Ba ²⁺	0.008	0.004	0.003	0.002	0.002	0.000	0.003	b.d.	0.002	0.004	b.d.	b.d.
Na⁺	0.028	0.028	0.018	0.028	0.071	0.071	0.048	0.040	0.025	0.025	0.097	0.024
K+	0.972	0.971	0.992	0.992	0.940	0.926	0.949	0.974	0.976	0.985	0.924	0.988
Rb⁺	b.d.											
O ²⁻	8.000	8.001	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.13. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5U pegmatite dike.

Sample	R5U-F	R5U-F	R5U-F	R5U-G	R5U-G	R5U-G	R5U-G	R5U-I	R5U-I	R5U-I	R5U-I	R5U-I
Unit	Rau 5U											
Mineral	*Kfs	Kfs										
SiO ₂ (wt.%)	64.72	64.74	64.44	64.87	63.90	64.68	64.23	64.65	64.53	64.27	64.94	64.21
Al ₂ O ₃	18.28	18.33	18.42	18.47	18.75	18.29	18.27	18.38	18.48	18.47	18.38	18.38
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.07
$FeO_{(max)}{}^{\dagger}$	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	0.00
MgO	b.d.											
CaO	b.d.	b.d.	b.d.	0.04	0.03	b.d.						
BaO	0.12	0.17	0.21	0.18	0.19	0.29	0.23	0.21	0.11	0.16	0.38	0.17
Na ₂ O	0.74	0.33	0.25	0.81	0.17	0.22	0.31	0.24	0.31	0.25	0.30	0.17
K ₂ O	16.15	16.66	16.75	15.83	16.61	16.84	16.67	17.00	16.70	16.89	16.67	16.56
Rb ₂ O	b.d.											
Total	100.00	100.22	100.08	100.27	99.64	100.32	99.71	100.48	100.23	100.04	100.68	99.56
Si ⁴⁺ (<i>apfu</i>)	2.996	2.996	2.989	2.992	2.975	2.995	2.991	2.990	2.988	2.985	2.995	2.991
Al ³⁺	0.997	1.000	1.007	1.004	1.029	0.998	1.003	1.002	1.008	1.011	0.999	1.009
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.002
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	0.000
Mg ²⁺	b.d.											
Ca ²⁺	b.d.	b.d.	b.d.	0.002	0.001	b.d.						
Ba ²⁺	0.002	0.003	0.004	0.003	0.003	0.005	0.004	0.004	0.002	0.003	0.007	0.003
Na⁺	0.066	0.029	0.023	0.072	0.015	0.020	0.028	0.022	0.028	0.023	0.027	0.015
K ⁺	0.953	0.983	0.991	0.931	0.987	0.995	0.990	1.003	0.986	1.000	0.981	0.984
Rb⁺	b.d.											
O ²⁻	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.002	8.000	8.000	8.001

Table A.13. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 5U pegmatite dike.

Sample	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R6-A	R6-A	R6-A	R6-A	R6-A
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6
Mineral	*Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs	Kfs
SiO ₂ (wt.%)	64.03	64.24	64.67	64.62	63.27	63.62	65.14	65.00	65.13	65.78	65.41
Al ₂ O ₃	18.28	18.51	18.41	18.43	18.34	18.18	18.57	18.41	18.48	18.41	18.64
$Fe_2O_{3(min)}{}^\dagger$	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00
FeO _(max) [†]	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.
BaO	b.d.	0.19	0.25	0.29	0.45	0.24	0.13	b.d.	0.37	b.d.	0.21
Na ₂ O	0.45	0.82	0.48	0.86	0.32	0.31	0.35	1.14	1.12	1.10	0.60
K ₂ O	16.63	16.01	16.43	15.81	16.49	16.78	16.70	15.34	15.41	15.61	16.08
Total	99.39	99.83	100.24	100.02	98.87	99.12	100.89	99.92	100.50	100.97	100.93
Si ⁴⁺ (<i>apfu</i>)	2.988	2.982	2.992	2.991	2.978	2.986	2.992	2.998	2.995	3.004	2.995
Al ³⁺	1.006	1.013	1.004	1.005	1.017	1.006	1.005	1.000	1.001	0.991	1.006
$Fe^{3+}(min)^{\dagger}$	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	0.003	0.005	0.005	0.008	0.004	0.002	b.d.	0.007	b.d.	0.004
Na⁺	0.041	0.074	0.043	0.077	0.029	0.028	0.031	0.102	0.100	0.097	0.053
K ⁺	0.990	0.948	0.970	0.934	0.990	1.004	0.979	0.903	0.904	0.910	0.939
O ²⁻	8.000	8.001	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.001	8.000

Table A.14. Chemical compositions and structural formulae of K-feldspar in the Rau 6 pegmatite dike.

Magnesium, Mn, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit; – = not analyzed.

Sample	R7-A	R7-A	R7-A	R7-A	R7-A	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b
Unit	Rau 7	Rau 8								
Mineral	*Kfs	Kfs								
SiO ₂ (wt.%)	65.50	65.61	65.10	64.98	65.98	64.88	65.31	65.01	64.96	65.34
Al ₂ O ₃	18.44	18.34	18.37	18.64	18.54	18.38	18.31	18.38	18.34	18.51
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.07	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	b.d.	0.00	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	0.05	0.03	b.d.	0.04						
MnO	b.d.	0.06	0.08							
BaO	b.d.	b.d.	0.16	0.42	0.13	0.19	0.14	0.21	0.24	b.d.
Na₂O	0.65	0.75	0.33	0.63	1.01	0.28	0.30	0.26	0.20	1.32
K ₂ O	16.32	16.17	16.57	15.62	15.86	16.74	16.92	16.86	16.84	15.35
Total	100.95	100.97	100.53	100.30	101.57	100.46	100.98	100.70	100.64	100.65
Si ⁴⁺ (<i>apfu</i>)	3.000	3.003	3.000	2.993	3.000	2.996	3.001	2.996	2.997	2.994
Al ³⁺	0.995	0.989	0.998	1.012	0.994	1.000	0.991	0.998	0.997	1.000
$Fe^{3+}(min)^{\dagger}$	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	0.000	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.002	0.001	b.d.	0.002						
Mn ²⁺	b.d.	0.002	0.003							
Ba ²⁺	b.d.	b.d.	0.003	0.008	0.002	0.004	0.003	0.004	0.004	b.d.
Na⁺	0.057	0.067	0.030	0.056	0.089	0.025	0.027	0.023	0.018	0.117
K⁺	0.954	0.944	0.974	0.918	0.920	0.986	0.992	0.991	0.991	0.897
O ^{2_}	8.000	8.001	8.000	8.000	8.001	8.000	8.000	8.000	8.000	8.000

Table A.15. Chemical compositions and structural formulae of K-feldspar in the Rau 7 and 8 pegmatite dikes.

Magnesium, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit; – = not analyzed.

Sample	R9a-4c	R9a-4c
Unit	Rau 9	Rau 0
Mineral	*Kfs	Kfs
SiO ₂ (wt.%)	65.07	65.07
Al ₂ O ₃	18.25	18.59
BaO	b.d.	0.29
Na ₂ O	0.51	0.49
K ₂ O	16.36	16.69
Total	100.18	101.12
Si ⁴⁺ (<i>apfu</i>)	3.003	2.988
Al ³⁺	0.993	1.006
Ba ²⁺	b.d.	0.005
Na⁺	0.045	0.043
K ⁺	0.963	0.978
O ²⁻	8.000	8.000
Na⁺	0.045	0.043

Table A.16. Chemical compositions and structural formulae of K-feldspar in the Rau 9 pegmatite dike.

The formulae were calculated on the basis of 8 O atoms per formula unit. Iron, Ca, Mg, Mn, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit; - = not analyzed.

Sample	R10-1a	R10-1c	R10-1c	R10-1c							
Unit	Rau 10										
Mineral	*Kfs	Kfs									
SiO ₂ (wt.%)	64.75	64.76	64.24	63.63	64.17	63.27	63.93	64.34	65.55	65.34	65.42
Al ₂ O ₃	18.46	18.35	18.27	18.59	18.42	18.47	18.30	18.66	18.16	18.16	18.28
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.	b.d.	b.d.	b.d.
CaO	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	0.05	b.d.	b.d.	b.d.
Na ₂ O	0.57	0.29	0.31	0.27	0.51	0.29	0.57	0.66	0.73	0.55	0.61
K ₂ O	16.19	16.74	16.58	16.56	16.28	16.68	16.47	16.03	16.36	16.38	16.29
Total	99.97	100.13	99.41	99.05	99.41	98.72	99.33	99.74	100.80	100.42	100.60
Si ⁴⁺ (<i>apfu</i>)	2.994	2.996	2.994	2.978	2.988	2.975	2.985	2.982	3.008	3.008	3.005
Al ³⁺	1.006	1.000	1.003	1.025	1.011	1.024	1.007	1.019	0.982	0.985	0.990
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	0.002	b.d.	b.d.	b.d.
Na⁺	0.051	0.026	0.028	0.025	0.046	0.026	0.051	0.059	0.065	0.049	0.054
K+	0.955	0.988	0.986	0.988	0.967	1.001	0.981	0.948	0.958	0.962	0.955
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.001	8.000	8.000	8.000	8.000

Table A.17. Chemical compositions and structural formulae of K-feldspar in the Rau 10 pegmatite dike.

Magnesium, Mn, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit; – = not analyzed.

Sample	R10-1c	R10-1c	R10-1c
Unit	Rau 10	Rau 10	Rau 10
Mineral	*Kfs	Kfs	Kfs
SiO ₂ (wt.%)	66.02	65.20	65.37
Al ₂ O ₃	18.26	18.27	17.58
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.08	0.02
$FeO_{(max)}{}^{\dagger}$	b.d.	0.00	0.00
CaO	b.d.	0.03	b.d.
Na ₂ O	1.22	1.19	0.33
K ₂ O	15.40	15.00	16.82
Total	100.91	99.76	100.20
Si ⁴⁺ (<i>apfu</i>)	3.012	3.006	3.024
Al ³⁺	0.982	0.993	0.959
Fe^{3+} (min) †	0.000	0.003	0.001
$Fe^{2+}(max)^{\dagger}$	b.d.	0.000	0.000
Ca ²⁺	b.d.	0.001	b.d.
Na⁺	0.108	0.106	0.030
K+	0.897	0.882	0.993
O ²⁻	8.000	8.001	8.000

Table A.17. (Continued) Chemical compositions and structural formulae of K-feldspar in the Rau 10 pegmatite dike.

Magnesium, Mn, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit; – = not analyzed.
Sample	R2-3	R2-3	R2-3	R2-3	R1-J	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1				
Mineral	*Ab	Ab	Ab	Ab	Ab	Ab	Ab	Ab	Ab
SiO ₂ (wt.%)	68.73	67.88	67.85	68.06	68.83	69.40	69.17	69.21	69.04
Al ₂ O ₃	19.63	19.66	19.55	19.34	19.22	19.23	19.34	19.51	19.78
CaO	0.07	0.18	0.27	0.03	-	-	-	-	0.41
Na ₂ O	11.22	11.24	11.30	11.32	11.83	11.98	11.80	12.22	11.61
K ₂ O	0.19	0.13	0.16	0.09	0.14	b.d.	0.11	b.d.	0.24
Total	99.85	99.09	99.13	98.85	100.01	100.61	100.42	100.94	101.07
Si ⁴⁺ (<i>apfu</i>)	3.001	2.989	2.989	3.002	3.006	3.011	3.007	2.997	2.987
Al ³⁺	1.010	1.020	1.015	1.005	0.989	0.983	0.991	0.995	1.008
Ca ²⁺	0.003	0.008	0.013	0.001	-	-	-	-	0.019
Na⁺	0.950	0.959	0.965	0.968	1.001	1.007	0.994	1.026	0.974
K⁺	0.011	0.007	0.009	0.005	0.008	b.d.	0.006	b.d.	0.013
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.18. Chemical compositions and structural formulae of albite in the Rau 1 pegmatite dike.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Iron, Mg, Mn, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit; - = not analyzed

Sample	R3-2d	R3-3	R3-3	R8-1b	R9b-2c	R9b-2c	R9b-2c	R10-1c
Unit	Rau 3	Rau 3	Rau 3	Rau 8	Rau 9	Rau 9	Rau 9	Rau 10
Mineral	*Ab	Ab	Ab	Ab	Ab	Ab	Ab	Ab
SiO ₂ (wt.%)	67.80	69.88	68.75	69.18	69.29	69.28	69.08	67.79
Al ₂ O ₃	19.16	19.33	19.41	19.70	19.56	19.54	19.67	20.39
$Fe_2O_{3(\text{min})}^\dagger$	0.09	0.06	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.00	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	0.00	b.d.	b.d.	b.d.	b.d.	b.d.	0.20	b.d.
CaO	0.15	0.02	b.d.	0.11	0.04	0.03	0.13	1.19
Na ₂ O	8.25	11.61	11.70	11.51	11.50	11.36	11.37	10.83
K ₂ O	4.76	b.d.	0.03	0.11	0.07	0.10	0.31	0.17
Total	100.22	100.90	99.90	100.61	100.45	100.31	100.76	100.38
Si ⁴⁺ (<i>apfu</i>)	3.001	3.018	3.002	2.999	3.006	3.009	2.994	2.955
Al ³⁺	0.999	0.984	0.999	1.007	1.000	1.000	1.005	1.048
$Fe^{3+}(min)^{\dagger}$	0.003	0.002	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	0.013	b.d.
Ca ²⁺	0.007	0.001	b.d.	0.005	0.002	0.001	0.006	0.056
Na⁺	0.708	0.972	0.991	0.968	0.967	0.957	0.956	0.916
K+	0.269	b.d.	0.002	0.006	0.004	0.005	0.017	0.010
O ^{2_}	8.002	8.001	8.000	8.000	8.000	8.000	8.000	8.000

Table A.19. Chemical compositions and structural formulae of albite in the Rau 3, 8, 9, and 10 pegmatite dikes.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Manganese, Ba, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit; - = not analyzed.

Sample	R2-3								
Unit	Rau 1								
Туре	Primary								
Zone	Rim	Rim	Rim	Core	Rim	Core	Rim	Core	Core
Mineral	*Ms	Ms							
SiO ₂ (wt.%)	50.47	49.13	50.17	49.46	49.84	48.12	49.04	49.78	49.14
Al ₂ O ₃	27.68	26.58	26.67	28.13	26.59	29.63	29.34	26.59	26.55
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	1.33	1.10	0.98	0.83	1.78	0.99	0.96	1.23	1.41
MgO	3.43	3.92	3.59	2.46	3.40	1.78	2.17	3.11	3.95
Na₂O	0.06	0.10	0.09	0.13	0.09	0.10	0.13	0.06	0.11
K ₂ O	11.34	11.30	11.27	11.16	11.14	11.35	11.37	11.27	11.37
Rb ₂ O	0.13	0.27	0.22	0.20	0.19	0.21	0.27	0.22	0.25
F	1.89	1.78	1.90	1.30	1.48	1.03	0.97	1.54	2.12
H_2O^{\ddagger}	3.56	3.50	3.49	3.75	3.67	3.86	3.94	3.62	3.35
−(O=F,CI)	-0.80	-0.75	-0.80	-0.55	-0.62	-0.43	-0.41	-0.65	-0.89
Total	99.11	96.94	97.58	96.88	97.55	96.65	97.77	96.76	97.36
Si ⁴⁺ (<i>apfu</i>)	3.397	3.390	3.428	3.393	3.416	3.318	3.341	3.432	3.384
Al ³⁺	2.196	2.162	2.148	2.275	2.148	2.408	2.356	2.161	2.155
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.075	0.063	0.056	0.048	0.102	0.057	0.055	0.071	0.081
Mg ²⁺	0.344	0.403	0.366	0.252	0.348	0.183	0.220	0.319	0.406
Na⁺	0.008	0.013	0.012	0.017	0.011	0.014	0.017	0.009	0.015
K+	0.974	0.995	0.982	0.977	0.974	0.998	0.988	0.991	0.999
Rb⁺	0.006	0.012	0.010	0.009	0.008	0.009	0.012	0.010	0.011
F ⁻	0.403	0.389	0.411	0.283	0.320	0.224	0.209	0.337	0.461
OH-	1.597	1.611	1.589	1.717	1.680	1.776	1.791	1.663	1.539
vacancy	0.988	0.981	1.003	1.032	0.986	1.033	1.028	1.017	0.974

Table A.20. Chemical compositions and structural formulae of muscovite in the Rau 1 pegmatite dike.

Sample	R2-3								
Unit	Rau 1								
Туре	Primary								
Zone	Rim	Rim	Rim	Core	Rim	Core	Rim	Core	Core
Mineral	*Ms	Ms							
O ²⁻ (apfu)	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Titanium, Cr, Ca, Mn, Cs, and Cl were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-1b										
Unit	Rau 3										
Туре	-	_	-	_	-	-	-	_	-	-	Secondary
Zone	Rim	Rim	Rim	Rim	Core	Rim	Rim	Rim	Rim	-	_
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	45.73	46.52	45.91	47.01	47.74	46.89	46.43	45.87	46.28	45.57	46.79
TiO ₂	0.12	b.d.	0.08	b.d.							
Al ₂ O ₃	31.97	32.31	30.94	32.31	30.07	35.14	34.15	34.45	35.67	34.89	32.12
Cr ₂ O ₃	b.d.										
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	4.45	3.42	4.69	3.31	3.17	1.07	2.71	1.87	1.14	1.02	3.18
MgO	0.10	0.11	1.28	0.47	1.68	0.10	0.18	0.12	0.09	0.08	0.61
CaO	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	0.06	b.d.	0.06	0.06	b.d.
MnO	0.07	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.25	0.28	0.26	0.24	0.17	0.32	0.30	0.33	0.35	0.41	0.26
K ₂ O	10.87	10.90	10.92	11.20	10.91	10.95	10.49	10.74	11.12	10.89	10.85
Rb ₂ O	0.18	0.14	0.22	0.22	0.17	0.18	0.14	0.11	0.08	0.11	0.24
Cs ₂ O	b.d.	0.08	b.d.	b.d.							
F	0.50	b.d.	0.79	b.d.	0.49	b.d.	b.d.	0.53	b.d.	b.d.	b.d.
Cl	b.d.	b.d.	0.06	0.03	b.d.						
H_2O^{\ddagger}	4.11	4.37	3.96	4.41	4.16	4.48	4.44	4.15	4.48	4.40	4.39
−(O=F,Cl)	-0.21	0.00	-0.34	-0.01	-0.21	0.00	0.00	-0.22	0.00	0.00	0.00
Total	98.14	98.08	98.70	99.19	98.44	99.11	98.90	97.95	99.34	97.51	98.45
Si ⁴⁺ (<i>apfu</i>)	3.157	3.189	3.163	3.191	3.261	3.139	3.136	3.122	3.099	3.107	3.193
Ti ⁴⁺	0.006	b.d.	0.004	b.d.							
Al ³⁺	2.601	2.610	2.513	2.585	2.421	2.773	2.718	2.764	2.815	2.803	2.584
Cr ³⁺	b.d.										
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-1b										
Unit	Rau 3										
Туре	-	_	-	-	-	-	-	-	-	-	Secondary
Zone	Rim	Rim	Rim	Rim	Core	Rim	Rim	Rim	Rim	-	-
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.257	0.196	0.271	0.188	0.181	0.060	0.153	0.106	0.064	0.058	0.181
Mg ²⁺	0.010	0.011	0.132	0.048	0.171	0.010	0.018	0.012	0.009	0.008	0.062
Ca ²⁺	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	0.004	0.005	b.d.
Mn ²⁺	0.004	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.034	0.037	0.035	0.031	0.022	0.041	0.039	0.044	0.046	0.054	0.035
K+	0.958	0.953	0.960	0.970	0.950	0.935	0.904	0.933	0.950	0.947	0.944
Rb⁺	0.008	0.006	0.010	0.010	0.008	0.008	0.006	0.005	0.003	0.005	0.011
Cs⁺	b.d.	0.002	b.d.	b.d.							
F ⁻	0.108	b.d.	0.172	b.d.	0.105	b.d.	b.d.	0.115	b.d.	b.d.	b.d.
Cl	b.d.	b.d.	0.007	0.003	b.d.						
OH ⁻	1.892	2.000	1.822	1.997	1.895	2.000	2.000	1.885	2.000	2.000	2.000
vacancy	0.964	0.995	0.922	0.988	0.961	1.018	0.974	0.995	1.012	1.020	0.980
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Secondary	Secondary	-	_	-	-	-	-	-	-	-
Zone	-	-	-	_	-	Rim	Core	Rim	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.47	46.24	46.56	47.52	46.55	46.98	46.44	46.64	46.04	46.73	47.66
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	32.05	31.95	34.60	30.57	31.86	35.77	35.50	35.31	33.73	35.04	29.25
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	0.07	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.03	3.53	1.48	3.04	2.75	1.23	1.34	1.31	2.66	1.36	2.33
MgO	0.39	0.26	0.27	1.66	1.25	0.00	0.01	0.00	0.21	0.02	3.41
CaO	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	0.07	b.d.	b.d.	0.11
Na ₂ O	0.27	0.25	0.31	0.30	0.27	0.33	0.30	0.29	0.28	0.30	0.27
K ₂ O	10.93	10.73	10.90	10.91	10.86	11.04	11.13	11.14	10.81	11.24	10.94
Rb ₂ O	0.21	0.17	0.11	0.26	0.23	0.10	0.15	0.14	0.18	0.15	0.19
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	0.47	b.d.	0.44	0.87	0.76	b.d.	0.51	b.d.	b.d.	b.d.	1.23
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	4.14	4.35	4.24	3.99	4.02	4.52	4.24	4.48	4.40	4.47	3.82
−(O=F,CI)	-0.20	0.00	-0.18	-0.37	-0.32	0.00	-0.21	0.00	0.00	0.00	-0.52
Total	97.81	97.47	98.72	98.74	98.24	100.04	99.56	99.38	98.39	99.32	98.69
Si ⁴⁺ (<i>apfu</i>)	3.193	3.190	3.138	3.238	3.183	3.119	3.107	3.122	3.135	3.133	3.247
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.596	2.598	2.748	2.455	2.567	2.799	2.799	2.787	2.707	2.768	2.349
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	0.004	b.d.	b.d.
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Secondary	Secondary	-	-	-	-	-	-	-	-	-
Zone	-	-	-	-	-	Rim	Core	Rim	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Fe ²⁺ (max) [†] (apfu)	0.174	0.204	0.084	0.173	0.157	0.068	0.075	0.073	0.152	0.076	0.133
Mg ²⁺	0.040	0.027	0.027	0.168	0.127	0.000	0.001	0.000	0.022	0.002	0.346
Ca ²⁺	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	0.004	b.d.	b.d.	0.006
Na⁺	0.035	0.034	0.040	0.039	0.036	0.043	0.039	0.038	0.037	0.040	0.036
K ⁺	0.958	0.944	0.937	0.949	0.948	0.935	0.950	0.952	0.939	0.961	0.951
Rb⁺	0.009	0.008	0.005	0.011	0.010	0.004	0.006	0.006	0.008	0.006	0.009
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F ⁻	0.103	b.d.	0.093	0.188	0.164	b.d.	0.108	b.d.	b.d.	b.d.	0.264
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH ⁻	1.897	2.000	1.907	1.812	1.836	2.000	1.892	2.000	2.000	2.000	1.736
vacancy	0.996	0.982	1.004	0.965	0.964	1.009	1.010	1.014	0.982	1.020	0.919
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	_	Primary									
Zone	Core	Rim	Rim	Rim	Rim	Core	Core	Rim	Rim	Rim	Core
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	46.56	46.99	46.39	46.76	47.23	47.31	46.56	47.68	47.64	45.60	45.79
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	0.10	b.d.
Al ₂ O ₃	34.74	35.65	35.43	35.31	34.55	33.17	34.11	29.68	29.97	29.40	29.35
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.61	1.15	1.46	1.73	1.98	1.86	2.52	3.79	3.20	5.03	5.09
MgO	0.01	0.25	0.28	0.22	0.09	1.07	0.89	2.32	2.49	2.97	3.15
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	0.08	b.d.	0.08
Na ₂ O	0.28	0.26	0.27	0.27	0.25	0.25	0.24	0.19	0.24	0.22	0.20
K ₂ O	10.89	11.02	10.90	10.93	10.95	10.75	10.47	11.21	11.25	10.88	11.03
Rb ₂ O	0.08	0.10	0.10	0.11	0.13	0.19	0.17	0.24	0.18	0.26	0.27
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	b.d.	0.44	b.d.	0.38	b.d.	0.54	0.40	0.81	1.29	1.05	1.08
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.06	0.05
H_2O^{\ddagger}	4.45	4.31	4.48	4.32	4.49	4.20	4.28	4.03	3.81	3.83	3.83
−(O=F,CI)	0.00	-0.18	0.00	-0.16	0.00	-0.23	-0.17	-0.34	-0.54	-0.45	-0.46
Total	98.62	99.97	99.32	99.86	99.67	99.11	99.59	99.67	99.61	98.95	99.45
Si ⁴⁺ (<i>apfu</i>)	3.139	3.120	3.106	3.118	3.156	3.181	3.123	3.239	3.231	3.151	3.152
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	0.005	b.d.
Al ³⁺	2.761	2.790	2.796	2.775	2.721	2.629	2.697	2.376	2.396	2.394	2.381
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b	R3-1b
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	-	Primary									
Zone	Core	Rim	Rim	Rim	Rim	Core	Core	Rim	Rim	Rim	Core
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.091	0.064	0.082	0.096	0.110	0.105	0.142	0.215	0.181	0.290	0.293
Mg ²⁺	0.001	0.024	0.028	0.021	0.009	0.107	0.089	0.235	0.252	0.306	0.323
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	0.004	b.d.	0.005
Na⁺	0.036	0.033	0.035	0.035	0.032	0.032	0.031	0.025	0.032	0.030	0.027
K+	0.936	0.934	0.931	0.929	0.934	0.923	0.896	0.971	0.974	0.959	0.968
Rb⁺	0.004	0.004	0.005	0.005	0.005	0.008	0.007	0.010	0.008	0.012	0.012
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F ⁻	b.d.	0.092	b.d.	0.080	b.d.	0.114	0.086	0.174	0.277	0.229	0.234
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	0.006
OH ⁻	2.000	1.908	2.000	1.920	2.000	1.886	1.914	1.826	1.723	1.764	1.760
vacancy	1.008	1.001	0.989	0.990	1.003	0.978	0.945	0.931	0.936	0.853	0.846
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-1b	R3-2a	R3-2a	R3-2a	R3-2a						
Unit	Rau 3										
Туре	Primary										
Zone	-	-	_	_	_	-	-	Rim	Core	Rim	Rim
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	45.56	46.36	46.00	47.12	47.70	47.89	46.12	48.78	46.60	46.40	48.01
TiO ₂	b.d.										
Al ₂ O ₃	34.83	35.63	35.45	31.08	29.75	30.23	30.08	29.31	29.08	29.28	28.62
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	0.07
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.48	0.93	1.26	3.54	3.59	2.92	5.01	3.18	4.38	4.41	3.65
MgO	0.37	0.03	0.20	1.63	1.94	1.74	2.23	2.24	2.59	2.63	2.53
CaO	0.04	b.d.	0.08	b.d.							
MnO	b.d.										
Na ₂ O	0.23	0.24	0.20	0.19	0.22	0.25	0.23	0.20	0.30	0.20	0.14
K ₂ O	10.89	11.09	10.72	11.04	10.90	11.06	10.78	11.25	10.96	11.09	11.15
Rb ₂ O	0.11	0.08	0.15	0.25	0.31	0.26	0.25	0.26	0.24	0.28	0.30
Cs ₂ O	b.d.										
F	b.d.	b.d.	b.d.	0.94	0.98	0.96	0.93	1.07	1.50	0.96	1.32
CI	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	0.06	b.d.	0.04	0.03	b.d.
H_2O^{\ddagger}	4.41	4.47	4.45	3.96	3.93	3.95	3.91	3.93	3.63	3.89	3.76
– O=F,CI)	0.00	0.00	0.00	-0.40	-0.41	-0.40	-0.40	-0.45	-0.64	-0.41	-0.55
Total	97.93	98.83	98.42	99.38	98.90	98.94	99.18	99.79	98.68	98.84	98.99
Si ⁴⁺ (<i>apfu</i>)	3.099	3.112	3.102	3.202	3.256	3.257	3.169	3.295	3.214	3.198	3.283
Ti ⁴⁺	b.d.										
Al ³⁺	2.792	2.819	2.818	2.489	2.393	2.423	2.436	2.334	2.364	2.378	2.307
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	0.004
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-1b	R3-2a	R3-2a	R3-2a	R3-2a						
Unit	Rau 3										
Туре	Primary										
Zone	-	-	-	-	-	-	-	Rim	Core	Rim	Rim
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.084	0.052	0.071	0.201	0.205	0.166	0.288	0.180	0.253	0.254	0.209
Mg ²⁺	0.038	0.003	0.020	0.165	0.197	0.177	0.228	0.226	0.266	0.270	0.258
Ca ²⁺	0.003	b.d.	0.006	b.d.							
Mn ²⁺	b.d.										
Na ⁺	0.031	0.031	0.027	0.025	0.029	0.033	0.030	0.026	0.040	0.027	0.018
K+	0.945	0.950	0.922	0.957	0.949	0.960	0.945	0.970	0.964	0.975	0.973
Rb⁺	0.005	0.004	0.006	0.011	0.014	0.011	0.011	0.011	0.011	0.012	0.013
Cs⁺	b.d.										
F⁻	b.d.	b.d.	b.d.	0.201	0.212	0.206	0.201	0.228	0.327	0.209	0.285
Cl	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	0.007	b.d.	0.005	0.004	b.d.
OH-	2.000	2.000	2.000	1.796	1.788	1.794	1.792	1.772	1.668	1.787	1.715
vacancy	0.988	1.014	0.989	0.943	0.949	0.973	0.880	0.966	0.903	0.900	0.940
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	Rim	Middle	Rim	Rim	Middle	Rim	Rim	Rim	Rim	Core	Rim
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	47.91	47.17	45.58	46.26	46.26	47.03	46.90	47.68	47.20	45.50	44.68
TiO ₂	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	0.30	b.d.	0.10	b.d.	b.d.
Al ₂ O ₃	28.09	29.81	29.15	28.92	29.79	29.13	26.32	29.80	29.91	29.34	29.09
Cr ₂ O ₃	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.70	3.09	5.29	4.82	5.29	4.27	4.17	3.79	3.46	6.05	6.47
MgO	2.62	1.90	2.42	2.59	2.50	2.40	4.19	2.00	2.07	2.58	2.63
CaO	0.09	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	0.05	b.d.	b.d.
MnO	0.08	b.d.	b.d.	b.d.	0.17	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
Na ₂ O	0.10	0.14	0.26	0.20	0.23	0.18	0.11	0.23	0.20	0.22	0.18
K ₂ O	11.08	11.19	11.13	11.04	10.81	10.75	11.24	10.83	10.86	10.99	10.95
Rb ₂ O	0.26	0.20	0.28	0.28	0.26	0.24	0.37	0.19	0.25	0.30	0.27
Cs ₂ O	b.d.										
F	1.50	1.10	0.99	0.82	1.08	1.33	1.64	0.95	0.91	1.05	1.31
CI	b.d.	b.d.	0.03	0.03	0.04	0.03	b.d.	b.d.	b.d.	0.07	0.06
H_2O^{\ddagger}	3.65	3.83	3.83	3.94	3.86	3.72	3.53	3.95	3.95	3.82	3.65
– O=F,CI)	-0.63	-0.46	-0.42	-0.35	-0.46	-0.57	-0.69	-0.40	-0.38	-0.46	-0.56
Total	98.45	97.95	98.54	98.65	99.82	98.59	98.08	99.02	98.65	99.45	98.73
Si ⁴⁺ (<i>apfu</i>)	3.296	3.248	3.170	3.200	3.167	3.235	3.267	3.250	3.230	3.146	3.123
Ti ⁴⁺	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	0.016	b.d.	0.005	b.d.	b.d.
Al ³⁺	2.278	2.418	2.389	2.358	2.403	2.362	2.161	2.394	2.413	2.391	2.396
Cr ³⁺	b.d.										
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	Rim	Middle	Rim	Rim	Middle	Rim	Rim	Rim	Rim	Core	Rim
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.213	0.178	0.308	0.279	0.303	0.246	0.243	0.216	0.198	0.350	0.378
Mg ²⁺	0.269	0.195	0.251	0.267	0.255	0.246	0.435	0.203	0.211	0.266	0.274
Ca ²⁺	0.007	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	0.004	b.d.	b.d.
Mn ²⁺	0.004	b.d.	b.d.	b.d.	0.010	b.d.	b.d.	b.d.	0.004	b.d.	b.d.
Na⁺	0.014	0.018	0.035	0.027	0.030	0.024	0.014	0.030	0.027	0.029	0.024
K+	0.973	0.983	0.987	0.974	0.944	0.944	0.999	0.942	0.948	0.969	0.977
Rb⁺	0.012	0.009	0.013	0.013	0.011	0.011	0.017	0.008	0.011	0.013	0.012
Cs⁺	b.d.										
F ⁻	0.326	0.239	0.218	0.179	0.233	0.290	0.361	0.205	0.197	0.231	0.290
Cl	b.d.	b.d.	0.003	0.004	0.005	0.004	b.d.	b.d.	b.d.	0.008	0.007
OH ⁻	1.674	1.761	1.778	1.817	1.762	1.706	1.639	1.795	1.803	1.761	1.704
vacancy	0.940	0.961	0.882	0.891	0.862	0.912	0.878	0.937	0.939	0.847	0.828
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	Core	Rim	Rim	Core	Rim	-	-	_	_	_	-
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	47.99	45.05	47.41	44.90	46.01	45.47	47.61	47.19	47.58	45.02	45.13
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	30.44	29.56	29.97	29.48	28.87	29.35	30.25	29.46	29.57	29.29	29.16
Cr ₂ O ₃	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.30	5.62	3.21	5.59	4.64	5.39	3.01	3.48	2.57	5.18	4.98
MgO	2.02	2.49	1.92	2.33	2.62	2.36	1.91	2.31	1.79	2.35	2.39
CaO	b.d.	b.d.	0.04	b.d.	0.04	0.04	0.04	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	0.13	b.d.								
Na₂O	0.26	0.24	0.20	0.26	0.19	0.24	0.22	0.14	0.17	0.24	0.21
K ₂ O	10.94	11.05	11.01	10.91	11.15	11.02	10.99	11.18	10.72	11.13	10.89
Rb ₂ O	0.31	0.29	0.26	0.31	0.26	0.28	0.24	0.24	0.32	0.25	0.33
Cs ₂ O	b.d.										
F	0.87	0.87	0.81	0.95	1.08	1.03	1.07	1.25	0.95	0.91	0.91
CI	b.d.	0.06	b.d.	0.06	b.d.	0.05	b.d.	b.d.	b.d.	0.07	0.05
H_2O^{\ddagger}	4.03	3.89	3.99	3.83	3.80	3.81	3.89	3.77	3.90	3.83	3.83
−(O=F,CI)	-0.37	-0.38	-0.34	-0.41	-0.46	-0.45	-0.45	-0.53	-0.40	-0.40	-0.39
Total	99.79	98.87	98.48	98.20	98.22	98.70	98.80	98.50	97.17	97.87	97.49
Si ⁴⁺ (apfu)	3.241	3.131	3.245	3.138	3.198	3.158	3.245	3.241	3.284	3.153	3.166
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.423	2.422	2.418	2.428	2.365	2.403	2.429	2.385	2.405	2.417	2.411
Cr ³⁺	b.d.										
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	Core	Rim	Rim	Core	Rim	-	-	-	-	-	-
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.186	0.327	0.184	0.327	0.270	0.313	0.172	0.200	0.148	0.304	0.292
Mg ²⁺	0.203	0.258	0.196	0.243	0.272	0.245	0.194	0.236	0.184	0.245	0.250
Ca ²⁺	b.d.	b.d.	0.003	b.d.	0.003	0.003	0.003	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	0.008	b.d.								
Na⁺	0.034	0.032	0.027	0.035	0.025	0.033	0.030	0.019	0.023	0.033	0.028
K+	0.942	0.980	0.961	0.973	0.989	0.976	0.956	0.980	0.944	0.995	0.974
Rb⁺	0.014	0.013	0.012	0.014	0.012	0.012	0.011	0.011	0.014	0.011	0.015
Cs⁺	b.d.										
F ⁻	0.186	0.190	0.176	0.210	0.238	0.227	0.230	0.271	0.207	0.202	0.202
Cl	b.d.	0.008	b.d.	0.007	b.d.	0.006	b.d.	b.d.	b.d.	0.008	0.006
OH-	1.814	1.802	1.824	1.784	1.762	1.767	1.770	1.729	1.793	1.790	1.792
vacancy	0.947	0.855	0.957	0.863	0.896	0.877	0.961	0.938	0.978	0.881	0.880
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	-	-	-	_	_	-	-	-	_	_	_
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	47.13	47.95	47.61	45.21	45.16	45.42	47.05	44.30	44.79	44.89	46.18
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.11	b.d.	b.d.	0.15	0.08
Al ₂ O ₃	28.64	28.99	28.92	29.07	29.81	30.14	30.11	29.49	29.36	29.62	29.40
Cr ₂ O ₃	0.07	b.d.									
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.83	3.24	3.08	5.04	4.87	5.35	3.73	5.96	6.31	5.69	4.76
MgO	2.59	2.30	2.15	2.27	2.24	2.34	1.83	2.62	2.53	2.47	2.75
CaO	b.d.										
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	0.11	0.13	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.16	0.17	0.19	0.22	0.24	0.23	0.20	0.23	0.23	0.25	0.21
K ₂ O	11.04	11.11	11.24	10.85	10.80	11.17	10.98	10.81	10.82	11.05	11.16
Rb ₂ O	0.30	0.26	0.26	0.25	0.30	0.33	0.24	0.33	0.26	0.31	0.33
Cs ₂ O	b.d.										
F	1.09	1.31	1.25	0.73	1.09	1.16	1.18	0.94	1.13	1.14	0.93
CI	0.03	b.d.	b.d.	0.07	0.05	0.07	b.d.	0.07	0.09	0.06	0.04
H_2O^{\ddagger}	3.82	3.76	3.76	3.90	3.77	3.79	3.82	3.81	3.74	3.76	3.91
−(O=F,CI)	-0.47	-0.55	-0.53	-0.32	-0.47	-0.50	-0.50	-0.41	-0.50	-0.49	-0.40
Total	98.24	98.53	97.93	97.29	97.86	99.62	98.88	98.15	98.76	98.90	99.35
Si ⁴⁺ (<i>apfu</i>)	3.254	3.284	3.282	3.175	3.151	3.130	3.220	3.107	3.123	3.121	3.176
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	0.008	0.004
Al ³⁺	2.330	2.340	2.349	2.406	2.452	2.448	2.429	2.438	2.413	2.427	2.382
Cr ³⁺	0.004	b.d.									
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2a										
Unit	Rau 3										
Туре	Primary										
Zone	-	-	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.221	0.186	0.178	0.296	0.284	0.309	0.214	0.349	0.368	0.331	0.274
Mg ²⁺	0.266	0.234	0.221	0.238	0.233	0.240	0.186	0.274	0.263	0.256	0.282
Ca ²⁺	b.d.										
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	0.007	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.022	0.023	0.025	0.030	0.033	0.031	0.027	0.031	0.031	0.034	0.028
K+	0.973	0.971	0.989	0.972	0.962	0.982	0.959	0.967	0.962	0.980	0.979
Rb⁺	0.013	0.012	0.012	0.011	0.013	0.015	0.011	0.015	0.012	0.014	0.015
Cs⁺	b.d.										
F ⁻	0.238	0.283	0.273	0.162	0.241	0.252	0.255	0.209	0.250	0.251	0.202
Cl	0.004	b.d.	b.d.	0.009	0.006	0.008	0.000	0.008	0.010	0.008	0.005
OH-	1.758	1.717	1.727	1.829	1.753	1.740	1.745	1.783	1.740	1.742	1.793
vacancy	0.925	0.956	0.970	0.885	0.881	0.868	0.938	0.832	0.833	0.857	0.882
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Primary	Secondary	Secondary	Secondary	-	-	-	-	-	-	-
Zone	-	-	-	_	-	-	Rim	Core	Core	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	45.80	46.03	45.90	46.05	47.27	47.16	45.46	45.79	45.31	45.93	47.97
TiO ₂	0.08	b.d.	b.d.	b.d.	0.11	b.d.	0.08	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.98	29.48	29.08	29.14	29.36	29.55	29.86	29.07	29.56	29.44	27.85
Cr ₂ O ₃	b.d.	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	5.37	4.79	4.78	4.60	3.00	3.20	5.58	5.59	5.85	5.10	3.60
MgO	2.50	2.58	2.69	2.47	2.36	1.90	2.73	2.53	2.54	2.55	2.73
CaO	b.d.	b.d.	b.d.	0.05	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.21	0.25	0.23	0.25	0.26	0.25	0.23	0.21	0.23	0.20	0.15
K ₂ O	10.95	10.96	11.05	10.96	10.94	10.85	11.03	10.76	11.04	11.04	11.24
Rb ₂ O	0.24	0.31	0.26	0.29	0.23	0.21	0.26	0.29	0.32	0.25	0.33
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	1.01	1.35	1.26	0.91	1.15	1.42	1.16	0.84	1.13	1.13	1.43
Cl	0.04	0.05	0.04	0.05	b.d.	b.d.	0.07	0.07	0.06	0.05	0.03
H_2O^{\ddagger}	3.88	3.69	3.72	3.87	3.81	3.67	3.79	3.91	3.78	3.79	3.67
−(O=F,CI)	-0.43	-0.58	-0.54	-0.40	-0.49	-0.60	-0.50	-0.37	-0.49	-0.49	-0.61
Total	99.61	98.91	98.54	98.25	98.04	97.61	99.77	98.69	99.33	98.99	98.38
Si ⁴⁺ (<i>apfu</i>)	3.145	3.177	3.182	3.195	3.250	3.257	3.127	3.177	3.136	3.172	3.305
Ti ⁴⁺	0.004	b.d.	b.d.	b.d.	0.006	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.426	2.398	2.376	2.383	2.379	2.405	2.421	2.376	2.411	2.396	2.261
Cr ³⁺	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a	R3-2a
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Primary	Secondary	Secondary	Secondary	-	-	-	-	-	-	-
Zone	-	-	-	_	-	-	Rim	Core	Core	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
$Fe^{2+}(max)^{\dagger}(apfu)$	0.308	0.277	0.277	0.267	0.172	0.185	0.321	0.324	0.338	0.294	0.207
Mg ²⁺	0.256	0.265	0.278	0.255	0.242	0.196	0.280	0.261	0.262	0.262	0.280
Ca ²⁺	b.d.	b.d.	b.d.	0.003	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.028	0.033	0.031	0.034	0.035	0.033	0.031	0.028	0.031	0.027	0.021
K ⁺	0.959	0.966	0.977	0.970	0.959	0.956	0.968	0.953	0.974	0.973	0.987
Rb⁺	0.010	0.014	0.012	0.013	0.010	0.009	0.012	0.013	0.014	0.011	0.014
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F ⁻	0.218	0.296	0.276	0.201	0.251	0.310	0.251	0.184	0.246	0.247	0.311
Cl	0.005	0.005	0.005	0.006	0.000	0.000	0.008	0.008	0.006	0.006	0.003
OH ⁻	1.777	1.699	1.718	1.794	1.749	1.690	1.741	1.808	1.747	1.747	1.686
vacancy	0.861	0.883	0.882	0.899	0.951	0.958	0.847	0.861	0.852	0.875	0.947
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c
Unit	Rau 3	Rau 3									
Туре	-	-	-	-	-	-	-	-	-	-	-
Zone	Rim	Rim	Core	Rim	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms								
SiO ₂ (wt.%)	45.62	46.96	46.65	45.99	46.37	46.49	46.38	48.43	46.05	45.88	48.13
TiO ₂	b.d.	b.d.	b.d.	0.11	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.21	30.01	29.90	29.58	30.33	29.71	29.31	28.38	28.60	30.09	29.38
Cr ₂ O ₃	b.d.	b.d.									
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	4.99	4.22	3.85	4.87	4.59	4.44	4.93	4.02	4.94	5.37	3.24
MgO	2.55	2.21	2.12	2.47	2.20	2.82	2.82	2.68	2.94	2.50	2.33
CaO	b.d.	b.d.	0.03	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	0.09	b.d.	b.d.	0.09	b.d.	0.08	b.d.	b.d.	b.d.	0.09	b.d.
Na ₂ O	0.20	0.26	0.20	0.25	0.26	0.19	0.20	0.11	0.17	0.22	0.12
K ₂ O	10.72	10.98	11.14	11.08	11.18	11.00	11.09	11.11	11.19	11.15	11.48
Rb ₂ O	0.24	0.23	0.25	0.30	0.23	0.30	0.32	0.35	0.34	0.28	0.22
Cs ₂ O	b.d.	b.d.									
F	1.02	1.10	0.85	1.18	0.87	1.23	0.95	1.13	1.16	0.86	1.25
CI	0.05	0.06	0.04	0.05	0.04	0.03	0.03	0.03	0.05	0.06	b.d.
H_2O^{\ddagger}	3.81	3.86	3.95	3.78	3.97	3.79	3.91	3.87	3.76	3.96	3.82
−(O=F,CI)	-0.44	-0.48	-0.37	-0.51	-0.37	-0.53	-0.41	-0.48	-0.50	-0.38	-0.53
Total	98.06	99.40	98.62	99.28	99.67	99.55	99.54	99.61	98.71	100.08	99.44
Si ⁴⁺ (<i>apfu</i>)	3.175	3.206	3.208	3.167	3.169	3.181	3.183	3.295	3.194	3.141	3.270
Ti ⁴⁺	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.396	2.415	2.423	2.401	2.443	2.396	2.371	2.275	2.338	2.428	2.353
Cr ³⁺	b.d.	b.d.									
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2a	R3-2a	R3-2a	R3-2a	R3-2c						
Unit	Rau 3										
Туре	-	-	-	-	-	-	-	-	-	-	-
Zone	Rim	Rim	Core	Rim	-	-	-	-	-	-	-
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.291	0.241	0.221	0.281	0.262	0.254	0.283	0.229	0.286	0.308	0.184
Mg ²⁺	0.264	0.225	0.218	0.254	0.224	0.288	0.289	0.272	0.304	0.256	0.236
Ca ²⁺	b.d.	b.d.	0.002	0.003	b.d.						
Mn ²⁺	0.005	b.d.	b.d.	0.005	b.d.	0.005	b.d.	b.d.	b.d.	0.005	b.d.
Na⁺	0.027	0.034	0.026	0.033	0.035	0.025	0.026	0.014	0.023	0.029	0.016
K+	0.952	0.956	0.978	0.973	0.975	0.960	0.971	0.964	0.990	0.974	0.995
Rb⁺	0.011	0.010	0.011	0.013	0.010	0.013	0.014	0.015	0.015	0.012	0.010
Cs⁺	b.d.										
F ⁻	0.225	0.237	0.185	0.256	0.188	0.267	0.206	0.242	0.254	0.187	0.268
Cl	0.006	0.006	0.005	0.006	0.004	0.004	0.004	0.003	0.006	0.007	b.d.
OH ⁻	1.769	1.756	1.810	1.738	1.808	1.730	1.790	1.754	1.740	1.807	1.732
vacancy	0.868	0.914	0.930	0.886	0.901	0.877	0.874	0.929	0.877	0.863	0.957
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c						
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3						
Туре	-	-	-	-	-	-	-	_	-	-	_
Zone	-	-	_	_	Core	Rim	Rim	Core	Rim	Rim	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.03	45.83	45.62	47.75	46.95	47.18	47.71	46.31	46.87	46.60	47.05
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.37	0.17	b.d.	0.15	b.d.
Al ₂ O ₃	28.33	29.99	28.97	27.90	29.88	29.02	26.10	29.67	28.33	27.04	28.43
Cr_2O_3	b.d.	0.07	b.d.	b.d.	b.d.						
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	5.02	4.93	4.84	3.79	4.01	4.62	4.78	4.35	4.20	5.19	4.50
MgO	2.47	2.34	2.72	2.63	2.42	2.56	5.27	2.52	2.67	4.11	2.91
CaO	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	0.11	b.d.	b.d.	b.d.	b.d.	0.13	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.16	0.21	0.24	0.15	0.20	0.18	0.13	0.19	0.13	0.15	0.16
K ₂ O	10.53	11.11	11.03	10.93	11.13	11.22	11.33	11.03	11.22	10.84	11.40
Rb ₂ O	0.29	0.23	0.26	0.22	0.26	0.27	0.44	0.25	0.29	0.35	0.30
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.						
F	1.46	1.06	0.96	1.35	0.88	0.64	1.37	1.50	0.81	1.95	1.22
CI	b.d.	0.05	0.04	b.d.	0.03	0.03	b.d.	b.d.	b.d.	0.04	0.05
H_2O^{\ddagger}	3.64	3.84	3.84	3.70	3.96	4.07	3.75	3.65	3.94	3.39	3.77
−(O=F,CI)	-0.62	-0.46	-0.41	-0.57	-0.38	-0.28	-0.58	-0.63	-0.34	-0.83	-0.52
Total	98.50	99.12	98.09	97.85	99.35	99.66	100.67	99.08	98.12	98.98	99.26
Si ⁴⁺ (<i>apfu</i>)	3.250	3.158	3.178	3.301	3.206	3.226	3.250	3.182	3.249	3.227	3.235
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.019	0.009	b.d.	0.008	b.d.
Al ³⁺	2.308	2.435	2.379	2.273	2.405	2.339	2.096	2.403	2.315	2.207	2.304
Cr ³⁺	b.d.	0.004	b.d.	b.d.	b.d.						
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2c										
Unit	Rau 3										
Туре	-	-	-	-	-	-	-	-	-	-	-
Zone	-	-	-	-	Core	Rim	Rim	Core	Rim	Rim	-
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.290	0.284	0.282	0.219	0.229	0.264	0.273	0.250	0.243	0.300	0.259
Mg ²⁺	0.255	0.241	0.282	0.271	0.247	0.261	0.535	0.258	0.276	0.424	0.298
Ca ²⁺	0.004	b.d.									
Mn ²⁺	0.007	b.d.	b.d.	b.d.	b.d.	0.008	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.021	0.029	0.032	0.020	0.027	0.024	0.017	0.026	0.018	0.020	0.021
K+	0.928	0.976	0.980	0.964	0.969	0.978	0.984	0.967	0.992	0.957	1.000
Rb⁺	0.013	0.010	0.012	0.010	0.011	0.012	0.019	0.011	0.013	0.016	0.013
Cs⁺	b.d.										
F ⁻	0.320	0.231	0.212	0.296	0.191	0.139	0.295	0.326	0.178	0.428	0.265
Cl	b.d.	0.006	0.005	b.d.	0.003	0.004	b.d.	b.d.	b.d.	0.005	0.006
OH ⁻	1.680	1.763	1.783	1.704	1.806	1.858	1.705	1.674	1.822	1.568	1.729
vacancy	0.890	0.882	0.879	0.935	0.913	0.902	0.827	0.896	0.918	0.835	0.904
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2d	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e
Unit	Rau 3	Rau 3	Rau 3	Rau 3							
Туре	-	_	-	-	_	_	_	Primary	Primary	Primary	Primary
Zone	-	_	-	-	_	_	_	_	_	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms						
SiO ₂ (wt.%)	46.49	49.07	45.83	46.97	48.50	47.11	46.52	46.69	46.93	47.62	47.65
TiO ₂	b.d.	0.20	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	28.56	27.09	29.40	29.93	28.74	29.87	29.28	35.15	32.96	28.46	29.02
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.							
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	4.77	3.20	5.40	3.89	3.13	3.74	4.25	1.40	2.71	4.27	4.38
MgO	2.94	3.73	2.68	2.03	2.52	2.16	2.73	b.d.	0.05	1.92	1.80
CaO	0.04	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.34	b.d.	b.d.	0.08	b.d.
Na ₂ O	0.14	0.06	0.28	0.24	0.14	0.23	0.18	0.29	0.19	0.15	0.10
K ₂ O	11.17	11.12	10.70	11.13	11.26	11.04	11.14	10.69	10.59	11.03	11.11
Rb ₂ O	0.28	0.36	0.32	0.24	0.35	0.26	0.31	0.16	0.22	0.32	0.30
Cs ₂ O	b.d.	b.d.	b.d.	b.d.							
F	0.89	1.43	1.18	0.84	1.26	1.03	1.14	b.d.	0.46	1.08	0.88
CI	0.03	b.d.	0.04	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.91	3.73	3.77	3.98	3.81	3.89	3.82	4.47	4.19	3.83	3.95
−(O=F,CI)	-0.38	-0.60	-0.51	-0.36	-0.53	-0.43	-0.49	0.00	-0.19	-0.45	-0.37
Total	98.85	99.48	99.09	98.89	99.17	98.90	99.24	98.86	98.18	98.29	98.80
Si ⁴⁺ (<i>apfu</i>)	3.212	3.334	3.164	3.219	3.301	3.224	3.196	3.135	3.195	3.288	3.271
Ti ⁴⁺	b.d.	0.010	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.325	2.169	2.392	2.417	2.305	2.409	2.371	2.781	2.645	2.316	2.349
Cr ³⁺	b.d.	b.d.	b.d.	b.d.							
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2d	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e
Unit	Rau 3	Rau 3	Rau 3	Rau 3							
Туре	-	-	-	-	-	-	_	Primary	Primary	Primary	Primary
Zone	-	-	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms						
Fe ²⁺ (max) [†] (apfu)	0.276	0.182	0.311	0.223	0.178	0.214	0.244	0.079	0.154	0.246	0.251
Mg ²⁺	0.303	0.378	0.276	0.207	0.256	0.220	0.280	b.d.	0.006	0.197	0.184
Ca ²⁺	0.003	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.020	b.d.	b.d.	0.004	b.d.
Na ⁺	0.019	0.007	0.038	0.032	0.019	0.031	0.024	0.038	0.024	0.019	0.013
K⁺	0.984	0.964	0.943	0.973	0.978	0.964	0.976	0.916	0.919	0.971	0.973
Rb⁺	0.013	0.016	0.014	0.011	0.015	0.011	0.014	0.007	0.010	0.014	0.013
Cs⁺	b.d.	b.d.	b.d.	b.d.							
F⁻	0.195	0.308	0.258	0.183	0.272	0.223	0.247	b.d.	0.099	0.235	0.191
Cl	0.004	b.d.	0.005	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
OH-	1.801	1.692	1.738	1.817	1.728	1.777	1.750	2.000	1.901	1.765	1.809
vacancy	0.885	0.928	0.857	0.935	0.960	0.932	0.889	1.006	1.000	0.948	0.945
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-2e	R3-2e	R3-2e	R3-2e	R3-3						
Unit	Rau 3										
Туре	Primary										
Zone	Core	Core	_	_	Rim	Core	-	Rim	Rim	Core	Core
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	46.45	48.56	48.47	45.26	45.91	46.79	48.10	48.65	45.07	48.56	46.14
TiO ₂	b.d.										
Al ₂ O ₃	29.52	30.42	29.35	30.09	28.87	28.91	29.38	28.53	29.74	29.90	29.90
Cr ₂ O ₃	b.d.	0.08									
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.93	2.52	2.96	6.16	4.86	4.07	3.43	3.34	5.61	2.87	4.76
MgO	2.49	1.76	2.31	2.56	3.05	2.61	2.17	2.52	2.49	2.08	2.34
CaO	b.d.	b.d.	b.d.	0.05	b.d.						
MnO	b.d.										
Na₂O	0.15	0.23	0.20	0.24	0.12	0.16	0.17	0.13	0.20	0.15	0.21
K ₂ O	10.87	11.12	11.15	10.86	11.22	11.27	11.04	11.12	10.92	10.98	11.16
Rb ₂ O	0.30	0.24	0.30	0.31	0.21	0.17	0.16	0.19	0.21	0.19	0.17
Cs ₂ O	b.d.										
F	1.42	1.18	1.41	1.04	1.47	1.29	1.44	1.10	1.11	1.17	1.38
CI	0.03	b.d.	b.d.	0.07	0.03	0.04	b.d.	b.d.	0.06	b.d.	0.04
H_2O^{\ddagger}	3.66	3.89	3.75	3.85	3.63	3.72	3.72	3.88	3.77	3.88	3.70
−(O=F,CI)	-0.61	-0.50	-0.59	-0.45	-0.62	-0.55	-0.61	-0.47	-0.48	-0.49	-0.59
Total	98.22	99.41	99.31	100.02	98.74	98.48	98.99	98.99	98.70	99.30	99.28
Si ⁴⁺ (<i>apfu</i>)	3.208	3.277	3.288	3.112	3.180	3.229	3.277	3.313	3.131	3.283	3.171
Ti ⁴⁺	b.d.										
Al ³⁺	2.403	2.419	2.346	2.438	2.357	2.352	2.359	2.289	2.435	2.383	2.422
Cr ³⁺	b.d.	0.004									
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-2e	R3-2e	R3-2e	R3-2e	R3-3						
Unit	Rau 3										
Туре	Primary										
Zone	Core	Core	-	-	Rim	Core	-	Rim	Rim	Core	Core
Mineral	*Ms	Ms									
Fe ²⁺ (max) [†] (apfu)	0.227	0.142	0.168	0.354	0.281	0.235	0.195	0.190	0.326	0.162	0.273
Mg ²⁺	0.257	0.177	0.234	0.262	0.315	0.268	0.220	0.256	0.258	0.210	0.240
Ca ²⁺	b.d.	b.d.	b.d.	0.004	b.d.						
Mn ²⁺	b.d.										
Na⁺	0.021	0.029	0.027	0.032	0.016	0.021	0.022	0.017	0.027	0.020	0.027
K+	0.958	0.957	0.965	0.953	0.992	0.993	0.959	0.966	0.968	0.947	0.978
Rb⁺	0.013	0.010	0.013	0.014	0.009	0.008	0.007	0.008	0.009	0.008	0.007
Cs⁺	b.d.										
F ⁻	0.311	0.251	0.302	0.226	0.321	0.281	0.310	0.238	0.244	0.251	0.299
Cl-	0.004	b.d.	b.d.	0.008	0.004	0.005	b.d.	b.d.	0.007	b.d.	0.004
OH ⁻	1.686	1.749	1.698	1.765	1.675	1.715	1.690	1.762	1.749	1.749	1.697
vacancy	0.905	0.985	0.964	0.834	0.867	0.916	0.950	0.953	0.850	0.962	0.890
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Sample	R3-3	R3-3	R3-3	R3-3	R3-3
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Primary	Primary	Primary	Secondary	Secondary
Zone	Rim	Core	Rim	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.84	45.89	46.05	46.11	45.81
TiO ₂	0.25	b.d.	0.21	b.d.	b.d.
Al ₂ O ₃	26.25	29.25	26.76	35.19	34.62
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.96	5.22	5.26	0.84	0.82
MgO	4.66	2.65	4.20	0.00	0.07
CaO	b.d.	b.d.	0.05	b.d.	b.d.
MnO	b.d.	0.08	b.d.	b.d.	b.d.
Na ₂ O	0.10	0.24	0.13	0.21	0.25
K ₂ O	11.25	11.24	11.26	10.73	10.68
Rb ₂ O	0.35	0.15	0.24	b.d.	0.06
Cs ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.
F	2.07	1.31	1.93	0.42	0.55
CI	b.d.	0.06	0.04	b.d.	b.d.
H_2O^{\ddagger}	3.33	3.71	3.38	4.22	4.12
−(O=F,CI)	-0.87	-0.56	-0.82	-0.18	-0.23
Total	98.20	99.23	98.69	97.55	96.74
Si ⁴⁺ (<i>apfu</i>)	3.259	3.168	3.210	3.127	3.136
Ti ⁴⁺	0.013	b.d.	0.011	b.d.	b.d.
Al ³⁺	2.152	2.380	2.198	2.813	2.793
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000

Table A.21. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 3 pegmatite dike.

Sample	R3-3	R3-3	R3-3	R3-3	R3-3
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Туре	Primary	Primary	Primary	Secondary	Secondary
Zone	Rim	Core	Rim	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms
Fe ²⁺ (max) [†] (<i>apfu</i>)	0.230	0.301	0.306	0.048	0.047
Mg ²⁺	0.483	0.273	0.436	0.000	0.007
Ca ²⁺	b.d.	b.d.	0.004	b.d.	b.d.
Mn ²⁺	b.d.	0.005	b.d.	b.d.	b.d.
Na⁺	0.014	0.032	0.018	0.028	0.033
K ⁺	0.999	0.990	1.001	0.929	0.933
Rb⁺	0.016	0.007	0.011	0.000	0.002
Cs⁺	b.d.	b.d.	b.d.	b.d.	b.d.
F ⁻	0.455	0.285	0.425	0.090	0.119
Cl-	b.d.	0.007	0.004	b.d.	b.d.
OH ⁻	1.545	1.707	1.570	1.910	1.881
vacancy	0.862	0.872	0.839	1.012	1.017
O ²⁻	10.000	10.000	10.000	10.000	10.000

Sample	R4-A										
Unit	Rau 4										
Туре	Primary										
Zone	_	_	_	-	-	_	_	Rim	Core	Rim	Middle
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	45.62	47.49	48.52	45.43	45.95	48.92	48.71	49.02	48.00	49.20	49.36
TiO ₂	b.d.										
Al ₂ O ₃	27.95	28.33	27.62	27.08	27.08	28.00	27.69	27.57	26.27	27.37	27.68
Cr ₂ O ₃	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	5.87	3.78	2.89	5.02	5.56	2.27	3.03	2.28	2.98	2.96	1.77
MgO	3.22	2.82	2.60	3.18	3.87	2.94	2.41	3.06	4.91	2.39	3.62
CaO	b.d.	b.d.	b.d.	0.04	b.d.						
MnO	b.d.	b.d.	b.d.	0.08	b.d.						
Na ₂ O	0.22	0.19	0.16	0.22	0.20	0.18	0.11	0.11	0.15	0.13	0.19
K ₂ O	11.09	11.08	11.28	11.00	11.16	11.13	11.34	11.41	11.24	11.58	11.36
Rb ₂ O	0.25	0.23	0.21	0.26	0.23	0.16	0.22	0.19	0.23	0.18	0.22
F	1.58	1.04	1.61	1.66	1.56	1.58	1.39	1.78	2.03	1.15	1.48
Cl	0.07	b.d.	b.d.	0.07	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.54	3.86	3.59	3.43	3.54	3.64	3.70	3.53	3.39	3.82	3.72
−(O=F,CI)	-0.68	-0.44	-0.68	-0.71	-0.67	-0.67	-0.59	-0.75	-0.85	-0.49	-0.62
Total	98.72	98.39	97.79	96.73	98.53	98.16	98.02	98.21	98.34	98.30	98.78
Si ⁴⁺ (<i>apfu</i>)	3.182	3.270	3.344	3.222	3.208	3.343	3.350	3.356	3.307	3.374	3.351
Ti ⁴⁺	b.d.										
Al ³⁺	2.297	2.299	2.244	2.264	2.228	2.255	2.245	2.224	2.134	2.212	2.215
Cr ³⁺	b.d.										
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.342	0.218	0.167	0.298	0.325	0.130	0.175	0.131	0.172	0.170	0.100

Table A.22. Chemical compositions and structural formulae of muscovite in the Rau 4 pegmatite dike.

Sample	R4-A										
Unit	Rau 4										
Туре	Primary										
Zone	-	-	-	-	-	-	-	Rim	Core	Rim	Middle
Mineral	*Ms	Ms									
Mg ²⁺ (<i>apfu</i>)	0.335	0.290	0.267	0.336	0.402	0.300	0.247	0.312	0.504	0.244	0.366
Ca ²⁺	b.d.	b.d.	b.d.	0.003	b.d.						
Mn ²⁺	b.d.	b.d.	b.d.	0.005	b.d.						
Na⁺	0.030	0.026	0.021	0.030	0.027	0.024	0.014	0.015	0.020	0.017	0.025
K+	0.986	0.973	0.992	0.995	0.994	0.971	0.995	0.996	0.988	1.013	0.984
Rb⁺	0.011	0.010	0.009	0.012	0.010	0.007	0.010	0.008	0.010	0.008	0.010
F ⁻	0.348	0.227	0.350	0.371	0.345	0.343	0.303	0.386	0.443	0.250	0.317
Cl	0.008	b.d.	b.d.	0.008	0.007	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.645	1.773	1.650	1.621	1.647	1.657	1.697	1.614	1.557	1.750	1.683
vacancy	0.844	0.924	0.978	0.875	0.837	0.972	0.983	0.977	0.883	1.000	0.968
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R4-A	R4-A	R4-A	R4-2d	R4-2d	R4-2d	R4-2d
Unit	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4
Туре	Primary	Primary	Primary	Secondary	Primary	-	-
Zone	Core	Rim	Core	-	Rim	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	48.53	46.15	48.09	50.76	45.93	46.86	48.65
TiO ₂	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	28.09	26.70	28.08	27.43	29.40	30.14	29.11
Cr ₂ O ₃	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.86	5.20	2.45	1.01	5.27	3.41	2.78
MgO	2.48	3.65	2.35	3.07	2.46	1.88	2.89
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	0.09	b.d.	0.23	b.d.	b.d.	b.d.
Na ₂ O	0.18	0.18	0.18	0.04	0.17	0.21	0.18
K ₂ O	11.22	11.17	11.20	10.89	10.97	11.23	11.55
Rb ₂ O	0.20	0.25	0.24	0.41	0.22	0.28	0.24
F	1.27	1.35	1.50	1.45	1.00	0.76	1.27
CI	b.d.	0.06	b.d.	b.d.	0.07	0.03	b.d.
H_2O^{\ddagger}	3.77	3.62	3.62	3.75	3.85	4.00	3.84
−(O=F,CI)	-0.53	-0.58	-0.63	-0.61	-0.44	-0.32	-0.54
Total	98.12	97.94	97.08	98.44	98.91	98.48	99.98
Si ⁴⁺ (<i>apfu</i>)	3.331	3.236	3.332	3.431	3.175	3.219	3.283
Ti ⁴⁺	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.272	2.206	2.293	2.185	2.395	2.440	2.315
Cr ³⁺	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.164	0.305	0.142	0.057	0.305	0.196	0.157

Table A.22. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 4 pegmatite dike.

Sample	R4-A	R4-A	R4-A	R4-2d	R4-2d	R4-2d	R4-2d
Unit	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4
Туре	Primary	Primary	Primary	Secondary	Primary	-	-
Zone	Core	Rim	Core	-	Rim	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (<i>apfu</i>)	0.254	0.382	0.243	0.310	0.253	0.193	0.291
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	0.006	b.d.	0.013	b.d.	b.d.	b.d.
Na⁺	0.024	0.025	0.024	0.006	0.023	0.029	0.023
K+	0.982	0.999	0.990	0.939	0.967	0.984	0.994
Rb⁺	0.009	0.011	0.011	0.018	0.010	0.012	0.010
F-	0.275	0.300	0.328	0.310	0.218	0.165	0.272
Cl	b.d.	0.007	b.d.	b.d.	0.009	0.003	b.d.
OH-	1.725	1.694	1.672	1.690	1.774	1.832	1.728
vacancy	0.976	0.861	0.991	1.004	0.872	0.952	0.954
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-A	R5-B1	R5-B1								
Unit	Rau 5										
Туре	Primary										
Zone	-	_	_	_	Core	Rim	_	_	-	_	Core
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	46.69	47.51	46.23	47.22	47.71	47.60	48.17	47.76	47.14	46.81	46.42
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.12	b.d.	b.d.	0.10	b.d.	b.d.
Al ₂ O ₃	31.92	28.43	28.09	28.54	29.36	29.38	29.31	30.72	31.11	29.03	28.58
Cr ₂ O ₃	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	1.70	2.40	4.58	3.27	2.50	2.50	2.61	2.04	2.15	4.45	4.97
MgO	0.77	2.44	2.76	1.90	1.68	1.46	1.87	1.34	0.87	1.70	1.80
CaO	b.d.	0.06									
MnO	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	0.08
Na ₂ O	0.23	0.17	0.23	0.18	0.14	0.15	0.20	0.13	0.14	0.17	0.22
K ₂ O	11.41	11.59	11.27	11.43	11.66	11.67	11.15	11.50	11.55	11.33	11.29
Rb ₂ O	0.09	0.22	0.20	0.26	0.18	0.20	0.22	0.16	0.11	0.17	0.23
F	0.56	1.55	1.27	1.26	0.85	0.86	1.25	1.06	0.69	1.04	1.08
CI	b.d.	b.d.	0.04	b.d.	0.04						
H_2O^{\ddagger}	4.09	3.59	3.68	3.71	3.95	3.93	3.78	3.88	4.03	3.83	3.78
−(O=F,CI)	-0.24	-0.65	-0.55	-0.53	-0.36	-0.36	-0.53	-0.45	-0.29	-0.44	-0.46
Total	97.24	97.25	97.90	97.23	97.67	97.50	98.05	98.14	97.60	98.17	98.09
Si ⁴⁺ (<i>apfu</i>)	3.212	3.296	3.226	3.287	3.289	3.288	3.301	3.263	3.240	3.245	3.235
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	0.005	b.d.	b.d.
Al ³⁺	2.588	2.325	2.310	2.341	2.386	2.392	2.367	2.473	2.520	2.371	2.348
Cr ³⁺	b.d.										
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.098	0.139	0.267	0.190	0.144	0.145	0.150	0.116	0.124	0.258	0.289

Table A.23. Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-A	R5-B1	R5-B1								
Unit	Rau 5										
Туре	Primary										
Zone	-	-	-	-	Core	Rim	-	-	-	-	Core
Mineral	*Ms	Ms									
Mg ²⁺ (apfu)	0.079	0.252	0.287	0.197	0.172	0.150	0.191	0.136	0.089	0.175	0.187
Ca ²⁺	b.d.	0.005									
Mn ²⁺	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	0.005
Na⁺	0.031	0.023	0.032	0.024	0.018	0.021	0.027	0.017	0.019	0.022	0.029
K+	1.002	1.026	1.004	1.015	1.025	1.028	0.975	1.002	1.013	1.001	1.004
Rb⁺	0.004	0.010	0.009	0.011	0.008	0.009	0.010	0.007	0.005	0.008	0.010
F ⁻	0.123	0.340	0.281	0.278	0.185	0.188	0.272	0.230	0.151	0.229	0.238
Cl	b.d.	b.d.	0.005	b.d.	0.005						
OH-	1.877	1.660	1.714	1.722	1.815	1.812	1.728	1.770	1.849	1.771	1.757
vacancy	1.024	0.988	0.903	0.984	1.008	1.019	0.991	1.012	1.023	0.946	0.936
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.
Sample	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-C	R5-C
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Primary	Primary	Secondary	Secondary	Secondary	_	_	_	Secondary	Secondary
Zone	Rim	Core	-	-	-	_	_	_	-	Core
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.91	48.65	45.26	45.32	45.61	46.87	46.72	45.93	47.51	46.71
TiO ₂	b.d.	0.17	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.21	30.32	35.88	34.18	36.05	28.16	28.44	35.18	30.37	33.33
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.77	2.35	0.04	1.00	0.83	4.04	4.38	0.27	2.27	2.03
MgO	1.52	1.66	0.07	0.47	0.14	2.20	2.08	0.19	1.23	0.00
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	b.d.
Na ₂ O	0.18	0.10	0.73	0.42	0.43	0.12	0.16	0.69	0.17	0.24
K ₂ O	11.60	11.39	10.62	11.04	11.19	11.52	11.54	10.89	11.47	11.26
Rb ₂ O	0.21	0.20	0.35	0.35	0.36	0.24	0.24	0.31	0.14	0.08
F	0.99	0.91	b.d.	0.41	b.d.	1.16	1.21	b.d.	1.02	b.d.
CI	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.88	4.01	4.41	4.17	4.46	3.75	3.74	4.42	3.88	4.40
−(O=F,CI)	-0.42	-0.38	0.00	-0.18	0.00	-0.49	-0.51	0.00	-0.43	0.00
Total	97.85	99.39	97.36	97.20	99.07	97.55	98.09	97.89	97.67	98.06
Si ⁴⁺ (<i>apfu</i>)	3.300	3.282	3.079	3.113	3.068	3.269	3.249	3.113	3.266	3.182
Ti ⁴⁺	b.d.	0.009	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.372	2.411	2.877	2.767	2.858	2.315	2.332	2.811	2.461	2.676
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.159	0.133	0.002	0.058	0.047	0.235	0.255	0.015	0.130	0.116

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-B1	R5-C	R5-C
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Primary	Primary	Secondary	Secondary	Secondary	-	-	-	Secondary	Secondary
Zone	Rim	Core	-	-	-	-	-	-	-	Core
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.156	0.167	0.007	0.048	0.014	0.228	0.215	0.020	0.126	0.000
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.003	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.
Na⁺	0.025	0.014	0.097	0.056	0.057	0.016	0.022	0.090	0.022	0.031
K+	1.019	0.981	0.922	0.967	0.961	1.025	1.024	0.942	1.006	0.979
Rb⁺	0.009	0.009	0.015	0.015	0.016	0.011	0.011	0.014	0.006	0.004
F⁻	0.215	0.193	b.d.	0.088	b.d.	0.256	0.266	b.d.	0.221	b.d.
Cl-	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.785	1.807	2.000	1.909	2.000	1.744	1.734	2.000	1.779	2.000
vacancy	1.013	0.998	1.035	1.015	1.014	0.952	0.943	1.041	1.017	1.027
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	_	Secondary							
Zone	Rim	_	Core	Rim	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.18	47.34	46.85	46.65	45.22	47.84	46.67	46.02	45.76	46.53
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	30.79	31.26	29.48	30.06	35.04	29.73	32.27	33.83	32.55	32.17
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.73	2.02	3.47	3.40	0.28	2.94	1.78	1.30	1.70	2.30
MgO	0.68	1.24	0.95	1.24	0.11	1.16	0.30		0.14	0.31
CaO	b.d.	0.06	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	0.05
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.13	0.14	0.24	0.24	0.61	0.29	0.16	0.25	0.18	0.17
K ₂ O	11.77	11.40	11.53	11.54	10.53	10.95	11.39	11.36	11.45	11.40
Rb ₂ O	0.19	0.18	0.20	0.28	0.57	0.18	0.18	0.17	0.23	0.18
F	0.80	0.96	0.88	0.89	0.49	0.75	0.51	b.d.	b.d.	0.71
Cl	b.d.	0.02	b.d.	0.03	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.98	3.93	3.88	3.90	4.14	4.00	4.11	4.37	4.32	4.02
−(O=F,CI)	-0.34	-0.41	-0.37	-0.38	-0.20	-0.32	-0.22	0.00	0.00	-0.30
Total	97.90	98.14	97.11	97.85	96.83	97.53	97.15	97.31	96.41	97.55
Si ⁴⁺ (apfu)	3.248	3.234	3.266	3.231	3.102	3.294	3.213	3.155	3.179	3.201
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.499	2.517	2.422	2.454	2.834	2.413	2.618	2.733	2.665	2.609
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.157	0.115	0.202	0.197	0.016	0.169	0.103	0.075	0.099	0.133

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C	R5-C
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	-	Secondary							
Zone	Rim	-	Core	Rim	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.069	0.126	0.099	0.128	0.011	0.119	0.030	0.000	0.014	0.032
Ca ²⁺	b.d.	0.004	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	0.004
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.018	0.019	0.032	0.032	0.081	0.039	0.021	0.033	0.024	0.023
K ⁺	1.033	0.994	1.025	1.020	0.922	0.962	1.001	0.994	1.015	1.001
Rb⁺	0.008	0.008	0.009	0.012	0.025	0.008	0.008	0.007	0.010	0.008
F ⁻	0.174	0.207	0.194	0.195	0.105	0.164	0.112	b.d.	b.d.	0.155
Cl-	b.d.	0.002	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH ⁻	1.826	1.790	1.806	1.801	1.895	1.836	1.888	2.000	2.000	1.845
vacancy	1.027	1.007	1.011	0.990	1.036	1.005	1.036	1.038	1.039	1.025
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-C	R5-C	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	Secondary	Primary	Primary	-	-	Primary	Primary	Primary	Primary	Secondary
Zone	-	-	Rim	Core	Core	Rim	_	_	Core	Middle	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.18	45.92	46.96	46.79	45.91	47.01	47.01	47.41	46.04	46.98	47.56
TiO ₂	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	33.29	33.15	30.06	31.38	29.20	29.79	29.20	33.02	28.60	32.34	31.00
Cr ₂ O ₃	b.d.	b.d.	0.08	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.26	1.67	4.12	2.46	5.28	4.15	4.32	1.28	4.14	1.81	2.16
MgO	0.10	0.00	1.20	0.51	1.83	1.20	2.32	0.59	2.18	0.45	1.05
CaO	b.d.	b.d.	0.04	b.d.	0.06	0.04	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.25	0.21	0.20	0.19	0.21	0.18	0.22	0.26	0.16	0.23	0.16
K ₂ O	11.14	11.04	11.33	11.27	11.17	11.40	11.15	11.35	11.53	11.50	11.37
Rb ₂ O	0.12	0.11	0.24	0.20	0.16	0.20	0.23	0.25	0.22	0.20	0.15
F	0.49	b.d.	1.03	0.87	0.88	1.02	0.80	0.56	1.06	0.00	0.92
CI	b.d.	b.d.	b.d.	b.d.	0.05	0.03	0.03	b.d.	0.04	b.d.	b.d.
H_2O^{\ddagger}	4.13	4.34	3.87	3.93	3.88	3.86	3.98	4.17	3.77	4.39	3.95
−(O=F,CI)	-0.20	0.00	-0.43	-0.37	-0.38	-0.43	-0.34	-0.23	-0.45	0.00	-0.39
Total	96.75	96.44	98.79	97.33	98.24	98.46	98.91	98.64	97.29	97.90	97.93
Si ⁴⁺ (<i>apfu</i>)	3.179	3.174	3.227	3.228	3.196	3.242	3.230	3.205	3.227	3.211	3.254
Ti ⁴⁺	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.700	2.701	2.434	2.552	2.396	2.422	2.365	2.631	2.363	2.605	2.500
Cr ³⁺	b.d.	b.d.	0.004	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.072	0.096	0.237	0.142	0.308	0.240	0.248	0.072	0.243	0.104	0.123

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-C	R5-C	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1	R5-D1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	Secondary	Primary	Primary	-	-	Primary	Primary	Primary	Primary	Secondary
Zone	-	-	Rim	Core	Core	Rim	-	-	Core	Middle	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.011	0.000	0.123	0.052	0.190	0.123	0.237	0.059	0.228	0.046	0.107
Ca ²⁺	b.d.	b.d.	0.003	b.d.	0.004	0.003	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.034	0.029	0.026	0.025	0.028	0.025	0.029	0.034	0.022	0.031	0.022
K+	0.979	0.973	0.994	0.992	0.992	1.003	0.977	0.979	1.031	1.002	0.993
Rb⁺	0.005	0.005	0.011	0.009	0.007	0.009	0.010	0.011	0.010	0.009	0.007
F ⁻	0.106	b.d.	0.224	0.190	0.193	0.222	0.174	0.119	0.234	0.000	0.198
Cl	b.d.	b.d.	b.d.	b.d.	0.006	0.004	0.004	b.d.	0.005	b.d.	b.d.
OH-	1.894	2.000	1.776	1.810	1.801	1.775	1.823	1.881	1.761	2.000	1.802
vacancy	1.038	1.028	0.969	1.020	0.912	0.974	0.920	1.033	0.940	1.034	1.015
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-D1	R5-D1	R5-D1	R5-D1	R5-E1	R5-E1	R5-E1	R5-E1	R5-E1	R5-E1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	Secondary	Primary	Primary	Secondary	Secondary	Secondary	Secondary	_	Secondary
Zone	-	-	Core	Rim	-	-	-	-	_	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.69	46.86	47.63	46.87	47.64	48.42	47.57	47.53	47.98	46.34
TiO ₂	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	28.97	31.14	30.18	31.62	30.72	28.76	27.39	29.86	30.54	27.87
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.39	2.16	4.17	2.37	2.51	2.79	3.35	2.60	1.70	4.59
MgO	1.86	0.64	0.78	0.49	0.98	1.89	2.87	1.16	1.34	1.74
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10
MnO	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.22	0.18	0.17	0.25	0.22	0.20	0.19	0.17	0.18	0.17
K ₂ O	11.35	11.32	11.11	11.40	11.09	11.24	11.40	11.34	11.40	10.93
Rb ₂ O	0.22	0.14	0.19	0.22	0.24	0.15	0.21	0.22	0.20	0.27
F	1.04	0.57	0.66	0.48	1.01	1.37	1.50	0.83	1.26	1.12
CI	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07
H_2O^{\ddagger}	3.87	4.06	4.06	4.13	3.90	3.72	3.60	3.95	3.79	3.69
−(O=F,CI)	-0.44	-0.25	-0.28	-0.20	-0.43	-0.58	-0.63	-0.35	-0.53	-0.49
Total	98.25	96.84	98.66	97.71	97.88	97.96	97.46	97.30	97.87	96.41
Si ⁴⁺ (apfu)	3.281	3.243	3.263	3.222	3.265	3.324	3.308	3.284	3.281	3.274
Ti ⁴⁺	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.349	2.540	2.437	2.562	2.481	2.327	2.245	2.431	2.461	2.320
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.195	0.125	0.239	0.136	0.144	0.160	0.195	0.150	0.097	0.271

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-D1	R5-D1	R5-D1	R5-D1	R5-E1	R5-E1	R5-E1	R5-E1	R5-E1	R5-E1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5
Туре	Secondary	Secondary	Primary	Primary	Secondary	Secondary	Secondary	Secondary	-	Secondary
Zone	-	-	Core	Rim	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.190	0.066	0.079	0.050	0.100	0.193	0.298	0.119	0.137	0.183
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.008
Mn ²⁺	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.029	0.024	0.022	0.034	0.029	0.027	0.025	0.023	0.024	0.023
K+	0.996	0.999	0.971	1.000	0.969	0.984	1.012	0.999	0.995	0.985
Rb⁺	0.010	0.006	0.008	0.010	0.010	0.007	0.010	0.010	0.009	0.012
F⁻	0.225	0.125	0.143	0.105	0.219	0.297	0.329	0.180	0.273	0.250
Cl	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.009
OH-	1.775	1.872	1.857	1.895	1.781	1.703	1.671	1.820	1.727	1.741
vacancy	0.979	1.027	0.982	1.025	1.010	0.996	0.954	1.015	1.025	0.952
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sampla		D5 E1			D5 E1		D5 E2	D5 E2		
Sample	RJ-EI									
Unit	Rau 5									
Туре	Secondary									
Zone	Core	Rim	_	_	_	_	_	-	_	Rim
Mineral	*Ms	Ms								
SiO ₂ (wt.%)	46.72	47.70	46.64	47.22	46.52	46.84	45.80	47.08	46.21	46.21
TiO ₂	b.d.	b.d.	0.12	b.d.						
Al ₂ O ₃	28.81	27.98	27.96	29.97	32.61	32.74	33.96	34.25	33.57	28.22
Cr ₂ O ₃	b.d.									
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	4.02	3.17	4.29	2.18	2.05	1.43	1.06	1.04	1.21	4.25
MgO	1.48	2.00	2.20	1.21	0.11	0.61	0.10		0.19	2.18
CaO	b.d.	b.d.	0.04	b.d.	b.d.	0.04	0.06	0.04	0.04	b.d.
MnO	b.d.									
Na ₂ O	0.17	0.19	0.21	0.15	0.16	0.17	0.30	0.32	0.23	0.22
K ₂ O	11.37	11.06	10.97	11.20	10.88	11.35	11.17	11.30	11.18	11.23
Rb ₂ O	0.27	0.22	0.18	0.16	0.11	0.12	0.11	0.18	0.12	0.26
F	0.99	0.89	1.21	0.92	0.64	0.63	b.d.	0.50	0.50	0.84
CI	0.03	0.02	0.06	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	0.04
H_2O^{\ddagger}	3.82	3.87	3.69	3.88	4.05	4.09	4.37	4.21	4.14	3.86
−(O=F,CI)	-0.42	-0.38	-0.52	-0.39	-0.27	-0.27	0.00	-0.21	-0.21	-0.36
Total	97.26	96.74	97.04	96.49	96.86	97.78	96.93	98.70	97.19	96.94
Si ⁴⁺ (<i>apfu</i>)	3.264	3.325	3.267	3.279	3.204	3.197	3.145	3.174	3.167	3.246
Ti ⁴⁺	b.d.	b.d.	0.006	b.d.						
Al ³⁺	2.372	2.299	2.308	2.453	2.647	2.634	2.749	2.721	2.712	2.337
Cr ³⁺	b.d.									
$Fe^{3+}{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.235	0.185	0.252	0.127	0.118	0.082	0.061	0.058	0.070	0.250

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-E1	R5-E1	R5-E1	R5-E1	R5-E1	R5-E2	R5-E2	R5-E2	R5-E2	R5-E2
Unit	Rau 5									
Туре	Secondary									
Zone	Core	Rim	-	-	-	-	-	-	-	Rim
Mineral	*Ms	Ms								
Mg ²⁺ (<i>apfu</i>)	0.154	0.208	0.230	0.125	0.012	0.062	0.011	0.000	0.020	0.228
Ca ²⁺	b.d.	b.d.	0.003	b.d.	b.d.	0.003	0.004	0.003	0.003	b.d.
Mn ²⁺	b.d.									
Na⁺	0.023	0.026	0.029	0.020	0.021	0.023	0.040	0.042	0.030	0.029
K+	1.013	0.983	0.980	0.992	0.956	0.988	0.978	0.972	0.977	1.006
Rb⁺	0.012	0.010	0.008	0.007	0.005	0.005	0.005	0.008	0.005	0.012
F ⁻	0.218	0.197	0.267	0.201	0.140	0.136	b.d.	0.107	0.108	0.187
Cl-	0.004	0.003	0.007	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	0.005
OH ⁻	1.778	1.800	1.726	1.799	1.860	1.861	2.000	1.893	1.892	1.808
vacancy	0.975	0.984	0.938	1.015	1.019	1.025	1.035	1.047	1.032	0.939
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-E2	R5-E2	R5-E2	R5-E2	R5-E2	R5-E2	R5-F1	R5-F1	R5-F1	R5-F1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5					
Туре	Secondary	Secondary	Secondary	Secondary	Secondary	Secondary	Primary	Primary	Primary	Primary
Zone	Core	-	_	-	-	_	Core	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.15	47.38	46.94	47.18	49.22	46.22	46.79	47.91	44.97	47.60
TiO ₂	0.12	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	28.61	33.31	30.47	29.94	29.40	28.56	26.84	30.44	27.63	26.86
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(\text{max})}^{\dagger}$	4.01	1.33	4.18	2.95	2.31	5.55	3.46	2.15	5.24	3.43
MgO	1.86	0.05	0.52	1.21	2.48	2.76	4.01	0.77	2.63	3.01
CaO	b.d.	0.05	b.d.	b.d.	b.d.	0.05	0.03	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.22	0.26	0.21	0.14	0.15	0.26	0.15	0.14	0.18	0.14
K ₂ O	11.16	11.04	11.28	10.73	11.48	11.04	11.40	11.28	11.08	11.53
Rb ₂ O	0.28	0.14	0.16	0.17	0.16	0.24	0.18	0.14	0.20	0.27
F	0.91	0.47	0.62	0.74	1.27	0.71	1.59	0.86	1.18	1.20
CI	0.04	b.d.	b.d.	0.03	b.d.	0.06	0.03	b.d.	0.07	0.04
H_2O^{\ddagger}	3.83	4.20	4.05	3.96	3.85	3.99	3.53	3.95	3.63	3.72
−(O=F,CI)	-0.39	-0.20	-0.26	-0.32	-0.54	-0.31	-0.68	-0.36	-0.51	-0.51
Total	96.80	98.03	98.17	96.75	99.79	99.09	97.34	97.28	96.40	97.30
Si ⁴⁺ (apfu)	3.241	3.213	3.238	3.272	3.310	3.196	3.270	3.295	3.201	3.322
Ti ⁴⁺	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.368	2.662	2.477	2.448	2.330	2.327	2.210	2.467	2.318	2.209
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.235	0.075	0.241	0.171	0.130	0.321	0.202	0.124	0.312	0.200

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-E2	R5-E2	R5-E2	R5-E2	R5-E2	R5-E2	R5-F1	R5-F1	R5-F1	R5-F1
Unit	Rau 5	Rau 5	Rau 5	Rau 5	Rau 5					
Туре	Secondary	Secondary	Secondary	Secondary	Secondary	Secondary	Primary	Primary	Primary	Primary
Zone	Core	-	-	-	-	-	Core	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.195	0.005	0.054	0.125	0.249	0.284	0.417	0.078	0.279	0.313
Ca ²⁺	b.d.	0.004	b.d.	b.d.	b.d.	0.003	0.003	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.030	0.034	0.028	0.019	0.019	0.034	0.021	0.018	0.025	0.020
K+	0.999	0.955	0.993	0.949	0.985	0.974	1.017	0.990	1.006	1.026
Rb⁺	0.013	0.006	0.007	0.008	0.007	0.011	0.008	0.006	0.009	0.012
F ⁻	0.203	0.101	0.135	0.162	0.271	0.154	0.352	0.187	0.267	0.265
Cl	0.004	b.d.	b.d.	0.004	b.d.	0.007	0.003	b.d.	0.008	0.004
OH-	1.793	1.899	1.865	1.834	1.729	1.839	1.645	1.813	1.725	1.730
vacancy	0.953	1.045	0.991	0.984	0.981	0.872	0.901	1.036	0.884	0.955
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5-F1	R5F-A3	R5F-A3								
Unit	Rau 5										
Туре	Primary										
Zone	-	Rim	_	Rim	Rim	Rim	Core	Core	Core	_	-
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	47.29	45.82	47.60	48.44	45.21	46.12	45.50	48.15	46.19	48.66	47.71
TiO ₂	b.d.	0.08	b.d.	b.d.							
Al ₂ O ₃	29.74	27.28	27.07	30.13	28.04	27.98	29.13	27.44	32.62	32.54	32.76
Cr_2O_3	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.34	5.15	3.47	2.24	6.09	4.83	2.82	3.13	1.39	1.65	2.01
MgO	0.96	3.51	4.37	1.22	2.53	2.92	0.69	2.86	0.00	1.27	1.01
CaO	0.04	b.d.	0.04	0.05	b.d.						
MnO	b.d.	0.08	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	0.09	b.d.	b.d.
Na ₂ O	0.14	0.19	0.20	0.14	0.24	0.21	0.13	0.21	0.24	0.20	0.16
K ₂ O	11.26	10.95	11.29	11.03	11.03	10.89	10.64	11.49	11.12	11.31	11.20
Rb ₂ O	0.18	0.23	0.17	0.20	0.28	0.20	0.16	0.27	0.13	b.d.	b.d.
F	0.81	1.64	1.73	1.10	1.23	1.50	0.88	1.18	0.00	1.23	1.07
CI	b.d.	0.04	0.03	b.d.	0.06	0.06	0.03	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.92	3.49	3.53	3.87	3.66	3.56	3.74	3.78	4.33	3.93	3.96
−(O=F,CI)	-0.34	-0.70	-0.74	-0.46	-0.53	-0.65	-0.38	-0.50	0.00	-0.52	-0.45
Total	96.35	97.67	98.77	97.96	97.92	97.63	93.35	98.01	96.19	100.26	99.43
Si ⁴⁺ (<i>apfu</i>)	3.293	3.216	3.273	3.307	3.182	3.225	3.274	3.325	3.200	3.234	3.203
Ti ⁴⁺	b.d.	0.004	b.d.	b.d.							
Al ³⁺	2.440	2.257	2.194	2.425	2.326	2.306	2.471	2.233	2.664	2.548	2.592
Cr ³⁺	b.d.										
$Fe^{3+}{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.136	0.302	0.200	0.128	0.359	0.283	0.170	0.181	0.081	0.092	0.113

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5-F1	R5F-A3	R5F-A3								
Unit	Rau 5										
Туре	Primary										
Zone	-	Rim	-	Rim	Rim	Rim	Core	Core	Core	-	-
Mineral	*Ms	Ms									
Mg ²⁺ (<i>apfu</i>)	0.100	0.367	0.448	0.124	0.265	0.304	0.074	0.295	0.000	0.126	0.101
Ca ²⁺	0.003	b.d.	0.003	0.003	b.d.						
Mn ²⁺	b.d.	0.005	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	0.005	b.d.	b.d.
Na⁺	0.019	0.026	0.027	0.018	0.032	0.029	0.018	0.028	0.032	0.026	0.021
K+	1.000	0.980	0.990	0.961	0.990	0.971	0.977	1.012	0.983	0.959	0.960
Rb⁺	0.008	0.010	0.008	0.009	0.013	0.009	0.007	0.012	0.006	b.d.	b.d.
F ⁻	0.179	0.363	0.376	0.238	0.274	0.333	0.201	0.257	0.000	0.259	0.228
Cl	b.d.	0.005	0.004	b.d.	0.007	0.007	0.004	b.d.	b.d.	b.d.	b.d.
OH-	1.821	1.632	1.620	1.762	1.719	1.660	1.796	1.743	2.000	1.741	1.772
vacancy	1.030	0.853	0.885	1.017	0.863	0.882	1.011	0.967	1.046	1.000	0.990
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5F-A3							
Unit	Rau 5							
Туре	Primary							
Zone	Core	Rim	Rim	Rim	Rim	Rim	Core	Rim
Mineral	*Ms	Ms						
SiO ₂ (wt.%)	47.49	48.50	47.99	48.57	47.87	47.75	47.44	47.64
TiO ₂	b.d.							
Al ₂ O ₃	29.64	31.28	30.02	30.61	30.51	32.74	35.32	32.59
Cr ₂ O ₃	b.d.							
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.99	2.69	3.94	2.77	3.23	2.18	1.21	2.42
MgO	2.42	1.79	2.43	2.01	2.39	0.76	0.34	0.77
CaO	b.d.							
MnO	b.d.							
Na ₂ O	0.24	0.25	0.20	0.19	0.24	0.11	0.36	0.15
K ₂ O	11.04	10.92	11.00	10.89	10.84	11.39	11.01	10.90
Rb ₂ O	b.d.							
F	1.55	1.39	1.62	1.52	1.54	1.03	0.63	0.94
CI	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.67	3.82	3.67	3.74	3.72	3.97	4.23	4.00
−(O=F,CI)	-0.65	-0.59	-0.69	-0.64	-0.65	-0.43	-0.27	-0.40
Total	99.39	100.05	100.22	99.67	99.69	99.49	100.27	99.00
Si ⁴⁺ (<i>apfu</i>)	3.233	3.245	3.235	3.263	3.229	3.208	3.140	3.212
Ti ⁴⁺	b.d.							
Al ³⁺	2.378	2.467	2.385	2.424	2.425	2.593	2.755	2.589
Cr ³⁺	b.d.							
$Fe^{3+}{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.227	0.151	0.222	0.156	0.182	0.122	0.067	0.136

Table A.23. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5 pegmatite dike.

Sample	R5F-A3							
Unit	Rau 5							
Туре	Primary							
Zone	Core	Rim	Rim	Rim	Rim	Rim	Core	Rim
Mineral	*Ms	Ms						
Mg ²⁺ (<i>apfu</i>)	0.245	0.178	0.244	0.202	0.240	0.076	0.033	0.077
Ca ²⁺	b.d.							
Mn ²⁺	b.d.							
Na⁺	0.031	0.032	0.026	0.025	0.031	0.015	0.046	0.019
K+	0.959	0.932	0.946	0.933	0.933	0.977	0.930	0.937
Rb⁺	b.d.							
F ⁻	0.333	0.295	0.345	0.323	0.327	0.219	0.133	0.200
Cl	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.667	1.705	1.652	1.677	1.673	1.781	1.867	1.800
vacancy	0.917	0.960	0.914	0.955	0.924	1.000	1.005	0.985
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-A										
Unit	Rau 5U										
Туре	Primary										
Zone	Rim	Core	Rim	Core	_	_	_	Rim	Rim	Core	Rim
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	47.86	46.99	47.56	46.92	48.76	44.80	46.90	47.46	47.76	48.79	46.62
TiO ₂	b.d.										
Al ₂ O ₃	29.90	27.69	28.98	28.04	28.17	29.19	30.68	29.67	30.14	29.29	29.48
Cr_2O_3	b.d.										
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	3.46	4.02	3.23	4.22	1.95	6.41	3.65	3.72	3.03	1.71	4.48
MgO	1.20	4.01	2.05	2.25	3.27	2.36	0.66	0.90	1.08	2.09	0.70
CaO	b.d.	0.06	b.d.	b.d.	b.d.						
MnO	b.d.										
Na ₂ O	0.13	0.22	0.19	0.17	0.28	0.27	0.21	0.23	0.20	0.21	0.15
K ₂ O	11.24	11.17	11.25	11.11	11.02	10.97	11.03	11.32	11.05	11.40	11.20
Rb ₂ O	0.17	0.19	0.23	0.23	0.20	0.28	0.20	0.20	0.20	0.21	0.21
F	1.02	1.36	1.14	1.20	1.23	1.05	0.68	0.68	0.80	1.01	0.55
CI	b.d.	0.03	b.d.	0.04	b.d.	0.07	b.d.	b.d.	0.02	b.d.	b.d.
H_2O^{\ddagger}	3.89	3.70	3.81	3.72	3.81	3.78	4.02	4.02	3.98	3.92	4.03
−(O=F,Cl)	-0.43	-0.58	-0.48	-0.51	-0.52	-0.46	-0.29	-0.29	-0.34	-0.42	-0.23
Total	98.44	98.80	97.97	97.38	98.16	98.72	97.75	97.98	97.92	98.20	97.20
Si ⁴⁺ (<i>apfu</i>)	3.278	3.237	3.279	3.274	3.327	3.130	3.237	3.275	3.278	3.324	3.256
Ti ⁴⁺	b.d.										
Al ³⁺	2.413	2.248	2.355	2.307	2.266	2.404	2.496	2.413	2.438	2.352	2.427
Cr ³⁺	b.d.										
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.198	0.232	0.186	0.247	0.111	0.374	0.211	0.215	0.174	0.097	0.261

Table A.24. Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-A										
Unit	Rau 5U										
Туре	Primary										
Zone	Rim	Core	Rim	Core	-	-	-	Rim	Rim	Core	Rim
Mineral	*Ms	Ms									
Mg ²⁺ (<i>apfu</i>)	0.122	0.412	0.210	0.234	0.333	0.246	0.068	0.092	0.110	0.212	0.073
Ca ²⁺	b.d.	0.005	b.d.	b.d.	b.d.						
Mn ²⁺	b.d.										
Na⁺	0.018	0.029	0.026	0.023	0.037	0.036	0.028	0.031	0.027	0.028	0.020
K+	0.982	0.982	0.990	0.989	0.959	0.978	0.971	0.997	0.967	0.991	0.998
Rb⁺	0.007	0.008	0.010	0.010	0.009	0.013	0.009	0.009	0.009	0.009	0.010
F ⁻	0.222	0.296	0.248	0.264	0.265	0.232	0.149	0.149	0.174	0.217	0.122
Cl	b.d.	0.004	b.d.	0.005	b.d.	0.008	b.d.	b.d.	0.003	b.d.	b.d.
OH-	1.778	1.700	1.752	1.731	1.735	1.760	1.851	1.851	1.824	1.783	1.878
vacancy	0.988	0.871	0.969	0.938	0.963	0.845	0.989	1.005	0.999	1.015	0.983
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-A	R5U-A	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Primary	Primary	Primary	_	Primary	Secondary	Secondary	Primary	Primary	Primary
Zone	Rim	Core	_	_	_	-	-	_ ,	Rim	Rim	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.16	47.81	49.73	49.30	47.70	48.57	47.39	48.14	47.45	47.34	48.25
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	31.77	30.36	31.30	33.14	32.22	32.29	30.71	30.21	29.67	30.26	30.00
Cr ₂ O ₃	b.d.	b.d.	0.07	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.19	3.61	1.16	0.70	2.67	2.37	3.81	4.04	4.33	4.16	3.08
MgO	0.31	0.92	1.59	0.75	0.79	0.91	1.42	1.53	1.57	1.74	1.79
CaO	b.d.	0.07	0.06	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	b.d.
Na ₂ O	0.21	0.18	0.07	0.08	0.12	0.09	0.19	0.14	0.17	0.15	0.15
K ₂ O	11.32	11.01	11.07	10.46	11.35	11.27	11.37	11.47	11.45	11.34	11.23
Rb ₂ O	0.20	0.24	0.26	0.24	0.09	0.21	0.22	0.22	0.24	0.23	0.22
F	1.03	0.85	1.00	0.57	0.82	1.01	0.73	1.19	0.97	1.18	0.95
CI	b.d.	0.03	0.03	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.90	3.98	4.03	4.24	4.06	4.02	4.07	3.88	3.92	3.85	3.97
−(O=F,CI)	-0.43	-0.37	-0.43	-0.25	-0.35	-0.42	-0.31	-0.50	-0.41	-0.50	-0.40
Total	98.65	98.68	99.93	99.35	99.54	100.40	99.61	100.41	99.36	99.75	99.25
Si ⁴⁺ (<i>apfu</i>)	3.220	3.266	3.305	3.271	3.214	3.237	3.220	3.250	3.245	3.220	3.273
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.557	2.444	2.452	2.591	2.559	2.536	2.459	2.404	2.391	2.426	2.398
Cr ³⁺	b.d.	b.d.	0.004	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.182	0.206	0.065	0.039	0.150	0.132	0.216	0.228	0.247	0.237	0.175

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-A	R5U-A	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-B	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Primary	Primary	Primary	-	Primary	Secondary	Secondary	Primary	Primary	Primary
Zone	Rim	Core	-	-	-	-	-	-	Rim	Rim	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.031	0.094	0.157	0.074	0.079	0.091	0.144	0.154	0.160	0.176	0.181
Ca ²⁺	b.d.	0.005	0.004	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.
Na⁺	0.028	0.024	0.009	0.010	0.015	0.011	0.025	0.018	0.022	0.020	0.020
K+	0.986	0.959	0.938	0.885	0.976	0.958	0.986	0.988	0.999	0.985	0.972
Rb⁺	0.009	0.010	0.011	0.010	0.004	0.009	0.010	0.010	0.010	0.010	0.009
F ⁻	0.222	0.184	0.210	0.120	0.175	0.212	0.156	0.254	0.211	0.255	0.205
Cl	b.d.	0.004	0.003	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.778	1.812	1.787	1.876	1.825	1.788	1.844	1.746	1.789	1.745	1.795
vacancy	1.010	0.990	1.017	1.024	0.993	0.999	0.960	0.959	0.956	0.941	0.973
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Primary	Secondary	Secondary	Primary	Primary	Primary	-	Primary	Primary	Primary
Zone	Core	Rim	-	-	Core	Rim	Rim	-	Rim	Core	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.83	47.82	48.26	47.33	45.33	48.06	48.36	47.70	47.51	47.72	46.82
TiO ₂	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	30.04	30.21	31.47	31.32	29.58	30.15	30.24	31.88	32.58	29.60	33.00
Cr ₂ O ₃	b.d.	0.07	b.d.	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	4.54	3.53	2.21	3.02	5.19	1.47	1.07	2.69	2.13	3.70	1.93
MgO	1.77	1.82	1.40	1.28	2.48	2.69	2.80	0.95	0.85	2.09	0.87
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.10	0.16	0.17	0.13	0.24	0.21	0.22	0.09	0.17	0.16	0.18
K ₂ O	11.12	11.38	11.42	11.49	11.21	11.43	11.38	11.23	11.09	11.69	11.73
Rb ₂ O	0.19	0.18	0.23	0.18	0.27	0.22	0.25	0.16	0.12	0.31	0.18
F	1.06	1.22	0.75	0.97	1.50	1.07	1.01	0.58	0.66	1.25	0.91
CI	0.04	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.86	3.85	4.10	3.96	3.59	3.92	3.96	4.16	4.13	3.82	4.00
−(O=F,CI)	-0.45	-0.51	-0.32	-0.41	-0.64	-0.45	-0.43	-0.24	-0.28	-0.52	-0.38
Total	99.09	99.83	99.70	99.35	98.81	98.86	98.86	99.21	98.97	99.81	99.24
Si ⁴⁺ (<i>apfu</i>)	3.211	3.239	3.245	3.213	3.147	3.257	3.267	3.224	3.207	3.247	3.167
Ti ⁴⁺	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.427	2.412	2.494	2.506	2.420	2.408	2.408	2.539	2.592	2.373	2.631
Cr ³⁺	b.d.	0.004	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.260	0.200	0.124	0.171	0.302	0.083	0.061	0.152	0.120	0.211	0.109

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Primary	Secondary	Secondary	Primary	Primary	Primary	-	Primary	Primary	Primary
Zone	Core	Rim	-	-	Core	Rim	Rim	-	Rim	Core	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (<i>apfu</i>)	0.181	0.184	0.140	0.130	0.256	0.271	0.282	0.096	0.086	0.212	0.088
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.013	0.021	0.022	0.018	0.033	0.028	0.029	0.012	0.022	0.022	0.024
K+	0.972	0.984	0.980	0.995	0.993	0.988	0.981	0.969	0.955	1.014	1.012
Rb⁺	0.008	0.008	0.010	0.008	0.012	0.010	0.011	0.007	0.005	0.013	0.008
F ⁻	0.229	0.261	0.159	0.209	0.330	0.229	0.216	0.123	0.142	0.268	0.194
Cl	0.004	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.767	1.739	1.841	1.791	1.665	1.771	1.784	1.877	1.858	1.732	1.806
vacancy	0.921	0.957	0.998	0.976	0.876	0.976	0.982	0.988	0.994	0.958	1.005
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-C	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Secondary	Primary								
Zone	-	-	-	Rim	Core	Core	_	_	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	48.88	46.00	47.76	48.44	45.35	48.94	48.06	47.55	47.81	48.71	47.57
TiO ₂	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	31.52	31.11	30.42	31.54	29.62	30.75	31.21	33.17	32.40	31.17	30.32
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.11
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	1.86	4.49	3.41	1.06	5.36	2.31	3.68	1.85	2.17	2.11	2.57
MgO	1.62	1.87	1.60	1.87	2.71	2.21	1.22	0.90	0.94	1.60	1.81
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.18	0.27	0.23	0.25	0.25	0.19	0.19	0.12	0.13	0.15	0.14
K ₂ O	11.41	11.20	11.52	11.52	11.19	11.37	11.08	11.16	11.52	11.34	11.34
Rb ₂ O	0.15	0.27	0.24	0.20	0.29	0.28	0.24	0.15	0.19	0.13	0.24
F	0.72	0.90	1.07	1.04	0.99	0.99	1.16	0.62	b.d.	1.11	0.87
CI	b.d.	0.03	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	4.15	3.96	3.92	3.98	3.86	4.03	3.91	4.17	4.46	3.95	3.98
−(O=F,CI)	-0.30	-0.39	-0.45	-0.44	-0.43	-0.42	-0.49	-0.26	0.00	-0.47	-0.37
Total	100.18	99.71	99.71	99.47	99.43	100.65	100.25	99.44	99.61	99.79	98.59
Si ⁴⁺ (apfu)	3.260	3.142	3.239	3.250	3.132	3.263	3.233	3.191	3.214	3.265	3.247
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.477	2.505	2.432	2.494	2.411	2.416	2.474	2.623	2.567	2.462	2.439
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.104	0.256	0.194	0.059	0.310	0.129	0.207	0.104	0.122	0.118	0.147

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-C	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D	R5U-D
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Secondary	Primary								
Zone	-	-	-	Rim	Core	Core	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (<i>apfu</i>)	0.161	0.190	0.162	0.187	0.279	0.220	0.123	0.090	0.094	0.160	0.184
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.023	0.036	0.030	0.033	0.034	0.024	0.025	0.015	0.017	0.020	0.019
K+	0.971	0.976	0.997	0.986	0.986	0.967	0.951	0.955	0.988	0.969	0.988
Rb⁺	0.006	0.012	0.010	0.009	0.013	0.012	0.010	0.007	0.008	0.006	0.011
F ⁻	0.153	0.195	0.229	0.221	0.216	0.209	0.247	0.132	b.d.	0.235	0.189
Cl	b.d.	0.003	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.847	1.802	1.771	1.779	1.778	1.791	1.753	1.868	2.000	1.765	1.811
vacancy	0.999	0.906	0.973	1.010	0.859	0.973	0.963	0.991	1.004	0.994	0.978
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-D	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Secondary	Secondary	Secondary	-	Secondary	Secondary	Secondary	Secondary	Secondary
Zone	-	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.25	48.65	46.82	47.46	47.10	47.43	48.50	46.44	48.94	47.00
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.	0.09	b.d.
Al ₂ O ₃	31.80	30.32	30.28	30.35	33.91	35.54	31.25	30.18	30.34	32.06
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	2.90	1.71	3.86	3.68	2.24	1.07	2.13	5.07	2.46	2.16
MgO	0.74	2.19	2.06	1.95	0.30	0.03	1.36	2.31	1.91	0.98
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.10	0.14	0.19	0.19	0.21	0.21	0.16	0.22	0.14	0.14
K ₂ O	11.75	11.27	11.08	11.21	11.26	10.94	11.41	11.17	11.29	11.40
Rb ₂ O	0.15	0.20	0.20	0.23	0.15	0.17	0.12	0.31	0.26	0.18
F	0.83	0.99	1.23	0.85	0.92	0.54	0.86	1.24	1.11	b.d.
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.
H_2O^{\ddagger}	4.02	3.97	3.80	4.01	4.03	4.27	4.05	3.80	3.94	4.40
−(O=F,CI)	-0.35	-0.42	-0.52	-0.36	-0.39	-0.23	-0.36	-0.53	-0.47	0.00
Total	99.20	99.02	99.00	99.58	99.73	99.98	99.64	100.24	100.03	98.32
Si ⁴⁺ (apfu)	3.210	3.283	3.203	3.223	3.161	3.145	3.258	3.166	3.283	3.203
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	0.005	b.d.
Al ³⁺	2.547	2.412	2.441	2.430	2.682	2.778	2.474	2.425	2.399	2.575
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.165	0.097	0.221	0.209	0.126	0.060	0.120	0.289	0.138	0.123

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-D	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Primary	Secondary	Secondary	Secondary	-	Secondary	Secondary	Secondary	Secondary	Secondary
Zone	-	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (apfu)	0.075	0.220	0.211	0.197	0.030	0.003	0.136	0.235	0.191	0.100
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.014	0.018	0.026	0.025	0.027	0.026	0.020	0.030	0.019	0.018
K⁺	1.018	0.970	0.967	0.971	0.964	0.926	0.978	0.971	0.966	0.991
Rb⁺	0.006	0.009	0.009	0.010	0.006	0.007	0.005	0.013	0.011	0.008
F ⁻	0.179	0.212	0.266	0.183	0.195	0.113	0.183	0.267	0.236	b.d.
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.
OH-	1.821	1.788	1.734	1.817	1.805	1.887	1.817	1.728	1.764	2.000
vacancy	1.003	0.988	0.924	0.941	1.001	1.014	1.006	0.886	0.985	0.999
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-G
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U				
Туре	Primary	Primary	Primary	Primary	Secondary	Secondary	Secondary	Secondary	Secondary	-
Zone	Rim	Core	Rim	Core	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	48.52	47.01	48.91	47.24	48.58	47.82	46.41	47.51	47.99	47.97
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	31.98	32.46	30.13	32.37	31.06	30.89	34.10	32.13	31.44	30.02
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.48	2.09	2.51	2.29	2.24	2.35	2.23	2.02	2.43	2.85
MgO	0.99	0.68	1.49	0.73	1.62	2.09		0.93	1.08	2.14
CaO	b.d.	0.05	0.06	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	0.07
Na ₂ O	0.09	0.18	0.07	0.16	0.16	0.20	0.20	0.11	0.17	0.20
K ₂ O	11.61	11.61	11.48	11.32	11.54	11.49	11.59	11.49	11.31	11.15
Rb ₂ O	0.18	0.21	0.18	0.13	0.20	0.17	0.19	0.15	0.22	0.20
F	0.83	1.11	0.81	0.62	1.46	1.42	0.38	0.89	1.05	0.82
CI	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	4.09	3.89	4.06	4.13	3.77	3.77	4.25	4.00	3.94	4.03
−(O=F,CI)	-0.35	-0.47	-0.34	-0.26	-0.62	-0.60	-0.16	-0.38	-0.44	-0.34
Total	100.41	98.82	99.47	98.73	100.04	99.60	99.20	98.87	99.27	99.11
Si ⁴⁺ (<i>apfu</i>)	3.241	3.195	3.300	3.205	3.260	3.229	3.139	3.218	3.244	3.257
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.518	2.600	2.396	2.589	2.456	2.458	2.718	2.565	2.504	2.402
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.139	0.119	0.142	0.130	0.126	0.133	0.126	0.115	0.137	0.162

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F	R5U-G
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U				
Туре	Primary	Primary	Primary	Primary	Secondary	Secondary	Secondary	Secondary	Secondary	-
Zone	Rim	Core	Rim	Core	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (<i>apfu</i>)	0.098	0.069	0.150	0.074	0.162	0.210	0.000	0.094	0.109	0.217
Ca ²⁺	b.d.	0.004	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	0.004
Na⁺	0.011	0.024	0.010	0.021	0.021	0.026	0.027	0.015	0.023	0.026
K+	0.990	1.006	0.989	0.980	0.988	0.990	1.000	0.993	0.975	0.966
Rb⁺	0.008	0.009	0.008	0.006	0.009	0.007	0.008	0.006	0.010	0.009
F ⁻	0.176	0.238	0.172	0.133	0.310	0.302	0.081	0.192	0.224	0.175
Cl	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.824	1.762	1.828	1.867	1.686	1.698	1.919	1.808	1.776	1.825
vacancy	1.004	1.018	1.006	1.003	0.997	0.970	1.016	1.008	1.000	0.958
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R5U-G	R5U-I								
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Secondary	Primary								
Zone	_	Rim	Core	_	Rim	_	Core	Rim	Core	_
Mineral	*Ms	Ms								
SiO ₂ (wt.%)	48.30	47.74	47.04	47.73	48.11	46.52	47.36	48.74	45.28	47.05
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.24	32.21	28.71	31.47	29.06	29.24	32.03	30.75	29.26	29.89
Cr ₂ O ₃	b.d.	0.06	b.d.							
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	2.97	2.09	3.63	2.83	2.42	4.51	2.36	2.52	5.68	4.26
MgO	2.50	1.09	3.47	1.04	2.56	2.93	1.04	1.82	2.83	2.33
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.
MnO	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	0.13	b.d.	b.d.	b.d.
Na ₂ O	0.17	0.18	0.11	0.14	0.14	0.20	0.08	0.15	0.16	0.16
K ₂ O	11.32	11.36	11.26	11.60	11.48	10.98	11.48	11.48	11.51	11.33
Rb ₂ O	0.20	0.22	0.18	0.22	0.24	0.25	0.19	0.21	0.27	0.25
F	1.20	0.71	1.21	0.92	1.34	0.96	1.05	1.31	0.91	0.92
CI	0.02	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	0.07	0.03
H_2O^{\ddagger}	3.84	4.12	3.80	4.00	3.75	3.90	3.93	3.85	3.88	3.96
−(O=F,CI)	-0.51	-0.30	-0.51	-0.39	-0.56	-0.41	-0.44	-0.55	-0.40	-0.39
Total	99.33	99.49	98.89	99.57	98.53	99.18	99.20	100.28	99.45	99.79
Si ⁴⁺ (apfu)	3.279	3.214	3.227	3.229	3.288	3.194	3.207	3.265	3.136	3.206
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.340	2.556	2.320	2.509	2.341	2.366	2.557	2.428	2.388	2.400
Cr ³⁺	b.d.	0.003	b.d.							
$Fe^{3+}_{(min)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.169	0.118	0.208	0.160	0.138	0.259	0.134	0.141	0.329	0.243

Table A.24. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 5U pegmatite dike.

Sample	R5U-G	R5U-I								
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Туре	Secondary	Primary								
Zone	-	Rim	Core	-	Rim	_	Core	Rim	Core	-
Mineral	*Ms	Ms								
Mg ²⁺ (<i>apfu</i>)	0.253	0.109	0.354	0.105	0.261	0.299	0.105	0.182	0.293	0.237
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	b.d.	b.d.	b.d.
Na⁺	0.023	0.023	0.015	0.018	0.018	0.026	0.010	0.019	0.021	0.021
K ⁺	0.981	0.976	0.985	1.001	1.001	0.962	0.992	0.981	1.017	0.985
Rb⁺	0.009	0.010	0.008	0.010	0.011	0.011	0.008	0.009	0.012	0.011
F⁻	0.257	0.150	0.263	0.196	0.290	0.208	0.224	0.279	0.199	0.198
Cl-	0.003	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	0.008	0.004
OH-	1.740	1.850	1.737	1.804	1.710	1.787	1.776	1.721	1.793	1.798
vacancy	0.955	0.999	0.891	0.998	0.973	0.881	0.990	0.984	0.855	0.914
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R6-A	R6-A	R6-A	R6-A	R6-A	R6-A	R7-A	R7-A	R7-A	R7-A
Unit	Rau 6	Rau 7	Rau 7	Rau 7	Rau 7					
Туре	Secondary	Secondary	Secondary	Secondary	Secondary	Secondary	Primary	Secondary	Secondary	Primary
Zone	-	-	Rim	Core	Rim	Core	Rim	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.80	48.33	47.30	47.28	47.88	46.91	46.18	47.11	47.49	47.29
Al ₂ O ₃	31.98	32.00	30.21	29.74	32.20	29.34	28.81	29.39	29.86	29.56
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.00	2.52	3.98	3.98	2.33	4.77	5.27	4.04	4.03	4.14
MgO	0.63	1.06	2.08	2.26	0.96	2.53	3.00	2.71	2.03	2.82
CaO	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.14	0.12	0.25	0.27	0.12	0.16	0.18	0.18	0.22	0.20
K ₂ O	11.14	11.35	11.00	10.90	11.31	11.09	11.06	11.31	11.21	10.82
Rb ₂ O	b.d.	0.11	0.20	0.13	0.12	0.14	0.16	0.23	0.21	0.11
F	0.72	1.02	1.25	0.89	0.79	1.33	1.76	1.54	1.21	1.50
CI	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	0.04	b.d.	b.d.	0.03
H_2O^{\ddagger}	4.10	4.00	3.82	3.97	4.08	3.74	3.50	3.66	3.83	3.69
−(O=F,CI)	-0.30	-0.43	-0.53	-0.37	-0.33	-0.57	-0.75	-0.65	-0.51	-0.64
Total	99.20	100.17	99.62	99.05	99.48	99.49	99.21	99.53	99.57	99.52
Si ⁴⁺ (<i>apfu</i>)	3.229	3.234	3.216	3.228	3.222	3.210	3.186	3.218	3.233	3.218
Al ³⁺	2.547	2.524	2.420	2.393	2.554	2.366	2.343	2.366	2.396	2.371
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.170	0.141	0.226	0.227	0.131	0.273	0.304	0.231	0.229	0.236
Mg ²⁺	0.063	0.106	0.211	0.230	0.096	0.258	0.308	0.276	0.206	0.287
Ca ²⁺	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.018	0.016	0.033	0.036	0.016	0.022	0.024	0.024	0.029	0.027

Table A.25. Chemical compositions and structural formulae of muscovite in the Rau 6 and 7 pegmatite dikes.

Sample	R6-A	R6-A	R6-A	R6-A	R6-A	R6-A	R7-A	R7-A	R7-A	R7-A
Unit	Rau 6	Rau 7	Rau 7	Rau 7	Rau 7					
Туре	Secondary	Secondary	Secondary	Secondary	Secondary	Secondary	Primary	Secondary	Secondary	Primary
Zone	-	-	Rim	Core	Rim	Core	Rim	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
K ⁺ (apfu)	0.960	0.969	0.954	0.950	0.971	0.968	0.973	0.985	0.973	0.939
Rb⁺	b.d.	0.005	0.009	0.006	0.005	0.006	0.007	0.010	0.009	0.005
F ⁻	0.154	0.215	0.270	0.192	0.168	0.287	0.383	0.332	0.260	0.324
Cl-	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	0.004	b.d.	b.d.	0.004
OH-	1.846	1.785	1.730	1.808	1.832	1.708	1.613	1.668	1.740	1.673
vacancy	0.991	0.990	0.927	0.921	0.996	0.892	0.860	0.910	0.936	0.889
O ^{2_}	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Titanium, Cr, and Cs were also sought but were below the detection limit of the EMP in all analyses.

Sample	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b
Unit	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8					
Туре	Primary	Primary	Primary	Primary	Primary	Primary	-	-	Primary	Primary	Primary	Primary
Zone	Rim	Core	-	-	Rim	Core	Rim	Core	Rim	Core	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.34	46.35	48.20	45.69	46.91	46.72	49.26	46.89	47.98	46.07	46.61	45.35
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.12	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.95	29.32	31.01	29.90	30.28	29.72	28.07	29.22	29.09	30.35	29.33	29.42
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	4.32	4.86	2.48	4.47	3.15	3.61	3.06	4.22	3.87	4.60	3.93	5.18
MgO	1.80	1.84	1.46	1.80	1.54	2.14	3.16	2.20	1.88	1.56	2.11	2.10
CaO	b.d.	0.04	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.18	0.17	0.27	0.21	0.22	0.20	0.08	0.15	0.18	0.22	0.13	0.24
K ₂ O	11.13	10.91	11.07	10.88	11.22	11.09	11.42	11.21	11.15	11.26	11.00	10.93
Rb ₂ O	0.17	0.14	b.d.	0.11	0.09	0.14	0.22	0.22	0.14	0.23	0.17	0.20
F	1.13	0.88	0.89	1.36	0.90	1.05	1.90	0.91	1.18	1.11	1.27	0.86
CI	0.03	0.05	b.d.	0.03	b.d.	b.d.	b.d.	0.04	b.d.	0.05	b.d.	0.12
H_2O^{\ddagger}	3.80	3.89	4.02	3.65	3.93	3.85	3.54	3.91	3.82	3.81	3.72	3.85
−(O=F,CI)	-0.48	-0.38	-0.37	-0.58	-0.38	-0.44	-0.80	-0.39	-0.50	-0.48	-0.54	-0.39
Total	98.37	98.08	99.01	97.56	97.84	98.19	99.90	98.57	98.79	98.77	97.74	97.90
Si ⁴⁺ (<i>apfu</i>)	3.201	3.215	3.257	3.183	3.232	3.219	3.328	3.231	3.283	3.178	3.231	3.168
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.438	2.397	2.470	2.455	2.458	2.413	2.235	2.374	2.346	2.468	2.396	2.422
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.250	0.282	0.140	0.261	0.182	0.208	0.173	0.243	0.222	0.265	0.228	0.303
Mg ²⁺	0.186	0.191	0.147	0.187	0.158	0.220	0.318	0.226	0.192	0.161	0.218	0.219
Ca ²⁺	b.d.	0.003	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.003

Table A.26. Chemical compositions and structural formulae of muscovite in the Rau 8 pegmatite dike.

Sample	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b
Unit	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8					
Туре	Primary	Primary	Primary	Primary	Primary	Primary	-	-	Primary	Primary	Primary	Primary
Zone	Rim	Core	-	-	Rim	Core	Rim	Core	Rim	Core	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mn ²⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ⁺	0.024	0.023	0.035	0.028	0.029	0.026	0.010	0.020	0.024	0.029	0.018	0.033
K⁺	0.981	0.966	0.955	0.967	0.986	0.974	0.984	0.986	0.973	0.991	0.973	0.974
Rb⁺	0.008	0.006	b.d.	0.005	0.004	0.006	0.009	0.010	0.006	0.010	0.008	0.009
F⁻	0.246	0.194	0.190	0.300	0.196	0.230	0.407	0.197	0.256	0.242	0.279	0.191
Cl-	0.004	0.005	b.d.	0.004	b.d.	b.d.	b.d.	0.004	b.d.	0.006	b.d.	0.014
OH-	1.750	1.801	1.810	1.696	1.804	1.770	1.593	1.799	1.744	1.752	1.721	1.795
vacancy	0.926	0.915	0.986	0.914	0.970	0.935	0.947	0.926	0.958	0.928	0.928	0.889
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Cesium was also sought but were below the detection limit of the EMP in all analyses.

Sample	R9b-2c	R9b-2c	R9b-2c	R9b-2c	R9b-2c	R9b-2c
Unit	Rau 9	Rau 9	Rau 9	Rau 9	Rau 9	Rau 9
Туре	Primary	Primary	-	Primary	Primary	Primary
Zone	Core	Rim	-	Rim	Core	Rim
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	44.59	44.47	46.40	46.32	44.32	46.56
Al ₂ O ₃	30.31	30.16	29.73	30.65	29.79	30.08
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	7.21	6.85	4.11	4.04	7.41	5.16
MgO	1.55	1.48	1.32	1.45	1.72	1.42
Na ₂ O	0.22	0.20	0.14	0.13	0.18	0.17
K ₂ O	11.00	11.12	10.64	11.08	10.96	11.12
Rb ₂ O	0.27	0.29	0.20	0.22	0.23	0.19
F	0.68	0.84	0.52	0.00	1.09	0.53
CI	0.12	0.09	b.d.	b.d.	0.11	b.d.
H_2O^{\ddagger}	3.96	3.87	4.05	4.35	3.74	4.11
−(O=F,CI)	-0.31	-0.37	-0.22	0.00	-0.48	-0.22
Total	99.61	99.00	96.91	98.24	99.08	99.12
Si ⁴⁺ (<i>apfu</i>)	3.096	3.104	3.236	3.192	3.099	3.200
Al ³⁺	2.481	2.482	2.443	2.489	2.455	2.436
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.418	0.400	0.240	0.233	0.434	0.297
Mg ²⁺	0.161	0.155	0.137	0.149	0.179	0.146
Na⁺	0.030	0.026	0.019	0.018	0.024	0.022
K+	0.974	0.990	0.947	0.974	0.978	0.975
Rb⁺	0.012	0.013	0.009	0.010	0.011	0.009
F-	0.150	0.186	0.115	0.000	0.240	0.116
Cl	0.014	0.011	b.d.	b.d.	0.014	b.d.
OH-	1.836	1.804	1.885	2.000	1.746	1.884
vacancy	0.844	0.860	0.944	0.937	0.833	0.921
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000

Table A.27. Chemical compositions and structural formulae of muscovite in the Rau 9 pegmatite dike.

Titanium, Cr, Ca, Mn, and Cs was also sought but were below the detection limit of the EMP in all analyses.

Sample	R10-1a	R10-1a	R10-1a	R10-1a	R10-1a						
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10						
Туре	Primary	-	Primary	Primary	Primary						
Zone	Rim	Rim	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	48.72	47.27	46.66	47.03	48.07	49.25	48.04	48.09	48.01	47.26	48.22
TiO ₂	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.18	33.87	34.09	32.85	32.47	31.30	31.11	32.81	31.74	32.78	30.89
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}{}^{\dagger}$	1.25	1.21	1.15	1.11	1.79	1.08	1.80	1.38	1.27	1.52	1.41
MgO	3.22	0.48	0.31	0.66	0.89	2.12	1.84	1.09	1.60	0.90	1.93
CaO	b.d.	b.d.	b.d.	0.07	0.04	b.d.	b.d.	0.06	0.05	b.d.	b.d.
MnO	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.14	0.21	0.23	0.19	0.25	0.10	0.19	0.27	0.26	0.27	0.22
K₂O	11.09	10.65	11.03	10.78	11.29	11.65	10.89	11.14	10.95	11.29	10.92
Rb ₂ O	0.13	0.08	0.11	0.10	0.07	0.12	0.17	0.13	0.11	0.13	0.12
F	1.31	0.64	0.42	0.45	0.71	1.29	0.85	0.60	1.04	0.54	0.87
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.80	4.14	4.22	4.18	4.13	3.90	4.02	4.20	3.95	4.18	4.01
−(O=F,CI)	-0.55	-0.27	-0.18	-0.19	-0.30	-0.54	-0.36	-0.25	-0.44	-0.23	-0.37
Total	98.29	98.28	98.05	97.24	99.57	100.28	98.57	99.52	98.53	98.63	98.22
Si ⁴⁺ (apfu)	3.306	3.187	3.163	3.209	3.223	3.274	3.252	3.217	3.242	3.198	3.268
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.334	2.691	2.723	2.642	2.566	2.452	2.482	2.587	2.526	2.614	2.467
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.071	0.068	0.065	0.063	0.100	0.060	0.102	0.077	0.072	0.086	0.080
Mg ²⁺	0.326	0.049	0.031	0.067	0.089	0.211	0.185	0.109	0.161	0.091	0.195
Ca ²⁺	b.d.	b.d.	b.d.	0.005	0.003	b.d.	b.d.	0.004	0.004	b.d.	b.d.

Table A.28. Chemical compositions and structural formulae of muscovite in the Rau 10 pegmatite dike.
Sample	R10-1a	R10-1a	R10-1a	R10-1a	R10-1a						
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10						
Туре	Primary	-	Primary	Primary	Primary						
Zone	Rim	Rim	-	-	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mn ²⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.018	0.027	0.030	0.025	0.033	0.013	0.025	0.035	0.034	0.035	0.029
K ⁺	0.959	0.916	0.954	0.939	0.966	0.988	0.940	0.951	0.943	0.974	0.944
Rb⁺	0.006	0.004	0.005	0.004	0.003	0.005	0.008	0.006	0.005	0.006	0.005
F ⁻	0.281	0.136	0.091	0.098	0.151	0.271	0.182	0.126	0.222	0.115	0.186
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
OH-	1.719	1.864	1.909	1.902	1.849	1.729	1.815	1.874	1.778	1.885	1.814
vacancy	0.964	1.006	1.018	1.019	1.014	1.003	0.979	1.010	1.000	1.012	0.990
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + Cl + OH) = 2 per formula unit.

Chromium and Cs was also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R10-1a	R10-1a	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10
Туре	Primary	Primary	-	-	Primary	Secondary	Secondary	Secondary
Zone	Rim	Core	-	-	Core	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	48.60	46.31	46.66	46.61	46.02	46.45	46.26	46.90
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	29.61	33.56	32.97	34.18	32.92	33.10	35.04	34.47
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.99	1.08	2.56	1.37	2.35	1.88	0.96	1.36
MgO	2.98	0.43	0.12	0.08	0.00	0.09	0.05	0.05
CaO	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	0.07	0.04
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.16	0.19	0.21	0.18	0.29	0.20	0.25	0.14
K ₂ O	11.48	11.09	11.03	11.01	11.13	11.08	11.14	11.06
Rb ₂ O	0.15	0.08	0.08	b.d.	0.07	0.03	0.12	0.09
F	1.54	0.53	0.74	b.d.	b.d.	b.d.	b.d.	b.d.
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.69	4.13	4.04	4.42	4.35	4.37	4.44	4.45
−(O=F,CI)	-0.65	-0.22	-0.31	0.00	0.00	0.00	0.00	0.00
Total	98.56	97.18	98.09	97.88	97.13	97.20	98.32	98.56
Si ⁴⁺ (<i>apfu</i>)	3.293	3.168	3.184	3.162	3.172	3.186	3.126	3.161
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	2.365	2.706	2.652	2.733	2.674	2.676	2.790	2.738
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.056	0.062	0.146	0.078	0.135	0.108	0.054	0.076
Mg ²⁺	0.301	0.044	0.012	0.008	0.000	0.009	0.005	0.005
Ca ²⁺	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	0.005	0.003

Table A.28. (Continued) Chemical compositions and structural formulae of muscovite in the Rau 10 pegmatite dike.

Sample	R10-1a	R10-1a	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10
Туре	Primary	Primary	-	-	Primary	Secondary	Secondary	Secondary
Zone	Rim	Core	-	-	Core	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mn ²⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.021	0.026	0.028	0.024	0.038	0.027	0.033	0.019
K⁺	0.992	0.968	0.960	0.953	0.979	0.969	0.960	0.951
Rb⁺	0.007	0.004	0.003	b.d.	0.003	0.001	0.005	0.004
F ⁻	0.330	0.114	0.160	b.d.	b.d.	b.d.	b.d.	b.d.
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
OH-	1.670	1.886	1.840	2.000	2.000	2.000	2.000	2.000
vacancy	0.985	1.020	1.006	1.019	1.019	1.022	1.025	1.020
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 12 anions and (F + Cl + OH) = 2 per formula unit.

Chromium and Cs was also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1				
Mineral	*Zrc	Zrc	Zrc	Zrc	Zrc	Zrc	Zrc	Zrc	Zrc	Zrc	Zrc
P ₂ O ₅ (wt.%)	0.41	0.21	0.41	0.28	0.59	0.17	0.33	0.22	0.19	0.18	0.13
SiO ₂	31.73	30.91	30.66	30.73	31.21	30.85	31.13	30.79	30.67	29.79	31.76
ZrO ₂	43.49	55.37	55.64	53.33	35.71	55.13	56.53	55.65	54.14	53.16	57.65
HfO ₂	27.21	5.11	5.07	5.24	36.41	5.53	5.58	5.45	5.25	5.88	7.98
ThO ₂	b.d.	1.54	1.07	2.50	0.09	1.52	0.48	0.99	1.93	1.53	0.25
UO ₂	0.74	5.80	4.16	6.55	0.64	5.34	2.76	4.96	6.02	5.12	2.27
Sc ₂ O ₃	0.08	0.14	0.29	0.20	0.09	0.16	0.34	0.22	0.17	0.19	0.22
Y ₂ O ₃	0.27	0.58	1.40	0.95	0.50	0.64	0.94	0.75	0.63	0.66	0.38
Dy ₂ O ₃	0.07	0.11	0.25	0.18	0.21	0.13	0.18	0.10	0.13	0.14	0.10
Er ₂ O ₃	0.36	0.17	0.28	0.18	0.40	0.15	0.15	0.19	0.12	0.17	0.10
Yb ₂ O ₃	0.65	0.36	0.84	0.53	0.73	0.35	0.62	0.44	0.32	0.41	0.31
F	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
−(O=F)	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	105.00	100.28	100.10	100.67	106.56	99.98	99.03	99.75	99.56	97.21	101.15
P ⁵⁺ (<i>apfu</i>)	0.011	0.006	0.011	0.008	0.017	0.005	0.009	0.006	0.005	0.005	0.003
Si ⁴⁺	1.029	1.003	0.992	1.005	1.035	1.004	1.005	1.001	1.007	1.001	1.006
Zr ⁴⁺	0.688	0.877	0.878	0.851	0.577	0.875	0.890	0.882	0.866	0.871	0.891
Hf ⁴⁺	0.252	0.047	0.047	0.049	0.345	0.051	0.051	0.051	0.049	0.056	0.072
Th ⁴⁺	0.000	0.011	0.008	0.019	0.001	0.011	0.004	0.007	0.014	0.012	0.002
U ⁴⁺	0.005	0.042	0.030	0.048	0.005	0.039	0.020	0.036	0.044	0.038	0.016
Sc ³⁺	0.002	0.004	0.008	0.006	0.002	0.005	0.010	0.006	0.005	0.005	0.006
Y ³⁺	0.005	0.010	0.024	0.017	0.009	0.011	0.016	0.013	0.011	0.012	0.006
Dy ³⁺	0.001	0.001	0.003	0.002	0.002	0.001	0.002	0.001	0.001	0.001	0.001
Er ³⁺	0.004	0.002	0.003	0.002	0.004	0.002	0.002	0.002	0.001	0.002	0.001
Yb ³⁺	0.006	0.004	0.008	0.005	0.007	0.003	0.006	0.004	0.003	0.004	0.003

Table A.29. Chemical compositions and structural formulae of zircon in the Rau 1 pegmatite dike.

Sample	R1-J										
Unit	Rau 1										
Mineral	*Zrc	Zrc									
F⁻(<i>apfu</i>)	b.d.	b.d.	0.005	b.d.							
O ²⁻	4.000	4.000	3.998	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000

Titanium, AI, Fe, and Ca were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit.

Sample	R1-J	R1-J	R1-J	R1-J		R5F-A3	R5F-A3	R5F-A3
Unit	Rau 1	Rau 1	Rau 1	Rau 1	-	Rau 5	Rau 5	Rau 5
Mineral	*FI	FI	FI	FI	-	FI	FI	FI
P ₂ O ₅ (wt.%)	b.d.	b.d.	b.d.	b.d.		b.d.	b.d.	0.02
ThO ₂	b.d.	b.d.	b.d.	0.06		b.d.	b.d.	b.d.
Y ₂ O ₃	0.79	0.84	0.63	b.d.		0.11	b.d.	0.09
La ₂ O ₃	0.19	0.34	b.d.	b.d.		b.d.	b.d.	b.d.
Ce ₂ O ₃	0.69	0.79	b.d.	b.d.		0.44	b.d.	b.d.
Pr ₂ O ₃	b.d.	b.d.	b.d.	b.d.		0.10	b.d.	b.d.
Nd ₂ O ₃	0.51	0.53	b.d.	b.d.		0.33	b.d.	b.d.
Sm ₂ O ₃	0.15	0.15	b.d.	b.d.		0.11	b.d.	b.d.
Dy ₂ O ₃	b.d.	0.15	b.d.	b.d.		b.d.	b.d.	b.d.
Er ₂ O ₃	0.10	b.d.	b.d.	b.d.		b.d.	b.d.	b.d.
CaO	48.86	48.56	50.24	51.24		50.65	52.16	51.36
SrO	b.d.	b.d.	0.08	b.d.		b.d.	b.d.	b.d.
Na ₂ O	0.14	0.12	b.d.	b.d.		b.d.	b.d.	b.d.
F	47.29	47.36	47.61	48.11		48.46	49.22	48.67
Total	98.71	98.86	98.55	99.34		100.25	101.38	100.15
P ⁵⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.		b.d.	b.d.	0.000
Th ⁴⁺	b.d.	b.d.	b.d.	0.000		b.d.	b.d.	b.d.
Y ³⁺	0.008	0.008	0.006	b.d.		0.001	b.d.	0.001
La ³⁺	0.001	0.002	b.d.	b.d.		b.d.	b.d.	b.d.
Ce ³⁺	0.005	0.005	b.d.	b.d.		0.003	b.d.	b.d.
Pr ³⁺	b.d.	b.d.	b.d.	b.d.		0.001	b.d.	b.d.
Nd ³⁺	0.003	0.004	b.d.	b.d.		0.002	b.d.	b.d.
Sm ³⁺	0.001	0.001	b.d.	b.d.		0.001	b.d.	b.d.
Dy ³⁺	b.d.	0.001	b.d.	b.d.		b.d.	b.d.	b.d.
Er ³⁺	0.001	b.d.	b.d.	b.d.		b.d.	b.d.	b.d.
Ca ²⁺	0.976	0.974	0.993	1.000		0.992	1.000	0.999
Sr ²⁺	b.d.	b.d.	0.001	b.d.		b.d.	b.d.	b.d.
Na⁺	0.005	0.004	b.d.	b.d.		b.d.	b.d.	b.d.
F⁻	2.788	2.803	2.777	2.771		2.802	2.786	2.794

Table A.30. Chemical compositions and structural formulae of fluorite in the Rau 1 and 5 pegmatite dikes.

Silicon, Mg, Gd, Yb, Ba, Pb, K and Cl were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit.

Sample	R2-2a	R2-2a	R2-2a	R2-2a	R2-2a
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1
Zone	-	_	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr
WO ₃ (wt.%)	0.10	b.d.	0.20	0.06	b.d.
Nb ₂ O ₅	6.21	5.62	22.50	8.45	9.80
Ta ₂ O ₅	71.07	69.06	51.10	70.30	67.53
SiO ₂	0.07	0.51	0.02	b.d.	b.d.
TiO ₂	0.58	0.71	0.67	0.06	0.23
ZrO ₂	b.d.	0.20	0.05	b.d.	b.d.
SnO ₂	0.14	0.74	0.30	0.58	0.75
ThO ₂	b.d.	0.07	0.03	0.04	0.04
UO ₂	0.29	0.44	0.55	0.30	0.67
Al ₂ O ₃	0.06	0.16	0.16	0.06	0.07
Sc ₂ O ₃	b.d.	0.06	0.04	0.10	0.04
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.02	0.01	0.01	0.01
$FeO_{(max)}^{\dagger}$	0.14	0.37	0.75	0.49	0.49
Y_2O_3	0.02	0.09	0.02	0.03	b.d.
Sb ₂ O ₃	b.d.	0.11	0.08	b.d.	b.d.
Bi ₂ O ₃	b.d.	b.d.	0.20	b.d.	0.35
MgO	b.d.	0.02	0.03	b.d.	b.d.
CaO	11.89	12.58	15.88	13.40	13.35
MnO	0.01	0.02	0.10	0.07	0.06
ZnO	b.d.	b.d.	0.03	b.d.	b.d.
PbO	0.11	0.07	b.d.	b.d.	b.d.
Na ₂ O	5.15	4.30	4.37	3.84	4.78
F	3.71	3.50	3.48	3.20	3.40
-(O=F)	-1.56	-1.47	-1.47	-1.35	-1.43
Total	97.99	97.18	99.09	99.63	100.14
W ⁶⁺ (apfu)	0.002	b.d.	0.004	0.001	b.d.
Nb ⁵⁺	0.244	0.221	0.792	0.326	0.372
Ta⁵+	1.679	1.633	1.082	1.633	1.543
Si ⁴⁺	0.006	0.045	0.002	b.d.	b.d.
Ti ⁴⁺	0.038	0.047	0.039	0.004	0.015
Zr ⁴⁺	b.d.	0.008	0.002	b.d.	b.d.
Sn ⁴⁺	0.005	0.026	0.009	0.020	0.025
Th ⁴⁺	b.d.	0.001	0.001	0.001	0.001
U ⁴⁺	0.006	0.009	0.009	0.006	0.013
Al ³⁺	0.006	0.016	0.014	0.006	0.007

Table A.31. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 1 pegmatite dike.

Sample	R2-2a	R2-2a	R2-2a	R2-2a	R2-2a
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1
Zone	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr
Sc ³⁺ (<i>apfu</i>)	b.d.	0.005	0.003	0.007	0.003
Fe^{3+} (min) [†]	0.000	0.001	0.001	0.001	0.001
$Fe^{2+}(max)^{\dagger}$	0.010	0.027	0.049	0.035	0.034
Y ³⁺	0.001	0.004	0.001	0.001	b.d.
Sb ³⁺	b.d.	0.004	0.003	b.d.	b.d.
Bi ³⁺	b.d.	b.d.	0.004	b.d.	0.008
Mg ²⁺	b.d.	0.002	0.003	b.d.	b.d.
Ca ²⁺	1.107	1.172	1.325	1.227	1.201
Mn ²⁺	0.001	0.002	0.006	0.005	0.004
Zn ²⁺	b.d.	b.d.	0.001	b.d.	b.d.
Pb ²⁺	0.003	0.002	b.d.	b.d.	b.d.
Na⁺	0.867	0.726	0.659	0.636	0.779
F⁻	1.021	0.963	0.858	0.864	0.903
O ²⁻	5.979	6.037	6.143	6.137	6.098

The formulae were calculated on the basis of 7 anions per formula unit. *Fclmcr = fluorcalciomicrolite; [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e	R3-2e
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	-	-	_	_	_	-	-	Core	Rim	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr						
WO₃ (wt.%)	b.d.	b.d.	b.d.	b.d.	0.07	0.01	b.d.	b.d.	b.d.	0.01	b.d.
Nb_2O_5	7.88	6.59	35.12	32.03	16.24	15.86	10.21	12.54	12.60	8.92	6.45
Ta ₂ O ₅	68.05	70.33	34.73	35.54	59.25	61.54	66.17	63.60	62.83	68.03	71.17
SiO ₂	0.06	0.07	0.05	0.12	0.04	b.d.	b.d.	0.04	0.04	0.02	0.03
TiO ₂	1.07	1.07	1.46	2.84	1.22	0.81	1.22	1.76	1.83	0.76	1.15
ZrO ₂	0.03	b.d.	b.d.	0.09	0.17	0.14	0.05	0.09	b.d.	b.d.	0.06
SnO ₂	0.91	0.92	1.03	1.15	0.32	0.40	0.68	0.37	0.55	0.81	0.47
ThO ₂	0.11	0.05	0.06	0.11	b.d.	0.01	0.01	0.01	0.06	0.05	b.d.
UO ₂	0.49	0.39	1.27	2.11	0.04	0.03	0.55	0.85	0.81	0.45	0.42
Al ₂ O ₃	0.05	0.02	0.14	0.12	0.07	0.05	0.06	0.04	0.05	0.06	0.07
Sc ₂ O ₃	0.02	0.03	b.d.	0.04	0.11	0.06	b.d.	b.d.	0.03	b.d.	0.05
$Fe_2O_{3(\text{min})}^\dagger$	0.03	0.02	0.02	0.03	0.00	0.00	0.00	0.00	0.02	0.01	0.00
$FeO_{(max)}^{\dagger}$	0.11	0.04	0.39	0.36	0.36	0.31	0.27	0.34	0.30	0.18	0.17
Y_2O_3	0.02	b.d.	0.01	0.01	0.07	b.d.	0.14	0.04	b.d.	0.05	0.09
Sb ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.14	b.d.	b.d.	0.18	0.20
Bi ₂ O ₃	b.d.	0.01	b.d.	0.06	0.01	0.03	0.28	b.d.	b.d.	0.41	b.d.
MgO	0.01	0.01	b.d.	b.d.	b.d.	0.02	b.d.	0.01	b.d.	0.00	0.02
CaO	12.11	12.28	13.96	13.64	12.93	13.04	12.42	12.95	13.30	12.46	11.79
MnO	b.d.	0.02	b.d.	b.d.	0.90	0.16	b.d.	b.d.	0.02	0.05	0.01
ZnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.02	0.09	b.d.
PbO	0.08	b.d.	b.d.	0.07	b.d.	0.01	b.d.	b.d.	0.07	0.04	0.08
Na ₂ O	5.17	5.21	5.83	5.10	4.56	5.20	5.33	5.12	5.35	5.42	5.44
F	3.81	3.79	3.95	3.72	3.60	3.83	3.69	3.66	3.52	3.64	3.64
–(O=F)	-1.60	-1.59	-1.66	-1.56	-1.52	-1.61	-1.55	-1.54	-1.48	-1.53	-1.53

Table A.32. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 3 pegmatite dike.

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e	R3-2e
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	_	-	-	-	-	-	-	Core	Rim	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr						
Total	98.38	99.23	96.34	95.57	98.43	99.91	99.66	99.87	99.92	100.12	99.80
W ⁶⁺ (apfu)	b.d.	b.d.	b.d.	b.d.	0.002	0.000	b.d.	b.d.	b.d.	0.000	b.d.
Nb ⁵⁺	0.303	0.253	1.177	1.091	0.595	0.576	0.384	0.462	0.463	0.338	0.248
Ta⁵+	1.576	1.627	0.700	0.728	1.305	1.344	1.497	1.409	1.390	1.552	1.645
Si ⁴⁺	0.005	0.006	0.004	0.009	0.003	b.d.	b.d.	0.004	0.003	0.002	0.002
Ti ⁴⁺	0.068	0.068	0.081	0.161	0.074	0.049	0.077	0.108	0.112	0.048	0.074
Zr ⁴⁺	0.001	b.d.	b.d.	0.003	0.007	0.006	0.002	0.004	b.d.	b.d.	0.002
Sn ⁴⁺	0.031	0.031	0.030	0.035	0.010	0.013	0.022	0.012	0.018	0.027	0.016
Th ⁴⁺	0.002	0.001	0.001	0.002	b.d.	0.000	0.000	0.000	0.001	0.001	b.d.
U ⁴⁺	0.009	0.007	0.021	0.035	0.001	0.001	0.010	0.015	0.015	0.008	0.008
Al ³⁺	0.005	0.002	0.012	0.010	0.007	0.005	0.006	0.004	0.005	0.006	0.007
Sc ³⁺	0.002	0.002	b.d.	0.002	0.008	0.004	b.d.	b.d.	0.002	b.d.	0.004
$Fe^{3+}(min)^{\dagger}$	0.002	0.001	0.001	0.002	0.000	0.000	0.000	0.000	0.001	0.001	0.000
$Fe^{2+}(max)^{\dagger}$	0.008	0.003	0.024	0.023	0.024	0.021	0.019	0.023	0.020	0.013	0.012
Y ³⁺	0.001	b.d.	0.000	0.000	0.003	b.d.	0.006	0.002	b.d.	0.002	0.004
Sb ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	0.006	0.007
Bi ³⁺	b.d.	0.000	b.d.	0.001	0.000	0.001	0.006	b.d.	b.d.	0.009	b.d.
Mg ²⁺	0.001	0.001	b.d.	b.d.	b.d.	0.002	b.d.	0.001	b.d.	0.001	0.003
Ca ²⁺	1.105	1.120	1.108	1.101	1.122	1.122	1.107	1.130	1.159	1.120	1.074
Mn ²⁺	b.d.	0.002	b.d.	b.d.	0.062	0.011	b.d.	b.d.	0.001	0.004	0.001
Zn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	0.006	b.d.
Pb ²⁺	0.002	b.d.	b.d.	0.001	b.d.	0.000	b.d.	b.d.	0.002	0.001	0.002
Na⁺	0.853	0.859	0.838	0.745	0.717	0.810	0.860	0.808	0.843	0.882	0.897
F⁻	1.025	1.019	0.926	0.885	0.923	0.974	0.970	0.942	0.905	0.965	0.979
O ²⁻	5.976	5.981	6.075	6.116	6.077	6.026	6.030	6.058	6.096	6.036	6.021

Sample	R3-1b	R3-1b	R3-1b	R3-1b	R3-2d	R3-2d	R3-2e	R3-2e	R3-2e	R3-2e	R3-2e
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	-	-	-	_	_	_	_	Core	Rim	_
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr						

*FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-2e	R3-3	R3-3	R3-3	R3-3	R3-3	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	_	Rim	Core	_	_	-		
Mineral	*Fclmcr	Fclmcr						
WO₃ (wt.%)	b.d.	0.15	b.d.	0.36	0.01	0.12	0.37	0.25
Nb_2O_5	5.95	10.53	11.33	13.99	11.75	26.45	27.89	28.24
Ta ₂ O ₅	71.31	66.07	65.18	63.91	65.78	44.97	41.87	39.26
SiO ₂	0.04	b.d.	0.02	0.17	0.11	0.13	b.d.	0.07
TiO ₂	0.58	0.06	0.08	b.d.	b.d.	2.12	2.49	1.86
ZrO ₂	b.d.	b.d.	b.d.	0.01	0.07	b.d.	b.d.	b.d.
SnO ₂	0.47	0.49	0.56	0.49	0.36	0.18	0.61	0.54
ThO ₂	0.13	0.08	0.06	0.18	0.01	0.38	0.16	0.11
UO ₂	0.50	0.56	0.78	0.12	0.06	1.16	2.87	1.85
Al ₂ O ₃	0.18	b.d.	0.03	0.12	0.28	0.20	0.24	2.14
Sc ₂ O ₃	b.d.	0.01	0.05	b.d.	0.03	0.04	0.09	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.04	0.02	0.02	0.05	0.00	0.12	0.05	0.03
$FeO_{(max)}^{\dagger}$	0.22	0.68	0.60	0.45	0.41	0.49	0.44	0.43
Y_2O_3	b.d.	0.04	0.03	b.d.	0.02	0.09	0.04	0.02
Sb ₂ O ₃	0.17	0.03	0.10	0.19	0.03	0.03	b.d.	b.d.
Bi ₂ O ₃	0.08	0.02	0.22	0.15	0.37	b.d.	b.d.	b.d.
MgO	0.04	0.10	b.d.	0.01	b.d.	0.05	b.d.	b.d.
CaO	13.30	12.86	12.38	13.30	13.83	13.85	13.37	12.74
MnO	b.d.	b.d.	0.10	0.04	0.07	0.08	b.d.	b.d.
ZnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
PbO	b.d.	0.10	0.08	0.03	b.d.	b.d.	b.d.	b.d.
Na ₂ O	5.11	5.06	4.90	5.04	4.61	4.76	5.27	4.35
F	3.64	3.65	3.47	3.88	3.58	3.77	4.06	3.53
−(O=F)	-1.53	-1.54	-1.46	-1.63	-1.51	-1.59	-1.71	-1.49

Table A.32. (Continued) Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 3 pegmatite dike.

Sample	R3-2e	R3-3	R3-3	R3-3	R3-3	R3-3	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	Rim	Core	_	_	_		
Mineral	*Fclmcr	Fclmcr						
Total	100.19	98.99	98.52	100.85	99.87	97.39	98.09	93.93
W ⁶⁺ (apfu)	b.d.	0.003	b.d.	0.008	0.000	0.002	0.007	0.005
Nb ⁵⁺	0.228	0.402	0.435	0.511	0.439	0.916	0.952	0.986
Ta⁵+	1.646	1.515	1.504	1.406	1.479	0.937	0.860	0.824
Si ⁴⁺	0.003	b.d.	0.002	0.014	0.009	0.010	b.d.	0.005
Ti ⁴⁺	0.037	0.004	0.005	b.d.	b.d.	0.122	0.141	0.108
Zr ⁴⁺	b.d.	b.d.	b.d.	0.000	0.003	b.d.	b.d.	b.d.
Sn ⁴⁺	0.016	0.016	0.019	0.016	0.012	0.006	0.018	0.017
Th ⁴⁺	0.002	0.002	0.001	0.003	0.000	0.007	0.003	0.002
U ⁴⁺	0.009	0.011	0.015	0.002	0.001	0.020	0.048	0.032
Al ³⁺	0.018	b.d.	0.003	0.012	0.027	0.018	0.021	0.195
Sc ³⁺	b.d.	0.001	0.004	b.d.	0.002	0.002	0.006	b.d.
$Fe^{3+}(min)^{\dagger}$	0.002	0.002	0.001	0.003	0.000	0.007	0.003	0.002
$Fe^{2+}(max)^{\dagger}$	0.015	0.048	0.043	0.031	0.028	0.032	0.028	0.028
Y ³⁺	b.d.	0.002	0.002	b.d.	0.001	0.004	0.001	0.001
Sb ³⁺	0.006	0.001	0.004	0.006	0.001	0.001	b.d.	b.d.
Bi ³⁺	0.002	0.000	0.005	0.003	0.008	b.d.	b.d.	b.d.
Mg ²⁺	0.005	0.013	b.d.	0.001	b.d.	0.006	b.d.	b.d.
Ca ²⁺	1.209	1.162	1.125	1.152	1.225	1.136	1.082	1.054
Mn ²⁺	b.d.	b.d.	0.007	0.002	0.005	0.005	b.d.	b.d.
Zn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Pb ²⁺	b.d.	0.002	0.002	0.001	b.d.	b.d.	b.d.	b.d.
Na⁺	0.841	0.828	0.805	0.790	0.738	0.707	0.771	0.650
F⁻	0.978	0.974	0.931	0.993	0.936	0.913	0.971	0.863
O ²⁻	6.023	6.027	6.070	6.009	6.064	6.090	6.031	6.138

Sample	R3-2e	R3-3	R3-3	R3-3	R3-3	R3-3	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	Rim	Core	-	-	-		
Mineral	*FcImcr	Fclmcr						

*FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Table A.33. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 4 pegmatite dike.

Sample	R4-2d	R4-2d
Unit	Rau 4	Rau 4
Mineral	*FcImcr	Fclmcr
WO₃ (wt.%)	0.57	b.d.
Nb_2O_5	11.93	12.20
Ta ₂ O ₅	62.52	62.71
SiO ₂	0.06	0.09
TiO ₂	1.62	1.06
ZrO ₂	0.02	0.04
SnO ₂	1.08	1.73
ThO ₂	0.03	0.04
UO ₂	0.20	1.00
Al ₂ O ₃	0.03	0.07
Sc ₂ O ₃	0.02	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.01	0.01
FeO _(max) †	0.09	0.11
Y ₂ O ₃	0.02	b.d.
Sb ₂ O ₃	0.05	0.02
MgO	0.03	0.02
CaO	12.74	11.26
MnO	b.d.	0.06
ZnO	0.06	b.d.
PbO	b.d.	0.07
Na ₂ O	5.38	4.82
F	3.97	3.65
−(O=F)	-1.67	-1.54
Total	98.76	97.43
W ⁶⁺ (apfu)	0.012	b.d.
Nb ⁵⁺	0.442	0.465
Ta⁵⁺	1.393	1.440
Si ⁴⁺	0.005	0.008
Ti ⁴⁺	0.100	0.067
Zr ⁴⁺	0.001	0.001
Sn ⁴⁺	0.035	0.058
Th ⁴⁺	0.001	0.001
U ⁴⁺	0.004	0.019
Al ³⁺	0.003	0.006
Sc ³⁺	0.001	b.d.
Fe ³⁺ (min) [†]	0.001	0.001

Sample	R4-2d	R4-2d
Unit	Rau 4	Rau 4
Mineral	*Fclmcr	Fclmcr
Fe ²⁺ (max) [†] (<i>apfu</i>)	0.006	0.008
Y ³⁺	0.001	b.d.
Sb ³⁺	0.002	0.001
Mg ²⁺	0.004	0.003
Ca ²⁺	1.118	1.018
Mn ²⁺	b.d.	0.004
Zn ²⁺	0.004	b.d.
Pb ²⁺	b.d.	0.002
Na⁺	0.855	0.789
F-	1.029	0.975
O ^{2_}	5.971	6.025

The formulae were calculated on the basis of 7 anions per formula unit. Bismuth was also sought but was below the detection limit of the EMP in all analyses.

*FcImcr = fluorcalciomicrolite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-B
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	-	-	-	-	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclprc	Fclprc	Fclprc
WO ₃ (wt.%)	b.d.	b.d.	0.26	0.08	0.99	b.d.	0.55	0.36	0.58	0.66	0.56
Nb ₂ O ₅	4.83	7.35	29.35	30.04	18.35	21.77	26.47	24.73	37.36	34.51	27.29
Ta ₂ O ₅	73.15	70.53	41.94	40.57	57.17	51.89	43.25	47.88	29.28	32.87	43.18
SiO ₂	0.14	0.02	0.01	0.07	0.03	0.01	0.04	0.07	0.05	0.07	0.19
TiO ₂	0.27	0.39	2.02	1.75	0.85	1.33	2.08	1.92	3.40	3.11	1.90
ZrO ₂	0.13	0.02	0.06	0.07	0.02	0.09	0.09	0.06	b.d.	0.10	b.d.
SnO ₂	1.05	1.29	1.07	1.95	0.51	1.53	0.84	0.49	0.86	0.90	1.41
ThO ₂	b.d.	0.01	0.10	0.07	b.d.	b.d.	b.d.	0.10	0.46	0.27	0.20
UO ₂	0.23	0.12	0.70	1.22	0.27	0.59	0.93	0.64	1.50	1.50	1.39
Al ₂ O ₃	0.18	0.15	0.15	0.23	0.15	0.16	0.35	0.22	0.24	0.21	0.28
Sc ₂ O ₃	b.d.	b.d.	0.03	0.02	0.02	0.02	0.02	b.d.	0.03	0.07	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.03	0.02	0.00	0.00	0.00	0.03	0.14	0.08	0.06
$FeO_{(max)}^{\dagger}$	0.36	0.18	0.33	0.22	0.37	0.35	0.27	0.45	0.33	0.45	0.41
Y_2O_3	0.02	b.d.	b.d.	0.09	b.d.	0.01	0.02	b.d.	0.05	0.07	0.06
Sb ₂ O ₃	b.d.	b.d.	b.d.	0.06	b.d.	0.08	0.05	b.d.	0.10	b.d.	b.d.
Bi ₂ O ₃	0.14	b.d.	0.05	0.24	b.d.	0.27	b.d.	0.19	0.07	b.d.	b.d.
MgO	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	b.d.	0.01	0.03	0.01	0.01
CaO	12.53	11.31	14.50	13.41	13.85	13.30	13.85	13.67	14.41	14.83	12.75
MnO	b.d.	0.03	b.d.	0.06	0.03	b.d.	0.03	0.03	b.d.	b.d.	0.06
ZnO	b.d.	b.d.	0.12	b.d.	b.d.	0.01	b.d.	0.08	b.d.	b.d.	b.d.
PbO	b.d.	b.d.	0.01	b.d.	b.d.	0.05	b.d.	0.03	b.d.	0.14	0.23
Na ₂ O	5.13	5.48	5.69	5.64	5.62	5.65	5.42	5.85	5.58	5.41	3.12
F	3.91	3.83	4.02	3.79	4.01	3.88	3.93	3.96	3.89	3.80	3.45
−(O=F)	-1.65	-1.61	-1.69	-1.60	-1.69	-1.63	-1.65	-1.67	-1.64	-1.60	-1.45

Table A.34. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 5U pegmatite dike.

Sample	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-B
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	-	-	-	-	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclprc	Fclprc	Fclprc
Total	100.40	99.09	98.74	98.00	100.54	99.35	96.54	99.08	96.70	97.46	95.09
W ⁶⁺ (apfu)	b.d.	b.d.	0.005	0.002	0.020	b.d.	0.011	0.007	0.011	0.012	0.012
Nb ⁵⁺	0.186	0.284	0.984	1.019	0.649	0.765	0.917	0.850	1.214	1.132	0.972
Ta⁵+	1.694	1.639	0.846	0.828	1.216	1.096	0.901	0.990	0.573	0.649	0.925
Si ⁴⁺	0.012	0.001	0.000	0.006	0.002	0.001	0.003	0.005	0.003	0.005	0.015
Ti ⁴⁺	0.018	0.025	0.113	0.099	0.050	0.078	0.120	0.110	0.184	0.170	0.113
Zr ⁴⁺	0.005	0.001	0.002	0.003	0.001	0.004	0.003	0.002	b.d.	0.003	b.d.
Sn ⁴⁺	0.036	0.044	0.032	0.058	0.016	0.047	0.026	0.015	0.025	0.026	0.044
Th ⁴⁺	b.d.	0.000	0.002	0.001	b.d.	b.d.	b.d.	0.002	0.008	0.004	0.004
U ⁴⁺	0.004	0.002	0.012	0.020	0.005	0.010	0.016	0.011	0.024	0.024	0.024
Al ³⁺	0.018	0.015	0.013	0.020	0.014	0.014	0.032	0.019	0.020	0.018	0.026
Sc ³⁺	b.d.	b.d.	0.002	0.002	0.001	0.001	0.001	b.d.	0.002	0.005	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.002	0.001	0.000	0.000	0.000	0.002	0.008	0.004	0.004
$Fe^{2+}(max)^{\dagger}$	0.026	0.013	0.021	0.014	0.024	0.023	0.017	0.028	0.020	0.027	0.027
Y ³⁺	0.001	b.d.	b.d.	0.003	b.d.	0.000	0.001	b.d.	0.002	0.003	0.002
Sb ³⁺	b.d.	b.d.	b.d.	0.002	b.d.	0.002	0.001	b.d.	0.003	b.d.	b.d.
Bi ³⁺	0.003	b.d.	0.001	0.005	b.d.	0.005	b.d.	0.004	0.001	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	0.001	0.003	0.001	0.001
Ca ²⁺	1.143	1.036	1.153	1.078	1.161	1.107	1.137	1.113	1.110	1.154	1.076
Mn ²⁺	b.d.	0.002	b.d.	0.004	0.002	b.d.	0.002	0.002	b.d.	b.d.	0.004
Zn ²⁺	b.d.	b.d.	0.006	b.d.	b.d.	0.000	b.d.	0.004	b.d.	b.d.	b.d.
Pb ²⁺	b.d.	b.d.	0.000	b.d.	b.d.	0.001	b.d.	0.001	b.d.	0.003	0.005
Na⁺	0.846	0.908	0.818	0.821	0.851	0.851	0.805	0.861	0.778	0.761	0.476
F⁻	1.053	1.036	0.943	0.900	0.991	0.952	0.951	0.951	0.884	0.873	0.860
O ²⁻	5.947	5.964	6.058	6.101	6.009	6.048	6.049	6.050	6.120	6.129	6.142

Sample	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-A	R5U-B
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	-	-	-	-	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclprc	Fclprc	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclprc	Fclprc	Fclprc

The formulae were calculated on the basis of 7 anions per formula unit. *FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sampla						DELLO					
			Rou EU	Rou EU							
Unit	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50	Rau 50
Zone	-	RIM		RIM							
Mineral	*Fclmcr	Fclprc	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclprc
WO₃ (wt.%)	0.02	0.47	0.70	1.25	0.52	0.36	0.71	0.57	0.16	0.09	0.56
Nb ₂ O ₅	14.95	28.14	25.19	31.69	27.22	24.87	24.64	16.34	24.37	30.84	29.77
Ta₂O₅	60.24	44.53	48.34	40.66	47.57	50.07	49.51	57.35	49.52	38.80	40.82
SiO ₂	0.10	b.d.	0.03	0.07	b.d.	0.10	0.20	0.02	0.07	0.04	0.06
TiO ₂	1.61	1.05	1.10	1.38	1.24	0.87	0.74	1.98	1.35	2.03	2.09
ZrO ₂	0.11	0.16	0.18	0.19	0.23	0.07	0.03	0.57	0.04	b.d.	b.d.
SnO ₂	0.65	0.52	0.58	0.74	0.85	0.40	0.82	1.09	0.91	1.21	0.98
ThO ₂	0.01	0.01	0.10	b.d.	b.d.	b.d.	0.02	0.05	0.03	0.13	0.02
UO ₂	0.25	0.02	b.d.	b.d.	0.04	0.15	0.17	0.07	0.07	1.43	1.50
Al ₂ O ₃	0.12	0.09	0.10	0.17	0.12	0.27	0.35	0.56	0.12	0.21	0.31
Sc ₂ O ₃	0.07	0.07	0.06	0.28	0.01	0.01	0.03	0.50	0.10	b.d.	0.02
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.03	0.00	0.00	0.00	0.01	0.01	0.01	0.04	0.01
$FeO_{(max)}^{\dagger}$	0.26	0.63	0.48	0.49	0.46	0.27	0.26	0.14	0.31	0.50	0.32
Y ₂ O ₃	0.03	0.05	0.03	0.06	0.02	0.07	0.06	0.01	b.d.	0.04	b.d.
Sb ₂ O ₃	b.d.	b.d.	0.06	0.18	b.d.	b.d.	b.d.	b.d.	0.23	0.27	b.d.
Bi ₂ O ₃	0.05	0.06	b.d.	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	0.12	0.12
MgO	b.d.	b.d.	0.02	0.01	0.01	b.d.	b.d.	b.d.	b.d.	b.d.	0.01
CaO	13.35	15.66	15.43	14.46	14.39	13.32	14.23	13.59	14.26	13.85	14.26
MnO	b.d.	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	0.05	0.04	b.d.	b.d.
ZnO	b.d.	b.d.	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
PbO	0.10	b.d.	b.d.	0.11	0.05	b.d.	0.41	0.08	0.11	0.06	0.11
Na ₂ O	5.61	5.78	5.86	6.04	5.71	6.03	5.53	5.25	5.52	5.49	5.47
F	4.06	4.36	4.20	4.38	4.18	4.08	4.25	3.85	4.12	3.78	3.83
−(O=F)	-1.71	-1.84	-1.77	-1.85	-1.76	-1.72	-1.79	-1.62	-1.73	-1.59	-1.61

Table A.34. (Continued) Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 5U pegmatite dike.

Sample	R5U-B	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-D	R5U-D	R5U-E	R5U-E
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	Rim	Middle	Rim	_	-	-	_	-	-	-
Mineral	*Fclmcr	Fclprc	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclprc
Total	99.86	99.76	100.79	100.31	100.87	99.23	100.18	100.48	99.61	97.32	98.63
W ⁶⁺ (apfu)	0.000	0.009	0.013	0.023	0.010	0.007	0.014	0.011	0.003	0.002	0.011
Nb ⁵⁺	0.538	0.940	0.848	1.034	0.911	0.858	0.841	0.575	0.836	1.046	1.001
Ta ⁵⁺	1.303	0.895	0.979	0.798	0.958	1.039	1.017	1.213	1.022	0.792	0.826
Si ⁴⁺	0.008	b.d.	0.002	0.005	b.d.	0.007	0.015	0.001	0.005	0.003	0.005
Ti ⁴⁺	0.097	0.058	0.062	0.075	0.069	0.050	0.042	0.116	0.077	0.115	0.117
Zr ⁴⁺	0.004	0.006	0.007	0.007	0.008	0.003	0.001	0.022	0.002	b.d.	b.d.
Sn ⁴⁺	0.020	0.015	0.017	0.021	0.025	0.012	0.025	0.034	0.027	0.036	0.029
Th ⁴⁺	0.000	0.000	0.002	b.d.	b.d.	b.d.	0.000	0.001	0.001	0.002	0.000
U ⁴⁺	0.004	0.000	b.d.	b.d.	0.001	0.003	0.003	0.001	0.001	0.024	0.025
Al ³⁺	0.011	0.008	0.009	0.014	0.010	0.024	0.031	0.052	0.010	0.018	0.027
Sc ³⁺	0.005	0.005	0.004	0.018	0.001	0.000	0.002	0.034	0.006	b.d.	0.001
Fe^{3+} (min) [†]	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.000
$Fe^{2+}(max)^{\dagger}$	0.017	0.039	0.030	0.030	0.029	0.017	0.017	0.009	0.020	0.032	0.020
Y ³⁺	0.001	0.002	0.001	0.002	0.001	0.003	0.002	0.001	b.d.	0.001	b.d.
Sb ³⁺	b.d.	b.d.	0.002	0.005	b.d.	b.d.	b.d.	b.d.	0.007	0.008	b.d.
Bi ³⁺	0.001	0.001	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	0.002	0.002
Mg ²⁺	b.d.	b.d.	0.002	0.001	0.001	b.d.	b.d.	b.d.	b.d.	b.d.	0.001
Ca ²⁺	1.138	1.240	1.232	1.118	1.142	1.089	1.151	1.133	1.159	1.113	1.136
Mn ²⁺	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	0.003	0.003	b.d.	b.d.
Zn ²⁺	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Pb ²⁺	0.002	b.d.	b.d.	0.002	0.001	b.d.	0.008	0.002	0.002	0.001	0.002
Na⁺	0.866	0.829	0.847	0.845	0.820	0.892	0.810	0.792	0.812	0.798	0.789
F⁻	1.023	1.019	0.990	1.000	0.980	0.986	1.014	0.946	0.988	0.896	0.900
O ²⁻	5.977	5.981	6.011	6.000	6.020	6.014	5.986	6.055	6.012	6.105	6.100

Sample	R5U-B	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-D	R5U-D	R5U-E	R5U-E
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	Rim	Middle	Rim	-	-	-	-	-	-	-
Mineral	*Fclmcr	Fclprc	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclprc

The formulae were calculated on the basis of 7 anions per formula unit. *FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	_	Core	_	-	_	-	_	_	Core	_
Mineral	*Fclmcr	Fclprc	Fclmcr								
WO₃ (wt.%)	0.46	0.21	0.23	b.d.	b.d.	0.30	0.30	b.d.	0.07	b.d.	b.d.
Nb_2O_5	25.64	32.33	16.90	23.41	20.29	28.46	16.29	7.06	25.62	3.43	25.02
Ta ₂ O ₅	46.79	39.73	59.09	52.04	55.64	45.92	59.28	72.14	49.09	75.91	48.59
SiO ₂	0.03	0.02	b.d.	0.06	b.d.	b.d.	0.04	0.05	0.26	b.d.	0.11
TiO ₂	1.73	1.74	1.73	1.43	1.16	0.98	0.46	0.54	0.76	0.78	1.26
ZrO ₂	b.d.	0.13	0.04	0.01	b.d.	b.d.	b.d.	0.04	0.04	0.01	0.06
SnO ₂	0.81	0.78	0.53	0.22	0.39	0.83	0.66	0.55	0.50	0.75	1.39
ThO ₂	0.09	0.15	b.d.	0.12	b.d.	b.d.	0.13	b.d.	0.13	0.03	0.01
UO ₂	1.20	0.57	0.13	0.26	0.16	0.28	0.22	0.18	0.33	0.17	0.67
Al ₂ O ₃	0.23	0.17	0.08	0.07	0.08	0.12	0.29	0.09	0.59	0.05	0.17
Sc ₂ O ₃	b.d.	0.01	0.03	0.04	0.05	0.09	0.15	0.02	0.08	0.02	0.01
$Fe_2O_{3(\text{min})}^\dagger$	0.03	0.04	0.00	0.04	0.00	0.00	0.04	0.00	0.04	0.01	0.00
$FeO_{(max)}{}^{\dagger}$	0.32	0.47	0.28	0.33	0.38	0.47	0.48	0.27	0.45	0.09	0.22
Y_2O_3	0.05	0.08	b.d.	0.04	b.d.	0.02	0.01	0.03	0.07	0.02	b.d.
Sb ₂ O ₃	0.10	0.03	b.d.	b.d.	b.d.	b.d.	0.23	b.d.	b.d.	0.08	b.d.
Bi ₂ O ₃	0.33	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.29	b.d.	0.08	b.d.
MgO	b.d.	b.d.	b.d.	0.04	b.d.	0.04	b.d.	b.d.	b.d.	0.00	0.02
CaO	13.27	15.11	14.37	14.45	13.91	14.06	12.76	11.93	13.24	12.17	13.54
MnO	0.01	b.d.	0.01	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	0.02	0.02
ZnO	b.d.	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08
PbO	0.14	0.11	0.10	0.02	b.d.	b.d.	b.d.	b.d.	0.03	0.04	b.d.
Na ₂ O	5.61	5.67	5.25	5.65	5.54	5.84	5.42	5.56	5.70	5.50	5.74
F	3.86	4.14	4.06	4.07	4.14	4.07	3.95	3.84	3.98	3.79	3.89
−(O=F)	-1.62	-1.74	-1.71	-1.72	-1.74	-1.71	-1.66	-1.62	-1.68	-1.60	-1.64

Table A.34. (Continued) Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 5U pegmatite dike.

Sample	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	Core	-	-	-	-	-	-	Core	-
Mineral	*Fclmcr	Fclprc	Fclmcr								
Total	99.07	99.74	101.11	100.58	100.00	99.76	99.03	100.96	99.31	101.35	99.15
W ⁶⁺ (apfu)	0.009	0.004	0.005	b.d.	b.d.	0.006	0.006	b.d.	0.001	b.d.	b.d.
Nb ⁵⁺	0.884	1.060	0.595	0.801	0.711	0.960	0.594	0.268	0.878	0.132	0.863
Ta ⁵⁺	0.971	0.784	1.251	1.072	1.174	0.932	1.299	1.649	1.012	1.761	1.008
Si ⁴⁺	0.002	0.001	b.d.	0.004	b.d.	b.d.	0.003	0.004	0.020	b.d.	0.009
Ti ⁴⁺	0.099	0.095	0.101	0.082	0.068	0.055	0.028	0.034	0.043	0.050	0.072
Zr ⁴⁺	b.d.	0.005	0.001	0.000	b.d.	b.d.	b.d.	0.002	0.001	0.000	0.002
Sn ⁴⁺	0.024	0.023	0.017	0.007	0.012	0.025	0.021	0.018	0.015	0.025	0.042
Th ⁴⁺	0.002	0.002	b.d.	0.002	b.d.	b.d.	0.002	b.d.	0.002	0.001	0.000
U ⁴⁺	0.020	0.009	0.002	0.004	0.003	0.005	0.004	0.003	0.006	0.003	0.011
Al ³⁺	0.021	0.015	0.007	0.006	0.007	0.010	0.027	0.009	0.053	0.005	0.015
Sc ³⁺	b.d.	0.000	0.002	0.003	0.004	0.006	0.011	0.002	0.005	0.002	0.001
Fe^{3+} (min) †	0.002	0.002	0.000	0.002	0.000	0.000	0.002	0.000	0.002	0.001	0.000
$Fe^{2+}(max)^{\dagger}$	0.020	0.029	0.018	0.021	0.025	0.029	0.032	0.019	0.028	0.007	0.014
Y ³⁺	0.002	0.003	b.d.	0.002	b.d.	0.001	0.000	0.001	0.003	0.001	b.d.
Sb ³⁺	0.003	0.001	b.d.	b.d.	b.d.	b.d.	0.008	b.d.	b.d.	0.003	b.d.
Bi ³⁺	0.007	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	0.002	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	0.004	b.d.	0.004	b.d.	b.d.	b.d.	0.001	0.003
Ca ²⁺	1.085	1.174	1.198	1.173	1.156	1.124	1.102	1.074	1.075	1.112	1.107
Mn ²⁺	0.000	b.d.	0.001	b.d.	b.d.	0.001	b.d.	b.d.	b.d.	0.002	0.001
Zn ²⁺	b.d.	b.d.	b.d.	0.001	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005
Pb ²⁺	0.003	0.002	0.002	0.000	b.d.	b.d.	b.d.	b.d.	0.001	0.001	b.d.
Na⁺	0.830	0.797	0.792	0.829	0.833	0.844	0.847	0.906	0.838	0.911	0.850
F⁻	0.931	0.950	1.000	0.975	1.016	0.960	1.007	1.021	0.955	1.023	0.938
O ²⁻	6.070	6.051	6.000	6.026	5.984	6.040	5.994	5.979	6.046	5.977	6.062

Sample	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-E	R5U-F	R5U-F	R5U-F	R5U-F	R5U-F
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	Core	-	-	-	-	-	-	Core	-
Mineral	*Fclmcr	Fclprc	Fclmcr								

The formulae were calculated on the basis of 7 anions per formula unit. *FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R5U-G	R5U-G	R5U-G	R5U-G	R5U-I	R5U-I	R5U-I
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Core	Rim	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr
WO ₃ (wt.%)	b.d.	b.d.	0.45	0.14	0.35	0.34	0.05
Nb ₂ O ₅	6.39	8.21	10.20	8.63	13.82	24.63	15.95
Ta ₂ O ₅	72.10	67.18	66.78	68.87	61.47	47.97	60.36
SiO ₂	0.04	1.66	0.02	0.03	0.05	0.06	b.d.
TiO ₂	0.17	0.06	0.12	0.07	0.81	0.85	0.77
ZrO ₂	b.d.	0.06	b.d.	0.06	b.d.	b.d.	b.d.
SnO ₂	0.26	0.37	0.33	0.51	1.17	1.43	0.95
ThO ₂	0.06	b.d.	0.15	0.04	b.d.	b.d.	0.03
UO ₂	0.15	0.22	0.11	0.26	0.35	0.62	0.32
Al ₂ O ₃	0.08	0.61	0.58	0.17	1.41	0.72	0.37
Sc ₂ O ₃	b.d.	b.d.	0.01	b.d.	0.02	0.05	0.03
$Fe_2O_{3(\text{min})}^\dagger$	0.02	0.00	0.04	0.01	0.00	0.00	0.01
$FeO_{(max)}^{\dagger}$	0.19	0.32	0.45	0.54	0.21	0.33	0.30
Y ₂ O ₃	0.01	b.d.	0.08	0.12	0.02	b.d.	0.03
Sb ₂ O ₃	0.03	b.d.	0.30	b.d.	0.15	0.08	0.09
Bi ₂ O ₃	b.d.	0.15	0.13	0.11	b.d.	b.d.	b.d.
MgO	b.d.	0.03	0.02	b.d.	b.d.	b.d.	0.03
CaO	12.72	11.86	12.41	11.77	12.90	14.16	13.21
MnO	b.d.	0.04	0.02	b.d.	0.01	b.d.	b.d.
ZnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.15
PbO	b.d.	0.05	b.d.	b.d.	b.d.	0.09	0.05
Na₂O	5.62	5.25	5.40	5.46	5.58	5.80	5.54
F	3.83	3.70	3.79	3.85	3.86	3.93	3.93
−(O=F)	-1.61	-1.56	-1.60	-1.62	-1.62	-1.65	-1.66

Table A.34. (Continued) Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 5U pegmatite dike.

Sample	R5U-G	R5U-G	R5U-G	R5U-G	R5U-I	R5U-I	R5U-I
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Core	Rim	_	_	_	_	_
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr
Total	100.06	98.22	99.77	99.00	100.55	99.41	100.52
W ⁶⁺ (apfu)	b.d.	b.d.	0.010	0.003	0.007	0.007	0.001
Nb ⁵⁺	0.245	0.310	0.384	0.332	0.496	0.845	0.573
Ta ⁵⁺	1.666	1.523	1.510	1.593	1.326	0.990	1.304
Si ⁴⁺	0.004	0.138	0.001	0.002	0.004	0.004	b.d.
Ti ⁴⁺	0.011	0.004	0.008	0.004	0.049	0.049	0.046
Zr ⁴⁺	b.d.	0.002	b.d.	0.003	b.d.	b.d.	b.d.
Sn ⁴⁺	0.009	0.012	0.011	0.017	0.037	0.043	0.030
Th ⁴⁺	0.001	b.d.	0.003	0.001	b.d.	b.d.	0.001
U ⁴⁺	0.003	0.004	0.002	0.005	0.006	0.011	0.006
Al ³⁺	0.008	0.060	0.057	0.017	0.132	0.065	0.035
Sc ³⁺	b.d.	b.d.	0.000	b.d.	0.001	0.003	0.002
Fe^{3+} (min) †	0.001	0.000	0.003	0.001	0.000	0.000	0.001
$Fe^{2+}(max)^{\dagger}$	0.013	0.023	0.031	0.038	0.014	0.021	0.020
Y ³⁺	0.001	b.d.	0.003	0.005	0.001	b.d.	0.001
Sb ³⁺	0.001	b.d.	0.010	b.d.	0.005	0.002	0.003
Bi ³⁺	b.d.	0.003	0.003	0.002	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	0.003	0.003	b.d.	b.d.	b.d.	0.004
Ca ²⁺	1.158	1.060	1.106	1.073	1.096	1.152	1.124
Mn ²⁺	b.d.	0.003	0.001	b.d.	0.000	b.d.	b.d.
Zn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.009
Pb ²⁺	b.d.	0.001	b.d.	b.d.	b.d.	0.002	0.001
Na⁺	0.927	0.849	0.870	0.900	0.859	0.854	0.854
F⁻	1.030	0.974	0.997	1.036	0.968	0.942	0.988
O ²⁻	5.971	6.026	6.005	5.964	6.032	6.058	6.012

Sample	R5U-G	R5U-G	R5U-G	R5U-G	R5U-I	R5U-I	R5U-I
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Core	Rim	-	-	-	-	-
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr

*FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6
Mineral	*Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr	Fclmcr
WO ₃ (wt.%)	0.71	b.d.	b.d.	b.d.	0.76	b.d.	b.d.
Nb ₂ O ₅	18.94	16.30	17.28	21.25	17.42	18.13	17.58
Ta ₂ O ₅	58.65	59.92	60.36	53.43	58.78	57.36	60.38
SiO ₂	0.60	0.55	0.55	0.52	0.51	0.56	0.55
TiO ₂	0.67	0.41	0.79	1.17	0.72	0.63	0.53
ZrO ₂	b.d.	0.29	b.d.	b.d.	0.17	b.d.	0.19
SnO ₂	0.46	0.94	0.67	1.20	0.56	0.53	0.38
UO ₂	0.94	0.68	0.64	1.63	0.40	0.75	0.32
Al ₂ O ₃	0.07	0.06	0.09	0.10	0.09	0.08	0.04
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.26	0.19	0.39	0.20	0.32	0.65	0.24
CaO	12.03	11.71	12.10	12.09	12.33	12.27	12.13
Na ₂ O	5.18	5.14	5.17	5.21	5.20	5.02	5.05
F	3.55	3.88	3.52	3.59	3.76	3.54	3.72
-(O=F)	-1.49	-1.63	-1.48	-1.51	-1.58	-1.49	-1.57
Total	100.58	98.42	100.07	98.87	99.43	98.04	99.54
W ⁶⁺ (apfu)	0.015	b.d.	b.d.	b.d.	0.016	b.d.	b.d.
Nb ⁵⁺	0.676	0.599	0.624	0.757	0.628	0.662	0.636
Ta⁵⁺	1.259	1.324	1.310	1.145	1.275	1.261	1.314
Si ⁴⁺	0.047	0.045	0.044	0.041	0.041	0.045	0.044
Ti ⁴⁺	0.040	0.025	0.047	0.069	0.043	0.038	0.032
Zr ⁴⁺	b.d.	0.011	b.d.	b.d.	0.007	b.d.	0.007
Sn ⁴⁺	0.015	0.030	0.021	0.038	0.018	0.017	0.012
U ⁴⁺	0.017	0.012	0.011	0.029	0.007	0.013	0.006
Al ³⁺	0.007	0.006	0.009	0.010	0.009	0.008	0.004
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.017	0.013	0.026	0.013	0.021	0.044	0.016
Ca ²⁺	1.017	1.020	1.035	1.020	1.054	1.063	1.040
Na⁺	0.793	0.811	0.800	0.796	0.805	0.787	0.783
F⁻	0.886	0.997	0.890	0.896	0.948	0.904	0.941
O ^{2_}	6.114	6.003	6.110	6.104	6.052	6.096	6.059

Table A.35. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 6 pegmatite dike.

Thorium, Sc, Mg, and Mn were also sought but were below the detection limit of the EMP in all analyses.

*FcImcr = fluorcalciomicrolite; [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R9b-2c	R9b-2c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 9	Rau 9	Rau 10	Rau 10	Rau 10	Rau 10
Mineral	*Fclmcr	Fclprc	Fclprc	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclprc	Fclprc
WO₃ (wt.%)	0.08	0.47	b.d.	0.61	0.18	b.d.	0.08	0.88	0.48	0.55	0.51
Nb ₂ O ₅	22.57	27.96	31.84	31.01	25.11	10.83	13.83	30.31	25.00	36.10	31.18
Ta₂O₅	48.79	40.27	37.34	37.91	48.45	62.31	60.72	32.04	45.78	33.28	40.29
SiO ₂	0.49	0.01	0.07	0.04	0.01	0.11	0.31	0.08	0.09	0.05	0.01
TiO ₂	0.13	0.38	0.34	2.39	0.96	0.11	0.10	5.10	1.79	1.82	1.99
ZrO ₂	b.d.	0.37	0.03	0.30	0.06	b.d.	0.10	b.d.	0.21	0.04	0.03
SnO ₂	2.02	1.61	1.90	0.81	2.12	1.55	1.31	0.54	0.77	0.44	0.93
ThO ₂	b.d.	0.08	b.d.	0.21	b.d.	0.02	b.d.	0.52	0.12	0.17	0.12
UO ₂	1.68	2.33	2.16	0.85	0.54	0.84	1.10	3.99	1.24	1.23	1.59
Al ₂ O ₃	0.23	0.22	0.25	0.12	0.11	0.12	0.22	0.11	0.15	0.15	0.17
Sc ₂ O ₃	0.11	0.13	0.10	0.03	b.d.	0.03	0.01	b.d.	0.02	0.07	0.06
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.02	0.00	0.06	0.00	0.01	0.00	0.16	0.04	0.05	0.04
FeO _(max) †	0.74	1.15	1.00	0.41	0.35	0.64	0.81	0.72	0.55	1.46	0.56
Y_2O_3	0.02	0.01	0.05	0.03	b.d.	b.d.	0.03	0.04	b.d.	b.d.	0.02
Sb ₂ O ₃	b.d.	b.d.	b.d.	0.10	0.17	b.d.	0.11	0.02	b.d.	b.d.	0.04
Bi ₂ O ₃	b.d.	b.d.	0.30	b.d.	b.d.	0.05	0.15	0.41	0.28	0.07	0.07
MgO	b.d.	b.d.	0.01	0.01	0.01	b.d.	0.04	b.d.	b.d.	0.02	b.d.
CaO	12.92	13.44	12.49	15.70	14.24	13.12	13.93	14.53	15.43	12.54	15.36
MnO	b.d.	0.02	b.d.	0.01	0.03	0.01	0.03	0.11	0.09	0.36	0.07
ZnO	b.d.	0.13	b.d.	b.d.	0.06	0.04	b.d.	0.04	0.05	b.d.	b.d.
PbO	0.15	0.09	0.09	b.d.	0.09	b.d.	b.d.	0.05	b.d.	b.d.	0.13
Na ₂ O	5.30	5.54	5.76	5.52	5.74	4.92	3.58	4.65	3.51	5.59	4.95
F	3.70	3.44	3.64	3.99	4.14	3.43	2.74	3.18	3.06	3.39	3.36
−(O=F)	-1.56	-1.45	-1.53	-1.68	-1.74	-1.44	-1.15	-1.34	-1.29	-1.43	-1.42
Total	97.37	96.22	95.83	98.42	100.60	96.70	98.03	96.12	97.35	95.93	100.06

Table A.36. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the Rau 8, 9, and 10 pegmatite dikes.

Sample	R8-1b	R8-1b	R8-1b	R8-1b	R8-1b	R9b-2c	R9b-2c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 8	Rau 8	Rau 8	Rau 8	Rau 8	Rau 9	Rau 9	Rau 10	Rau 10	Rau 10	Rau 10
Mineral	*Fclmcr	Fclprc	Fclprc	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclprc	Fclprc
W ⁶⁺ (apfu)	0.002	0.010	b.d.	0.012	0.003	b.d.	0.002	0.017	0.010	0.011	0.010
Nb ⁵⁺	0.809	0.988	1.109	1.026	0.855	0.420	0.525	1.027	0.881	1.217	1.037
Ta⁵+	1.051	0.856	0.782	0.755	0.992	1.452	1.386	0.653	0.970	0.675	0.806
Si ⁴⁺	0.039	0.000	0.005	0.003	0.000	0.009	0.026	0.006	0.007	0.003	0.001
Ti ⁴⁺	0.008	0.022	0.020	0.132	0.054	0.007	0.006	0.287	0.105	0.102	0.110
Zr ⁴⁺	b.d.	0.014	0.001	0.011	0.002	b.d.	0.004	b.d.	0.008	0.001	0.001
Sn ⁴⁺	0.064	0.050	0.058	0.024	0.064	0.053	0.044	0.016	0.024	0.013	0.027
Th ⁴⁺	b.d.	0.001	b.d.	0.003	b.d.	0.000	b.d.	0.009	0.002	0.003	0.002
U ⁴⁺	0.030	0.040	0.037	0.014	0.009	0.016	0.020	0.067	0.022	0.020	0.026
Al ³⁺	0.022	0.020	0.022	0.010	0.010	0.012	0.021	0.010	0.013	0.013	0.015
Sc ³⁺	0.007	0.009	0.007	0.002	b.d.	0.002	0.001	b.d.	0.001	0.005	0.004
Fe^{3+} (min) [†]	0.000	0.001	0.000	0.003	0.000	0.000	0.000	0.009	0.002	0.003	0.002
$Fe^{2+}(max)^{\dagger}$	0.049	0.075	0.064	0.025	0.022	0.046	0.057	0.045	0.036	0.091	0.034
Y ³⁺	0.001	0.001	0.002	0.001	b.d.	b.d.	0.001	0.001	b.d.	b.d.	0.001
Sb ³⁺	b.d.	b.d.	b.d.	0.003	0.005	b.d.	0.004	0.001	b.d.	b.d.	0.001
Bi ³⁺	b.d.	b.d.	0.006	b.d.	b.d.	0.001	0.003	0.008	0.006	0.001	0.001
Mg ²⁺	b.d.	b.d.	0.002	0.001	0.001	b.d.	0.005	b.d.	b.d.	0.003	b.d.
Ca ²⁺	1.097	1.126	1.031	1.231	1.149	1.204	1.253	1.167	1.288	1.002	1.210
Mn ²⁺	b.d.	0.001	b.d.	0.001	0.002	0.001	0.002	0.007	0.006	0.023	0.004
Zn ²⁺	b.d.	0.008	b.d.	b.d.	0.003	0.002	b.d.	0.002	0.003	b.d.	b.d.
Pb ²⁺	0.003	0.002	0.002	b.d.	0.002	b.d.	b.d.	0.001	b.d.	b.d.	0.003
Na⁺	0.814	0.840	0.861	0.784	0.838	0.817	0.582	0.676	0.530	0.808	0.706
F⁻	0.928	0.851	0.887	0.925	0.985	0.929	0.728	0.754	0.753	0.798	0.782
O ^{2_}	6.072	6.149	6.113	6.077	6.015	6.071	6.272	6.251	6.248	6.203	6.219

*FcImcr = fluorcalciomicrolite, FcIprc = fluorcalciopyrochlore; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-2d	R3-2d		R5F-A3	R5F-A3	R5F-A3	R5U-F
Unit	Rau 3	Rau 3	-	Rau 5	Rau 5	Rau 5	Rau 5U
Zone	-	-		-	-	_	-
Mineral	*Tnt-(Mn)	Tnt-(Mn)	-	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Mn)
WO ₃ (wt.%)	0.12	0.44		2.04	1.66	0.24	0.01
Nb ₂ O ₅	22.19	24.31		63.24	56.45	51.72	40.37
Ta ₂ O ₅	59.55	56.52		15.25	20.52	29.51	41.84
SiO ₂	0.03	0.02		b.d.	0.14	b.d.	0.07
TiO ₂	0.68	1.28		0.17	1.09	0.49	0.34
ZrO ₂	0.18	0.17		b.d.	b.d.	0.08	0.13
SnO ₂	0.27	0.23		b.d.	b.d.	b.d.	b.d.
ThO ₂	b.d.	0.01		b.d.	b.d.	b.d.	0.02
UO ₂	b.d.	0.03		b.d.	b.d.	b.d.	0.01
Al ₂ O ₃	0.01	b.d.		b.d.	b.d.	b.d.	0.02
Sc ₂ O ₃	0.06	0.11		b.d.	0.18	0.35	0.27
$Fe_2O_{3(\text{min})}^\dagger$	0.40	0.59		0.00	0.00	0.00	0.11
$FeO_{(max)}^{\dagger}$	0.00	0.00		16.89	16.76	11.55	0.56
Y ₂ O ₃	0.06	0.06		0.05	b.d.	0.06	0.01
Sb ₂ O ₃	b.d.	0.18		b.d.	b.d.	b.d.	b.d.
Bi ₂ O ₃	0.12	0.47		b.d.	b.d.	b.d.	0.10
MgO	b.d.	b.d.		0.19	0.09	0.17	b.d.
CaO	b.d.	0.72		b.d.	b.d.	b.d.	0.64
MnO	16.12	15.67		2.77	2.24	6.91	17.54
ZnO	0.02	0.03		b.d.	b.d.	b.d.	0.04
PbO	b.d.	b.d.		b.d.	b.d.	b.d.	0.02
Na ₂ O	0.01	0.61		b.d.	b.d.	b.d.	0.05
F	0.10	0.45		b.d.	b.d.	b.d.	0.01
−(O=F,Cl)	-0.04	-0.19		0.00	0.00	0.00	-0.01
Total	99.88	101.70		100.59	99.13	101.08	102.14
W ⁶⁺ (apfu)	0.002	0.008		0.032	0.027	0.004	0.000
Nb ⁵⁺	0.739	0.777		1.707	1.574	1.464	1.197
Ta⁵+	1.193	1.087		0.248	0.344	0.503	0.746
Si ⁴⁺	0.002	0.001		0.000	0.009	0.000	0.004
Ti ⁴⁺	0.038	0.068		0.008	0.051	0.023	0.017
Zr ⁴⁺	0.006	0.006		b.d.	b.d.	0.003	0.004
Sn ⁴⁺	0.008	0.007		b.d.	b.d.	b.d.	b.d.
Th ⁴⁺	b.d.	0.000		b.d.	b.d.	b.d.	0.000
U ⁴⁺	b.d.	0.000		b.d.	b.d.	b.d.	0.000
Al ³⁺	0.001	b.d.		b.d.	b.d.	b.d.	0.001

Table A.37. Chemical compositions and structural formulae of columbite group minerals in the Rau 3, 5, and 5U pegmatite dikes.

Sample	R3-2d	R3-2d	R5F-A3	R5F-A3	R5F-A3	R5U-F
Unit	Rau 3	Rau 3	Rau 5	Rau 5	Rau 5	Rau 5U
Zone	-	-	-	-	-	-
Mineral	*Tnt-(Mn)	Tnt-(Mn)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Mn)
Sc ³⁺ (apfu)	0.004	0.007	b.d.	0.010	0.019	0.015
Fe^{3+} (min) †	0.022	0.031	0.000	0.000	0.000	0.005
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.844	0.865	0.605	0.031
Y ³⁺	0.002	0.002	0.002	b.d.	0.002	0.000
Sb ³⁺	b.d.	0.005	b.d.	b.d.	b.d.	b.d.
Bi ³⁺	0.002	0.009	b.d.	b.d.	b.d.	0.002
Mg ²⁺	b.d.	b.d.	0.017	0.008	0.016	b.d.
Ca ²⁺	b.d.	0.054	b.d.	b.d.	b.d.	0.045
Mn ²⁺	1.005	0.938	0.140	0.117	0.367	0.974
Zn ²⁺	0.001	0.002	b.d.	b.d.	b.d.	0.002
Pb ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.000
Na⁺	0.002	0.084	b.d.	b.d.	b.d.	0.006
F⁻	0.024	0.101	b.d.	b.d.	b.d.	0.003
O ²⁻	5.987	5.914	6.000	6.000	6.000	6.000

*Tnt = tantalite, Col = columbite; † Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R10-1c	R10-1c	R10-1c
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 10	Rau 10	Rau 10
Zone	Rim	Core	Rim	-	-		-	-
Mineral	*Col-(Fe)	Col-(Fe)						
WO ₃ (wt.%)	1.68	1.94	2.13	1.95	1.63	0.97	0.78	0.42
Nb ₂ O ₅	56.21	58.97	57.99	56.75	62.83	56.14	57.77	61.96
Ta ₂ O ₅	21.67	20.91	19.42	21.24	17.92	21.10	19.56	14.87
SiO ₂	0.20	0.27	0.22	0.18	0.15	0.11	0.06	0.08
TiO ₂	1.95	1.73	1.90	1.68	0.68	1.90	2.16	2.29
ZrO ₂	b.d.	b.d.	b.d.	0.18	b.d.	0.13	0.27	0.30
SnO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.	0.16
ThO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.14	0.04	0.10
UO ₂	b.d.	b.d.	b.d.	b.d.	0.30	0.06	0.10	0.04
Sc ₂ O ₃	0.28	0.22	0.24	0.26	0.10	0.05	1.12	0.57
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	15.46	15.99	16.59	16.22	16.94	14.42	13.56	13.61
Y ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.32	0.45	0.37
Sb ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.26	b.d.	0.06
MgO	0.19	0.22	0.22	0.15	0.15	0.14	0.18	0.09
CaO	0.19	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	b.d.
MnO	2.47	2.51	2.16	2.41	2.55	5.20	4.99	5.90
PbO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.09
Na ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	0.02
Total	100.32	102.75	100.87	101.03	103.26	101.08	101.06	100.95
W ⁶⁺ (apfu)	0.026	0.030	0.033	0.031	0.025	0.015	0.012	0.006
Nb ⁵⁺	1.543	1.574	1.572	1.550	1.661	1.536	1.558	1.644
Ta⁵⁺	0.358	0.336	0.317	0.349	0.285	0.347	0.317	0.237
Si ⁴⁺	0.012	0.016	0.013	0.011	0.009	0.006	0.003	0.005

Table A.38. Chemical compositions and structural formulae of columbite group minerals in the Rau 6 and 10 pegmatite dikes.

Sample	R6-1b	R6-1b	R6-1b	R6-1b	R6-1b	R10-1c	R10-1c	R10-1c
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 10	Rau 10	Rau 10
Zone	Rim	Core	Rim	-	-	-	-	-
Mineral	*Col-(Fe)	Col-(Fe)						
Ti ⁴⁺ (<i>apfu</i>)	0.089	0.077	0.086	0.076	0.030	0.087	0.097	0.101
Zr ⁴⁺	b.d.	b.d.	b.d.	0.005	b.d.	0.004	0.008	0.009
Sn ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	0.004
Th ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	0.001	0.001
U ⁴⁺	b.d.	b.d.	b.d.	b.d.	0.004	0.001	0.001	0.001
Sc ³⁺	0.015	0.011	0.013	0.014	0.005	0.003	0.058	0.029
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.785	0.789	0.832	0.819	0.829	0.730	0.677	0.668
Y ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.010	0.014	0.012
Sb ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	0.002
Mg ²⁺	0.018	0.020	0.019	0.014	0.013	0.013	0.016	0.008
Ca ²⁺	0.012	b.d.	b.d.	b.d.	b.d.	0.003	b.d.	b.d.
Mn ²⁺	0.127	0.126	0.110	0.123	0.126	0.267	0.252	0.293
Pb ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001
Na⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	0.002
O ^{2_}	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000

Aluminum, Bi, Zn, and F were also sought but were below the detection limit of the EMP in all analyses.

*Col = columbite; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-A	R3-A	R5F-A3	R5U_d
Unit	Rau 3	Rau 3	Rau 5	Rau 5U
Mineral	*Bst-(Ce)	Bst-(Ce)	Bst-(Ce)	Bst-(Ce)
P ₂ O ₅ (wt.%)	b.d.	b.d.	b.d.	1.65
SiO ₂	0.18	0.12	0.18	1.10
ZrO ₂	b.d.	b.d.	b.d.	0.54
ThO ₂	4.98	2.51	0.21	4.38
Al ₂ O ₃	0.11	b.d.	b.d.	1.24
Y_2O_3	0.55	0.76	0.82	0.51
La_2O_3	9.23	12.16	5.80	10.75
Ce ₂ O ₃	36.32	35.48	33.81	34.70
Pr ₂ O ₃	4.67	4.33	6.31	3.90
Nd ₂ O ₃	11.62	11.44	20.02	9.78
Sm ₂ O ₃	2.06	2.01	6.04	1.29
Gd_2O_3	0.47	0.36	1.21	0.48
Dy ₂ O ₃	0.23	b.d.	0.52	b.d.
CaO	0.65	0.41	0.27	5.82
F	6.87	7.13	8.30	6.44
CI	b.d.	b.d.	b.d.	0.04
CO_2^\dagger	18.98	18.66	20.19	24.84
H_2O^{\ddagger}	0.63	0.44	0.20	2.02
−(O=F)	-2.89	-3.00	-3.50	-2.71
Total	94.64	92.80	100.38	106.76
P⁵+ (<i>apfu</i>)	b.d.	b.d.	b.d.	0.041
Si ⁴⁺	0.007	0.005	0.006	0.032
Zr ⁴⁺	b.d.	b.d.	b.d.	0.008
Th ⁴⁺	0.044	0.022	0.002	0.029
Al ³⁺	0.005	b.d.	b.d.	0.043
Y ³⁺	0.011	0.016	0.016	0.008
La ³⁺	0.131	0.176	0.078	0.117
Ce ³⁺	0.513	0.510	0.449	0.375
Pr ³⁺	0.066	0.062	0.083	0.042
Nd ³⁺	0.160	0.160	0.259	0.103
Sm³⁺	0.027	0.027	0.075	0.013
Gd ³⁺	0.006	0.005	0.015	0.005
Dy ³⁺	0.003	b.d.	0.006	b.d.
Ca ²⁺	0.027	0.017	0.011	0.184
F⁻	0.839	0.884	0.952	0.601
CI⁻	b.d.	b.d.	b.d.	0.002

Table A.39. Chemical compositions and structural formulae of bastnäsite-(Ce) in the Rau 3, 5, and 5U pegmatite dikes.
Sample	R3-A	R3-A	R5F-A3	R5U_d
Unit	Rau 3	Rau 3	Rau 5	Rau 5U
Mineral	*Bst-(Ce)	Bst-(Ce)	Bst-(Ce)	Bst-(Ce)
C ^{4+†} (apfu)	1.000	1.000	1.000	1.000
OH⁻	0.161	0.116	0.048	0.397
O ^{2_}	3.173	3.120	3.046	3.381

The formulae were calculated on the basis of 1 *A* and *B* site cations per formula unit.

Titanium, U, As, Sc, Fe, Er, Tb, Ho, Yb, Tm, Eu, Mg, Mn, Sr, Ba, Pb, Na, K, and S were also sought but were below the detection limit of the EMP in all analyses.

*Bst = bastnäsite; $^{\dagger}CO_2$ was fixed at 1 *apfu* C; $^{\ddagger}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-1b	R3-1b	R3-A
Unit	Rau 3	Rau 3	Rau 3
Zone	Rim	Core	-
Mineral	*Prs-(Ce)	Prs-(Ce)	Prs-(Ce)
SiO ₂ (wt.%)	b.d.	0.43	0.12
ThO ₂	1.34	1.39	2.29
Y_2O_3	0.21	0.22	0.21
La_2O_3	7.82	8.35	10.00
Ce ₂ O ₃	33.84	35.25	31.59
Pr ₂ O ₃	4.45	4.52	3.92
Nd_2O_3	11.16	12.08	11.21
Sm ₂ O ₃	2.17	1.99	1.88
Gd_2O_3	0.36	b.d.	0.34
Tm ₂ O ₃	0.24	b.d.	b.d.
CaO	10.31	10.91	11.14
K ₂ O	b.d.	0.01	b.d.
F	5.62	4.69	6.81
CO_2^\dagger	24.39	25.77	25.00
H_2O^{\ddagger}	0.66	1.29	0.18
-(O=F)	-2.37	-1.97	-2.87
Total	100.22	104.93	101.81
Si ⁴⁺ (<i>apfu</i>)	b.d.	0.037	0.010
Th ⁴⁺	0.028	0.027	0.046
Y ³⁺	0.010	0.010	0.010
La ³⁺	0.260	0.262	0.324
Ce ³⁺	1.116	1.100	1.016
Pr ³⁺	0.146	0.141	0.126
Nd ³⁺	0.359	0.368	0.352
Sm ³⁺	0.067	0.058	0.057
Gd ³⁺	0.011	b.d.	0.010
Tm³+	0.007	b.d.	b.d.
Ca ²⁺	0.996	0.996	1.049
K⁺	b.d.	0.001	b.d.
F⁻	1.603	1.264	1.892
C ^{4+†}	3.000	3.000	3.000
OH-‡	0.397	0.736	0.108
O ²⁻	9.215	9.401	9.057

Table A.40. Chemical compositions and structural formulae of parisite-(Ce) in the Rau 3 pegmatite dike.

The formulae were calculated on the basis of 3 *A* and *B* site cations per formula unit.

Phosphorus, Ti, Zr, U, Al, Fe, As, Eu, Dy, Er, Mg, Sr, Ba, Pb, Na, and S were also sought but were below the detection limit of the EMP in all analyses. *Prs = parisite; [†]CO₂ was fixed at 3 *apfu* C; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	-	-	-	-	-	-	-	Rim
Mineral	*Prs-(Ce)	Prs-(Ce)								
SiO ₂ (wt.%)	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	0.09	b.d.	b.d.
ThO ₂	0.76	0.92	0.97	0.71	1.07	0.91	0.98	0.85	1.09	0.75
Al ₂ O ₃	b.d.	0.08	b.d.	b.d.	0.19	b.d.	0.18	0.34	0.35	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Y ₂ O ₃	0.23	0.35	0.30	0.25	0.24	0.36	0.38	0.32	0.34	0.24
La_2O_3	10.15	9.76	9.71	10.11	9.81	9.64	9.30	9.75	9.19	10.02
Ce ₂ O ₃	34.25	34.32	34.41	34.51	34.50	33.86	33.25	34.43	33.35	33.42
Pr ₂ O ₃	4.38	4.26	4.24	4.40	4.26	4.34	4.20	4.42	4.24	4.41
Nd ₂ O ₃	11.89	11.87	12.00	11.89	11.94	12.12	11.81	11.77	11.46	11.68
Sm ₂ O ₃	2.03	1.96	1.87	1.95	1.79	1.99	2.04	1.99	2.02	1.92
Gd_2O_3	0.49	0.47	0.41	0.25	0.36	0.41	0.51	0.44	0.41	0.36
Tm ₂ O ₃	b.d.	0.27	b.d.	0.24	0.35	0.26	0.25	0.18	b.d.	0.22
CaO	10.72	10.86	10.98	10.68	10.93	10.80	11.64	10.66	12.16	10.61
F	6.74	6.66	6.65	6.74	6.74	6.76	6.59	6.88	6.47	6.89
CO_2^{\ddagger}	25.46	25.63	25.59	25.48	25.85	25.44	25.94	25.77	26.32	25.07
H_2O^{\S}	0.28	0.34	0.34	0.28	0.33	0.27	0.42	0.25	0.52	0.15
–(O=F)	-2.84	-2.80	-2.80	-2.84	-2.84	-2.85	-2.77	-2.90	-2.73	-2.90
Total	104.52	104.94	104.68	104.66	105.60	104.31	104.71	105.24	105.18	102.83
Si ⁴⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	0.008	b.d.	b.d.
Th ⁴⁺	0.015	0.018	0.019	0.014	0.021	0.018	0.019	0.016	0.021	0.015
Al ³⁺	b.d.	0.008	b.d.	b.d.	0.019	b.d.	0.018	0.034	0.034	b.d.
$Fe^{3+}(min)^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺ (max) [†]	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.41. Chemical compositions and structural formulae of parisite-(Ce) in the Rau 5U pegmatite dike.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C	R5U-C
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	-	-	-	-	-	-	-	-	-	Rim
Mineral	*Prs-(Ce)	Prs-(Ce)								
Y ³⁺ (<i>apfu</i>)	0.010	0.016	0.014	0.012	0.011	0.016	0.017	0.014	0.015	0.011
La ³⁺	0.323	0.309	0.308	0.322	0.307	0.307	0.291	0.307	0.283	0.324
Ce ³⁺	1.082	1.077	1.082	1.090	1.074	1.071	1.031	1.075	1.019	1.073
Pr ³⁺	0.138	0.133	0.133	0.138	0.132	0.137	0.130	0.137	0.129	0.141
Nd ³⁺	0.367	0.363	0.368	0.366	0.362	0.374	0.357	0.359	0.342	0.366
Sm ³⁺	0.060	0.058	0.055	0.058	0.052	0.059	0.060	0.059	0.058	0.058
Gd ³⁺	0.014	0.013	0.012	0.007	0.010	0.012	0.014	0.012	0.011	0.011
Tm ³⁺	b.d.	0.007	b.d.	0.006	0.009	0.007	0.007	0.005	b.d.	0.008
Ca ²⁺	0.991	0.998	1.010	0.987	0.995	0.999	1.057	0.974	1.088	0.996
F [.]	1.841	1.806	1.807	1.837	1.812	1.846	1.765	1.856	1.709	1.911
C ^{4+‡}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
OH⁻§	0.159	0.194	0.193	0.163	0.188	0.154	0.235	0.144	0.291	0.089
O ²⁻	9.092	9.107	9.101	9.095	9.110	9.086	9.099	9.097	9.112	9.054

The formulae were calculated on the basis of 3 A and B site cations per formula unit.

Phosphorus, Ti, Zr, U, As, Eu, Dy, Er, Mg, Sr, Ba, Pb, Na, K, and S were also sought but were below the detection limit of the EMP in all analyses.

*Prs = parisite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 3 *apfu* C; [§]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-E	R5U-G	R5U-G
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Middle	Core	Core	Rim	-	_	-
Mineral	*Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)
SiO ₂ (wt.%)	b.d.	b.d.	b.d.	b.d.	b.d.	0.11	b.d.
ThO ₂	0.97	0.75	0.87	1.00	0.97	0.91	0.84
Al ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.93	0.12
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.15	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	0.00	b.d.
Y_2O_3	0.49	0.40	0.48	0.34	0.29	0.31	0.37
La_2O_3	9.65	9.55	10.22	9.85	9.97	9.87	10.13
Ce ₂ O ₃	34.27	33.94	33.94	34.48	32.96	33.60	33.99
Pr ₂ O ₃	4.36	4.38	4.18	4.29	4.21	4.17	4.30
Nd ₂ O ₃	12.02	11.73	11.33	11.89	11.02	11.49	11.26
Sm ₂ O ₃	2.03	1.94	1.84	1.99	1.69	1.80	1.86
Gd_2O_3	0.54	0.51	0.47	0.55	0.40	0.46	0.52
Tm ₂ O ₃	0.30	0.23	0.24	0.21	b.d.	0.20	0.17
CaO	11.01	11.40	11.48	10.83	10.29	11.05	11.27
F	6.59	6.60	6.63	6.68	5.69	6.59	6.72
CO_2^{\ddagger}	25.81	25.82	25.91	25.64	24.41	26.32	25.81
H_2O^{\S}	0.40	0.39	0.39	0.33	0.63	0.47	0.34
–(O=F)	-2.78	-2.78	-2.79	-2.81	-2.40	-2.77	-2.83
Total	105.66	104.87	105.20	105.28	100.14	105.64	104.86
Si ⁴⁺ (apfu)	b.d.	b.d.	b.d.	b.d.	b.d.	0.009	b.d.
Th ⁴⁺	0.019	0.015	0.017	0.020	0.020	0.017	0.016
Al ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.092	0.012
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.009	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.

Table A.41. (Continued) Chemical compositions and structural formulae of parisite-(Ce) in the Rau 5U pegmatite dike.

Sample	R5U-C	R5U-C	R5U-C	R5U-C	R5U-E	R5U-G	R5U-G
Unit	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Middle	Core	Core	Rim	-	-	-
Mineral	*Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)	Prs-(Ce)
Y ³⁺ (apfu)	0.022	0.018	0.022	0.016	0.014	0.014	0.017
La ³⁺	0.303	0.300	0.320	0.311	0.331	0.304	0.318
Ce ³⁺	1.068	1.058	1.054	1.082	1.086	1.027	1.059
Pr ³⁺	0.135	0.136	0.129	0.134	0.138	0.127	0.133
Nd ³⁺	0.366	0.357	0.343	0.364	0.354	0.343	0.342
Sm ³⁺	0.060	0.057	0.054	0.059	0.052	0.052	0.054
Gd ³⁺	0.015	0.014	0.013	0.016	0.012	0.013	0.015
Tm ³⁺	0.008	0.006	0.006	0.006	b.d.	0.005	0.005
Ca ²⁺	1.005	1.040	1.043	0.994	0.993	0.988	1.028
F⁻	1.775	1.777	1.778	1.810	1.620	1.739	1.809
C ^{4+‡}	3.000	3.000	3.000	3.000	3.000	3.000	3.000
OH-§	0.225	0.223	0.222	0.190	0.380	0.261	0.191
O ^{2_}	9.120	9.099	9.098	9.108	9.204	9.145	9.089

The formulae were calculated on the basis of 3 A and B site cations per formula unit.

Phosphorus, Ti, Zr, U, As, Eu, Dy, Er, Mg, Sr, Ba, Pb, Na, K, and S were also sought but were below the detection limit of the EMP in all analyses.

*Prs = parisite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 3 *apfu* C; [§]H₂O contents calculated on stoichiometry; b.d. = below detection limit.

Somolo	D2 1h	D2 1h	D2 20	D 2 2	D2 2					
Sample	RJ-ID Day 2	R3-10	RJ-20	R3-3	R3-3	R3-A			R3-A	RJ-A
	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 5
Zone	-	-	_	—	_	_	-	_	_	-
Mineral	*Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)	Snc-(Ce)
SiO ₂ (wt.%)	0.12	0.34	0.20	0.30	1.35	0.09	0.09	0.09	0.08	0.18
ThO ₂	1.04	3.19	2.22	2.03	6.08	3.16	2.97	1.94	2.70	3.23
Al ₂ O ₃	b.d.	0.11	b.d.	0.00	b.d.	0.08	0.06	b.d.	b.d.	0.13
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.40	0.29	0.42	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	0.00	0.00	0.00	b.d.	b.d.	0.00	0.00	0.00
As ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.01	b.d.	b.d.	b.d.	b.d.
Y_2O_3	1.06	3.36	0.87	3.43	2.85	1.00	1.04	1.02	1.19	1.38
La ₂ O ₃	5.45	4.85	5.78	5.45	5.72	8.09	8.22	7.86	6.55	6.56
Ce ₂ O ₃	25.95	23.78	24.06	20.31	21.70	27.06	26.87	24.73	24.86	23.63
Pr ₂ O ₃	3.62	3.74	3.48	3.22	3.19	3.71	3.42	3.32	3.54	3.37
Nd ₂ O ₃	10.93	10.50	10.92	9.44	10.23	10.44	10.20	10.27	10.64	11.22
Sm ₂ O ₃	2.70	3.39	3.21	2.80	2.60	2.18	2.32	2.31	2.60	2.86
Gd_2O_3	0.77	1.48	0.93	1.11	1.19	0.46	0.71	0.65	0.79	0.93
Dy ₂ O ₃	b.d.	b.d.	b.d.	b.d.	0.38	b.d.	b.d.	0.21	0.25	0.26
Tm ₂ O ₃	0.26	0.52	0.49	0.37	0.27	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	17.25	14.41	17.46	15.08	14.95	15.10	15.97	18.33	18.47	17.47
SrO	b.d.	b.d.	b.d.	b.d.	0.16	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	b.d.	b.d.	b.d.	0.16	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
K₂O	0.04	b.d.	b.d.	0.22	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	4.72	4.18	4.51	4.58	4.31	6.06	5.90	6.13	5.46	5.56
CO_2^{\ddagger}	27.43	26.26	27.73	25.63	27.22	26.73	27.31	28.29	28.54	27.98
H ₂ O§	3.38	3.39	3.54	3.08	3.53	2.60	2.79	2.88	3.25	3.09
-(O=F)	-1.99	-1.76	-1.90	-1.93	-1.81	-2.55	-2.49	-2.58	-2.30	-2.34

Table A.42. Chemical compositions and structural formulae of synchysite-(Ce) in the Rau 3 pegmatite dike.

Sample	R3-1b	R3-1b	R3-2e	R3-3	R3-3	R3-A	R3-A	R3-A	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	-	_	_	_	_	_	_	_	_	-
Mineral	*Snc-(Ce)	Snc-(Ce)								
Total	102.72	101.76	103.90	95.54	104.39	104.21	105.38	105.44	106.62	105.49
Si ⁴⁺ (<i>apfu</i>)	0.006	0.019	0.011	0.017	0.073	0.005	0.005	0.005	0.004	0.010
Th ⁴⁺	0.013	0.041	0.027	0.026	0.075	0.039	0.036	0.023	0.031	0.039
Al ³⁺	b.d.	0.007	b.d.	0.000	b.d.	0.005	0.004	b.d.	b.d.	0.008
Fe^{3+} (min) [†]	0.000	0.000	0.016	0.013	0.017	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	0.000	0.000	0.000	b.d.	b.d.	0.000	0.000	0.000
As ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.000	b.d.	b.d.	b.d.	b.d.
Y ³⁺	0.030	0.100	0.025	0.104	0.082	0.029	0.030	0.028	0.033	0.039
La ³⁺	0.107	0.100	0.113	0.115	0.114	0.163	0.163	0.150	0.124	0.127
Ce ³⁺	0.507	0.486	0.465	0.425	0.428	0.543	0.528	0.469	0.467	0.453
Pr ³⁺	0.071	0.076	0.067	0.067	0.063	0.074	0.067	0.063	0.066	0.064
Nd ³⁺	0.208	0.209	0.206	0.193	0.197	0.204	0.195	0.190	0.195	0.210
Sm ³⁺	0.050	0.065	0.058	0.055	0.048	0.041	0.043	0.041	0.046	0.052
Gd ³⁺	0.014	0.027	0.016	0.021	0.021	0.008	0.013	0.011	0.013	0.016
Dy ³⁺	b.d.	b.d.	b.d.	b.d.	0.007	b.d.	b.d.	0.003	0.004	0.004
Tm ³⁺	0.004	0.009	0.008	0.007	0.004	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	0.987	0.861	0.988	0.924	0.862	0.887	0.918	1.017	1.016	0.980
Sr ²⁺	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.
Na ⁺	b.d.	b.d.	b.d.	0.018	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
K⁺	0.002	b.d.	b.d.	0.016	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	0.797	0.738	0.754	0.827	0.733	1.051	1.001	1.004	0.886	0.921
C ^{4+‡}	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
OH-§	1.203	1.262	1.246	1.173	1.267	0.949	0.999	0.996	1.114	1.079
O ²⁻	6.115	6.230	6.140	6.106	6.262	6.053	6.061	6.003	6.067	6.074

The formulae were calculated on the basis of 2 A and B site cations per formula unit.

Phosphorus, Ti, Zr, U, Eu, Er, Ba, Pb, and S were also sought but were below the detection limit of the EMP in all analyses.

*Snc = synchysite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 2 *apfu* C; [§]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5F-A3	R5U-D	R5U-F
Unit	Rau 5	Rau 5U	Rau 5U
Zone	-		-
Mineral	*Snc-(Ce)	Snc-(Ce)	Snc-(Ce)
SiO ₂ (wt.%)	0.96	0.15	b.d.
ThO ₂	1.08	0.94	1.77
Al ₂ O ₃	0.70	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.32	0.00	0.00
FeO _(max) †	0.00	b.d.	b.d.
Y ₂ O ₃	0.84	0.97	0.79
La_2O_3	7.76	7.66	7.74
Ce ₂ O ₃	27.61	27.18	28.25
Pr ₂ O ₃	3.77	3.71	3.84
Nd ₂ O ₃	9.67	9.87	10.41
Sm_2O_3	2.06	1.72	1.83
Gd_2O_3	0.54	0.43	0.50
Dy ₂ O ₃	b.d.	0.33	b.d.
Tm ₂ O ₃	b.d.	0.28	0.28
CaO	16.29	17.68	17.77
BaO	0.01	b.d.	b.d.
K ₂ O	b.d.	0.04	b.d.
F	5.53	5.33	5.62
CO_2^{\ddagger}	28.47	28.16	28.61
H_2O^{\S}	3.21	3.24	3.19
−(O=F)	-2.33	-2.25	-2.37
Total	106.50	105.43	108.22
Si ⁴⁺ (apfu)	0.050	0.008	b.d.
Th ⁴⁺	0.013	0.011	0.021

Table A.43. Chemical compositions and structural formulae of synchysite-(Ce) in the Rau 5 and 5U pegmatite dikes.

Sample	R5F-A3	R5U-D	R5U-F
Unit	Rau 5	Rau 5U	Rau 5U
Zone	-	-	-
Mineral	*Snc-(Ce)	Snc-(Ce)	Snc-(Ce)
Al ³⁺ (<i>apfu</i>)	0.042	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.012	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	b.d.	b.d.
Y ³⁺	0.023	0.027	0.021
La ³⁺	0.147	0.147	0.146
Ce ³⁺	0.520	0.518	0.530
Pr ³⁺	0.071	0.070	0.072
Nd ³⁺	0.178	0.183	0.190
Sm ³⁺	0.037	0.031	0.032
Gd ³⁺	0.009	0.007	0.009
Dy ³⁺	b.d.	0.006	b.d.
Tm³+	b.d.	0.005	0.004
Ca ²⁺	0.898	0.985	0.975
Ba ²⁺	0.000	b.d.	b.d.
K ⁺	b.d.	0.003	b.d.
F⁻	0.900	0.877	0.910
C ^{4+‡}	2.000	2.000	2.000
OH-§	1.100	1.123	1.090
O ²⁻	6.126	6.076	6.068

The formulae were calculated on the basis of 2 *A* and *B* site cations per formula unit.

Phosphorus, Ti, Zr, As, U, Eu, Er, Mg, Sr, Ba, Pb, Na, and S were also sought but were below the detection limit of the EMP in all analyses.

*Snc = synchysite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 2 *apfu* C; [§]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10
Zone	Core	Core	Core	Rim	Rim	-
Mineral	*Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)
WO ₃ (wt.%)	1.02	1.60	2.80	1.62	1.46	0.78
P ₂ O ₅	b.d.	b.d.	b.d.	b.d.	b.d.	0.18
Nb ₂ O ₅	29.24	27.94	33.33	39.99	40.94	35.88
Ta ₂ O ₅	26.73	27.45	21.54	16.06	15.40	18.25
SiO ₂	0.18	0.15	0.18	0.13	0.14	0.83
TiO ₂	0.10	0.12	b.d.	0.27	0.14	0.74
ZrO ₂	0.94	0.85	0.81	1.05	1.17	b.d.
ThO ₂	7.66	7.29	7.98	7.99	7.88	3.59
UO ₂	4.93	5.31	3.24	3.17	2.10	0.83
Al ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.05
Sc ₂ O ₃	2.99	2.65	2.87	4.92	5.63	b.d.
$Fe_2O_{3(min)}^{\dagger}$	5.75	5.99	7.61	6.40	6.09	0.40
$FeO_{(max)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
Y_2O_3	5.05	5.08	7.18	10.26	10.59	13.15
Ce ₂ O ₃	1.01	0.93	0.62	0.42	0.63	0.54
Pr ₂ O ₃	0.44	0.36	0.28	b.d.	0.25	b.d.
Nd ₂ O ₃	2.41	2.45	1.94	1.37	1.55	1.91
Sm ₂ O ₃	1.93	1.90	1.91	0.79	0.79	2.05
Gd ₂ O ₃	1.60	1.56	1.82	0.93	0.89	2.19
Tb ₂ O ₃	0.12	0.12	0.15	b.d.	b.d.	0.34
Dy_2O_3	1.06	0.90	1.14	0.51	0.62	2.06
Ho ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.24
Er ₂ O ₃	0.35	0.34	0.36	0.31	0.44	1.26
Tm_2O_3	0.59	0.55	0.43	0.31	0.35	0.67
Lu ₂ O ₃	0.29	0.30	0.23	0.22	0.31	0.44
Yb ₂ O ₃	0.42	0.43	0.52	0.65	1.13	2.02
CaO	0.07	b.d.	b.d.	0.12	0.12	4.23
MnO	2.68	2.67	1.83	1.59	1.54	b.d.
Na ₂ O	b.d.	b.d.	b.d.	0.39	b.d.	0.56
F	0.17	0.17	0.14	0.13	0.17	1.22
-(O=F)	-0.07	-0.07	-0.06	-0.05	-0.07	-0.51
Total	97.62	97.02	98.83	99.54	100.25	93.87
W ⁶⁺ (apfu)	0.020	0.032	0.053	0.029	0.025	0.015
P ⁵⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.011
Nb ⁵⁺	1.005	0.975	1.099	1.230	1.243	1.195

Table A.44. Chemical compositions and structural formulae of euxenite-(Y) in the Rau 10 pegmatite dike.

Sample	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10	Rau 10
Zone	Core	Core	Core	Rim	Rim	_
Mineral	*Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)	Exn-(Y)
Ta⁵+ (<i>apfu</i>)	0.553	0.576	0.427	0.297	0.281	0.366
Si ⁴⁺	0.014	0.011	0.013	0.009	0.010	0.061
Ti ⁴⁺	0.006	0.007	b.d.	0.014	0.007	0.041
Zr ⁴⁺	0.035	0.032	0.029	0.035	0.038	b.d.
Th ⁴⁺	0.132	0.128	0.132	0.124	0.120	0.060
U ⁴⁺	0.083	0.091	0.053	0.048	0.031	0.014
Al ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.005
Sc ³⁺	0.198	0.178	0.183	0.292	0.330	b.d.
Fe^{3+} (min) †	0.329	0.348	0.418	0.328	0.308	0.022
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
Y ³⁺	0.204	0.208	0.279	0.372	0.378	0.515
Ce ³⁺	0.028	0.026	0.017	0.010	0.015	0.015
Pr ³⁺	0.012	0.010	0.007	b.d.	0.006	b.d.
Nd ³⁺	0.066	0.068	0.050	0.033	0.037	0.050
Sm ³⁺	0.050	0.051	0.048	0.018	0.018	0.052
Gd ³⁺	0.040	0.040	0.044	0.021	0.020	0.053
Tb ³⁺	0.003	0.003	0.004	b.d.	b.d.	0.008
Dy ³⁺	0.026	0.022	0.027	0.011	0.013	0.049
Ho ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.006
Er ³⁺	0.008	0.008	0.008	0.007	0.009	0.029
Tm ³⁺	0.014	0.013	0.010	0.007	0.007	0.015
Lu ³⁺	0.007	0.007	0.005	0.005	0.006	0.010
Yb ³⁺	0.010	0.010	0.011	0.013	0.023	0.045
Ca ²⁺	0.005	b.d.	b.d.	0.009	0.009	0.334
Mn ²⁺	0.172	0.175	0.113	0.091	0.087	b.d.
Na⁺	b.d.	b.d.	b.d.	0.051	b.d.	0.080
F ⁻	0.040	0.041	0.033	0.028	0.037	0.285
O ²⁻	5.980	5.979	5.984	5.986	5.982	5.858

The formulae were calculated on the basis of 6 O atoms per formula unit.

Arsenic, La, Mg, and Pb were also sought but were below the detection limit of the EMP in all analyses.

*Exn = euxenite; [†]Ratio of Fe2O3 and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-2e	R5F-A3
Unit	Rau 3	Rau 5
Mineral	*Mnz-(Ce)	Mnz-(Ce)
P ₂ O ₅ (wt.%)	29.50	28.76
SiO ₂	0.81	1.47
ZrO ₂	0.46	b.d.
ThO ₂	3.63	6.50
As ₂ O ₃	0.09	0.08
Y_2O_3	0.44	0.09
La_2O_3	9.21	9.39
Ce ₂ O ₃	33.29	36.62
Pr ₂ O ₃	5.03	4.64
Nd ₂ O ₃	14.47	11.35
Sm ₂ O ₃	3.40	1.34
Gd_2O_3	0.77	b.d.
Dy ₂ O ₃	0.14	b.d.
CaO	0.34	0.30
Total	101.57	100.53
P ⁵⁺ (<i>apfu</i>)	0.973	0.956
Si ⁴⁺	0.032	0.058
Zr ⁴⁺	0.009	0.000
Th ⁴⁺	0.032	0.058
As ³⁺	0.002	0.002
Y ³⁺	0.009	0.002
La ³⁺	0.132	0.136
Ce ³⁺	0.475	0.527
Pr ³⁺	0.071	0.066
Nd ³⁺	0.201	0.159
Sm ³⁺	0.046	0.018
Gd ³⁺	0.010	0.000
Dy ³⁺	0.002	0.000
Ca ²⁺	0.014	0.013
O ^{2_}	4.000	4.000

Table A.45. Chemical compositions and structural formulae of monazite-(Ce) in the Rau 3 and 5 pegmatite dikes.

The formulae were calculated on the basis of 4 O atoms per formula unit.

Titanium, U, Fe, Sc, Eu, Er, Sr, Pb, Na, and S were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); b.d. = below detection limit

Sample	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	Core	Core	Rim	Middle	Core	Core	Core	Middle	Middle	Rim	Rim	-
Mineral	*Czo	Aln	Aln	Ep	Aln	Aln	Aln	Ep	Ep	Ep	Ep	Ep
P ₂ O ₅ (wt.%)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	0.06	0.07	0.07	b.d.
SiO ₂	33.86	33.03	32.73	33.63	32.54	32.50	32.29	35.34	37.12	35.46	36.17	34.47
ThO ₂	3.95	4.05	0.59	5.11	2.15	1.91	1.23	5.49	6.35	6.10	6.08	5.17
UO ₂	b.d.	0.08	b.d.	0.10	b.d.	b.d.	b.d.	0.09	0.15	0.14	0.17	0.09
Al ₂ O ₃	20.19	19.48	19.00	19.24	19.58	19.61	19.08	19.87	20.38	19.79	19.99	18.23
Sc ₂ O ₃	b.d.	b.d.	0.18	0.09	0.13	0.20	0.18	0.20	0.24	0.06	0.07	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	5.05	2.36	2.91	8.33	0.71	0.57	0.78	7.39	8.03	8.79	9.43	9.15
$FeO_{(max)}^{\dagger}$	6.00	8.60	6.40	0.00	9.07	8.63	8.27	0.00	0.00	0.00	0.00	0.00
Y_2O_3	0.32	0.11	b.d.	0.33	0.19	0.19	0.12	0.22	0.18	0.19	0.17	0.24
La_2O_3	1.88	2.95	3.32	1.58	2.53	2.39	2.66	1.33	1.39	1.79	2.13	2.03
Ce ₂ O ₃	6.96	8.37	12.51	6.43	10.43	10.78	11.85	6.60	5.52	5.59	5.91	6.60
Pr ₂ O ₃	0.99	1.02	1.62	0.97	1.36	1.56	1.84	1.04	0.78	0.64	0.75	1.15
Nd ₂ O ₃	3.00	2.83	4.20	2.46	3.89	4.39	4.44	3.59	2.45	1.98	1.96	2.50
Sm ₂ O ₃	0.65	0.46	0.62	0.58	0.73	0.70	0.62	0.77	0.57	0.36	0.30	0.74
Gd ₂ O ₃	0.28	0.27	b.d.	0.19	0.21	b.d.	b.d.	0.26	b.d.	b.d.	b.d.	b.d.
MgO	0.45	0.62	1.14	0.69	0.83	0.88	1.32	0.79	0.53	0.46	0.41	0.14
CaO	15.04	14.26	12.41	10.13	12.83	12.74	12.11	10.32	11.03	11.04	11.19	10.52
MnO	0.63	0.41	0.70	0.51	0.70	0.75	0.67	0.56	0.62	0.55	0.50	0.50
SrO	b.d.	b.d.	b.d.	0.27	b.d.	b.d.	b.d.	0.16	0.20	0.20	0.20	b.d.
PbO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.
Na₂O	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	0.13	0.31	0.42	0.29	0.22
K ₂ O	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	0.04	0.02	0.09	0.03	b.d.
F	0.06	0.05	0.28	0.50	0.12	0.13	0.22	0.42	0.46	0.39	0.40	0.42
CI	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.02	0.05	b.d.	b.d.

Table A.46. Chemical compositions and structural formulae of epidote supergroup minerals in the Rau 3 pegmatite dike.

Sample	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Zone	Core	Core	Rim	Middle	Core	Core	Core	Middle	Middle	Rim	Rim	_
Mineral	*Czo	Aln	Aln	Ep	Aln	Aln	Aln	Ep	Ep	Ep	Ep	Ep
−(O=F,CI)	-0.02	-0.02	-0.12	-0.21	-0.05	-0.06	-0.09	-0.18	-0.20	-0.18	-0.17	-0.18
H_2O^{\ddagger}	1.69	1.65	1.64	3.69	1.63	1.62	1.61	4.54	5.42	4.50	4.59	4.61
Total	100.99	100.58	100.12	94.72	99.58	99.50	99.19	99.03	101.62	98.46	100.70	96.61
P ⁵⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	0.004	0.005	0.005	b.d.
Si ⁴⁺	3.000	3.000	3.000	3.000	3.000	3.000	3.000	2.995	2.996	2.995	2.995	3.000
Th ⁴⁺	0.080	0.084	0.012	0.104	0.045	0.040	0.026	0.106	0.117	0.117	0.115	0.102
U ⁴⁺	b.d.	0.002	b.d.	0.002	b.d.	b.d.	b.d.	0.002	0.003	0.003	0.003	0.002
Al ³⁺	2.108	2.086	2.052	2.023	2.128	2.134	2.089	1.985	1.939	1.970	1.951	1.870
Sc ³⁺	b.d.	b.d.	0.014	0.007	0.011	0.016	0.014	0.015	0.017	0.004	0.005	b.d.
$Fe^{3+}(min)^{\dagger}$	0.337	0.162	0.201	0.559	0.049	0.039	0.055	0.471	0.488	0.559	0.587	0.599
$Fe^{2+}(max)^{\dagger}$	0.445	0.653	0.491	0.000	0.699	0.666	0.643	0.000	0.000	0.000	0.000	0.000
Y ³⁺	0.015	0.005	b.d.	0.016	0.009	0.009	0.006	0.010	0.008	0.009	0.008	0.011
La ³⁺	0.061	0.099	0.112	0.052	0.086	0.081	0.091	0.041	0.041	0.056	0.065	0.065
Ce ³⁺	0.226	0.278	0.420	0.210	0.352	0.364	0.403	0.205	0.163	0.173	0.179	0.210
Pr ³⁺	0.032	0.034	0.054	0.031	0.046	0.052	0.062	0.032	0.023	0.020	0.023	0.036
Nd ³⁺	0.095	0.092	0.138	0.078	0.128	0.145	0.147	0.109	0.071	0.060	0.058	0.078
Sm ³⁺	0.020	0.014	0.019	0.018	0.023	0.022	0.020	0.022	0.016	0.011	0.009	0.022
Gd ³⁺	0.008	0.008	b.d.	0.006	0.006	b.d.	b.d.	0.007	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	0.059	0.084	0.156	0.092	0.114	0.121	0.183	0.100	0.064	0.057	0.051	0.019
Ca ²⁺	1.428	1.388	1.219	0.968	1.267	1.259	1.206	0.937	0.954	0.999	0.993	0.981
Mn ²⁺	0.047	0.031	0.054	0.039	0.055	0.058	0.052	0.040	0.042	0.039	0.035	0.037
Sr ²⁺	b.d.	b.d.	b.d.	0.014	b.d.	b.d.	b.d.	0.008	0.009	0.010	0.010	b.d.
Pb ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002	b.d.
Na⁺	b.d.	b.d.	b.d.	0.013	b.d.	b.d.	b.d.	0.021	0.049	0.068	0.046	0.037
K⁺	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	0.004	0.002	0.010	0.003	b.d.

Sample	R3-A											
Unit	Rau 3											
Zone	Core	Core	Rim	Middle	Core	Core	Core	Middle	Middle	Rim	Rim	-
Mineral	*Czo	Aln	Aln	Ep	Aln	Aln	Aln	Ep	Ep	Ep	Ep	Ep
F ⁻ (apfu)	0.016	0.014	0.081	0.142	0.035	0.039	0.066	0.112	0.117	0.104	0.106	0.117
Cl	b.d.	0.003	0.007	b.d.	b.d.							
OH-‡	1.000	1.000	1.000	2.196	1.000	1.000	1.000	2.568	2.915	2.533	2.535	2.679
O ²⁻	12.315	12.406	12.318	11.480	12.440	12.442	12.407	11.368	11.179	11.343	11.333	11.244

The formulae were calculated on the basis of 3 Si atoms per formula unit.

Titanium, Zr, Sn, Tb, Dy, Ho, Er, Yb, Tm, and Ba were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H2O contents based on stoichiometry; b.d. = below detection limit.

Sample	R1-J	R3-A	R3-A	R3-A
Unit	Rau 1	Rau 3	Rau 3	Rau 3
Mineral	*Brl	Brl	Brl	Brl
SiO ₂ (wt.%)	68.17	65.78	65.23	66.15
TiO ₂	0.01	b.d.	b.d.	b.d.
AI_2O_3	18.39	15.51	16.39	15.83
Cr ₂ O ₃	0.01	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.20	1.70	1.60	1.57
BeO [‡]	14.19	13.69	13.58	13.77
MgO	0.01	1.32	0.73	1.21
CaO	0.03	b.d.	b.d.	b.d.
MnO	0.02	b.d.	b.d.	b.d.
BaO	0.01	b.d.	b.d.	b.d.
Na ₂ O	0.17	1.54	1.16	1.43
Rb ₂ O	0.09	0.10	0.08	0.11
F	0.02	b.d.	b.d.	b.d.
CI	b.d.	b.d.	b.d.	b.d.
−(O=F,CI)	-0.01	0.00	0.00	0.00
Total	101.30	99.64	98.77	100.07
Si ⁴⁺ (<i>apfu</i>)	6.054	6.018	6.000	6.019
Ti ⁴⁺	0.001	b.d.	b.d.	b.d.
Al ³⁺	1.925	1.672	1.777	1.698
Cr ³⁺	0.001	b.d.	b.d.	b.d.
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.014	0.130	0.123	0.120
Be ^{2+‡}	3.000	3.000	3.000	3.000
Mg ²⁺	0.001	0.180	0.100	0.163
Ca ²⁺	0.003	b.d.	b.d.	b.d.
Mn ²⁺	0.002	b.d.	b.d.	b.d.
Ba ²⁺	0.000	b.d.	b.d.	b.d.
Na⁺	0.030	0.274	0.207	0.252
Rb⁺	0.005	0.006	0.005	0.007
F⁻	0.005	b.d.	b.d.	b.d.
Cl-	b.d.	b.d.	b.d.	b.d.
O ²⁻	18.03	17.99	17.99	18.00

Table A.47. Chemical compositions and structural formulae of beryl in the Rau 1 and 3 pegmatite dikes.

The formulae were calculated on the basis of 8 *T* and *M* site cations per formula unit.

Phosphorus, V, Sc, Zn, Cs, K, and S were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]BeO was fixed at 3 *apfu* Be; b.d. = below detection limit.

Sample	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c	R10-1c
Unit	Rau 10					
Zone	Core	Middle	Rim	Core	Rim	Core
Mineral	*Sps	Sps	Sps	Sps	Sps	Sps
SiO ₂ (wt.%)	36.55	35.91	36.62	35.52	36.01	35.54
AI_2O_3	20.61	20.37	20.22	20.61	20.38	20.49
$Fe_2O_{3(\text{min})}^\dagger$	16.78	17.84	16.64	18.67	17.44	17.16
$FeO_{(max)}^{\dagger}$	2.90	0.00	4.36	0.00	3.18	0.00
Y ₂ O ₃	b.d.	b.d.	b.d.	0.18	b.d.	0.15
MgO	b.d.	b.d.	0.04	b.d.	b.d.	b.d.
CaO	0.59	0.83	0.90	0.93	0.61	0.88
MnO	24.52	26.38	23.16	25.07	23.50	26.61
Na ₂ O	b.d.	0.10	b.d.	0.13	b.d.	0.08
F	0.18	0.59	0.06	0.76	0.24	0.84
-(O=F,CI)	-0.08	-0.25	-0.02	-0.32	-0.10	-0.35
Total	102.13	101.78	101.97	101.54	101.31	101.40
Si ⁴⁺ (<i>apfu</i>)	2.999	2.961	3.012	2.935	2.985	2.936
Al ³⁺	1.993	1.980	1.960	2.007	1.991	1.995
Fe^{3+} (min) †	1.093	1.107	1.029	1.161	1.125	1.067
$Fe^{2+}(max)^{\dagger}$	0.141	0.000	0.302	0.000	0.183	0.000
Y ³⁺	b.d.	b.d.	b.d.	0.008	b.d.	0.007
Mg ²⁺	b.d.	b.d.	0.005	b.d.	b.d.	b.d.
Ca ²⁺	0.052	0.073	0.079	0.082	0.054	0.078
Mn ²⁺	1.704	1.843	1.614	1.755	1.650	1.863
Na⁺	b.d.	0.016	b.d.	0.021	b.d.	0.012
F ⁻	0.047	0.154	0.014	0.198	0.062	0.220
O ²⁻	11.953	11.846	11.986	11.802	11.938	11.780

Table A.48. Chemical compositions and structural formulae of spessartine in the Rau 10 pegmatite dike.

The formulae were calculated on the basis of 12 anions per formula unit. Phosphorus, Ti, Cr, V, Zn, and K were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1	Rau 1
Mineral	*Sch	Sch	Sch	Sch	Sch	Sch	Sch	Sch	Sch
WO₃ (wt.%)	79.90	80.03	80.00	79.75	78.81	81.66	81.54	81.67	81.16
Nb ₂ O ₅	0.57	0.17	0.20	0.56	0.78	b.d.	b.d.	b.d.	b.d.
Ta ₂ O ₅	b.d.	b.d.	b.d.	b.d.	0.30	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.40	0.33	0.44	0.39	0.31	b.d.	b.d.	b.d.	0.20
CaO	19.42	19.43	19.49	19.31	19.01	19.17	19.62	19.57	19.24
MnO	0.11	0.07	0.09	0.19	0.10	b.d.	b.d.	b.d.	b.d.
Total	100.40	100.04	100.22	100.18	99.29	100.83	101.16	101.24	100.60
W ⁶⁺ (<i>apfu</i>)	0.986	0.993	0.990	0.987	0.984	1.007	1.001	1.002	1.003
Nb ⁵⁺	0.012	0.004	0.004	0.012	0.017	b.d.	b.d.	b.d.	b.d.
Ta⁵+	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.016	0.013	0.018	0.015	0.012	b.d.	b.d.	b.d.	0.008
Ca ²⁺	0.991	0.996	0.997	0.987	0.981	0.978	0.996	0.993	0.983
Mn ²⁺	0.004	0.003	0.003	0.008	0.004	b.d.	b.d.	b.d.	b.d.
O ²⁻	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000

Table A.49. Chemical compositions and structural formulae of scheelite in the Rau 1 pegmatite dike.

The formulae were calculated on the basis of 4 anions per formula unit.

Molybdenum, Si, Ti, Sn, Sc, Y, Sb, Bi, and Pb were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); † Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Table A.50. Chemical compositions and structural formulae of hingganite-(Ce) in the Rau 1 pegmatite dike.

Unit	Rau 1	Rau 1
Sample	R1-J	R1-J
Mineral	*Hng	Hng
SiO ₂ (wt.%)	26.81	26.93
ThO ₂	b.d.	0.29
$B_2O_3^{\dagger}$	5.82	6.02
$Fe_2O_{3(\text{min})}^{\ddagger}$	4.83	2.64
$FeO_{(max)}^{\ddagger}$	1.34	3.21
Y_2O_3	6.76	9.12
La ₂ O ₃	2.65	1.99
Ce ₂ O ₃	12.61	9.97
Pr ₂ O ₃	2.47	1.82
Nd ₂ O ₃	8.16	7.83
Sm_2O_3	1.94	2.29
Gd ₂ O ₃	0.80	1.21
Dy ₂ O ₃	0.37	0.53
Er_2O_3	0.19	0.32
Yr ₂ O ₃	0.43	0.63
BeO§	6.98	6.88
MgO	0.87	0.98
CaO	9.97	10.56
MnO	0.29	0.26
K ₂ O	0.05	0.14
F	0.82	0.73
H₂O [∥]	2.13	2.13
–(O=F)	-0.48	-0.43
Total	95.81	96.03
Si ⁴⁺ (<i>apfu</i>)	2.000	2.000
Th ⁴⁺	b.d.	0.005
B ^{3+†}	0.749	0.772
Fe ³⁺ (min) [‡]	0.271	0.147
$Fe^{2+}(max)^{\ddagger}$	0.084	0.199
Y ³⁺	0.268	0.361
La³+	0.073	0.054
Ce ³⁺	0.344	0.271
Pr ³⁺	0.067	0.049
Nd ³⁺	0.217	0.208
Sm ³⁺	0.050	0.059
Gd ³⁺	0.020	0.030

Unit	Rau 1	Rau 1
Sample	R1-J	R1-J
Mineral	*Hng	Hng
Dy ³⁺ (<i>apfu</i>)	0.009	0.013
Er ³⁺	0.005	0.007
Yb ³⁺	0.010	0.014
Be ^{2+§}	1.251	1.228
Mg ²⁺	0.097	0.109
Ca ²⁺	0.797	0.840
Mn ²⁺	0.019	0.017
K+	0.005	0.013
F⁻	0.192	0.171
OH⁻∥	1.059	1.057
O ^{2_}	8.749	8.772

The formulae were calculated on the basis of 2 Si atoms per formula unit. Phosphorus, Ti, Zr, U, Al, Sc, Tb, Sr, Ba, Pb, Na, and Cl were also sought but were below the detection limit of the EMP in all analyses. *Hng = hingganite; $^{+}B_2O_3$ was calculated based on the assumption that B = 2 anions – Be; $^{+}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{\$}BeO$ was fixed at 3 *apfu* Be; $^{\parallel}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A	R3-A
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Phl	Phl	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	39.10	38.25	45.67	47.78	47.49	47.22	48.61	47.42	44.86	47.54	47.17
TiO ₂	0.06	0.05	b.d.	b.d.	0.10	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	13.00	13.55	29.98	30.60	29.83	29.08	29.74	31.11	30.11	30.80	31.04
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	18.98	19.74	5.73	3.57	4.41	3.84	3.08	3.17	6.16	3.38	3.40
MgO	13.11	12.60	2.54	2.09	2.64	2.71	2.38	1.34	2.64	1.82	1.86
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MnO	0.46	0.42	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.03
Na ₂ O	0.13	0.16	0.23	0.27	0.19	0.12	0.17	0.21	0.23	0.25	0.26
K ₂ O	9.78	9.77	10.83	11.04	11.10	11.30	11.42	11.09	10.64	11.00	11.00
Rb ₂ O	0.18	0.17	0.15	0.11	0.18	0.14	0.16	0.14	0.17	0.15	0.19
F	4.39	4.13	1.31	1.33	1.52	1.51	1.67	0.98	1.23	1.24	1.20
CI	0.15	0.16	0.07	b.d.	0.07	0.04	b.d.	b.d.	0.06	b.d.	b.d.
H_2O^{\ddagger}	1.79	1.89	3.72	3.81	3.70	3.65	3.66	3.94	3.74	3.84	3.85
−(O=F,CI)	-1.88	-1.77	-0.57	-0.56	-0.65	-0.64	-0.70	-0.41	-0.53	-0.52	-0.51
Total	99.24	99.12	99.66	100.05	100.56	98.95	100.18	98.98	99.31	99.51	99.49
Si ⁴⁺	2.997	2.950	3.138	3.222	3.209	3.237	3.272	3.224	3.102	3.220	3.199
Ti ⁴⁺	0.003	0.003	b.d.	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Al ³⁺	1.175	1.232	2.428	2.432	2.375	2.350	2.359	2.493	2.453	2.459	2.481
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.217	1.273	0.329	0.202	0.249	0.220	0.173	0.180	0.356	0.191	0.193
Mg ²⁺	1.498	1.449	0.260	0.210	0.265	0.277	0.239	0.135	0.272	0.184	0.188
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.

Table A.51. Chemical compositions and structural formulae of mica group minerals in the Rau 3 pegmatite dike.

Sample	R3-A										
Unit	Rau 3										
Mineral	*Phl	Phl	Ms								
Mn ²⁺ (<i>apfu</i>)	0.030	0.028	b.d.	0.002							
Na⁺	0.019	0.024	0.030	0.036	0.025	0.016	0.022	0.028	0.031	0.033	0.034
K ⁺	0.957	0.962	0.949	0.950	0.957	0.988	0.980	0.962	0.939	0.951	0.952
Rb⁺	0.009	0.009	0.007	0.005	0.008	0.006	0.007	0.006	0.007	0.007	0.008
F⁻	1.064	1.006	0.285	0.285	0.324	0.327	0.355	0.211	0.269	0.266	0.257
Cl⁻	0.019	0.021	0.008	b.d.	0.008	0.004	b.d.	b.d.	0.007	b.d.	b.d.
$OH^{-\ddagger}$	0.917	0.973	1.707	1.715	1.668	1.669	1.645	1.789	1.724	1.734	1.743
vac.	0.080	0.066	0.845	0.934	0.896	0.916	0.956	0.968	0.817	0.946	0.937
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Sc, V, Zn, Ba, Cs, and S were also sought but were below the detection limit of the EMP in all analyses.

Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d
Unit	Rau 3										
Mineral	*Ms	Ms									
SiO ₂ (wt.%)	46.72	47.72	46.72	47.98	46.77	45.68	47.88	48.47	48.36	47.35	48.41
TiO ₂	b.d.	0.34	0.27								
Al ₂ O ₃	28.84	30.57	29.24	29.14	30.03	29.08	29.92	29.54	30.78	26.52	27.15
Cr ₂ O ₃	b.d.	0.08	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	4.23	3.10	4.49	3.53	3.90	5.17	2.86	2.20	2.53	4.06	3.21
MgO	2.62	1.85	2.79	2.47	2.17	2.47	2.08	2.02	1.80	4.46	4.24
CaO	b.d.	0.05	0.05	b.d.	b.d.						
MnO	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.13	0.18	0.21	0.15	0.22	0.19	0.18	0.15	0.19	0.11	0.09
K ₂ O	11.15	11.42	11.02	11.14	11.08	10.78	11.02	11.39	11.18	11.29	11.23
Rb ₂ O	0.29	0.25	0.26	0.31	0.27	0.25	0.29	0.27	0.28	0.43	0.34
F	1.05	1.07	1.02	1.05	0.87	1.13	0.91	0.89	0.97	1.72	1.57
CI	0.04	b.d.	0.04	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	0.03	b.d.
H_2O^{\ddagger}	3.83	3.92	3.88	3.91	3.96	3.76	3.97	3.98	3.99	3.53	3.66
−(O=F,CI)	-0.45	-0.45	-0.44	-0.44	-0.37	-0.49	-0.38	-0.37	-0.41	-0.73	-0.66
Total	98.52	99.70	99.23	99.24	98.91	98.15	98.79	98.59	99.72	99.09	99.50
Si ⁴⁺	3.227	3.231	3.205	3.269	3.205	3.180	3.261	3.300	3.256	3.264	3.295
Ti ⁴⁺	b.d.	0.017	0.014								
Al ³⁺	2.347	2.439	2.364	2.340	2.426	2.386	2.402	2.370	2.442	2.154	2.178
Cr ³⁺	b.d.	0.004	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.244	0.175	0.257	0.201	0.223	0.301	0.163	0.125	0.143	0.234	0.183
Mg ²⁺	0.270	0.187	0.286	0.251	0.222	0.256	0.211	0.205	0.181	0.458	0.430
Ca ²⁺	b.d.	0.003	0.003	b.d.	b.d.						

Table A.51. (Continued) Chemical compositions and structural formulae of mica group minerals in the Rau 3 pegmatite dike.

Sample	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2c	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d
Unit	Rau 3										
Mineral	*Ms	Ms									
Mn ²⁺ (<i>apfu</i>)	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Na⁺	0.017	0.023	0.028	0.020	0.029	0.026	0.024	0.020	0.025	0.014	0.011
K ⁺	0.982	0.986	0.964	0.969	0.969	0.957	0.957	0.989	0.960	0.992	0.975
Rb⁺	0.013	0.011	0.012	0.014	0.012	0.011	0.013	0.012	0.012	0.019	0.015
F⁻	0.230	0.228	0.222	0.225	0.189	0.249	0.196	0.191	0.206	0.376	0.338
Cl⁻	0.005	b.d.	0.005	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	0.003	b.d.
$OH^{-\ddagger}$	1.765	1.772	1.774	1.775	1.811	1.745	1.804	1.809	1.794	1.621	1.662
vac.	0.907	0.963	0.888	0.939	0.923	0.873	0.959	0.999	0.979	0.872	0.899
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Sc, V, Zn, Ba, Cs, and S were also sought but were below the detection limit of the EMP in all analyses.

Sample	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.98	48.88	47.65	48.77	47.91	47.92
TiO ₂	0.13	0.12	0.09	0.00	0.00	0.00
Al ₂ O ₃	25.37	28.12	29.93	30.53	30.40	29.52
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00
$\text{FeO}_{(\text{max})}^{\dagger}$	3.57	2.85	3.92	2.37	3.63	3.06
MgO	5.80	2.85	2.30	1.84	1.97	2.29
CaO	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na ₂ O	0.10	0.13	0.23	0.23	0.18	0.14
K ₂ O	11.09	11.13	11.12	11.11	11.25	10.86
Rb ₂ O	0.46	0.34	0.29	0.25	0.25	0.23
F	1.95	1.24	1.25	0.81	0.89	0.87
Cl	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
H_2O^{\ddagger}	3.44	3.82	3.83	4.07	4.02	3.98
−(O=F,CI)	-0.82	-0.52	-0.53	-0.34	-0.37	-0.36
Total	99.06	98.95	100.10	99.64	100.12	98.53
Si ⁴⁺	3.300	3.327	3.226	3.279	3.234	3.271
Ti ⁴⁺	0.007	0.006	0.005	0.000	0.000	0.000
Al ³⁺	2.056	2.255	2.388	2.419	2.418	2.374
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.205	0.162	0.222	0.133	0.205	0.175
Mg ²⁺	0.595	0.289	0.232	0.184	0.198	0.233
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.003

Table A.51. (Continued) Chemical compositions and structural formulae of mica group minerals in the Rau 3 pegmatite dike.

Sample	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d	R3-2d
Unit	Rau 3					
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
Mn ²⁺ (apfu)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	0.014	0.017	0.030	0.030	0.024	0.019
K+	0.973	0.966	0.961	0.953	0.968	0.946
Rb⁺	0.020	0.015	0.013	0.011	0.011	0.010
F-	0.423	0.267	0.268	0.173	0.190	0.187
CI⁻	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$OH^{-\ddagger}$	1.577	1.733	1.732	1.827	1.810	1.813
vac.	0.838	0.960	0.927	0.985	0.945	0.948
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Sc, V, Zn, Ba, Cs, and S were also sought but were below the detection limit of the EMP in all analyses.

Sample	R4-2d	R4-2d	R5U-I	R5U-I	R6-1b	R6-1b
Unit	Rau 4	Rau 4	Rau 5U	Rau 5U	Rau 6	Rau 6
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	46.75	46.24	49.09	48.62	47.50	47.23
TiO ₂	0.00	0.00	0.11	0.00	0.24	0.12
AI_2O_3	30.28	29.68	30.35	30.03	25.40	27.30
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.67	4.56	2.90	2.57	3.98	3.48
MgO	2.00	2.35	1.30	2.24	5.60	3.61
CaO	b.d.	b.d.	b.d.	b.d.	0.04	0.06
MnO	0.08	0.06	b.d.	b.d.	b.d.	0.14
Na ₂ O	0.24	0.20	0.07	0.12	0.13	0.18
K ₂ O	11.04	11.05	11.50	11.58	11.41	11.37
Rb ₂ O	0.27	0.27	0.36	0.20	0.19	0.13
Cs ₂ O	0.08	b.d.	b.d.	b.d.	b.d.	b.d.
F	1.02	1.29	1.28	1.45	2.04	1.76
CI	0.05	0.06	b.d.	b.d.	0.03	0.03
H_2O^{\ddagger}	3.88	3.72	3.86	3.76	3.37	3.48
−(O=F,CI)	-0.44	-0.56	-0.54	-0.61	-0.87	-0.75
Total	98.91	98.93	100.29	99.96	99.07	98.15
Si ⁴⁺	3.204	3.186	3.295	3.274	3.277	3.271
Ti ⁴⁺	0.000	0.000	0.006	0.000	0.013	0.006
Al ³⁺	2.445	2.410	2.401	2.383	2.065	2.228
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.210	0.263	0.163	0.145	0.230	0.202
Mg ²⁺	0.204	0.241	0.130	0.224	0.576	0.372
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.003	0.005
Mn ²⁺	0.005	0.004	b.d.	b.d.	b.d.	0.008

Table A.52. Chemical compositions and structural formulae of mica group minerals in the Rau 4, 5U, and 6 pegmatite dikes.

Sample	R4-2d	R4-2d	R5U-I	R5U-I	R6-1b	R6-1b
Unit	Rau 4	Rau 4	Rau 5U	Rau 5U	Rau 6	Rau 6
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms
Na⁺ (<i>apfu</i>)	0.032	0.027	0.010	0.015	0.017	0.024
K+	0.965	0.971	0.985	0.994	1.004	1.005
Rb⁺	0.012	0.012	0.016	0.008	0.008	0.006
Cs⁺	0.002	b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	0.222	0.282	0.273	0.309	0.445	0.387
CI⁻	0.005	0.007	b.d.	b.d.	0.004	0.004
$OH^{-\pm}$	1.773	1.711	1.727	1.691	1.551	1.610
vac.	0.932	0.896	1.006	0.974	0.840	0.913
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Sc, Cr, V, Zn, Ba, and S were also sought but were below the detection limit of the EMP in all analyses.

Sample	R9b-2c	R9a-4c	R9b-2c								
Unit	Rau 9										
Mineral	*Ann	Ms									
SiO ₂ (wt.%)	34.34	45.80	46.99	49.02	48.88	47.54	49.96	46.95	46.68	47.86	44.78
TiO ₂	b.d.	0.09									
AI_2O_3	15.15	28.92	29.42	27.89	27.79	29.06	29.00	29.54	29.84	30.27	29.73
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}{}^{\dagger}$	30.50	5.05	3.83	1.61	2.31	3.92	2.20	4.46	2.89	2.35	4.53
MgO	5.52	2.78	2.61	4.41	4.00	2.76	2.61	2.47	1.81	2.02	1.51
CaO	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	0.06	b.d.
MnO	0.22	b.d.									
Na₂O	0.07	0.13	0.15	0.08	0.13	0.21	0.07	0.24	0.18	0.20	0.12
K ₂ O	9.49	11.17	11.28	11.45	11.20	11.17	11.56	11.28	11.25	11.18	10.99
Rb ₂ O	0.30	0.12	0.17	0.16	0.10	0.11	0.23	0.12	0.12	0.14	0.19
Cs ₂ O	b.d.										
F	1.34	1.56	1.44	1.85	1.69	1.47	1.71	1.54	1.08	1.37	1.30
CI	0.55	0.05	0.04	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	0.06
H ₂ O [‡]	2.92	3.57	3.68	3.56	3.62	3.70	3.67	3.65	3.81	3.75	3.61
−(O=F,CI)	-0.69	-0.67	-0.61	-0.78	-0.71	-0.62	-0.72	-0.66	-0.45	-0.58	-0.56
Total	99.71	98.55	98.99	99.24	99.00	99.33	100.29	99.64	97.30	98.61	96.35
Si ⁴⁺	2.786	3.179	3.221	3.314	3.317	3.244	3.342	3.208	3.235	3.257	3.168
Ti ⁴⁺	b.d.	0.005									
Al ³⁺	1.448	2.366	2.377	2.222	2.223	2.337	2.286	2.379	2.437	2.428	2.479
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	2.069	0.293	0.219	0.091	0.131	0.224	0.123	0.255	0.168	0.134	0.268
Mg ²⁺	0.668	0.288	0.267	0.445	0.404	0.281	0.261	0.252	0.187	0.205	0.159
Ca ²⁺	b.d.	0.005	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	0.004	b.d.
Mn ²⁺	0.015	b.d.									

Table A.53. Chemical compositions and structural formulae of mica group minerals in the Rau 9 pegmatite dike.

Sample	R9b-2c	R9a-4c	R9b-2c								
Unit	Rau 9										
Mineral	*Ann	Ms									
Na⁺ (<i>apfu</i>)	0.011	0.018	0.020	0.011	0.017	0.028	0.009	0.032	0.024	0.026	0.017
K+	0.982	0.990	0.986	0.987	0.970	0.973	0.986	0.983	0.995	0.970	0.992
Rb⁺	0.016	0.005	0.007	0.007	0.004	0.005	0.010	0.005	0.005	0.006	0.009
Cs⁺	b.d.										
F⁻	0.343	0.343	0.311	0.395	0.363	0.317	0.363	0.333	0.236	0.296	0.291
Cl⁻	0.076	0.006	0.005	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	0.007
$OH^{-\ddagger}$	1.581	1.651	1.684	1.605	1.637	1.683	1.637	1.662	1.764	1.704	1.701
vac.	0.014	0.874	0.916	0.928	0.924	0.915	0.988	0.907	0.973	0.977	0.921
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Sc, Cr, V, Zn, Ba, and S were also sought but were below the detection limit of the EMP in all analyses.

Thin Section	R3-2c	R3-2c	R3-2c	R3-2c	R5U-I	R5U-I	R5U-I	R5U-I
Unit	Rau 3	Rau 3	Rau 3	Rau 3	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Core	Rim	Core	Rim	Core	Rim	Core	Rim
Species	*Srl	Oxy-srl	Srl	Srl	Srl	Srl	Srl	Srl
SiO ₂ (wt.%)	36.79	36.04	36.75	36.58	36.66	36.84	37.11	37.19
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.06	b.d.	0.05
$B_2O_3^{\dagger}$	10.47	10.31	10.37	10.40	10.51	10.56	10.49	10.64
Al ₂ O ₃	31.82	30.44	31.05	31.25	32.05	31.71	31.45	32.79
Fe_2O_3 [‡] (min)	0.00	3.14	0.00	0.00	0.00	0.00	0.00	0.00
$FeO^{\ddagger}(max)$	11.85	8.90	11.86	10.81	12.77	11.58	12.92	10.01
MgO	4.08	4.78	4.15	4.86	3.72	4.78	3.72	5.09
CaO	0.29	0.26	0.08	0.23	0.11	0.43	0.10	0.36
MnO	0.06	0.10	b.d.	0.07	0.06	0.07	b.d.	b.d.
Na ₂ O	2.33	2.71	1.86	2.49	1.93	2.40	2.10	2.69
K ₂ O	b.d.	0.06	0.04	0.04	b.d.	b.d.	b.d.	0.04
F	0.32	0.37	0.11	0.29	0.14	0.50	0.09	0.51
H_2O^{\S}	3.19	2.84	3.43	3.20	3.54	3.21	3.44	3.01
−(O=F)	-0.13	-0.16	-0.04	-0.12	-0.06	-0.21	-0.04	-0.21
Total	101.05	99.81	99.65	100.09	101.42	101.93	101.37	102.16
Si ⁴⁺ (<i>apfu</i>)	6.109	6.079	6.163	6.114	6.062	6.065	6.150	6.074
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	b.d.	0.006
B ^{3+†}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Al ³⁺	6.228	6.050	6.136	6.154	6.246	6.151	6.142	6.312
$Fe^{3+}(min)^{\ddagger}$	0.000	0.399	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\ddagger}$	1.646	1.255	1.663	1.510	1.766	1.594	1.791	1.367
Mg ²⁺	1.009	1.202	1.038	1.212	0.917	1.174	0.918	1.240
Ca ²⁺	0.052	0.048	0.015	0.041	0.020	0.075	0.018	0.064
Mn ²⁺	0.009	0.015	b.d.	0.009	0.009	0.009	b.d.	b.d.

Table A.54. Chemical compositions and structural formulae of tourmaline supergroup minerals in the Rau 3 and 5U pegmatite dikes.

Thin Section	R3-2c	R3-2c	R3-2c	R3-2c		R5U-I	R5U-I	R5U-I	R5U-I
Unit	Rau 3	Rau 3	Rau 3	Rau 3	-	Rau 5U	Rau 5U	Rau 5U	Rau 5U
Zone	Core	Rim	Core	Rim		Core	Rim	Core	Rim
Species	*Srl	Oxy-srl	Srl	Srl	-	Srl	Srl	Srl	Srl
Na⁺ (<i>apfu</i>)	0.749	0.887	0.604	0.807		0.618	0.766	0.673	0.852
K+	b.d.	0.012	0.009	0.008		b.d.	b.d.	b.d.	0.007
F⁻	0.168	0.199	0.056	0.151		0.072	0.261	0.048	0.262
OH⁻	3.533	3.200	3.839	3.569		3.900	3.528	3.802	3.278
O ²⁻	30.832	30.801	30.944	30.849		30.928	30.739	30.952	30.738

The formulae were calculated on the basis of 15 Y + Z + T cations [XY₃Z₆T₆O₁₈(BO₃)₃V₃W] per formula unit. Vanadium, Cr, Ni, Zn, Ba, and CI were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); ${}^{\dagger}B_2O_3$ was fixed at 3 *apfu* B; ${}^{\ddagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; ${}^{\$}H_2O$ contents based on stoichiometry; b.d. = below detection limit.
Thin Section	R9a-4c	R9a-4c	R9a-4c	R9a-4c	R9a-4c	R9a-4c
Unit	Rau 9					
Zone	Core	Middle	Middle	Rim	Core	Rim
Species	Srl	Drv	Drv	Srl	Srl	Srl
SiO ₂ (wt.%)	37.10	36.91	37.34	37.61	37.14	36.50
$B_2O_3^{\dagger}$	10.61	10.65	10.71	10.77	10.61	10.48
Al ₂ O ₃	32.02	33.02	32.91	33.04	32.11	31.70
Fe_2O_3 [‡] (min)	0.47	0.00	0.00	0.00	0.00	0.00
$FeO^{\ddagger}(max)$	12.49	9.36	9.62	9.37	11.37	10.79
MgO	3.98	5.56	5.53	5.77	4.75	5.09
CaO	0.11	0.39	0.39	0.39	0.21	0.49
Na ₂ O	1.76	2.70	2.83	2.86	2.24	2.72
K ₂ O	0.03	0.06	0.03	0.05	b.d.	0.05
F	0.12	0.51	0.55	0.53	0.25	0.59
CI	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
H ₂ O§	3.60	3.07	3.02	3.04	3.40	3.00
−(O=F,CI)	-0.05	-0.22	-0.23	-0.22	-0.11	-0.26
Total	102.26	102.01	102.70	103.21	101.99	101.19
Si ⁴⁺ (<i>apfu</i>)	6.077	6.022	6.061	6.067	6.083	6.053
B ^{3+†}	3.000	3.000	3.000	3.000	3.000	3.000
Al ³⁺	6.182	6.350	6.295	6.282	6.199	6.194
Fe^{3+} (min) [‡]	0.058	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\ddagger}$	1.711	1.277	1.305	1.264	1.558	1.496
Mg ²⁺	0.971	1.351	1.339	1.387	1.160	1.257
Ca ²⁺	0.020	0.068	0.068	0.068	0.037	0.087
Na⁺	0.558	0.853	0.891	0.896	0.712	0.875
K+	0.007	0.012	0.007	0.010	b.d.	0.011
F⁻	0.064	0.264	0.281	0.268	0.131	0.310
CI⁻	b.d.	b.d.	b.d.	b.d.	b.d.	0.010
OH⁻	3.936	3.342	3.269	3.274	3.719	3.321
O ²⁻	30.936	30.736	30.719	30.732	30.869	30.679

Table A.55. Chemical compositions and structural formulae of tourmaline supergroup minerals in the Rau 9 pegmatite dike.

The formulae were calculated on the basis of 15 Y + Z + T cations $[XY_3Z_6T_6O_{18}(BO_3)_3V_3W]$ per formula unit.

Titanium, V, Cr, Mn, Ni, Zn, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{\dagger}B_2O_3$ was fixed at 3 *apfu* B; $^{\ddagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{\$}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-2d
Unit	Rau 3
Mineral	*Rt
WO ₃ (wt.%)	4.15
Nb ₂ O ₅	8.26
Ta ₂ O ₅	2.75
SiO ₂	1.36
TiO ₂	80.73
ZrO ₂	0.03
ThO ₂	0.00
Al ₂ O ₃	1.19
Sc ₂ O ₃	0.01
$Fe_2O_{3(min)}^{\dagger}$	0.61
$FeO_{(max)}^{\dagger}$	0.00
Sb ₂ O ₃	0.01
Bi ₂ O ₃	0.14
MgO	0.13
CaO	0.40
Na ₂ O	0.05
F	0.13
−(O=F)	-0.07
Total	99.88
W ⁶⁺ (<i>apfu</i>)	0.015
Nb ⁵⁺	0.053
Ta ⁵⁺	0.011
Si ⁴⁺	0.019
Ti ⁴⁺	0.854
Zr ⁴⁺	0.000
Sn ⁴⁺	0.000
Th ⁴⁺	0.000
Al ³⁺	0.020
Sc ³⁺	0.000
Fe^{3+} (min) †	0.006
$Fe^{2+}(max)^{\dagger}$	0.000
Sb ³⁺	0.000
Bi ³⁺	0.001
Mg ²⁺	0.003
Ca ²⁺	0.006
Na ⁺	0.001

Table A.56. Chemical compositions and structural formulae of rutile in the Rau 3 pegmatite dike.

Sample	R3-2d
Unit	Rau 3
Mineral	*Rt
F⁻ (<i>apfu</i>)	0.006
O ^{2_}	1.994

The formulae were calculated on the basis of 2 anions per formula unit.

Tin, U, Y, Mn, Zn, and Pb were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula.

Sample	RApl-A1	Apl-3b	Apl-3b								
Unit	Aplite	Aplite	Aplite								
Zone	Rim	Core	Rim	Core	Rim	Core	Core	Rim	Core	Rim	Core
Mineral	*Ms	Ms	Ms	Ms							
SiO ₂ (wt.%)	47.02	47.23	47.97	46.31	47.19	46.86	46.77	46.86	47.09	46.32	47.04
TiO ₂	b.d.	0.14	b.d.	b.d.	0.10	0.11	0.09	b.d.	0.09	b.d.	b.d.
Al ₂ O ₃	32.87	31.88	29.71	34.24	33.29	30.06	33.88	30.09	31.02	33.59	30.87
Cr ₂ O ₃	b.d.	b.d.	b.d.								
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.38	2.58	1.82	1.27	1.51	3.29	1.52	2.36	1.94	0.78	1.43
MgO	1.14	1.63	2.98	0.77	1.17	2.44	0.71	2.34	2.09	0.67	1.44
CaO	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	0.04
MnO	b.d.	0.08	b.d.	b.d.							
Na₂O	0.29	0.22	0.23	0.27	0.26	0.23	0.27	0.24	0.21	0.24	0.27
K ₂ O	11.35	11.14	11.33	11.36	11.30	11.06	11.34	11.20	11.52	11.55	10.92
Rb ₂ O	0.16	0.17	0.10	0.13	0.07	0.23	0.11	0.14	0.15	0.04	0.05
Cs ₂ O	b.d.	b.d.	b.d.								
F	0.75	0.56	1.26	0.00	0.00	1.29	0.72	1.03	1.08	0.65	1.22
CI	b.d.	0.02	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	b.d.
H_2O^{\ddagger}	4.07	4.17	3.82	4.44	4.47	3.77	4.11	3.86	3.89	4.09	3.76
-(O=F,CI)	-0.32	-0.24	-0.53	0.00	0.00	-0.54	-0.30	-0.44	-0.45	-0.27	-0.51
Total	98.72	99.50	98.70	98.82	99.35	98.79	99.22	97.71	98.69	97.73	96.53
Si ⁴⁺ (<i>apfu</i>)	3.182	3.187	3.259	3.126	3.168	3.206	3.148	3.226	3.206	3.157	3.249
Ti ⁴⁺	b.d.	0.007	b.d.	b.d.	0.005	0.006	0.005	b.d.	0.005	b.d.	b.d.
Al ³⁺	2.621	2.536	2.379	2.724	2.634	2.424	2.688	2.441	2.489	2.699	2.513
Cr ³⁺	b.d.	b.d.	b.d.								
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.078	0.146	0.103	0.071	0.085	0.188	0.085	0.136	0.110	0.044	0.083

Table A.57. Chemical compositions and structural formulae of muscovite in the aplite dike.

Sample	RApl-A1	Apl-3b	Apl-3b								
Unit	Aplite	Aplite	Aplite								
Zone	Rim	Core	Rim	Core	Rim	Core	Core	Rim	Core	Rim	Core
Mineral	*Ms	Ms	Ms	Ms							
Mg ²⁺ (<i>apfu</i>)	0.115	0.164	0.302	0.077	0.117	0.248	0.072	0.240	0.212	0.068	0.148
Ca ²⁺	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	0.003
Mn ²⁺	b.d.	0.005	b.d.	b.d.							
Na⁺	0.038	0.029	0.031	0.035	0.033	0.031	0.035	0.032	0.027	0.032	0.036
K ⁺	0.980	0.959	0.982	0.978	0.968	0.966	0.974	0.983	1.001	1.004	0.962
Rb⁺	0.007	0.007	0.005	0.006	0.003	0.010	0.005	0.006	0.006	0.002	0.002
Cs⁺	b.d.	b.d.	b.d.								
F⁻	0.161	0.120	0.271	0.000	0.000	0.278	0.154	0.225	0.232	0.141	0.267
Cl	b.d.	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	b.d.
OH ^{-‡}	1.839	1.878	1.729	2.000	2.000	1.722	1.846	1.771	1.768	1.859	1.733
vacancy	1.005	0.960	0.957	1.001	0.992	0.927	1.003	0.957	0.973	1.031	1.008
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	Apl-3b	AplF-6a	ApIF-6a								
Unit	Aplite	Aplite									
Zone	Middle	Core	Rim	Core	Rim	Core	Rim	Middle	Core	-	-
Mineral	*Ms	Ms	Ms								
SiO ₂ (wt.%)	46.96	46.86	47.53	48.25	47.33	46.34	46.83	46.76	47.38	47.28	46.44
TiO ₂	b.d.	0.11	0.20	b.d.							
Al ₂ O ₃	32.72	33.66	28.57	30.63	33.02	33.59	31.60	33.84	31.71	30.44	33.93
Cr ₂ O ₃	b.d.	b.d.									
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.04	1.03	1.25	1.05	1.48	0.98	1.63	1.04	1.87	2.03	1.27
MgO	0.69	0.66	2.15	2.02	0.60	0.37	0.83	0.36	1.00	2.25	0.40
CaO	b.d.	b.d.	b.d.	0.05	b.d.	b.d.	0.06	b.d.	b.d.	b.d.	b.d.
MnO	b.d.	b.d.									
Na ₂ O	0.24	0.29	0.13	0.23	0.27	0.26	0.17	0.41	0.29	0.19	0.16
K₂O	11.03	11.12	10.87	10.98	11.09	11.01	11.31	11.10	11.27	11.18	11.26
Rb ₂ O	0.01	0.06	0.11	0.04	0.08	0.00	0.06	0.07	0.07	b.d.	b.d.
Cs ₂ O	b.d.	b.d.									
F	0.87	0.95	1.13	1.03	0.65	0.67	0.91	b.d.	0.89	1.50	0.52
CI	b.d.	b.d.									
H_2O^{\ddagger}	3.98	3.98	3.74	3.92	4.12	4.06	3.92	4.42	3.98	3.68	4.17
−(O=F,CI)	-0.36	-0.40	-0.47	-0.43	-0.27	-0.28	-0.38	0.00	-0.38	-0.63	-0.22
Total	97.17	98.20	95.00	97.77	98.36	97.00	96.94	97.99	98.19	98.13	97.92
Si ⁴⁺ (<i>apfu</i>)	3.210	3.173	3.332	3.280	3.203	3.172	3.228	3.170	3.227	3.229	3.156
Ti ⁴⁺	b.d.	0.006	0.010	b.d.							
Al ³⁺	2.636	2.686	2.360	2.454	2.634	2.710	2.567	2.704	2.545	2.450	2.718
Cr ³⁺	b.d.	b.d.									
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺ (max) [†]	0.059	0.058	0.073	0.060	0.084	0.056	0.094	0.059	0.106	0.116	0.072

Table A.57. (Continued) Chemical compositions and structural formulae of muscovite in the aplite dike.

Sample	Apl-3b	ApIF-6a	ApIF-6a								
Unit	Aplite	Aplite									
Zone	Middle	Core	Rim	Core	Rim	Core	Rim	Middle	Core	-	-
Mineral	*Ms	Ms	Ms								
Mg ²⁺ (<i>apfu</i>)	0.070	0.066	0.225	0.205	0.061	0.037	0.086	0.037	0.102	0.229	0.041
Ca ²⁺	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.
Mn ²⁺	b.d.	b.d.									
Na⁺	0.032	0.038	0.018	0.031	0.035	0.035	0.023	0.053	0.038	0.026	0.021
K+	0.962	0.960	0.972	0.953	0.958	0.962	0.995	0.960	0.979	0.974	0.976
Rb⁺	0.001	0.002	0.005	0.002	0.003	0.000	0.003	0.003	0.003	b.d.	b.d.
Cs⁺	b.d.	b.d.									
F ⁻	0.187	0.203	0.250	0.221	0.139	0.145	0.199	b.d.	0.192	0.324	0.111
Cl	b.d.	b.d.									
OH-‡	1.813	1.797	1.750	1.779	1.861	1.855	1.801	2.000	1.808	1.676	1.889
vacancy	1.025	1.016	1.009	1.002	1.018	1.025	1.025	1.030	1.015	0.965	1.013
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	AplF-6a	ApIF-6a	AplF-6a	ApIF-6a	ApIF-6a	ApIF-6a	AplF-6a
Unit	Aplite						
Zone	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
SiO ₂ (wt.%)	47.58	48.26	48.47	48.06	47.82	46.60	48.32
TiO ₂	b.d.						
Al ₂ O ₃	31.42	29.27	30.47	29.83	31.83	32.05	32.27
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	0.10	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	1.15	1.41	1.07	1.71	1.17	1.92	1.13
MgO	1.45	2.40	1.88	2.39	1.17	0.90	1.20
CaO	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
MnO	b.d.						
Na ₂ O	0.22	0.15	0.10	0.25	0.16	0.20	0.21
K ₂ O	11.02	11.16	11.36	11.03	11.15	11.08	11.02
Rb ₂ O	b.d.	b.d.	b.d.	0.13	b.d.	b.d.	0.05
Cs ₂ O	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.
F	0.88	1.57	1.37	1.62	1.09	1.22	0.93
Cl	b.d.						
H_2O^{\ddagger}	3.98	3.62	3.76	3.63	3.90	3.79	4.02
−(O=F,CI)	-0.37	-0.66	-0.58	-0.68	-0.46	-0.51	-0.39
Total	97.37	97.27	97.90	97.96	97.83	97.35	98.79
Si ⁴⁺ (<i>apfu</i>)	3.248	3.312	3.295	3.280	3.249	3.200	3.247
Ti ⁴⁺	b.d.						
Al ³⁺	2.528	2.367	2.441	2.400	2.549	2.594	2.555
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.005	b.d.
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.066	0.081	0.061	0.097	0.067	0.110	0.064

Table A.57. (Continued) Chemical compositions and structural formulae of muscovite in the aplite dike.

Sample	AplF-6a	AplF-6a	AplF-6a	AplF-6a	ApIF-6a	ApIF-6a	ApIF-6a
Unit	Aplite						
Zone	-	-	-	-	-	-	-
Mineral	*Ms	Ms	Ms	Ms	Ms	Ms	Ms
Mg ²⁺ (<i>apfu</i>)	0.147	0.246	0.190	0.243	0.118	0.093	0.120
Ca ²⁺	0.003	b.d.	b.d.	b.d.	b.d.	b.d.	0.003
Mn ²⁺	b.d.						
Na⁺	0.030	0.020	0.013	0.034	0.021	0.026	0.027
K+	0.960	0.977	0.985	0.960	0.967	0.971	0.945
Rb⁺	b.d.	b.d.	b.d.	0.005	b.d.	b.d.	0.002
Cs⁺	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	0.190	0.342	0.295	0.349	0.235	0.264	0.197
Cl	b.d.						
OH-‡	1.810	1.658	1.705	1.651	1.765	1.736	1.803
vacancy	1.010	0.995	1.014	0.980	1.017	0.998	1.014
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1	RApl-A1
Unit	Aplite	Aplite	Aplite	Aplite	Aplite	Aplite
Zone	Rim	Core	Rim	Core	Mid	Rim
Mineral	*Brl	Brl	Brl	Brl	Brl	Brl
SiO ₂ (wt.%)	66.16	67.26	67.10	67.07	66.62	66.61
Al ₂ O ₃	17.22	17.69	18.32	18.24	18.36	18.20
Sc ₂ O ₃	b.d.	0.04	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.56	0.50	0.21	0.21	0.17	0.28
BeO [‡]	13.77	14.00	13.97	13.96	13.87	13.86
MgO	0.89	0.61	0.26	0.05	b.d.	0.15
Na ₂ O	0.83	0.64	0.26	0.13	0.09	0.24
Rb ₂ O	b.d.	0.11	0.13	0.11	0.10	0.11
Total	99.43	100.84	100.24	99.75	99.20	99.46
Si ⁴⁺ (<i>apfu</i>)	5.998	6.014	6.015	6.042	6.029	6.021
Al ³⁺	1.839	1.864	1.935	1.936	1.958	1.939
Sc ³⁺	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.043	0.037	0.015	0.015	0.013	0.021
Be ^{2+‡}	3.000	3.000	3.000	3.000	3.000	3.000
Mg ²⁺	0.120	0.081	0.034	0.006	b.d.	0.020
Na⁺	0.146	0.110	0.044	0.023	0.015	0.042
Rb⁺	b.d.	0.006	0.008	0.006	0.006	0.007
O ²⁻	17.991	18.006	18.008	18.025	18.018	18.014

Table A.58. Chemical compositions and structural formulae of beryl in the aplite dike.

The formulae were calculated on the basis of 8 *T* and *M* site cations per formula unit.

Phosphorus, Ti, Cr, V, Ca, Mn, Zn, Ba, K, Cs, F, and Cl were sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]BeO was fixed at 3 *apfu*; b.d. = below detection limit.

Thin Section	RApl-A1	RApl-A1
Unit	Aplite	Aplite
Mineral	*Col-(Fe)	Col-(Fe)
WO ₃ (wt.%)	0.58	0.68
Nb ₂ O ₅	54.24	63.59
Ta ₂ O ₅	24.99	14.31
SiO ₂	0.04	0.15
TiO ₂	0.94	0.62
ZrO ₂	0.03	0.05
ThO ₂	0.04	b.d.
UO ₂	0.05	0.07
Al ₂ O ₃	0.07	0.05
Sc ₂ O ₃	0.39	0.21
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00
FeO _(max) †	17.43	17.86
Y_2O_3	0.02	0.07
Bi ₂ O ₃	b.d.	0.09
MgO	0.07	0.26
MnO	2.47	3.16
Na ₂ O	0.06	0.02
Total	101.43	101.17
W ⁶⁺ (<i>apfu</i>)	0.009	0.010
Nb ⁵⁺	1.505	1.693
Ta⁵+	0.417	0.229
Si ⁴⁺	0.002	0.009
Ti ⁴⁺	0.043	0.027
Zr ⁴⁺	0.001	0.001
Th ⁴⁺	0.001	b.d.
U ⁴⁺	0.001	0.001
Al ³⁺	0.005	0.003
Sc ³⁺	0.021	0.011
$Fe^{3+}(min)^{\dagger}$	0.000	0.000
Fe ²⁺ (max) [†]	0.894	0.880
Y ³⁺	0.001	0.002
Bi ³⁺	b.d.	0.001
Mg ²⁺	0.006	0.023
Mn ²⁺	0.128	0.157
Na⁺	0.007	0.003
O ²⁻	6.000	6.000

Table A.59. Chemical compositions and structural formulae of columbite-(Fe) in the aplite dike.

The formulae were calculated on the basis of 6 anions per formula unit. Tin, Sb, Ca, Zn, Pb, and F were sought but were below the detection limit of the EMP in all analyses. *Col = columbite; $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R5U-G										
Unit	Rau 5U										
Skarn type	Biotite										
Mineral	*Phl	Phl	Ms								
SiO ₂ (wt.%)	37.36	37.25	48.41	47.29	46.79	47.26	44.52	48.41	47.22	47.10	48.17
TiO ₂	0.11	b.d.	0.09	b.d.	b.d.	b.d.	b.d.	b.d.	0.18	0.11	b.d.
Al ₂ O ₃	13.04	12.90	29.08	30.24	30.25	28.73	29.38	29.04	27.82	27.96	28.97
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	20.49	21.15	2.30	2.79	3.63	3.60	6.04	2.86	3.32	3.48	2.94
MgO	12.00	12.49	2.78	1.82	1.82	2.69	2.51	2.71	4.15	4.19	2.53
CaO	0.06	0.07	b.d.								
MnO	0.31	0.37	b.d.								
Na ₂ O	0.08	0.12	0.19	0.22	0.21	0.14	0.18	0.17	0.16	0.19	0.20
K ₂ O	9.43	9.62	11.23	11.16	11.11	11.40	11.04	11.23	11.24	11.13	11.05
Rb ₂ O	0.35	0.34	0.19	0.27	0.31	0.26	0.33	0.20	0.25	0.19	0.20
F	3.30	3.57	1.58	0.76	0.95	1.40	1.46	1.34	1.65	1.27	0.99
Cl	0.26	0.26	b.d.	b.d.	b.d.	b.d.	0.07	0.03	0.03	0.04	b.d.
H_2O^{\ddagger}	2.17	2.07	3.66	4.01	3.92	3.69	3.57	3.77	3.58	3.76	3.92
−(O=F,CI)	-1.45	-1.56	-0.67	-0.32	-0.40	-0.59	-0.63	-0.57	-0.70	-0.55	-0.42
Total	97.52	98.64	98.86	98.25	98.59	98.59	98.49	99.19	98.90	98.88	98.54
Si ⁴⁺ (<i>apfu</i>)	2.946	2.919	3.290	3.241	3.213	3.253	3.117	3.287	3.241	3.232	3.289
Ti ⁴⁺	0.007	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	0.009	0.006	b.d.
Al ³⁺	1.212	1.192	2.329	2.443	2.448	2.330	2.425	2.324	2.251	2.261	2.332
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.351	1.386	0.131	0.160	0.209	0.207	0.354	0.163	0.191	0.200	0.168
Mg ²⁺	1.410	1.459	0.282	0.186	0.187	0.276	0.262	0.274	0.425	0.429	0.257
Ca ²⁺	0.005	0.006	b.d.								
Mn ²⁺	0.021	0.025	b.d.								

Table A.60. Chemical compositions and structural formulae of mica group minerals in the biotite-type endo-contact skarn bordering Rau 5U.

Sample	R5U-G										
Unit	Rau 5U										
Skarn type	Biotite										
Mineral	*Phl	Phl	Ms								
Na⁺ (<i>apfu</i>)	0.012	0.018	0.025	0.030	0.028	0.018	0.025	0.022	0.021	0.025	0.026
K ⁺	0.949	0.961	0.974	0.976	0.973	1.001	0.986	0.973	0.985	0.975	0.963
Rb⁺	0.018	0.017	0.008	0.012	0.014	0.011	0.015	0.009	0.011	0.008	0.009
F⁻	0.823	0.884	0.340	0.165	0.206	0.305	0.324	0.287	0.358	0.276	0.213
CI⁻	0.035	0.034	b.d.	b.d.	b.d.	b.d.	0.008	0.004	0.004	0.005	b.d.
OH⁻‡	1.142	1.082	1.660	1.835	1.794	1.695	1.668	1.709	1.638	1.719	1.787
vac.	0.053	0.019	0.963	0.971	0.944	0.933	0.842	0.951	0.884	0.872	0.954
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Cr, V, Sc, Zn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Table A.60. (Continued) Chemical compositions and structural formulae of mica group minerals in the biotite-type endo-contact skarn bordering Rau 5U.

Sample	R5U-G	R5U-G
Unit	Rau 5U	Rau 5U
Skarn type	Biotite	Biotite
Mineral	*Ms	Ms
SiO ₂ (wt.%)	47.18	47.78
TiO ₂	b.d.	b.d.
Al ₂ O ₃	28.26	30.48
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00
$FeO_{(max)}^{\dagger}$	3.41	2.34
MgO	4.05	1.82
CaO	b.d.	0.04
MnO	b.d.	b.d.
Na ₂ O	0.19	0.10
K ₂ O	11.31	11.53
Rb ₂ O	0.25	0.21
F	1.41	1.01
CI	0.03	b.d.
H_2O^{\ddagger}	3.70	3.93
-(O=F,CI)	-0.60	-0.42
Total	99.19	98.81
Si ⁴⁺ (<i>apfu</i>)	3.230	3.251
Ti ⁴⁺	b.d.	b.d.
Al ³⁺	2.280	2.444
Fe^{3+} (min) [†]	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.195	0.133
Mg ²⁺	0.413	0.184
Ca ²⁺	b.d.	0.003

Sample	R5U-G	R5U-G
Unit	Rau 5U	Rau 5U
Skarn type	Biotite	Biotite
Mineral	*Ms	Ms
Mn ²⁺ (<i>apfu</i>)	b.d.	b.d.
Na ⁺	0.025	0.014
K+	0.988	1.001
Rb⁺	0.011	0.009
F⁻	0.306	0.216
Cl⁻	0.004	b.d.
OH-‡	1.691	1.784
vac.	0.882	0.987
O ²⁻	10.000	10.000

Phosphorus, Cr, V, Sc, Zn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. =

below detection limit.

Sample	R6-A	R6-A	R6-1b							
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6
Skarn type	Amphibole	Amphibole	Biotite							
Mineral	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann
SiO ₂ (wt.%)	38.49	38.69	37.97	37.76	37.91	37.63	37.72	36.74	37.99	37.68
TiO ₂	0.14	0.14	0.10	b.d.						
Al ₂ O ₃	11.87	11.67	11.69	11.78	11.98	12.06	12.55	11.68	11.87	12.06
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	22.53	22.23	22.08	21.88	23.28	23.32	23.45	22.30	22.37	22.43
MgO	12.16	12.13	12.25	11.58	11.22	11.00	10.66	11.01	11.38	11.38
CaO	0.08	b.d.	b.d.	0.05	b.d.	b.d.	b.d.	b.d.	b.d.	0.04
MnO	0.35	0.40	0.32	0.38	0.39	0.36	0.28	0.38	0.32	0.41
Na ₂ O	0.15	b.d.	0.08	0.13	0.08	0.08	0.08	0.11	0.14	0.17
K ₂ O	9.15	9.69	9.62	9.71	9.81	9.73	9.71	9.55	9.48	9.54
Rb ₂ O	0.00	0.00	0.33	0.28	0.21	0.34	0.30	0.31	0.30	0.24
F	2.64	2.56	2.89	3.01	3.25	2.58	3.27	3.33	3.69	3.62
CI	0.28	0.32	0.18	0.22	0.23	0.28	0.21	0.28	0.29	0.27
H_2O^{\ddagger}	2.53	2.56	2.40	2.30	2.21	2.50	2.20	2.05	1.97	2.01
−(O=F,CI)	-1.17	-1.15	-1.26	-1.32	-1.42	-1.15	-1.43	-1.46	-1.62	-1.59
Total	99.19	99.24	98.65	97.77	99.15	98.73	99.02	96.28	98.17	98.25
Si ⁴⁺ (<i>apfu</i>)	2.992	3.009	2.982	2.995	2.980	2.974	2.969	2.976	3.002	2.979
Ti ⁴⁺	0.008	0.008	0.006	b.d.						
Al ³⁺	1.087	1.070	1.082	1.101	1.110	1.124	1.165	1.115	1.106	1.124
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.465	1.446	1.450	1.451	1.531	1.541	1.543	1.510	1.478	1.484
Mg ²⁺	1.410	1.406	1.434	1.369	1.315	1.296	1.251	1.329	1.341	1.341
Ca ²⁺	0.007	b.d.	b.d.	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	0.003

Table A.61. Chemical compositions and structural formulae of mica group minerals in the amphibole- and biotite-type endo-contact skarns bordering Rau 6.

Sample	R6-A	R6-A	R6-1b							
Unit	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6	Rau 6
Skarn type	Amphibole	Amphibole	Biotite							
Mineral	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann	Ann
Mn ²⁺ (<i>apfu</i>)	0.023	0.027	0.021	0.026	0.026	0.024	0.019	0.026	0.022	0.027
Na⁺	0.023	b.d.	0.012	0.020	0.013	0.013	0.012	0.018	0.021	0.027
K+	0.907	0.962	0.964	0.982	0.984	0.981	0.976	0.986	0.955	0.962
Rb⁺	0.000	0.000	0.017	0.014	0.011	0.017	0.015	0.016	0.015	0.012
F⁻	0.649	0.629	0.717	0.754	0.808	0.645	0.815	0.852	0.922	0.906
CI⁻	0.036	0.042	0.024	0.030	0.031	0.038	0.028	0.038	0.039	0.036
OH⁻‡	1.314	1.329	1.260	1.216	1.161	1.318	1.157	1.110	1.039	1.058
vac.	0.016	0.034	0.025	0.058	0.039	0.041	0.053	0.044	0.051	0.045
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Cr, V, Sc, Zn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R7-A	R9b-2c	R9b-2c	R9b-2c								
Unit	Rau 7	Rau 9	Rau 9	Rau 9								
Skarn type	Biotite											
Mineral	*Ann	Ann	Ann	Ann	Ann	Ann	Ms	Ms	Ms	Ann	Ann	Ann
SiO ₂ (wt.%)	37.16	37.76	38.07	38.00	37.88	37.21	51.11	51.34	51.40	34.72	34.88	34.34
TiO ₂	0.13	0.09	0.11	0.07	0.13	0.14	0.20	0.13	0.15	b.d.	b.d.	b.d.
Al ₂ O ₃	12.89	12.95	12.73	13.11	13.61	13.39	26.32	27.69	27.18	15.49	15.47	15.15
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	25.16	25.40	25.29	21.96	23.85	24.50	3.02	2.27	2.58	29.76	31.01	30.50
MgO	9.27	9.53	9.61	11.90	10.34	10.12	3.91	3.32	3.30	5.30	5.10	5.52
CaO	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	0.06	0.08	0.05	b.d.	b.d.
MnO	0.35	0.31	0.28	0.39	0.48	0.44	b.d.	b.d.	b.d.	0.30	0.22	0.22
Na ₂ O	0.13	0.10	0.15	0.11	0.19	0.14	0.06	0.08	0.08	0.05	0.07	0.07
K ₂ O	9.58	9.41	9.36	9.76	9.32	9.12	10.40	10.95	10.79	9.36	9.34	9.49
Rb ₂ O	b.d.	0.26	0.26	0.30								
F	3.20	3.22	3.37	3.91	3.24	3.22	2.07	1.89	1.97	1.32	1.49	1.34
CI	0.45	0.48	0.38	0.17	0.31	0.23	0.03	b.d.	b.d.	0.40	0.53	0.55
H_2O^{\ddagger}	2.15	2.18	2.14	1.98	2.26	2.24	3.48	3.62	3.57	2.98	2.89	2.92
−(O=F,CI)	-1.45	-1.47	-1.50	-1.68	-1.43	-1.41	-0.88	-0.79	-0.83	-0.65	-0.75	-0.69
Total	99.01	99.96	99.97	99.73	100.16	99.34	99.73	100.54	100.28	99.34	100.51	99.71
Si ⁴⁺ (apfu)	2.947	2.959	2.978	2.941	2.937	2.920	3.426	3.406	3.422	2.808	2.802	2.786
Ti ⁴⁺	0.008	0.005	0.007	0.004	0.007	0.008	0.010	0.006	0.008	0.000	0.000	0.000
Al ³⁺	1.205	1.196	1.173	1.196	1.243	1.238	2.080	2.165	2.133	1.477	1.464	1.448
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	1.669	1.665	1.654	1.421	1.546	1.607	0.169	0.126	0.144	2.012	2.083	2.069
Mg ²⁺	1.096	1.114	1.121	1.373	1.195	1.184	0.391	0.328	0.328	0.639	0.611	0.668
Ca ²⁺	b.d.	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	0.004	0.006	0.004	b.d.	b.d.
Mn ²⁺	0.023	0.020	0.019	0.025	0.031	0.029	b.d.	b.d.	b.d.	0.020	0.015	0.015

Table A.62. Chemical compositions and structural formulae of mica group minerals in the biotite-type endo-contact skarns bordering Rau 7 and 9.

Sample	R7-A	R9b-2c	R9b-2c	R9b-2c								
Unit	Rau 7	Rau 9	Rau 9	Rau 9								
Skarn type	Biotite											
Mineral	*Ann	Ann	Ann	Ann	Ann	Ann	Ms	Ms	Ms	Ann	Ann	Ann
Na⁺ (<i>apfu</i>)	0.019	0.015	0.022	0.016	0.028	0.022	0.008	0.010	0.010	0.008	0.011	0.011
K⁺	0.969	0.940	0.934	0.963	0.922	0.913	0.890	0.927	0.916	0.965	0.958	0.982
Rb⁺	b.d.	0.013	0.014	0.016								
F⁻	0.802	0.799	0.834	0.957	0.794	0.798	0.438	0.396	0.414	0.338	0.378	0.343
Cl⁻	0.061	0.064	0.050	0.022	0.040	0.031	0.004	b.d.	b.d.	0.055	0.072	0.076
OH-‡	1.137	1.137	1.116	1.021	1.166	1.171	1.558	1.604	1.586	1.607	1.550	1.581
vac.	0.052	0.041	0.049	0.039	0.040	0.014	0.924	0.968	0.966	0.044	0.025	0.014
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

Phosphorus, Cr, V, Sc, Zn, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R6-A								
Unit	Rau 6								
Skarn type	Amphibole								
Mineral	*Fac	Mhb	Mhb	Fed	Fhb	Act	Fed	Fhb	Fed
SiO ₂ (wt.%)	51.47	50.73	51.07	44.29	45.56	51.29	45.65	46.02	43.91
TiO ₂	b.d.	b.d.	b.d.	b.d.	b.d.	0.06	0.05	b.d.	0.06
Al ₂ O ₃	2.58	4.07	3.38	8.27	7.50	3.37	7.78	7.26	8.75
$Fe_2O_{3(\text{min})}^\dagger$	4.36	2.28	2.79	4.06	4.46	1.86	3.56	3.25	2.56
$FeO_{(max)}^{\dagger}$	18.29	15.33	14.94	19.59	18.00	15.18	17.72	19.07	19.62
MgO	9.90	12.34	12.50	7.47	8.46	12.63	9.13	8.21	7.59
CaO	11.79	12.28	12.25	11.96	11.74	12.35	12.16	12.03	11.93
MnO	0.75	0.71	0.60	0.89	0.75	0.75	0.79	0.84	0.67
Na ₂ O	0.65	0.96	0.73	1.38	1.27	0.78	1.33	1.09	1.25
K ₂ O	0.27	0.69	0.56	1.28	1.12	0.55	1.11	0.98	1.43
F	0.96	1.60	1.35	1.30	1.30	1.49	1.36	1.08	1.31
CI	0.03	0.05	0.04	0.13	0.10	0.04	0.11	0.09	0.22
H_2O^{\ddagger}	1.58	1.28	1.40	1.32	1.34	1.34	1.33	1.45	1.27
−(O=F,CI)	-0.41	-0.69	-0.58	-0.58	-0.57	-0.63	-0.59	-0.47	-0.60
Total	102.22	101.62	101.03	101.35	101.02	101.04	101.47	100.88	99.99
Si ⁴⁺	7.562	7.405	7.477	6.746	6.884	7.503	6.850	6.964	6.756
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.	b.d.	0.007	0.006	b.d.	0.006
Al ³⁺	0.447	0.700	0.582	1.484	1.336	0.580	1.376	1.294	1.587
$Fe^{3+}(min)^{\dagger}$	0.482	0.250	0.308	0.465	0.507	0.204	0.402	0.370	0.297
$Fe^{2+}(max)^{\dagger}$	2.247	1.871	1.829	2.495	2.274	1.857	2.224	2.413	2.525
Mg ²⁺	2.169	2.686	2.729	1.696	1.904	2.755	2.042	1.851	1.741
Ca ²⁺	1.856	1.920	1.921	1.952	1.901	1.936	1.955	1.950	1.967
Mn ²⁺	0.093	0.087	0.075	0.114	0.095	0.093	0.100	0.108	0.088

Table A.63. Chemical compositions and structural formulae of amphibole supergroup minerals in the amphibole-type endo-contact skarn bordering Rau 6.

Sample	R6-A								
Unit	Rau 6								
Skarn type	Amphibole								
Mineral	*Fac	Mhb	Mhb	Fed	Fhb	Act	Fed	Fhb	Fed
Na+ (<i>apfu</i>)	0.185	0.270	0.208	0.407	0.371	0.221	0.388	0.320	0.374
K ⁺	0.050	0.129	0.105	0.248	0.216	0.102	0.212	0.189	0.281
F⁻	0.446	0.741	0.627	0.625	0.621	0.688	0.643	0.516	0.639
CI⁻	0.008	0.012	0.010	0.034	0.025	0.009	0.027	0.022	0.057
$OH^{-\ddagger}$	1.545	1.247	1.363	1.341	1.354	1.303	1.329	1.462	1.304
O ²⁻	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000	22.000

The formulae were calculated on the basis of 13 [Si + Al + Ti + Fe³⁺ + Fe²⁺ + Mn + Mg] cations per formula unit.

Phosphorus, V, Cr, Sc, Zn, and Ni were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Fhb = ferro-hornblende; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R6-A	R6-A	R6-A	R6-A
Unit	Rau 6	Rau 6	Rau 6	Rau 6
Skarn type	Amphibole	Amphibole	Amphibole	Amphibole
Mineral	*Fed	Fed	Mhb	Mhb
SiO ₂ (wt.%)	45.74	42.58	50.36	50.82
TiO ₂	b.d.	b.d.	b.d.	b.d.
Al ₂ O ₃	7.21	9.69	2.58	3.38
$Fe_2O_{3(min)}^{\dagger}$	2.56	3.79	7.27	2.95
$FeO_{(max)}^{\dagger}$	20.18	19.33	16.55	14.36
MgO	7.67	7.15	9.47	12.69
CaO	11.85	11.95	11.33	12.25
MnO	0.85	0.69	0.91	0.74
Na ₂ O	1.23	1.34	0.53	0.74
K ₂ O	1.08	1.56	0.18	0.59
F	1.17	1.20	0.71	1.54
CI	0.10	0.23	0.05	0.04
H_2O^{\ddagger}	1.39	1.32	1.67	1.30
−(O=F,CI)	-0.51	-0.56	-0.31	-0.66
Total	100.51	100.27	101.30	100.75
Si ⁴⁺	6.979	6.569	7.474	7.458
Ti ⁴⁺	b.d.	b.d.	b.d.	b.d.
Al ³⁺	1.296	1.763	0.451	0.584
$Fe^{3+}(min)^{\dagger}$	0.294	0.440	0.812	0.326
$Fe^{2+}(max)^{\dagger}$	2.575	2.494	2.053	1.763
Mg ²⁺	1.746	1.644	2.095	2.777
Ca ²⁺	1.938	1.975	1.802	1.926
Mn ²⁺	0.109	0.090	0.114	0.092

Table A.63. (Continued) Chemical compositions and structural formulae of amphibole supergroup minerals in the amphibole-type endo-contact skarn bordering Rau 6.

Sample	R6-A	R6-A	R6-A	R6-A
Unit	Rau 6	Rau 6	Rau 6	Rau 6
Skarn type	Amphibole	Amphibole	Amphibole	Amphibole
Mineral	*Fed	Fed	Mhb	Mhb
Na⁺ (<i>apfu</i>)	0.365	0.401	0.152	0.211
K ⁺	0.210	0.307	0.033	0.110
F⁻	0.563	0.583	0.335	0.715
Cl⁻	0.027	0.061	0.013	0.011
$OH^{-\ddagger}$	1.410	1.356	1.652	1.274
O ^{2_}	22.000	22.000	22.000	22.000

The formulae were calculated on the basis of 13 [Si + Al + Ti + Fe³⁺

+ Fe^{2+} + Mn + Mg] cations per formula unit.

Phosphorus, V, Cr, Sc, Zn, and Ni were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); Fhb = ferro-hornblende; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R6-A	R6-A	R6-A	R9b-2c	R9b-2c	R9b-2c	R9b-2c	R9b-2c
Unit	Rau 6	Rau 6	Rau 6	Rau 9				
Skarn type		Amphibole		Biotite	Biotite	Biotite	Biotite	Biotite
Zone	Core	Rim	Core	Rim	Middle	-	Core	Rim
Mineral	*Aln	Czo	Aln	Czo	Ep	Ep	Ep	Ep
SiO ₂ (wt.%)	32.48	33.95	32.29	34.71	33.81	34.61	32.99	34.42
ThO ₂	1.04	1.77	1.19	1.12	5.51	3.87	6.95	3.58
UO ₂	b.d.	b.d.	b.d.	0.21	0.19	0.12	0.14	0.28
Al ₂ O ₃	17.91	19.63	18.18	21.35	19.22	20.43	17.56	20.24
Sc ₂ O ₃	0.14	b.d.	0.19	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	1.60	5.44	0.35	5.41	4.69	5.65	4.89	6.58
FeO _(max) †	10.84	7.27	11.27	6.41	8.02	6.61	9.07	6.47
Y ₂ O ₃	0.09	0.29	b.d.	1.76	0.55	0.57	0.42	0.57
La ₂ O ₃	3.69	2.45	3.60	0.65	1.92	1.57	1.81	2.12
Ce ₂ O ₃	11.66	8.00	12.07	3.62	5.40	4.82	6.41	5.07
Pr ₂ O ₃	1.47	1.05	1.53	0.85	0.79	0.71	0.92	0.76
Nd ₂ O ₃	4.37	3.01	4.72	3.74	2.42	2.38	2.41	1.97
Sm ₂ O ₃	0.67	0.43	0.54	1.38	0.45	0.48	0.40	0.35
Gd ₂ O ₃	b.d.	b.d.	b.d.	0.48	b.d.	b.d.	b.d.	b.d.
Tm ₂ O ₃	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	b.d.
MgO	0.60	0.27	0.65	0.08	0.20	0.17	0.11	0.16
CaO	11.67	15.27	11.46	16.51	15.56	16.89	14.43	16.66
MnO	0.67	0.33	0.66	0.34	0.33	0.31	0.77	0.37
PbO	0.01	0.01	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
F	0.22	0.02	0.28	b.d.	0.01	0.04	0.06	0.00
H_2O^{\ddagger}	1.61	1.69	1.61	1.73	1.68	1.72	1.64	1.72
−(O=F,CI)	-0.09	-0.01	-0.12	0.00	-0.01	-0.02	-0.02	0.00
Total	100.64	100.85	100.45	100.36	100.75	100.94	100.95	101.31
Si ⁴⁺ (<i>apfu</i>)	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Th ⁴⁺	0.022	0.036	0.025	0.022	0.111	0.076	0.144	0.071
U ⁴⁺	b.d.	b.d.	b.d.	0.004	0.004	0.002	0.003	0.005
Al ³⁺	1.950	2.045	1.991	2.174	2.009	2.087	1.882	2.080
Sc ³⁺	0.011	b.d.	0.015	b.d.	b.d.	b.d.	b.d.	b.d.
Fe^{3+} (min) [†]	0.270	0.426	0.155	0.374	0.490	0.470	0.497	0.384
$Fe^{2+}(max)^{\dagger}$	0.679	0.472	0.745	0.441	0.418	0.378	0.527	0.520
Y ³⁺	0.005	0.013	b.d.	0.081	0.026	0.026	0.020	0.026
La ³⁺	0.126	0.080	0.123	0.021	0.063	0.050	0.061	0.068
Ce ³⁺	0.394	0.259	0.410	0.115	0.175	0.153	0.213	0.162
Pr ³⁺	0.049	0.034	0.052	0.027	0.026	0.022	0.030	0.024

Table A.64. Chemical compositions and structural formulae of epidote supergroup minerals in the biotite-type endo-contact skarns bordering Rau 6 and 9.

Sample	R6-A	R6-A	R6-A		R9b-2c	R9b-2c	R9b-2c	R9b-2c	R9b-2c
Unit	Rau 6	Rau 6	Rau 6	-	Rau 9				
Skarn type		Amphibole		-	Biotite	Biotite	Biotite	Biotite	Biotite
Zone	Core	Rim	Core	_	Rim	Middle	-	Core	Rim
Mineral	*Aln	Czo	Aln	-	Czo	Ep	Ep	Ep	Ep
Nd ³⁺ (<i>apfu</i>)	0.144	0.095	0.157		0.115	0.077	0.074	0.078	0.061
Sm ³⁺	0.021	0.013	0.017		0.041	0.014	0.014	0.013	0.011
Gd ³⁺	b.d.	b.d.	b.d.		0.014	b.d.	b.d.	b.d.	b.d.
Tm ³⁺	b.d.	b.d.	b.d.		0.000	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	0.082	0.036	0.090		0.010	0.027	0.022	0.015	0.020
Ca ²⁺	1.155	1.446	1.141		1.529	1.479	1.569	1.406	1.556
Mn ²⁺	0.052	0.025	0.052		0.025	0.025	0.023	0.060	0.027
Pb ²⁺	0.000	0.000	b.d.		b.d.	b.d.	b.d.	b.d.	b.d.
F⁻	0.065	0.005	0.082		b.d.	0.004	0.010	0.016	0.001
OH-‡	1.000	1.000	1.000		1.000	1.000	1.000	1.000	1.000
O ^{2_}	12.935	12.995	12.918		13.000	12.996	12.990	12.984	12.999

The formulae were calculated on the basis of 3 Si atoms per formula unit.

Phosphorus, Ti, Zr, Sn, Tb, Dy, Ho, Er, Yb, Sr, Na, K, and Cl were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R7-A								
Unit	Rau 7								
Skarn type	Biotite								
Zone	Middle	Core	Core	Middle	Middle	Rim	-	-	-
Mineral	*Aln	Aln	Ep	Aln	Aln	Ep	Czo	Ep	Ep
P ₂ O ₅ (wt.%)	b.d.	0.10	0.05						
SiO ₂	31.89	34.26	34.42	31.88	33.93	34.24	34.56	34.42	33.96
ZrO ₂	b.d.	0.12	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
SnO ₂	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
ThO ₂	0.97	0.21	2.00	0.74	0.68	4.08	0.59	4.98	3.23
UO ₂	b.d.	b.d.	0.11	b.d.	b.d.	b.d.	b.d.	0.10	b.d.
Al ₂ O ₃	18.04	20.46	19.98	18.62	19.18	19.63	20.28	19.22	18.30
Sc ₂ O ₃	0.20	0.49	0.38	0.26	0.17	b.d.	0.28	b.d.	0.23
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.76	3.46	0.00	3.45	1.81	2.50	0.29	2.18
$FeO_{(max)}^{\dagger}$	10.85	9.17	8.29	10.48	8.95	11.11	8.42	10.96	10.50
Y ₂ O ₃	b.d.	0.19	0.59	b.d.	0.28	0.53	0.34	0.53	0.41
La ₂ O ₃	4.31	2.84	2.28	4.44	2.93	1.80	2.31	2.15	2.22
Ce ₂ O ₃	14.19	8.85	6.47	13.99	9.17	5.94	7.65	5.43	6.88
Pr ₂ O ₃	1.65	1.19	0.81	1.53	1.25	0.71	1.00	0.77	0.89
Nd ₂ O ₃	4.15	3.66	2.68	3.90	3.48	2.19	3.11	2.21	2.42
Sm ₂ O ₃	0.36	0.64	0.64	0.30	0.52	0.48	0.75	0.43	0.44
Gd ₂ O ₃	b.d.	b.d.	0.20	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
MgO	0.81	0.46	0.32	1.00	0.27	0.24	0.28	0.38	0.35
CaO	10.33	14.76	15.76	10.48	14.30	13.46	15.27	14.06	13.74
MnO	1.06	0.59	0.56	0.99	0.44	0.44	0.55	0.59	0.61
PbO	0.01	b.d.	0.02	b.d.	0.01	0.03	0.02	0.04	0.01
Na ₂ O	b.d.	b.d.	b.d.	0.09	b.d.	0.15	b.d.	0.15	0.14

Table A.65. Chemical compositions and structural formulae of epidote supergroup minerals in the biotite-type endo-contact skarn bordering Rau 7.

Sample	R7-A								
Unit	Rau 7								
Skarn type	Biotite								
Zone	Middle	Core	Core	Middle	Middle	Rim	-	-	_
Mineral	*Aln	Aln	Ep	Aln	Aln	Ep	Czo	Ep	Ep
F (wt.%)	0.17	0.09	0.06	0.22	0.07	0.30	0.05	0.34	0.20
CI	b.d.	b.d.	b.d.	0.02	b.d.	b.d.	b.d.	0.06	b.d.
H_2O^{\ddagger}	1.53	1.69	1.70	1.58	1.67	1.66	1.69	1.66	1.64
-(O=F,CI)	-0.07	-0.04	-0.02	-0.10	-0.03	-0.13	-0.02	-0.16	-0.08
Total	100.44	100.37	100.80	100.42	100.72	98.68	99.62	98.72	98.31
P ⁵⁺ (apfu)	b.d.	0.007	0.004						
Si ⁴⁺	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Zr ⁴⁺	b.d.	0.005	0.004	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Sn ⁴⁺	b.d.	b.d.	0.001	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Th ⁴⁺	0.021	0.004	0.040	0.016	0.014	0.081	0.012	0.099	0.065
U ⁴⁺	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	0.002	b.d.
Al ³⁺	2.000	2.111	2.053	2.065	1.998	2.027	2.074	1.969	1.902
Sc ³⁺	0.017	0.037	0.029	0.021	0.013	b.d.	0.021	b.d.	0.018
$Fe^{3+}(min)^{\dagger}$	0.092	0.409	0.459	0.000	0.549	0.822	0.661	0.816	0.919
$Fe^{2+}(max)^{\dagger}$	0.761	0.312	0.371	0.825	0.343	0.112	0.113	0.000	0.000
Y ³⁺	b.d.	0.009	0.027	b.d.	0.013	0.025	0.016	0.025	0.019
La ³⁺	0.150	0.092	0.073	0.154	0.095	0.058	0.074	0.069	0.072
Ce ³⁺	0.489	0.284	0.206	0.482	0.297	0.191	0.243	0.173	0.222
Pr ³⁺	0.057	0.038	0.026	0.053	0.040	0.023	0.032	0.024	0.028
Nd ³⁺	0.139	0.114	0.083	0.131	0.110	0.069	0.096	0.069	0.076
Sm ³⁺	0.012	0.019	0.019	0.010	0.016	0.014	0.022	0.013	0.013
Gd ³⁺	b.d.	b.d.	0.006	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Mg ²⁺	0.114	0.060	0.041	0.140	0.036	0.032	0.036	0.050	0.045
Ca ²⁺	1.041	1.384	1.472	1.057	1.354	1.264	1.420	1.310	1.299

Sample	R7-A								
Unit	Rau 7								
Skarn type	Biotite								
Zone	Middle	Core	Core	Middle	Middle	Rim	-	-	-
Mineral	*Aln	Aln	Ep	Aln	Aln	Ep	Czo	Ep	Ep
Mn ²⁺ (<i>apfu</i>)	0.085	0.044	0.042	0.079	0.033	0.033	0.041	0.044	0.045
Pb ²⁺	0.000	b.d.	0.000	b.d.	0.000	0.001	0.001	0.001	0.000
Na ⁺	b.d.	b.d.	b.d.	0.017	b.d.	0.025	b.d.	0.024	0.024
F⁻	0.052	0.024	0.016	0.065	0.019	0.084	0.013	0.094	0.056
Cl-	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	0.009	b.d.
OH ^{-‡}	1.000	1.000	1.000	0.902	1.000	1.000	1.000	1.182	1.062
O ²⁻	12.948	12.976	12.984	12.932	12.981	12.916	12.987	12.897	12.944

The formulae were calculated on the basis of 3 Si atoms per formula unit.

Titanium, Tb, Dy, Ho, Er, Yb, Sr, and K, were also sought but were below the detection limit of the EMP in all analyses. *Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R6-A	R6-A	R6-A	R6-A	R6-A	R6-A	R6-1b	R6-1b	R6-1b
Skarn type	Amphibole	Amphibole	Amphibole	Amphibole	Amphibole	Amphibole	Biotite	Biotite	Biotite
Zone	Rim	Rim	Core	Core	Core	Rim	-	-	-
Mineral	*Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr
WO ₃ (wt.%)	0.19	0.30	0.25	0.26	0.64	0.28	b.d.	b.d.	0.65
Nb ₂ O ₅	27.60	28.53	7.58	8.67	7.59	30.46	11.46	11.25	25.28
Ta ₂ O ₅	44.60	44.23	69.29	66.93	65.55	42.19	65.93	66.33	51.11
SiO ₂	b.d.	b.d.	b.d.	b.d.	1.85	b.d.	0.78	0.77	0.52
TiO ₂	0.58	0.42	0.91	0.88	1.06	0.92	b.d.	b.d.	0.51
ZrO ₂	b.d.	b.d.	b.d.	0.10	0.15	b.d.	0.18	b.d.	b.d.
SnO ₂	2.55	2.60	1.12	1.42	1.56	2.79	1.40	1.52	1.11
UO ₂	2.04	1.79	0.91	1.18	1.36	2.05	1.89	1.87	1.25
Al ₂ O ₃	0.10	0.15	b.d.	b.d.	0.27	b.d.	0.11	0.15	0.09
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.80	0.99	0.48	0.54	1.08	0.64	0.99	0.88	1.51
Y ₂ O ₃	0.04	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CaO	14.16	14.65	12.48	12.69	11.97	14.42	12.34	12.29	12.19
MnO	0.17	0.17	0.09	0.11	0.12	0.13	0.10	b.d.	0.10
Na ₂ O	2.96	3.16	3.17	3.00	3.15	3.20	3.79	3.78	5.46
F	3.09	3.14	3.13	3.13	3.02	3.25	2.58	2.85	3.50
-(O=F)	-1.30	-1.32	-1.32	-1.32	-1.27	-1.37	-1.09	-1.20	-1.47
Total	97.57	98.79	98.08	97.57	98.08	98.95	100.46	100.50	101.80
W ⁶⁺ (apfu)	0.004	0.006	0.006	0.006	0.014	0.005	b.d.	b.d.	0.013
Nb ⁵⁺	0.977	0.992	0.298	0.340	0.289	1.046	0.434	0.425	0.865
Ta⁵⁺	0.949	0.925	1.640	1.582	1.502	0.871	1.502	1.508	1.052
Si ⁴⁺	b.d.	b.d.	b.d.	b.d.	0.156	b.d.	0.065	0.065	0.039
Ti ⁴⁺	0.034	0.024	0.060	0.057	0.067	0.053	b.d.	b.d.	0.029

Table A.66. Chemical compositions and structural formulae of pyrochlore supergroup minerals in the amphibole- and biotite-type endo-contact skarns bordering Rau 6.

Sample	R6-A	R6-A	R6-A	R6-A	R6-A	R6-A	R6-1b	R6-1b	R6-1b
Skarn type	Amphibole	Amphibole	Amphibole	Amphibole	Amphibole	Amphibole	Biotite	Biotite	Biotite
Zone	Rim	Rim	Core	Core	Core	Rim	-	-	-
Mineral	*Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr	Fclprc	Fclmcr	Fclmcr	Fclmcr
Zr ⁴⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	0.004	0.006	b.d.	0.007	b.d.	b.d.
Sn ⁴⁺	0.079	0.080	0.039	0.049	0.052	0.084	0.047	0.051	0.033
U ⁴⁺	0.035	0.031	0.018	0.023	0.026	0.035	0.035	0.035	0.021
Al ³⁺	0.009	0.013	b.d.	b.d.	0.027	b.d.	0.011	0.015	0.008
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.053	0.064	0.035	0.039	0.076	0.040	0.070	0.061	0.096
Y ³⁺	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ca ²⁺	1.188	1.208	1.164	1.182	1.081	1.173	1.107	1.101	0.989
Mn ²⁺	0.011	0.011	0.006	0.008	0.008	0.008	0.007	b.d.	0.006
Na⁺	0.449	0.471	0.535	0.505	0.514	0.471	0.615	0.612	0.802
F-	0.765	0.763	0.862	0.859	0.805	0.780	0.685	0.754	0.837
O ²⁻	6.235	6.237	6.138	6.141	6.195	6.220	6.315	6.246	6.163

The formulae were calculated on the basis of 7 anions per formula unit.

Thorium, Sc, Sb, Bi, Mg, Zn and Pb were also sought but were below the detection limit of the EMP in all analyses.

*FcImcr = fluorcalciomicrolite; FcIprc = fluorcalciopyrochlore; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R5U-G	R6-1b	R9b-2c
Unit	Rau 5U	Rau 6	Rau 9
Skarn type	Biotite	Biotite	Biotite
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)
WO₃ (wt.%)	7.42	1.04	1.42
Nb ₂ O ₅	50.63	54.76	61.67
Ta ₂ O ₅	15.65	23.56	16.49
SiO ₂	0.04	0.25	0.02
TiO ₂	7.98	2.34	1.27
ZrO ₂	0.06	b.d.	0.10
SnO ₂	0.18	b.d.	0.27
ThO ₂	b.d.	b.d.	0.02
Al ₂ O ₃	0.02	b.d.	0.01
Sc ₂ O ₃	0.04	0.40	0.38
$Fe_2O_{3(min)}^{\dagger}$	3.09	b.d.	4.58
FeO _(max) †	16.06	14.53	15.57
Y ₂ O ₃	0.02	b.d.	0.04
Sb ₂ O ₃	b.d.	b.d.	0.08
Bi ₂ O ₃	0.02	b.d.	b.d.
MgO	0.09	0.17	0.13
CaO	b.d.	0.29	b.d.
MnO	0.82	2.45	1.64
PbO	b.d.	b.d.	0.07
Na ₂ O	0.02	b.d.	b.d.
Total	102.11	99.78	103.77
W ⁶⁺ (<i>apfu</i>)	0.112	0.017	0.022
Nb ⁵⁺	1.339	1.515	1.625
Ta ⁵⁺	0.249	0.392	0.261
Si ⁴⁺	0.002	0.015	0.001
Ti ⁴⁺	0.351	0.108	0.056
Zr ⁴⁺	0.002	b.d.	0.003
Sn ⁴⁺	0.004	b.d.	0.006
Th ⁴⁺	b.d.	b.d.	0.000
Al ³⁺	0.001	b.d.	0.001
Sc ³⁺	0.002	0.021	0.019
Fe^{3+} (min) †	0.000	b.d.	0.000
$Fe^{2+}(max)^{\dagger}$	0.921	0.744	0.960
Y ³⁺	0.001	b.d.	0.001
Sb ³⁺	b.d.	b.d.	0.002

Table A.67. Chemical compositions and structural formulae of columbite-(Fe) in the biotite-type endocontact skarns bordering Rau 5U, 6, and 9.

Sample	R5U-G	R6-1b	R9b-2c
Unit	Rau 5U	Rau 6	Rau 9
Skarn type	Biotite	Biotite	Biotite
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)
Bi ³⁺ (<i>apfu</i>)	0.000	b.d.	b.d.
Mg ²⁺	0.007	0.016	0.012
Ca ²⁺	b.d.	0.019	b.d.
Mn ²⁺	0.041	0.127	0.081
Pb ²⁺	b.d.	b.d.	0.001
Na⁺	0.002	b.d.	b.d.
O ²⁻	6.000	6.000	6.000

The formulae were calculated on the basis of 6 O atoms per formula unit.

Uranium, Zn, and F was also sought but were below the detection limit of the EMP in all analyses.

*Col = columbite; †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R6-A						
Unit	Rau 6						
Skarn type	Amphibole						
Mineral	*Fluor-Ap						
P ₂ O ₅ (wt.%)	41.94						
SiO ₂	0.15						
$Fe_2O_{3(min)}^{\dagger}$	0.00						
FeO _(max) †	0.14						
Y ₂ O ₃	0.19						
CaO	47.41						
F	3.86						
−(O=F)	-1.63						
Total	92.06						
P ⁵⁺ (apfu)	3.277						
Si ⁴⁺	0.014						
Fe^{3+} (min) [†]	0.000						
$Fe^{2+}(max)^{\dagger}$	0.011						
Y ³⁺	0.009						
Ca ²⁺	4.689						
F⁻	1.127						
O ²⁻	12.370						
The formulae w	vere						
calculated on th	ne basis of 8						
cations per form	cations per formula unit.						
Thorium, Al, La, Ce, Nd, Sr,							
Mg, Mn, Ba, Na, S, and Cl							
were also sought but were							
below the detection limit of							
the EMP in all analyses.							
names follow W	ADDreviations of mineral						

Table A.68. Chemical compositions and structural formulae of fluorapatite in the amphibole-type endocontact skarn bordering Rau 6.

Evans (2010) [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Table A.69. Chemical compositions and structural formulae of scheelite in the biotite-type endo-contact skarn bordering Rau 9.

Sample	R9b-2c	R9b-2c
Unit	Rau 9	Rau 9
Skarn type	Biotite	Biotite
Mineral	*Sch	Sch
WO ₃ (wt.%)	79.43	78.64
CaO	19.26	19.23
-(O=F)	-0.04	0.00
Total	98.74	97.87
W ⁶⁺ (apfu)	0.998	0.997
Ca ²⁺	1.000	1.008
F⁻	0.015	0.000
O ²⁻	3.993	4.000

The formulae were calculated on the basis of 4 anions per formula unit.

Molybdenum, Nb, Ta, Si, Ti, Al, Sc, Fe, Mg, Mn, Zn, Pb, and Na were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of minerals names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R6-A
Unit	Rau 6
Skarn type	Amphibole
Mineral	*Gdl-(Y)
SiO ₂ (wt.%)	29.97
ThO ₂	0.13
UO ₂	0.20
$B_2O_3^{\dagger}$	8.63
Al ₂ O ₃	b.d.
$Fe_2O_{3(min)}^{\ddagger}$	0.00
$FeO_{(max)}^{\ddagger}$	9.39
Y_2O_3	22.97
Ce ₂ O ₃	0.56
Pr ₂ O ₃	0.22
Nd ₂ O ₃	0.98
Sm ₂ O ₃	0.64
Gd_2O_3	1.37
Tb ₂ O ₃	0.11
Dy ₂ O ₃	1.21
Ho ₂ O ₃	0.21
Er ₂ O ₃	0.71
Tm_2O_3	0.14
Yb ₂ O ₃	2.01
BeO§	6.27
MgO	0.23
CaO	13.29
MnO	0.15
PbO	0.16
F	0.46
–(O=F)	-0.19
Total	101.97
Si ⁴⁺ (apfu)	2.000
Th ⁴⁺	0.002
U ⁴⁺	0.003
B ^{3+†}	0.994
$Fe^{3+}(min)^{\ddagger}$	0.000
$Fe^{2+}(max)^{\ddagger}$	0.524
Y ³⁺	0.816
Ce ³⁺	0.014

Table A.70. Chemical compositions and structural formulae of gadolinite-(Y) in the amphibole-type endo-contact skarn bordering Rau 6.
Sample	R6-A
Unit	Rau 6
Skarn type	Amphibole
Mineral	*GdI-(Y)
Pr³⁺ (<i>apfu</i>)	0.005
Nd ³⁺	0.023
Sm ³⁺	0.015
Gd ³⁺	0.030
Tb ³⁺	0.002
Dy ³⁺	0.026
Ho ³⁺	0.004
Er ³⁺	0.015
Tm ³⁺	0.003
Yb ³⁺	0.041
Be ^{2+§}	1.006
Mg ²⁺	0.023
Ca ²⁺	0.950
Mn ²⁺	0.008
Pb ²⁺	0.003
F⁻	0.097
OH-I	0.890
O ²⁻	9.013
The formula for	or gadolinite-
(Y) was calcul	ated on the
basis of 2 Si a	itoms per
Phosphorus	Ti Zr Al Sc
La, Na, K, and	d Cl in
gadolinite-(Y)	were also
sought but we	re below the
detection limit	of the EMP in
all analyses.	ites to O week
Gol = gadolin	sed on the
assumption th	at $B = 2$
anions - Be; ‡	Ratio of
Fe ₂ O ₃ and Fe	O calculated
to fit electrone	utral formula;
§BeO was cale	culated based
on assumed 1	2 total anions;
"H ₂ O contents	based on
detection limit	b.u. = below

Sample	R9b-2c
Unit	Rau 9
Skarn type	Biotite
Mineral	*Snc-(Ce)
SiO ₂ (wt.%)	0.68
ThO ₂	4.10
Al ₂ O ₃	0.11
$Fe_2O_{3(min)}$ [†]	0.00
$FeO_{(max)}^{\dagger}$	0.25
Y ₂ O ₃	2.06
La ₂ O ₃	7.51
Ce ₂ O ₃	23.83
Pr ₂ O ₃	3.47
Nd ₂ O ₃	10.51
Sm ₂ O ₃	2.85
Gd_2O_3	0.90
Tm ₂ O ₃	0.41
MgO	0.08
CaO	16.01
F	5.21
CO_2^{\ddagger}	27.86
H ₂ O§	0.40
-(O=F)	-2.19
Total	103.66
Si ⁴⁺ (<i>apfu</i>)	0.036
Th ⁴⁺	0.049
Al ³⁺	0.007
$Fe^{3+}(min)^{\dagger}$	0.000
$Fe^{2+}(max)^{\dagger}$	0.011
Y ³⁺	0.058
La ³⁺	0.146
Ce ³⁺	0.459
Pr ³⁺	0.067
Nd ³⁺	0.197
Sm ³⁺	0.052
Gd ³⁺	0.016
Tm ³⁺	0.007
Mg ²⁺	0.007
Ca ²⁺	0.902

Table A.71. Chemical compositions and structural formulae of synchysite-(Ce) in the biotite-type endocontact skarn bordering Rau 9.

Sample	R9b-2c
Unit	Rau 9
Skarn type	Biotite
Mineral	*Snc-(Ce)
F⁻ (<i>apfu</i>)	0.866
C ^{4+‡}	2.000
OH-§	0.134
O ²⁻	6.233

The formula for was calculated on the basis of 3 cations per formula unit.

Titanium, Sn, U, Sc, Tb, Dy, Ho, Er, Yb, Mn, Eu, Ba, Sr, Pb, Na, K, and Cl were also sought but were below the detection limit of the EMP in all analyses.

*Snc = synchysite; [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 2 *apfu* C in synchysite-(Ce); [§]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R9b-2a								
Unit	Rau 9								
Mineral	*Chn	Chn							
SiO ₂ (wt.%)	32.88	32.92	32.82	32.89	32.79	32.87	33.24	32.57	32.81
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	9.45	9.02	9.21	9.71	10.73	12.26	8.51	8.95	10.02
MgO	50.89	50.81	50.36	50.51	49.60	48.66	51.58	50.88	49.94
CaO	0.04	0.09	0.05	0.20	0.04	0.04	0.12	0.08	0.13
MnO	1.19	1.26	1.22	1.28	1.13	0.96	0.94	1.06	1.39
F	7.35	8.09	7.57	7.70	7.49	8.11	8.41	7.16	7.12
H_2O^{\ddagger}	1.60	1.23	1.44	1.43	1.48	1.17	1.10	1.66	1.67
-(O=F)	-3.48	-3.84	-3.59	-3.65	-3.55	-3.85	-3.99	-3.39	-3.38
Total	99.91	99.57	99.07	100.07	99.72	100.23	99.92	98.96	99.71
Si ⁴⁺ (<i>apfu</i>)	1.938	1.949	1.957	1.941	1.954	1.964	1.956	1.932	1.950
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.466	0.447	0.459	0.479	0.535	0.613	0.419	0.444	0.498
Mg ²⁺	4.472	4.485	4.476	4.444	4.405	4.336	4.527	4.498	4.424
Ca ²⁺	0.002	0.005	0.003	0.013	0.003	0.003	0.008	0.005	0.009
Mn ²⁺	0.060	0.063	0.062	0.064	0.057	0.049	0.047	0.053	0.070
F⁻	1.370	1.515	1.427	1.437	1.411	1.533	1.566	1.342	1.338
OH-‡	0.630	0.485	0.573	0.563	0.589	0.467	0.434	0.658	0.662
O ²⁻	8.739	8.606	8.716	8.684	8.764	8.702	8.556	8.743	8.810

Table A.72. Chemical compositions and structural formulae of chondrodite in the exo-contact skarn associated with Rau 9.

The formulae were calculated on the basis of 10 anions per formula unit.

Aluminum was also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R1-J	R1-J	R1-J	R1-J	R1-J	R1-J	R9b-2a	R9b-2a
Unit	Rau 1	Rau 9	Rau 9					
Mineral	*Nrb	Nrb						
P ₂ O ₅ (wt.%)	0.01	0.01	0.05	0.08	b.d.	b.d.	_	_
SiO ₂	29.90	29.26	29.69	29.42	29.06	29.43	29.15	29.19
TiO ₂	0.04	0.01	0.03	0.01	0.07	0.07	-	-
AI_2O_3	0.01	b.d.	b.d.	0.04	0.03	0.03	b.d.	b.d.
Cr ₂ O ₃	b.d.	b.d.	b.d.	0.01	b.d.	0.02	-	-
MgO	59.66	59.27	59.54	59.69	59.68	59.91	58.98	59.10
CaO	0.14	0.18	0.09	0.09	0.09	0.10	0.03	0.02
MnO	0.08	0.18	0.11	0.05	0.03	0.03	0.35	0.32
ZnO	0.08	0.07	0.10	0.08	0.03	0.02	-	-
FeO _(tot)	0.35	0.60	0.34	0.38	0.30	0.31	2.77	2.60
Na ₂ O	0.01	b.d.	0.01	b.d.	0.03	0.04	-	-
K ₂ O	b.d.	0.01	0.02	b.d.	0.03	0.01	-	-
F	16.74	16.92	16.63	16.85	17.93	17.67	13.22	15.06
H_2O^{\dagger}	1.03	0.84	1.04	0.93	0.36	0.55	2.71	1.84
–(O=F)	-7.05	-7.13	-7.00	-7.09	-7.55	-7.44	-5.56	-6.34
Total	101.00	100.23	100.64	100.54	100.08	100.72	101.63	101.78
P⁵+ (<i>apfu</i>)	0.000	0.000	0.001	0.002	b.d.	b.d.	_	_
Si ⁴⁺	1.001	0.990	0.997	0.990	0.984	0.989	0.974	0.975
Ti ⁴⁺	0.001	0.000	0.001	0.000	0.002	0.002	-	-
Al ³⁺	0.001	b.d.	b.d.	0.002	0.001	0.001	b.d.	b.d.
Cr ³⁺	b.d.	b.d.	b.d.	0.000	b.d.	0.000	_	-
Mg ²⁺	2.976	2.989	2.981	2.994	3.012	3.001	2.938	2.943
Ca ²⁺	0.005	0.007	0.003	0.003	0.003	0.004	0.001	0.001
Mn ²⁺	0.002	0.005	0.003	0.001	0.001	0.001	0.010	0.009
Zn ²⁺	0.002	0.002	0.003	0.002	0.001	0.000	_	_
Fe _(tot)	0.010	0.017	0.010	0.011	0.008	0.009	0.077	0.073
Na⁺	0.000	b.d.	0.001	b.d.	0.002	0.002	_	_
K+	b.d.	0.000	0.001	b.d.	0.001	0.000	_	_
F⁻	1.771	1.810	1.767	1.792	1.919	1.878	1.397	1.591
OH-†	0.229	0.190	0.233	0.208	0.081	0.122	0.603	0.409
O ²⁻	4.000	4.000	4.000	4.000	4.000	4.000	3.974	3.975

Table A.73. Chemical compositions and structural formulae of norbergite in the exo-contact skarns associated with Rau 1 and 9.

The formulae were calculated on the basis of 6 anions per formula unit.

*Abbreviations of mineral names follow Whitney & Evans (2010); ${}^{\dagger}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R1-J	R1-J	R1-J	R1-J
Unit	Rau 1	Rau 1	Rau 1	Rau 1
Mineral	*Flb	Flb	Flb	Flb
SiO ₂ (wt. %)	0.08	b.d.	b.d.	b.d.
TiO ₂	0.04	b.d.	b.d.	b.d.
B ₂ O ₃	18.98	19.24	19.02	19.13
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.
FeO _(tot)	0.33	0.13	0.34	0.11
MgO	65.49	66.74	65.81	66.33
CaO	0.10	0.04	0.05	0.07
MnO	0.08	b.d.	0.08	b.d.
ZnO	b.d.	b.d.	b.d.	b.d.
Na ₂ O	b.d.	b.d.	b.d.	b.d.
K ₂ O	b.d.	b.d.	b.d.	b.d.
F	23.41	24.20	23.50	24.09
H_2O^{\dagger}	3.64	3.46	3.63	3.43
-(O=F)	-9.86	-10.19	-9.89	-10.14
Total	102.29	103.63	102.54	103.00
Si ⁴⁺ (<i>apfu</i>)	0.002	b.d.	b.d.	b.d.
Ti ⁴⁺	0.001	b.d.	b.d.	b.d.
B ³⁺	1.000	1.000	1.000	1.000
Cr ³⁺	b.d.	b.d.	b.d.	b.d.
Fe ²⁺ (tot)	0.009	0.003	0.009	0.003
Mg ²⁺	2.980	2.995	2.987	2.995
Ca ²⁺	0.003	0.001	0.002	0.002
Mn ²⁺	0.002	b.d.	0.002	b.d.
Zn ²⁺	b.d.	b.d.	b.d.	b.d.
Na+	b.d.	b.d.	b.d.	b.d.
K+	b.d.	b.d.	b.d.	b.d.
F⁻	2.260	2.304	2.263	2.307
OH⁻	0.740	0.696	0.737	0.693
O ²⁻	3.000	3.000	3.000	3.000

Table A.74. Chemical compositions and structural formulae of fluoborite in the exo-contact skarn associated with Rau 1.

The formulae were calculated on the basis of 6 anions per formula unit.

Aluminum, V, and Ba were also sought but were below the detection limit of the EMP in all analyses.

*Flb = fluoborite; [†]H₂O contents based on stoichiometry;

b.d. = below detection limit.

Sample	R9b-2a								
Unit	Rau 9								
Mineral	*Flb	Flb							
SiO ₂ (wt. %)	b.d.	b.d.	b.d.	b.d.	0.05	b.d.	0.07	b.d.	b.d.
TiO ₂	b.d.								
B ₂ O ₃	18.43	18.44	18.41	18.52	18.45	18.46	18.57	18.65	18.52
FeO _(tot)	0.59	0.75	0.49	0.61	0.64	0.63	0.79	0.72	0.72
MgO	63.55	63.59	63.65	63.95	63.53	63.71	63.91	64.34	63.88
CaO	0.12	0.03	0.04	0.08	0.17	0.03	0.02	b.d.	0.06
MnO	0.09	b.d.	b.d.	b.d.	b.d.	0.06	0.08	0.08	b.d.
F	24.17	21.60	22.83	22.86	23.04	22.04	22.74	22.36	22.13
H_2O^{\dagger}	2.85	4.07	3.47	3.54	3.40	3.88	3.64	3.88	3.88
-(O=F)	-10.18	-9.10	-9.61	-9.62	-9.70	-9.28	-9.57	-9.42	-9.32
Total	99.62	99.39	99.28	99.93	99.57	99.53	100.25	100.62	99.86
Si ⁴⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	0.002	b.d.	b.d.
Ti ⁴⁺	b.d.								
B ³⁺	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Fe ²⁺ (tot)	0.015	0.020	0.013	0.016	0.017	0.017	0.021	0.019	0.019
Mg ²⁺	2.978	2.979	2.986	2.981	2.975	2.981	2.972	2.979	2.979
Ca ²⁺	0.004	0.001	0.001	0.003	0.006	0.001	0.001	b.d.	0.002
Mn ²⁺	0.003	b.d.	b.d.	b.d.	b.d.	0.002	0.002	0.002	b.d.
F⁻	2.403	2.147	2.272	2.261	2.289	2.187	2.243	2.196	2.190
OH⁻	0.597	0.853	0.728	0.739	0.711	0.813	0.757	0.804	0.810
O ^{2_}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000

Table A.75. Chemical compositions and structural formulae of fluoborite in the exo-contact skarn associated with Rau 9.

The formulae were calculated on the basis of 6 anions per formula unit.

Aluminum was also sought but were below the detection limit of the EMP in all analyses.

*Flb = fluoborite; ${}^{\dagger}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R9b-2a	R9b-2a	R9b-2a	R9b-2a	R9b-2a	R9b-2a
Unit	Rau 9					
Mineral	*Tlc	Tlc	*Tlc	*Tlc	*Tlc	*Tlc
SiO ₂ (wt.%)	44.78	44.51	43.74	44.60	45.22	45.19
AI_2O_3	0.25	0.09	0.19	0.25	0.14	0.17
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	5.12	4.33	4.72	4.98	4.16	4.42
MgO	38.00	38.65	37.66	37.94	38.70	37.94
CaO	0.31	0.41	0.27	0.19	0.27	0.34
MnO	0.22	0.11	0.15	0.14	0.11	0.14
K ₂ O	b.d.	b.d.	0.03	b.d.	0.04	0.04
F	2.33	2.97	2.59	2.38	2.57	2.81
H_2O^{\dagger}	2.28	1.94	2.07	2.24	2.18	2.07
-(O=F)	-0.98	-1.25	-1.09	-1.00	-1.08	-1.18
Total	92.28	91.76	90.32	91.72	92.30	91.94
Si ⁴⁺ (<i>apfu</i>)	3.974	3.990	3.980	3.974	3.985	3.982
Al ³⁺	0.026	0.010	0.020	0.026	0.015	0.018
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.380	0.325	0.359	0.371	0.307	0.326
Mg ²⁺	5.027	5.165	5.109	5.039	5.085	4.984
Ca ²⁺	0.029	0.040	0.026	0.018	0.025	0.032
Mn ²⁺	0.016	0.008	0.012	0.010	0.008	0.010
K+	b.d.	b.d.	0.003	b.d.	0.004	0.005
F⁻	0.653	0.841	0.745	0.671	0.718	0.784
$OH^{-\dagger}$	1.347	1.159	1.255	1.329	1.282	1.216
O ²⁻	12.439	12.534	12.497	12.426	12.419	12.345

Table A.76. Chemical compositions and structural formulae of talc in the exo-contact skarn associated with Rau 9.

The formulae were calculated on the basis of 4 Si atoms per formula unit. Titanium and Cr were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}H_2O$ contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mineral	*Cal	Cal	Cal	Cal	Cal	Cal	Cal	Cal	Dol	Dol	Dol
MgO (wt.%)	0.70	0.93	0.99	1.43	1.26	0.57	1.27	0.52	20.79	21.14	20.91
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
FeO	b.d.	b.d.	0.12	b.d.	0.13	b.d.	b.d.	b.d.	0.19	0.19	0.52
CaO	56.02	54.71	54.85	54.34	55.26	56.17	55.22	56.08	31.40	31.59	30.23
SrO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CO_2^\dagger	44.73	43.96	44.20	44.20	44.82	44.71	44.72	44.58	47.46	47.99	46.87
Total	101.44	99.60	100.15	99.96	101.46	101.45	101.21	101.19	99.84	100.91	98.53
Mg ²⁺ (<i>apfu</i>)	0.017	0.023	0.024	0.035	0.031	0.014	0.031	0.013	0.957	0.962	0.974
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ²⁺	b.d.	b.d.	0.002	b.d.	0.002	b.d.	b.d.	b.d.	0.005	0.005	0.014
Ca ²⁺	0.983	0.977	0.974	0.965	0.968	0.986	0.969	0.987	1.038	1.033	1.012
Sr ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
C ^{4+†}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	2.000	2.000	2.000
O ^{2_}	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	6.000	6.000	6.000

Table A.77. Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-4a	R3-4a	R3-4a	R3-4a	R3-5a						
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	20	20	20	20	20	20	20
Mineral	*Dol	Dol	Dol	Dol	Cal						
MgO (wt.%)	20.83	21.31	21.21	20.45	2.43	2.30	1.92	2.09	1.60	2.40	2.34
MnO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
FeO	0.22	0.21	b.d.	0.46	b.d.						
CaO	31.20	31.46	31.27	30.50	53.85	54.34	54.29	54.59	54.83	53.98	54.52
SrO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.09	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
CO_2^\dagger	47.37	48.09	47.70	46.55	44.92	45.16	44.71	45.16	44.78	44.98	45.34
Total	99.63	101.07	100.18	97.97	101.19	101.80	100.92	101.92	101.20	101.35	102.20
Mg ²⁺ (apfu)	0.960	0.968	0.971	0.959	0.059	0.056	0.047	0.050	0.039	0.058	0.056
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ²⁺	0.006	0.005	b.d.	0.012	b.d.						
Ca ²⁺	1.034	1.027	1.029	1.028	0.941	0.944	0.953	0.949	0.961	0.942	0.944
Sr ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.001	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
C ^{4+†}	2.000	2.000	2.000	2.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
O ^{2_}	6.000	6.000	6.000	6.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000

Table A.77. (Continued) Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-5a								
Closest pegmatite dike	Rau 3								
Proximity to pegmatite (m)	20	20	20	20	20	20	20	20	20
Mineral	*Cal	Dol							
MgO (wt.%)	2.46	20.95	21.03	21.44	20.99	21.12	21.45	21.07	21.39
MnO	b.d.								
FeO	b.d.	0.14	b.d.	b.d.	b.d.	0.16	b.d.	b.d.	b.d.
CaO	54.17	31.82	32.09	32.13	31.46	31.42	32.04	32.05	31.98
SrO	b.d.								
BaO	b.d.								
CO_2^\dagger	45.20	47.93	48.15	48.63	47.61	47.82	48.57	48.16	48.45
Total	101.84	100.84	101.28	102.20	100.06	100.52	102.06	101.28	101.82
Mg ²⁺ (<i>apfu</i>)	0.059	0.954	0.954	0.963	0.963	0.965	0.965	0.955	0.964
Mn ²⁺	b.d.								
Fe ²⁺	b.d.	0.003	b.d.	b.d.	b.d.	0.004	b.d.	b.d.	b.d.
Ca ²⁺	0.941	1.042	1.046	1.037	1.037	1.031	1.035	1.045	1.036
Sr ²⁺	b.d.								
Ba ²⁺	b.d.								
C ^{4+†}	1.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
O ^{2_}	3.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000

Table A.77. (Continued) Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R4-1										
Closest pegmatite dike	Rau 4										
Proximity to pegmatite (m)	1	1	1	1	1	1	1	1	1	1	1
Mineral	*Cal	Cal	Dol	Dol							
MgO (wt.%)	1.18	0.47	2.01	1.67	0.55	0.79	0.67	3.83	1.22	21.24	21.18
MnO	b.d.	b.d.	b.d.	b.d.	0.12	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
FeO	b.d.	0.16	0.12								
CaO	55.78	55.59	55.03	54.98	55.83	56.17	56.20	52.63	55.37	31.77	31.97
CO_2^\dagger	45.06	44.14	45.38	44.97	44.49	44.95	44.83	45.49	44.79	48.22	48.29
Total	102.01	100.20	102.41	101.63	101.00	101.92	101.69	101.95	101.37	101.38	101.56
Mg ²⁺ (<i>apfu</i>)	0.029	0.012	0.048	0.041	0.014	0.019	0.016	0.092	0.030	0.962	0.958
Mn ²⁺	b.d.	b.d.	b.d.	b.d.	0.002	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Fe ²⁺	b.d.	0.004	0.003								
Ca ²⁺	0.971	0.988	0.952	0.959	0.985	0.981	0.984	0.908	0.970	1.034	1.039
C ^{4+†}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	2.000	2.000
O ²⁻	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	6.000	6.000

Table A.78 Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 4 pegmatite dike.

Strontium and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R4-1						
Closest pegmatite dike	Rau 4						
Proximity to pegmatite (m)	1	1	1	1	1	1	1
Mineral	*Dol	Dol	Dol	Dol	Dol	Dol	Dol
MgO (wt.%)	20.94	21.59	20.95	21.04	21.30	21.44	21.22
MnO	0.34	0.15	0.15	b.d.	b.d.	b.d.	b.d.
FeO	0.16	0.16	0.15	b.d.	0.16	b.d.	0.13
CaO	31.43	31.40	31.28	31.59	31.01	31.86	31.75
CO_2^{\dagger}	47.84	48.40	47.60	47.77	47.69	48.41	48.16
Total	100.71	101.69	100.11	100.40	100.16	101.71	101.25
Mg ²⁺ (apfu)	0.956	0.974	0.961	0.962	0.975	0.967	0.962
Mn ²⁺	0.009	0.004	0.004	b.d.	b.d.	b.d.	b.d.
Fe ²⁺	0.004	0.004	0.004	b.d.	0.004	b.d.	0.003
Ca ²⁺	1.031	1.018	1.031	1.038	1.021	1.033	1.035
C ^{4+†}	2.000	2.000	2.000	2.000	2.000	2.000	2.000
O ²⁻	6.000	6.000	6.000	6.000	6.000	6.000	6.000

Table A.78. (Continued) Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 4 pegmatite dike.

Strontium and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R5U-4										
Closest pegmatite dike	Rau 5U										
Proximity to pegmatite (m)	0	0	0	0	0	0	0	0	0	0	0
Mineral	*Cal	Cal	Dol	Dol	Dol						
MgO (wt.%)	0.06	0.14	0.90	0.23	0.13	0.27	0.28	0.40	21.03	21.32	21.06
MnO	b.d.	0.09	b.d.								
FeO	b.d.	0.16	0.16	0.10							
CaO	56.84	56.86	56.08	56.44	56.98	56.42	55.66	56.22	31.73	31.57	31.72
CO_2^\dagger	44.68	44.83	44.99	44.55	44.86	44.58	43.98	44.55	47.96	48.16	47.96
Total	101.58	101.92	101.96	101.22	101.97	101.27	99.92	101.17	100.87	101.22	100.85
Mg ²⁺ (<i>apfu</i>)	0.001	0.003	0.022	0.006	0.003	0.007	0.007	0.010	0.958	0.967	0.959
Mn ²⁺	b.d.	0.001	b.d.								
Fe ²⁺	b.d.	0.004	0.004	0.003							
Ca ²⁺	0.999	0.995	0.978	0.994	0.997	0.993	0.993	0.990	1.038	1.029	1.038
C ^{4+†}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	2.000	2.000	2.000
O ²⁻	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	6.000	6.000	6.000

Table A.79. Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 5U pegmatite dike.

Strontium and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R5U-4						
Closest pegmatite dike	Rau 5U						
Proximity to pegmatite (m)	0	0	0	0	0	0	0
Mineral	*Dol	Dol	Dol	Dol	Dol	Dol	Dol
MgO (wt.%)	21.38	21.17	20.89	21.08	21.20	21.25	21.16
MnO	b.d.						
FeO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.09
CaO	31.62	31.67	31.04	32.14	32.30	31.60	31.65
CO_2^{\dagger}	48.16	47.97	47.17	48.23	48.50	48.00	48.00
Total	101.15	100.80	99.10	101.45	102.00	100.85	100.90
Mg ²⁺ (<i>apfu</i>)	0.970	0.964	0.967	0.954	0.955	0.967	0.963
Mn ²⁺	b.d.						
Fe ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.002
Ca ²⁺	1.030	1.036	1.033	1.046	1.045	1.033	1.035
C ^{4+†}	2.000	2.000	2.000	2.000	2.000	2.000	2.000
O ²⁻	6.000	6.000	6.000	6.000	6.000	6.000	6.000

Table A.79. (Continued) Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 5U pegmatite dike.

Strontium and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R6-2b	R6-2b									
Closest pegmatite dike	Rau 6	Rau 6									
Proximity to pegmatite (m)	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mineral	*Cal	Cal	Cal	Cal	Cal	Cal	Cal	Dol	Dol	Dol	Dol
MgO (wt.%)	0.64	0.80	0.41	0.57	0.56	0.65	0.36	20.86	20.23	21.42	22.28
FeO	b.d.	0.11	0.28								
CaO	55.36	55.46	56.08	56.08	56.35	55.59	56.64	31.92	32.57	31.16	26.20
SrO	0.09	0.14	b.d.	b.d.							
CO_2^\dagger	44.18	44.46	44.46	44.63	44.84	44.34	44.84	47.83	47.65	47.92	45.06
Total	100.27	100.87	100.94	101.29	101.75	100.58	101.84	100.62	100.46	100.62	93.83
Mg ²⁺ (<i>apfu</i>)	0.016	0.020	0.010	0.014	0.014	0.016	0.009	0.953	0.927	0.976	1.080
Fe ²⁺	b.d.	0.003	0.008								
Ca ²⁺	0.983	0.979	0.990	0.986	0.986	0.984	0.991	1.047	1.073	1.021	0.913
Sr ²⁺	0.001	0.001	b.d.	b.d.							
C ^{4+†}	1.000	1.000	1.000	1.000	1.000	1.000	1.000	2.000	2.000	2.000	2.000
O ²⁻	3.000	3.000	3.000	3.000	3.000	3.000	3.000	6.000	6.000	6.000	6.000

Table A.80. Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 6 pegmatite dike.

Manganese and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R6-2b	R6-2b	R6-2b	R6-2b
Closest pegmatite dike	Rau 6	Rau 6	Rau 6	Rau 6
Proximity to pegmatite (m)	< 1	< 1	< 1	< 1
Mineral	*Dol	Dol	Dol	Dol
MgO (wt.%)	21.08	21.18	21.29	21.73
FeO	b.d.	0.15	0.15	b.d.
CaO	31.34	31.39	31.08	31.66
SrO	b.d.	b.d.	b.d.	b.d.
CO_2^\dagger	47.61	47.86	47.73	48.57
Total	100.03	100.58	100.25	101.96
Mg ²⁺ (<i>apfu</i>)	0.967	0.967	0.974	0.977
Fe ²⁺	b.d.	0.004	0.004	b.d.
Ca ²⁺	1.033	1.030	1.022	1.023
Sr ²⁺	b.d.	b.d.	b.d.	b.d.
C ^{4+†}	2.000	2.000	2.000	2.000
O ²⁻	6.000	6.000	6.000	6.000

Table A.80. (Continued) Chemical compositions and structural formulae of carbonate minerals from the host rocks near the Rau 6 pegmatite dike.

Manganese and Ba was also sought but was below the detection limit of the EMP in all analyses.

Sample	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20	20	20	20
Mineral	*Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl	Phl
SiO ₂ (wt.%)	41.99	43.65	43.36	41.66	42.98	42.40	41.90	42.46	41.97	43.08	42.38	43.88
TiO ₂	0.96	0.68	0.30	0.79	0.33	0.43	0.66	0.54	0.50	0.20	0.29	0.14
Al ₂ O ₃	15.53	16.82	14.43	15.76	14.41	15.82	15.31	15.01	15.49	14.44	14.26	14.55
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.68	0.83	0.46	0.66	0.59	0.49	0.66	0.18	0.19	0.45	0.00	0.17
MgO	25.54	21.78	26.36	25.12	26.55	25.57	25.25	26.67	26.68	26.88	27.01	27.43
CaO	b.d.	2.38	0.06	b.d.	b.d.	b.d.	0.06	0.14	0.18	0.08	0.21	0.09
BaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.14	b.d.	0.19	0.22	b.d.
Na ₂ O	b.d.	0.61	b.d.	b.d.	b.d.	b.d.	b.d.	0.66	0.86	0.65	0.62	0.65
K ₂ O	10.00	8.67	9.91	10.12	10.06	10.19	10.29	8.93	9.06	8.31	8.60	8.60
F	0.81	1.06	1.08	0.76	1.02	0.90	0.54	0.71	1.07	0.95	1.02	1.43
CI	0.17	0.39	0.07	0.16	0.18	0.07	0.18	0.03	0.07	0.03	0.03	0.04
H_2O^{\ddagger}	3.88	3.76	3.80	3.87	3.79	3.88	3.97	3.98	3.80	3.86	3.79	3.70
−(O=F,CI)	-0.38	-0.53	-0.47	-0.36	-0.47	-0.39	-0.27	-0.30	-0.47	-0.41	-0.44	-0.61
Total	99.18	100.11	99.35	98.55	99.43	99.36	98.55	99.12	99.41	98.72	98.01	100.06
Si ⁴⁺ (apfu)	2.925	3.003	3.004	2.922	2.984	2.944	2.942	2.943	2.907	2.989	2.968	2.999
Ti ⁴⁺	0.050	0.035	0.016	0.042	0.017	0.022	0.035	0.028	0.026	0.011	0.016	0.007
Al ³⁺	1.275	1.364	1.179	1.303	1.179	1.294	1.267	1.226	1.264	1.181	1.177	1.172
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.040	0.048	0.026	0.039	0.034	0.029	0.039	0.010	0.011	0.026	0.000	0.010
Mg ²⁺	2.653	2.233	2.723	2.626	2.748	2.646	2.642	2.756	2.755	2.780	2.820	2.795
Ca ²⁺	b.d.	0.176	0.004	b.d.	b.d.	b.d.	0.005	0.010	0.013	0.006	0.016	0.007
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.004	b.d.	0.005	0.006	b.d.

Table A.81. Chemical compositions and structural formulae of mica group minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-4a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a						
Closest pegmatite dike	Rau 3											
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20	20	20	20
Mineral	*Phl	Phl										
Na⁺ (<i>apfu</i>)	b.d.	0.081	b.d.	b.d.	b.d.	b.d.	b.d.	0.088	0.115	0.087	0.084	0.086
K+	0.889	0.761	0.876	0.906	0.891	0.903	0.921	0.789	0.801	0.736	0.768	0.750
F-	0.178	0.230	0.236	0.169	0.225	0.197	0.121	0.155	0.234	0.209	0.226	0.309
Cl⁻	0.020	0.046	0.008	0.020	0.022	0.008	0.021	0.004	0.009	0.004	0.004	0.005
$OH^{-\ddagger}$	1.802	1.725	1.756	1.812	1.753	1.795	1.858	1.841	1.757	1.787	1.770	1.686
vacancy	0.057	0.317	0.052	0.068	0.037	0.065	0.076	0.037	0.036	0.013	0.020	0.017
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 11 O atoms per formula unit.

Chromium, Mn, Rb, and Cs were also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1
Closest pegmatite dike	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4
Proximity to pegmatite (m)	1	1	1	1	1	1	1	1
Mineral	*Fluoro-Phl	Phl	Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl
SiO ₂ (wt.%)	40.66	39.89	40.24	39.64	40.75	39.82	40.27	40.78
TiO ₂	0.15	b.d.	b.d.	b.d.	0.33	b.d.	b.d.	b.d.
Al ₂ O ₃	14.95	16.79	16.50	17.23	16.48	17.08	15.74	16.03
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	0.19	0.59	0.53	0.53	0.17	0.47	0.31	0.11
MgO	27.52	27.06	26.92	25.91	27.59	26.62	27.59	27.53
CaO	0.13	0.08	0.06	b.d.	0.08	b.d.	b.d.	b.d.
MnO	b.d.	b.d.	0.18	0.21	b.d.	b.d.	b.d.	b.d.
BaO	b.d.	b.d.	b.d.	b.d.	0.83	b.d.	b.d.	b.d.
Na ₂ O	0.38	0.34	0.37	0.41	0.36	0.35	0.34	0.41
K ₂ O	9.89	9.19	9.35	9.31	10.06	9.58	9.69	9.65
Rb ₂ O	1.40	2.39	1.79	1.94	0.11	2.07	1.33	1.80
Cs ₂ O	b.d.	0.09	b.d.	b.d.	b.d.	0.11	b.d.	0.08
F	5.30	3.71	3.94	4.98	4.93	4.84	4.95	5.20
H ₂ O [‡]	1.75	2.53	2.42	1.89	2.01	1.99	1.93	1.84
-(O=F)	-2.23	-1.56	-1.66	-2.10	-2.08	-2.04	-2.08	-2.19
Total	100.11	101.10	100.63	99.96	101.61	100.89	100.07	101.25
Si ⁴⁺ (<i>apfu</i>)	2.859	2.789	2.814	2.796	2.809	2.789	2.827	2.836
Ti ⁴⁺	0.008	b.d.	b.d.	b.d.	0.017	b.d.	b.d.	b.d.
Al ³⁺	1.239	1.383	1.359	1.432	1.339	1.410	1.302	1.314
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.011	0.034	0.031	0.031	0.010	0.028	0.018	0.006
Mg ²⁺	2.885	2.820	2.806	2.724	2.835	2.779	2.887	2.854
Ca ²⁺	0.010	0.006	0.004	b.d.	0.006	b.d.	b.d.	b.d.

Table A.82. Chemical compositions and structural formulae of mica group minerals from the host rocks near the Rau 4 pegmatite dike.

Sample	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1
Closest pegmatite dike	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4	Rau 4
Proximity to pegmatite (m)	1	1	1	1	1	1	1	1
Mineral	*Fluoro-Phl	Phl	Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl
Mn ²⁺ (<i>apfu</i>)	b.d.	b.d.	0.010	0.013	b.d.	b.d.	b.d.	b.d.
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	0.023	b.d.	b.d.	b.d.
Na ⁺	0.052	0.046	0.050	0.056	0.048	0.047	0.046	0.055
K ⁺	0.887	0.819	0.834	0.838	0.884	0.856	0.868	0.856
Rb⁺	0.063	0.107	0.081	0.088	0.005	0.093	0.060	0.081
Cs+	b.d.	0.003	b.d.	b.d.	b.d.	0.003	b.d.	0.002
F-	1.179	0.821	0.870	1.111	1.074	1.071	1.098	1.145
OH ^{-‡}	0.821	1.179	1.130	0.889	0.926	0.929	0.902	0.855
vacancy	-0.002	-0.026	-0.020	0.003	-0.009	-0.006	-0.035	-0.010
O ²⁻	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 11 O atoms per formula unit.

Chromium and CI were also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R5U-4	R5U-4	R5U-4	R5U-4	R5U-4	R6-2b	R6-2b	R6-2b	R6-2b
Closest pegmatite dike	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 6	Rau 6	Rau 6	Rau 6
Proximity to pegmatite (m)	0	0	0	0	0	< 1	< 1	< 1	< 1
Mineral	*Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Phl	Phl	Phl	Phl
SiO ₂ (wt.%)	42.18	42.84	43.32	40.76	40.83	40.77	43.29	40.88	40.70
TiO ₂	0.16	b.d.	0.14	b.d.	b.d.	b.d.	b.d.	0.22	b.d.
AI_2O_3	13.67	12.54	12.11	16.63	15.88	16.08	13.65	14.37	15.62
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.17	0.24	0.14	0.21	0.18	0.25	0.17	1.17	0.17
MgO	28.67	29.26	28.76	27.35	27.76	27.35	28.10	26.66	26.96
CaO	0.07	b.d.	0.09	0.18	0.09	0.14	0.13	b.d.	0.08
BaO	0.33	0.28	0.20	0.44	0.25	0.80	0.28	0.50	0.65
Na ₂ O	0.30	0.18	0.26	0.43	0.40	0.68	0.62	0.68	0.79
K ₂ O	9.81	9.75	10.14	10.12	10.04	9.17	9.46	9.18	9.38
Rb ₂ O	0.58	0.09	b.d.	b.d.	0.70	b.d.	b.d.	0.06	b.d.
F	5.78	5.80	7.27	5.11	4.68	2.54	3.22	3.22	2.82
H_2O^{\ddagger}	1.58	1.56	0.86	1.91	2.10	3.10	2.82	2.70	2.93
-(O=F)	-2.44	-2.44	-3.06	-2.15	-1.97	-1.07	-1.36	-1.35	-1.19
Total	100.85	100.09	100.23	100.99	100.94	99.81	100.39	98.29	98.91
Si ⁴⁺ (<i>apfu</i>)	2.926	2.979	3.013	2.818	2.834	2.840	2.983	2.902	2.862
Ti ⁴⁺	0.008	b.d.	0.007	b.d.	b.d.	b.d.	b.d.	0.012	b.d.
Al ³⁺	1.117	1.028	0.993	1.355	1.299	1.320	1.109	1.202	1.295
Fe^{3+} (min) [†]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.010	0.014	0.008	0.012	0.010	0.014	0.010	0.070	0.010
Mg ²⁺	2.965	3.033	2.982	2.819	2.873	2.840	2.886	2.821	2.826
Ca ²⁺	0.005	b.d.	0.007	0.013	0.007	0.011	0.010	b.d.	0.006
Ba ²⁺	0.009	0.008	0.005	0.012	0.007	0.022	0.007	0.014	0.018

Table A.83. Chemical compositions and structural formulae of mica group minerals from the host rocks near the Rau 5U and 6 pegmatite dikes.

Sample	R5U-4	R5U-4	R5U-4	R5U-4	R5U-4		R6-2b	R6-2b	R6-2b	R6-2b
Closest pegmatite dike	Rau 5U	Rau 5U	Rau 5U	Rau 5U	Rau 5U		Rau 6	Rau 6	Rau 6	Rau 6
Proximity to pegmatite (m)	0	0	0	0	0		< 1	< 1	< 1	< 1
Mineral	*Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl	Fluoro-Phl		Phl	Phl	Phl	Phl
Na⁺ (<i>apfu</i>)	0.040	0.025	0.035	0.058	0.054		0.092	0.083	0.094	0.107
K ⁺	0.868	0.865	0.900	0.893	0.889		0.814	0.832	0.831	0.842
Rb⁺	0.026	0.004	b.d.	b.d.	0.031		b.d.	b.d.	0.003	b.d.
F⁻	1.269	1.275	1.600	1.117	1.027		0.560	0.702	0.722	0.627
OH⁻‡	0.731	0.725	0.400	0.883	0.973		1.440	1.298	1.278	1.373
vacancy	-0.026	-0.053	-0.003	-0.004	-0.016	-	-0.014	0.012	-0.007	0.007
O ²⁻	10.000	10.000	10.000	10.000	10.000		10.000	10.000	10.000	10.000

The formulae were calculated on the basis of 11 O atoms per formula unit.

Chromium, Mn, Cs, and Cl were also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-5a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20	20
Mineral	*Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
SiO ₂ (wt.%)	57.60	57.42	56.71	57.66	57.25	57.75	57.96	58.20	56.23	56.10	55.97
TiO ₂	0.18	0.09	0.13	0.11	b.d.	0.07	0.12	b.d.	0.27	0.32	0.53
Al ₂ O ₃	1.03	1.32	1.64	1.49	1.22	1.57	1.69	1.19	2.56	2.90	3.46
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(\text{min})}^\dagger$	0.49	0.41	0.43	0.49	0.47	0.35	0.24	0.46	0.29	0.30	0.30
FeO _(max) †	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	24.44	23.90	23.97	24.06	24.34	24.31	23.87	24.38	23.92	23.83	23.78
CaO	14.01	13.99	13.47	13.76	13.78	13.67	13.99	13.68	13.64	13.56	13.56
Na ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.18	0.25	0.26
K ₂ O	0.10	0.10	0.12	0.14	0.09	0.10	0.09	0.12	0.12	0.09	0.11
F	b.d.	0.31	b.d.	0.34	0.38	b.d.	b.d.	b.d.	b.d.	0.31	b.d.
CI	0.03	0.05	0.03	0.04	0.04	0.06	0.05	0.04	b.d.	b.d.	b.d.
H ₂ O [‡]	2.21	2.04	2.18	2.04	2.01	2.20	2.21	2.21	2.20	2.05	2.21
–(O=F,Cl)	-0.01	-0.14	-0.01	-0.15	-0.17	-0.01	-0.01	-0.01	0.00	-0.13	0.00
Total	100.07	99.48	98.68	99.96	99.48	100.07	100.44	100.27	99.40	99.58	100.19
Si ⁴⁺ (<i>apfu</i>)	7.801	7.833	7.788	7.829	7.795	7.817	7.833	7.868	7.673	7.647	7.587
Ti ⁴⁺	0.018	0.009	0.014	0.011	b.d.	0.008	0.012	b.d.	0.027	0.033	0.054
Al ³⁺	0.164	0.213	0.266	0.239	0.196	0.251	0.269	0.190	0.412	0.465	0.552
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	0.008	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.050	0.042	0.045	0.050	0.049	0.036	0.024	0.047	0.030	0.030	0.031
$Fe^{2+}_{(\max)}^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.000	0.000	0.000	0.000
Mg ²⁺	4.935	4.859	4.907	4.870	4.940	4.906	4.809	4.913	4.865	4.843	4.806
Ca ²⁺	2.033	2.044	1.981	2.002	2.011	1.983	2.026	1.982	1.993	1.980	1.970

Table A.84. Chemical compositions and structural formulae of amphibole supergroup minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-4a	R3-5a	R3-5a	R3-5a							
Closest pegmatite dike	Rau 3										
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20	20
Mineral	*Tr	Tr									
Na⁺ (<i>apfu</i>)	b.d.	0.049	0.066	0.069							
K⁺	0.018	0.018	0.021	0.025	0.015	0.017	0.016	0.020	0.020	0.015	0.019
F⁻	b.d.	0.135	b.d.	0.145	0.165	b.d.	b.d.	b.d.	b.d.	0.134	b.d.
Cl⁻	0.007	0.011	0.007	0.009	0.008	0.013	0.012	0.009	b.d.	b.d.	b.d.
OH-‡	1.993	1.854	1.993	1.845	1.827	1.987	1.988	1.991	2.000	1.866	2.000
O ^{2_}	21.935	21.978	21.967	21.996	21.929	21.976	22.000	21.997	21.955	21.969	21.977

The formulae were calculated on the basis of 15 cations per formula unit.

Chromium and Mn were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	20	20	20	20	20	20	20	20
Mineral	*Tr	Tr	Tr	Tr	Tr	Tr	Prg	Prg
SiO ₂ (wt.%)	55.67	56.68	55.98	57.46	55.69	56.41	44.79	43.78
TiO ₂	0.41	0.28	0.54	0.17	0.29	0.28	1.17	1.21
AI_2O_3	2.76	2.66	2.98	1.70	3.01	2.60	15.22	15.71
Cr ₂ O ₃	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe_2O_{3(min)}^{\dagger}$	0.53	0.26	0.34	0.20	0.27	0.28	0.11	0.03
FeO _(max) †	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	23.90	23.99	23.84	24.50	23.68	23.97	19.74	19.53
CaO	13.32	13.59	13.48	13.97	13.83	13.55	13.55	13.44
Na ₂ O	0.20	0.17	0.26	0.16	0.27	0.23	2.15	2.26
K ₂ O	0.10	0.11	0.11	0.04	0.10	0.08	0.37	0.38
F	b.d.	b.d.	b.d.	b.d.	0.39	b.d.	b.d.	b.d.
CI	b.d.	b.d.	b.d.	b.d.	0.03	b.d.	0.04	0.05
H_2O^{\ddagger}	2.19	2.21	2.20	2.22	2.00	2.20	2.14	2.12
–(O=F,CI)	0.00	0.00	0.00	0.00	-0.17	0.00	-0.01	-0.01
Total	99.08	99.95	99.73	100.42	99.38	99.61	99.27	98.49
Si ⁴⁺ (<i>apfu</i>)	7.623	7.691	7.624	7.749	7.610	7.681	6.242	6.153
Ti ⁴⁺	0.043	0.029	0.055	0.017	0.030	0.028	0.122	0.128
Al ³⁺	0.445	0.425	0.478	0.271	0.485	0.418	2.500	2.602
Cr ³⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
$Fe^{3+}(min)^{\dagger}$	0.054	0.026	0.035	0.021	0.028	0.029	0.012	0.003
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg ²⁺	4.879	4.853	4.841	4.925	4.823	4.867	4.101	4.091
Ca ²⁺	1.955	1.976	1.967	2.018	2.025	1.977	2.023	2.024

Table A.84. (Continued) Chemical compositions and structural formulae of amphibole supergroup minerals from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-5a							
Closest pegmatite dike	Rau 3							
Proximity to pegmatite (m)	20	20	20	20	20	20	20	20
Mineral	*Tr	Tr	Tr	Tr	Tr	Tr	Prg	Prg
Na+(<i>apfu</i>)	0.053	0.046	0.070	0.042	0.072	0.060	0.582	0.616
K ⁺	0.018	0.019	0.019	0.006	0.017	0.015	0.065	0.068
F-	b.d.	b.d.	b.d.	b.d.	0.169	b.d.	b.d.	b.d.
Cl-	b.d.	b.d.	b.d.	b.d.	0.007	b.d.	0.010	0.012
OH-‡	2.000	2.000	2.000	2.000	1.824	2.000	1.990	1.988
O ²⁻	21.951	21.978	21.980	21.936	21.940	21.970	21.944	21.924

The formulae were calculated on the basis of 15 cations per formula unit.

Chromium and Mn were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); $^{+}$ Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; $^{+}$ H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R4-1	R4-1	R4-1	R4-1	R4-1	R4-1
Closest pegmatite dike	Rau 3	Rau 4										
Proximity to pegmatite (m)	20	20	20	20	20	20	1	1	1	1	1	1
Mineral	*Clc	Clc										
SiO ₂ (wt.%)	29.54	30.08	29.99	29.65	29.41	29.89	29.09	28.61	28.63	28.54	28.90	29.05
TiO ₂	0.06	0.08	b.d.	0.05	0.06	b.d.						
Al ₂ O ₃	22.11	22.29	22.11	22.40	21.99	21.94	22.94	23.96	24.66	24.38	23.87	23.30
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.33	0.28	0.20	0.20	0.13	0.32	0.16	0.18	0.21	0.21	0.20	0.18
MgO	33.39	34.08	33.85	33.70	33.95	33.24	33.75	33.34	33.13	33.57	33.61	33.16
CaO	b.d.	b.d.	0.03	0.03	0.05	b.d.	0.09	0.02	0.08	0.04	0.04	0.10
K ₂ O	0.10	b.d.	0.05	b.d.	b.d.	0.14	0.04	b.d.	0.06	0.08	b.d.	b.d.
F	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	1.46	1.22	1.26	1.12	1.32	1.27
H_2O^{\ddagger}	14.29	14.41	14.30	14.44	14.58	13.97	15.08	15.42	15.61	15.86	15.41	14.82
-(O=F)	0.00	0.00	0.00	0.00	0.00	0.00	-0.61	-0.51	-0.53	-0.47	-0.56	-0.54
Total	99.81	101.23	100.53	100.48	100.17	99.50	101.99	102.24	103.10	103.33	102.79	101.35
Si ⁴⁺ (<i>apfu</i>)	2.713	2.724	2.734	2.701	2.684	2.758	2.624	2.564	2.543	2.526	2.579	2.635
Ti ⁴⁺	0.004	0.005	b.d.	0.004	0.004	b.d.						
Al ³⁺	2.393	2.379	2.376	2.405	2.365	2.386	2.438	2.531	2.582	2.543	2.511	2.491
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.025	0.021	0.015	0.015	0.010	0.025	0.012	0.014	0.016	0.015	0.015	0.014
Mg ²⁺	4.571	4.600	4.600	4.577	4.620	4.572	4.538	4.453	4.388	4.429	4.471	4.485
Ca ²⁺	b.d.	b.d.	0.003	0.003	0.005	b.d.	0.009	0.002	0.008	0.003	0.003	0.010
K⁺	0.011	b.d.	0.005	b.d.	b.d.	0.017	0.004	b.d.	0.007	0.009	b.d.	b.d.
F⁻	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.415	0.345	0.353	0.313	0.374	0.365
OH-‡	8.750	8.704	8.694	8.775	8.880	8.599	9.072	9.214	9.252	9.364	9.175	8.967
O ²⁻	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000	18.000

Table A.85. Chemical compositions and structural formulae of clinochlore from the host rocks near the Rau 3 and 4 pegmatite dikes.

The formulae were calculated on the basis of 7 cations per formula unit.

Chromium, Mn, and Na were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); †Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; ‡H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R6-2b	R6-2b	R6-2b	R6-2b	R6-2b	R6-2b
Closest pegmatite dike	Rau 6					
Proximity to pegmatite (m)	< 1	< 1	< 1	< 1	< 1	< 1
Mineral	*Clc	Clc	Clc	Clc	Clc	Clc
SiO ₂ (wt.%)	29.00	28.29	28.59	29.10	27.97	28.51
Al ₂ O ₃	23.99	22.72	23.58	23.35	23.19	23.76
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.22	0.22	0.23	0.18	0.17	0.27
MgO	33.03	32.62	32.74	33.24	32.93	32.98
CaO	0.12	0.10	0.16	0.16	1.16	0.16
K ₂ O	b.d.	0.03	0.33	0.09	b.d.	b.d.
F	0.49	0.38	0.31	0.38	b.d.	0.30
H ₂ O [‡]	15.04	14.71	15.21	14.96	15.79	15.25
-(O=F)	-0.21	-0.16	-0.13	-0.16	0.00	-0.13
Total	101.69	98.92	101.00	101.31	101.21	101.12
Si ⁴⁺ (<i>apfu</i>)	2.609	2.615	2.586	2.628	2.516	2.573
Al ³⁺	2.543	2.475	2.514	2.485	2.458	2.527
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.017	0.017	0.017	0.013	0.013	0.020
Mg ²⁺	4.429	4.495	4.416	4.475	4.417	4.437
Ca ²⁺	0.011	0.010	0.015	0.016	0.112	0.016
K+	b.d.	0.004	0.038	0.010	b.d.	b.d.
F⁻	0.139	0.112	0.088	0.108	b.d.	0.085
OH-‡	9.023	9.070	9.178	9.013	9.478	9.181
O ²⁻	18.000	18.000	18.000	18.000	18.000	18.000

Table A.86. Chemical compositions and structural formulae of clinochlore from the host rocks near the Rau 6 pegmatite dike.

The formulae were calculated on the basis of 7 cations per formula unit.

Titanium, Cr. Mn, and Na were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]H₂O contents based on stoichiometry; b.d. = below detection limit.

Sample	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a	R3-4a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Mineral	*An	An	An	An	An	An	An	An	Kfs	Kfs
SiO ₂ (wt.%)	44.41	44.53	44.10	44.17	45.79	46.67	45.92	46.77	63.66	63.40
Al ₂ O ₃	35.40	35.01	36.05	35.72	35.77	34.90	34.47	33.47	18.55	18.72
$Fe_2O_{3(min)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.20	b.d.	b.d.	b.d.
MgO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.81	0.58	b.d.	b.d.
CaO	18.92	18.43	19.59	19.57	19.03	18.33	16.81	16.06	b.d.	0.06
BaO	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	1.02	1.69
Na ₂ O	0.77	1.02	0.52	0.38	0.62	1.17	1.05	1.73	0.42	0.41
K ₂ O	0.06	0.07	0.06	0.10	0.13	0.04	0.11	0.13	16.06	15.85
Total	99.57	99.05	100.32	99.94	101.35	101.10	99.36	98.74	99.72	100.13
Si ⁴⁺ (<i>apfu</i>)	2.060	2.074	2.034	2.044	2.083	2.123	2.975	2.964	2.120	2.169
Al ³⁺	1.935	1.922	1.960	1.948	1.917	1.871	1.022	1.031	1.876	1.829
Fe^{3+} (min) †	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.008	b.d.
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.055	0.040
Ca ²⁺	0.940	0.920	0.968	0.970	0.927	0.894	b.d.	0.003	0.832	0.798
Ba ²⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.019	0.031	b.d.	b.d.
Na ⁺	0.069	0.092	0.046	0.034	0.055	0.103	0.038	0.038	0.094	0.156
K+	0.004	0.004	0.003	0.006	0.007	0.002	0.958	0.945	0.006	0.007
O ²⁻	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000

Table A.87. Chemical compositions and structural formulae of feldspar group minerals from the host rocks near the Rau 3 pegmatite dike.

The formulae were calculated on the basis of 8 O atoms per formula unit.

Manganese, Rb, and Cs were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	R3-4a	R3-5a	R3-5a									
Closest pegmatite dike	Rau 3											
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20
Mineral	*Ttn	Ttn										
SiO ₂ (wt.%)	29.92	27.90	29.87	29.84	29.59	29.95	29.15	29.48	29.83	29.90	30.32	30.15
TiO ₂	37.48	34.20	37.00	36.80	36.23	37.11	35.67	36.69	37.15	36.31	36.67	35.79
Al ₂ O ₃	1.25	1.14	1.06	1.17	1.42	1.27	1.10	1.12	0.97	1.24	1.81	1.68
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	b.d.	0.40	b.d.	b.d.	0.25	b.d.						
CaO	28.25	29.65	28.16	28.30	27.67	27.86	27.79	28.11	28.61	28.55	28.51	28.68
MnO	b.d.	0.07	b.d.	b.d.	b.d.	b.d.						
SnO	0.22	0.29	0.18	0.14	0.45	0.27	0.23	0.18	b.d.	0.23	b.d.	b.d.
Na ₂ O	b.d.											
Nb_2O_5	0.38	0.27	0.18	b.d.	0.53	0.52	0.12	0.26	b.d.	b.d.	b.d.	b.d.
F	b.d.	0.46	b.d.	0.62	b.d.	0.40	0.59	b.d.	0.53	b.d.	0.40	b.d.
H_2O^{\ddagger}	0.00	0.43	0.00	0.59	0.00	0.38	0.56	0.00	0.50	0.00	0.38	0.00
–(O=F)	0.00	-0.19	0.00	-0.26	0.00	-0.17	-0.25	0.00	-0.22	0.00	-0.17	0.00
Total	97.50	94.56	96.45	97.20	96.13	97.60	94.97	95.90	97.45	96.24	97.91	96.29
Si ⁴⁺ (apfu)	1.002	0.977	1.011	1.005	1.006	1.004	1.006	1.005	1.002	1.015	1.009	1.020
Ti ⁴⁺	0.945	0.901	0.942	0.932	0.927	0.936	0.926	0.941	0.939	0.927	0.918	0.911
Al ³⁺	0.049	0.047	0.042	0.046	0.057	0.050	0.045	0.045	0.039	0.050	0.071	0.067
$Fe^{3+}(min)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg ²⁺	b.d.	0.021	b.d.	b.d.	0.012	b.d.						
Ca ²⁺	1.014	1.112	1.021	1.021	1.009	1.001	1.028	1.027	1.030	1.038	1.017	1.039
Mn ²⁺	b.d.	0.002	b.d.	b.d.	b.d.	b.d.						

Table A.88. Chemical compositions and structural formulae of titanite from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-4a	R3-5a	R3-5a									
Closest pegmatite dike	Rau 3											
Proximity to pegmatite (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	20	20
Mineral	*Ttn	Ttn										
Sn ²⁺ (<i>apfu</i>)	0.003	0.004	0.003	0.002	0.007	0.004	0.003	0.003	b.d.	0.004	b.d.	b.d.
Na⁺	b.d.											
Nb ⁵⁺	0.006	0.004	0.003	b.d.	0.008	0.008	0.002	0.004	b.d.	b.d.	b.d.	b.d.
F⁻	b.d.	0.051	b.d.	0.066	b.d.	0.042	0.065	b.d.	0.057	b.d.	0.042	b.d.
$OH^{-\ddagger}$	0.000	0.102	0.000	0.132	0.000	0.085	0.129	0.000	0.111	0.000	0.084	0.000
O ²⁻	5.000	4.949	5.000	4.934	5.000	4.958	4.935	5.000	4.943	5.000	4.958	5.000

The formulae were calculated on the basis of 5 anions per formula unit.

Tantalum was also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents calculated based on stoichiometry; b.d. = below detection limit.

Sample	R3-5a										
Closest pegmatite dike	Rau 3										
Proximity to pegmatite (m)	20	20	20	20	20	20	20	20	20	20	20
Mineral	*Ttn	Ttn									
SiO ₂ (wt.%)	29.95	30.16	30.07	29.72	28.78	30.24	29.35	29.61	29.35	29.53	30.41
TiO ₂	36.46	35.18	36.14	36.85	35.35	35.84	35.97	35.95	35.38	35.59	36.78
Al ₂ O ₃	1.55	1.66	1.67	1.23	1.23	1.73	1.26	1.59	1.83	1.81	1.78
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.08	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
$FeO_{(max)}^{\dagger}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	b.d.	b.d.	b.d.	b.d.	0.67	b.d.	0.52	b.d.	0.24	b.d.	0.04
CaO	28.44	28.32	28.54	28.39	28.34	28.21	28.10	28.05	28.19	28.19	28.43
MnO	b.d.										
SnO	b.d.										
Na ₂ O	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.04	b.d.	b.d.	b.d.	b.d.
Nb ₂ O ₅	b.d.	b.d.	b.d.	0.20	b.d.	b.d.	0.27	0.15	b.d.	b.d.	b.d.
F	b.d.	b.d.	0.59	0.36	0.49	0.55	0.63	0.52	0.62	0.41	b.d.
H_2O^{\ddagger}	0.00	-0.01	0.56	0.34	0.46	0.52	0.59	0.49	0.59	0.39	0.00
-(O=F)	0.00	0.00	-0.25	-0.15	-0.21	-0.23	-0.27	-0.22	-0.26	-0.17	0.00
Total	96.40	95.39	97.32	96.94	95.11	96.87	96.56	96.14	95.93	95.75	97.43
Si ⁴⁺ (<i>apfu</i>)	1.012	1.029	1.009	1.002	0.992	1.018	0.996	1.006	1.000	1.007	1.015
Ti ⁴⁺	0.927	0.903	0.912	0.935	0.917	0.907	0.918	0.919	0.907	0.913	0.923
Al ³⁺	0.062	0.067	0.066	0.049	0.050	0.069	0.051	0.064	0.073	0.073	0.070
$Fe^{3+}(min)^{\dagger}$	0.000	0.002	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg ²⁺	b.d.	b.d.	b.d.	b.d.	0.034	b.d.	0.026	b.d.	0.012	b.d.	0.002
Ca ²⁺	1.030	1.035	1.026	1.026	1.047	1.017	1.022	1.021	1.029	1.030	1.017
Mn ²⁺	b.d.										

Table A.88. (Continued) Chemical compositions and structural formulae of titanite from the host rocks near the Rau 3 pegmatite dike.

Sample	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a	R3-5a
Closest pegmatite dike	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3	Rau 3
Proximity to pegmatite (m)	20	20	20	20	20	20	20	20	20	20	20
Mineral	*Ttn	Ttn	Ttn	Ttn	Ttn	Ttn	Ttn	Ttn	Ttn	Ttn	Ttn
Sn ²⁺ (<i>apfu</i>)	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
Na⁺	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	b.d.	b.d.
Nb ⁵⁺	b.d.	b.d.	b.d.	0.003	b.d.	b.d.	0.004	0.002	b.d.	b.d.	b.d.
F⁻	b.d.	b.d.	0.063	0.038	0.053	0.058	0.068	0.055	0.067	0.045	b.d.
OH-‡	0.000	-0.002	0.125	0.076	0.106	0.116	0.134	0.111	0.134	0.089	0.000
O ²⁻	5.000	5.000	4.937	4.962	4.947	4.942	4.932	4.945	4.933	4.955	5.000

The formulae were calculated on the basis of 5 anions.

Tantalum was also sought but was below the detection limit of the EMP in all analyses.

*Abbreviations of mineral names follow Whitney & Evans (2010); [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]H₂O contents calculated based on stoichiometry; b.d. = below detection limit

Sample	AplH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	AplH-4b-1
Closest dike	Rau 3	Rau 3	Rau 5	Rau 5	Rau 5
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)
WO ₃ (wt.%)	1.46	1.17	1.43	2.10	1.07
Nb ₂ O ₅	62.35	65.26	64.31	64.23	62.60
Ta ₂ O ₅	7.24	5.85	5.42	6.75	7.69
SiO ₂	0.01	0.05	0.27	0.12	0.10
TiO ₂	6.68	5.48	5.46	6.16	5.63
ZrO ₂	0.49	0.37	0.30	0.17	0.20
SnO ₂	0.04	0.20	b.d.	0.05	b.d.
ThO ₂	0.13	b.d.	0.13	0.05	0.37
UO ₂	0.09	0.02	0.21	b.d.	0.26
Al ₂ O ₃	b.d.	b.d.	0.07	0.01	0.15
Sc ₂ O ₃	2.03	2.27	2.54	1.26	1.22
$Fe_2O_{3(\text{min})}^\dagger$	0.00	0.00	0.00	0.00	0.00
FeO _(max) †	16.33	16.95	15.52	17.25	15.33
Y ₂ O ₃	0.12	0.02	1.00	0.03	0.49
Sb ₂ O ₃	0.07	0.02	b.d.	0.11	b.d.
Bi ₂ O ₃	0.06	b.d.	b.d.	0.11	0.21
MgO	0.31	0.33	0.32	0.27	0.28
CaO	b.d.	b.d.	b.d.	b.d.	0.55
MnO	2.38	2.26	2.54	2.25	2.16
ZnO	b.d.	b.d.	0.06	0.01	0.03
PbO	0.30	b.d.	b.d.	0.04	0.02
Na ₂ O	b.d.	0.04	0.01	b.d.	b.d.
Total	100.06	100.29	99.59	100.94	98.37
W ⁶⁺ (<i>apfu</i>)	0.021	0.017	0.021	0.030	0.016
Nb ⁵⁺	1.592	1.652	1.637	1.627	1.633
Ta⁵⁺	0.111	0.089	0.083	0.103	0.121
Si ⁴⁺	0.000	0.003	0.015	0.007	0.006
Ti ⁴⁺	0.284	0.231	0.231	0.260	0.244
Zr ⁴⁺	0.013	0.010	0.008	0.005	0.006
Sn ⁴⁺	0.001	0.005	b.d.	0.001	b.d.
Th ⁴⁺	0.002	b.d.	0.002	0.001	0.005
U ⁴⁺	0.001	0.000	0.003	b.d.	0.003
Al ³⁺	b.d.	b.d.	0.005	0.001	0.010
Sc ³⁺	0.100	0.111	0.125	0.061	0.061
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000	0.000

Table A.89. Chemical compositions and structural formulae of columbite-(Fe) from the host rocks near an aplite dike.
Sample	AplH-4b-1	AplH-4b-1	AplH-4b-1	AplH-4b-1	ApIH-4b-1
Closest dike	Rau 3	Rau 3	Rau 5	Rau 5	Rau 5
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)	Col-(Fe)
Fe ²⁺ (max) [†] (<i>apfu</i>)	0.771	0.794	0.731	0.808	0.740
Y ³⁺	0.004	0.001	0.030	0.001	0.015
Sb ³⁺	0.002	0.000	b.d.	0.002	b.d.
Bi ³⁺	0.001	b.d.	b.d.	0.002	0.003
Mg ²⁺	0.026	0.028	0.027	0.022	0.024
Ca ²⁺	b.d.	b.d.	b.d.	b.d.	0.034
Mn ²⁺	0.114	0.107	0.121	0.107	0.106
Zn ²⁺	b.d.	b.d.	0.002	0.001	0.001
Pb ²⁺	0.005	b.d.	b.d.	0.001	0.000
Na ⁺	b.d.	0.004	0.001	b.d.	b.d.
O ^{2_}	6.000	6.000	6.000	6.000	6.000

The formulae were calculated on the basis of 6 anions per formula unit. Fluorine was also sought but was below the detection limit of the EMP in all analyses.

*Col = columbite; $^{\dagger}Ratio$ of Fe₂O₃ and FeO calculated to fit electroneutral formula; b.d. = below detection limit.

Sample	ApIH-4b-1	AplH-4b-1	ApIH-4b-1	AplH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1
Mineral	*Brl	Brl	Brl	Brl
SiO ₂ (wt.%)	67.46	67.70	67.65	67.43
TiO ₂	b.d.	0.03	b.d.	0.01
Al ₂ O ₃	18.89	18.83	18.63	18.60
$Fe_2O_{3(min)}^\dagger$	0.00	0.00	0.00	0.00
FeO _(max) †	b.d.	b.d.	0.17	b.d.
BeO‡	13.18	12.89	13.28	13.55
MgO	0.09	0.03	0.07	0.06
Na ₂ O	0.16	0.15	0.10	0.12
Rb ₂ O	0.08	0.14	0.04	0.10
Total	99.86	99.75	99.94	99.86
Si ⁴⁺ (<i>apfu</i>)	6.005	6.022	6.024	6.031
Ti ⁴⁺	b.d.	0.002	b.d.	0.001
Al ³⁺	1.982	1.973	1.955	1.960
Fe ³⁺ (min) [†]	0.000	0.000	0.000	0.000
$Fe^{2+}(max)^{\dagger}$	b.d.	b.d.	0.013	b.d.
Be ^{2+‡}	3.000	3.000	3.000	3.000
Mg ²⁺	0.012	0.003	0.009	0.008
Na ⁺	0.027	0.025	0.017	0.021
Rb⁺	0.004	0.008	0.002	0.006
O ²⁻	18.012	18.026	18.011	18.026

Table A.90. Chemical compositions and structural formulae of beryl from the host rocks near an aplite dike.

The formulae were calculated on the basis of 8 T and M site cations per formula unit.

Phosphorus, Cr, Sc, Ca, Mn, Zn, Ba, K, Cs, F, and Cl were also sought but were below the detection limit of the EMP in all analyses.

*Abbreviations of minerals names follow Whitney & Evans (2010); †Ratio of Fe_2O_3 and FeO calculated to fit electroneutral formula; [‡]BeO was fixed at 3 *apfu* Be; b.d. = below detection limit,

Sample	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Sch	Imr	Imr	Snc-(Ce)	Asc
WO ₃ (wt.%)	70.00	b.d.	0.03	_	b.d.
Nb ₂ O ₅	1.41	21.62	23.01	-	25.28
Ta ₂ O ₅	b.d.	4.30	4.72	-	6.69
SiO ₂	0.68	0.01	0.11	1.19	0.29
TiO ₂	b.d.	65.86	64.49	0.00	23.22
ZrO ₂	-	0.02	0.07	b.d.	b.d.
SnO ₂	-	0.26	0.23	-	-
ThO ₂	-	b.d.	b.d.	1.63	22.04
UO ₂	-	0.03	b.d.	b.d.	1.09
Al ₂ O ₃	b.d.	0.13	0.14	0.01	b.d.
Sc ₂ O ₃	b.d.	0.21	0.23	b.d.	0.09
$Fe_2O_{3(min)}^{\dagger}$	0.00	8.63	8.94	0.37	0.72
$FeO_{(max)}^{\dagger}$	6.83	0.00	0.00	0.00	0.00
Y ₂ O ₃	-	b.d.	0.08	1.21	5.70
Sb ₂ O ₃	-	0.06	0.11	-	_
La ₂ O ₃	-	-	-	9.94	b.d.
Ce ₂ O ₃	-	-	_	24.56	1.25
Pr ₂ O ₃	-	-	_	3.14	0.47
Nd ₂ O ₃	-	-	_	9.49	3.94
Sm ₂ O ₃	-	-	_	1.76	2.89
Gd ₂ O ₃	-	-	-	0.67	1.58
Tb ₂ O ₃					0.17
Dy ₂ O ₃					0.69
Er ₂ O ₃					0.18
Tm_2O_3	-	-	-	0.27	0.47
Yb ₂ O ₃					0.25
Bi ₂ O ₃	-	0.08	b.d.	-	b.d.
MgO	0.14	0.01	0.01	b.d.	b.d.
CaO	15.54	b.d.	b.d.	15.44	2.57
ZnO	b.d.	0.02	b.d.	-	-
Na ₂ O	0.08	b.d.	b.d.	b.d.	b.d.
K ₂ O	-	-	-	0.04	b.d.
F	b.d.	b.d.	b.d.	5.16	0.30
CO_2^{\ddagger}	-	-	-	27.23	-
H_2O^{\S}	_	_	_	3.13	_

Table A.91. Chemical compositions and structural formula of scheelite, ilmenorutile, synchysite-(Ce), and aeschynite-(Ce) from the host rocks near an aplite dike.

Sample	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1	AplH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Sch	Imr	Imr	Snc-(Ce)	Asc
-(O=F)	_	_	-	-2.17	-0.13
Total	94.67	101.23	102.15	103.05	99.75
W ⁶⁺ (apfu)	0.804	b.d.	0.000	_	b.d.
Nb ⁵⁺	0.028	0.146	0.155	_	0.735
Ta⁵+	b.d.	0.017	0.019	_	0.117
Si ⁴⁺		0.000	0.002	0.064	0.019
Ti ⁴⁺	b.d.	0.740	0.725	0.000	1.123
Zr ⁴⁺	_	0.000	0.000	0.000	b.d.
Sn ⁴⁺	_	0.002	0.001	_	_
Th⁺	_	b.d.	b.d.	0.020	0.323
U+	_	0.000	b.d.	b.d.	0.016
Al ³⁺	b.d.	0.002	0.002	0.001	b.d.
Sc ³⁺	b.d.	0.003	0.003	b.d.	0.005
Fe ³⁺ (min) [†]	0.000	0.097	0.100	0.015	0.035
$Fe^{2+}(max)^{\dagger}$	0.253	0.000	0.000	0.000	0.000
Y ³⁺	_	b.d.	0.001	0.015	0.195
Sb ³⁺	_	0.000	0.00	_	_
La ³⁺	_	-	_	0.197	b.d.
Ce ³⁺	_	_	_	0.484	0.029
Pr ³⁺	_	-	_	0.062	0.011
Nd ³⁺	_	-	_	0.182	0.091
Sm ³⁺	_	_	_	0.033	0.064
Gd ³⁺	_	_	_	0.012	0.034
Tb ³⁺					0.004
Dy ³⁺					0.014
Er ³⁺					0.004
Tm ³⁺	_	-	-	0.004	0.009
Yb ³⁺					0.005
Bi ³⁺	_	0.000	0.000	_	b.d.
Mg ²⁺	0.009	0.000	0.000	0.000	b.d.
Ca ²⁺	0.74	b.d.	b.d.	0.890	0.177
Zn ²⁺	b.d.	0.000	b.d.	_	_
Na ⁺	0.006	b.d.	b.d.	b.d.	b.d.
K+	-	_	_	0.003	b.d.
F⁻	b.d.	0.000	0.000	0.877	0.060
C ^{4+‡}	-	-	-	2.000	-
OH⁻§	_	-	-	1.123	_

Sample	ApIH-4b-1	AplH-4b-1	ApIH-4b-1	ApIH-4b-1	ApIH-4b-1
Closest dike	Aplite	Aplite	Aplite	Aplite	Aplite
Proximity to dike (m)	< 1	< 1	< 1	< 1	< 1
Mineral	*Sch	Imr	Imr	Snc-(Ce)	Asc
O ²⁻ (apfu)	3.546	2.046	2.055	6.149	5.987

The formula for scheelite was calculated on the basis of 1 2+ cation, ilmenorutile on the basis of 1 Ti + Nb + Fe cation, synchysite on the basis of 3 cations, and aeschynite on the basis of 6 oxygen atoms per formula unit.

Manganese and Pb were sought in all minerals but were below the detection limit of the EMP in all analyses. Molybdenum was also sought in scheelite, P, Eu, Ba, Sr, Tb, Dy, Ho, Er, Yb, and Cl were also sought in synchysite, and W, P, Zr, Al, As, La, Ho, Lu, Bi, Mn, Na, and K were also sought in aeschynite.

*Abbreviations of mineral names follow Whitney & Evans (2010); Imr = ilmenorutile; Snc = synchysite; Asc = aeschynite [†]Ratio of Fe₂O₃ and FeO calculated to fit electroneutral formula; [‡]CO₂ was fixed at 1 *apfu* C; [§]H₂O contents based on stoichiometry; b.d. = below detection limit; - = not measured.

APPENDIX B

Supporting Information for Chapter 6: The Mineralogy Concept Inventory (MCI): A Statistically Validated Assessment to Measure Learning Gains and Compare Pedagogies

B.1 Expert Survey Results

Table B.1. Complete results of the expert survey about key topics in introductory mineralogy courses, ordered alphabetically by country.

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
AUSTRALIA									
James Cook University	< 1	Medium	Medium	High	High	Medium	Low	Not covered	50
CANADA									
Memorial University of Newfoundland	< 1	Medium	High	High	Medium	Low	High	Not covered	99
Thompson Rivers University	< 1	High	High	High	High	High	High	High	65
University of Alberta	< 1	Not covered	High	High	Medium	High	High	Medium	80
University of New Brunswick	> 2 to < 5	High	Medium	High	High	High	High	High	75
University of Ottawa	< 1	Not covered	Medium	Medium	High	Medium	High	Not covered	100
University of Toronto	< 1	Medium	Medium	Medium	High	Medium	Medium	Low	100
University of Winnipeg	< 1	Medium	Medium	High	High	Medium	Low	High	90
FRANCE									

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
University of Rennes 1	< 1	High	Low	High	Medium	Low	Low	Medium	100
GERMANY									
Freie Universität Berlin	< 1	High	High	High	High	Medium	Medium	High	100
GeoforschungsZe ntrum-Potsdam	> 2 to < 5	Medium	High	High		Medium	Medium	High	100
Kiel University	< 1	Not covered	Medium	High	Medium	High	Medium	High	100
University of Freiburg	< 1	Not covered	High	High	High	High	High	Not covered	80
GREECE									
University of Athens	> 1 to < 2	High	Medium	High	Medium	Medium	Medium	High	80
JORDAN									
University of Jordan	< 1	Not covered	High	High	High	High	High	Low	90
ITALY									
University of Messina	< 1	Medium	High	High	High	Medium	Medium	High	90
University of Parma	< 1	High	High	Medium	High	Medium	Medium	Medium	100
NEW ZEALAND									

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
Victoria University	Unanswer ed	High	Medium	Medium	Medium	Medium	Medium	Low	Unanswere d
NORWAY									
University of Oslo	< 1	Not covered	High	High	Low	High	Medium	Not covered	100
PHILIPPINES									
University of the Philippines	< 1	Not covered	Medium	High	High	High	Medium	Not covered	100
U.S.A									
Appalachian State University	< 1	High	High	High	Low	Medium	Medium	Not covered	70
Augustana College	< 1	Low	High	High	High	High	High	Low	100
Brigham Young University	< 1	Not covered	High	High	Medium	High	High	Not covered	100
Brown University	< 1	Medium	High	High	Medium	Low	Low	Medium	Unanswer ed
California Institute of Technology	< 1	Medium	Medium	High	High	High	Medium	High	75
California State University, Chico	< 1	Not covered	Medium	Medium	High	Low	Medium	Medium	50

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
California State University, Fresno	< 1	High	High	High	Medium	High	High	Not covered	80
California State University, Fullerton	> 1 to < 2	High	High	Medium	High	High	Medium	High	100
Carleton College	< 1	High	Medium	High	Medium	Medium	Medium	Not covered	100
Central Washington University	< 1	High	High	High	High	Medium	Low	Low	70
Colby College	< 1	High	High	Medium	Low	High	High	Low	~70
College of William & Mary	< 1	Medium	High	High	High	High	High	Low	90
Colorado State University	< 1	High	Medium	Medium	Low	Low	Medium	Low	65
Cornell College	< 1	High	High	High	Medium	Low	High	Not covered	100
Cornell University	< 1	High	High	High	High	Medium	High	High	~100
George Mason University	< 1	High	Medium	High	High	Medium	Medium	Medium	50
Grand Valley State University	< 1	Low	Medium	High	High	High	High	Medium	65
Hamilton College	< 1	Medium	Medium	Medium	High	Medium	Medium	Low	90

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
Indiana University - Purdue University Indianapolis	< 1	High	High	High	Medium	High	High	Low	80
Indiana University	> 1 to < 2	Low	High	High	High	Medium	Low	Medium	80
Lafayette College	< 1	High	Medium	High	High	High	Low	High	90
Lawrence University	< 1	Low	Low	Medium	Low	Low	Not covered	Medium	50
Michigan State University	< 1	High	High	High	Medium	High	Medium	Medium	70
Montana State University	> 2 to < 5	High	High	High	High	High	High	Medium	80
New Mexico State University	< 1	Not covered	Medium	Medium	High	Low	Medium	Low	90
North Dakota State University	< 1	High	High	High	High	High	High	Medium	100
Ohio State University	< 1	Medium	Low	High	High	High	Medium	Medium	80
Olivet Nazarene University	< 1	Medium	High	High	Medium	Medium	High	Not covered	90
Oregon State University	< 1	Not covered	Medium	High	High	High	Medium	Medium	95
Pennsylvania State University	> 1 to < 2	High	High	Medium	Low	Low	Low	High	80
Pomona College	> 1 to < 2	High	High	High	High	Medium	Medium	Medium	80

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
Potsdam State University	> 1 to < 2	High	High	High	Medium	High	High	High	90
Princeton University	< 1	Medium	High	High	Medium	Low	Medium	Low	70
Purdue University	< 1	High	High	High	Medium	Low	High	Low	90
Slippery Rock University	< 1	Medium	High	High	Medium	High	Medium	Not covered	100
Smith College	< 1	High	Medium	High	Medium	Medium	Medium	Low	80
Southern Illinois University	< 1	Medium	High	Medium	Medium	Medium	High	Medium	~90
Stockton University	> 1 to < 2	High	Medium	High	High	High	Low	Low	90
Texas A&M University- Kingsville	< 1	High	High	High	High	High	Medium	Low	~90
Tufts University	< 1	High	Medium	Medium	High	Medium	Medium	High	90
University of California, Los Angeles	< 1	High	High	High	High	High	High	High	90
University of Chicago	< 1	Medium	High	Medium	High	Low	High	Low	80
University of Dayton	< 1	High	Medium	High	High	Low	Medium	Medium	90
University of Georgia	< 1	High	High	High	High	Medium	High	Medium	80

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
University of Illinois at Chicago	> 2 to < 5	Not covered	High	High	High	High	High	Not covered	80
University of Minnesota	< 1	High	High	Medium	High	Medium	Medium	Medium	90
University of Missouri - Kansas City	< 1	High	High	High	High	Medium	Medium	Low	85
University of North Carolina Wilmington	< 1	Not covered	Medium	High	High	High	Medium	High	70
University of Northern Colorado	> 1 to < 2	High	High	High	Medium	High	High	Medium	85-90
University of Tennessee, Knoxville	< 1	High	High	High	Medium	High	Low	Medium	60
University of Wisconsin– Madison	< 1	High	High	High	Medium	Medium	High	Medium	90
Virginia Polytechnic Institute and State University	> 1 to < 2	Medium	Medium	Medium	High	High	Medium	Low	100
Washington University in St. Louis	< 1	Medium	Medium	High	Medium	Medium	High	Low	75-80

University where instructor teaches introductory mineralogy	Instructor last taught mineral- ogy (years)	Importance of optical mineralogy	Importance of crystal structure	Importance of mineral chemistry	Importance of physical properties of minerals	Importance of mineral classes and classify- cation	Importance of crystal symmetry	Importance of compositio n of the Earth's layers	Total course content included in previous topics (%)
West Virginia University	< 1	Not covered	Low	Medium	High	High	Medium	High	100
Western Colorado University	< 1	High	High	High	Medium	High	Medium	Not covered	90
Western Washington University	> 2 to < 5	Medium	Medium	High	High	Medium	Medium	High	80
Whitman College	< 1	High	High	High	Medium	High	Medium	High	87

Table B.1. (Continued) Complete results of the expert survey about key topics in introductory mineralogy courses, ordered alphabetically by country.

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
AUSTRALIA	
James Cook University	economic significance of mineral - medium importance
CANADA	
Memorial University of Newfoundland	Unanswered
Thompson Rivers University	occurrence, uses and significance of minerals. This is also very high importance because it gives context to the subject. I also talk about mineral diversity and how it has changed though time.
University of Alberta	 How minerals form: classical versus non-classical crystallization = high importance Silica polymerization, Bowen's reaction series and their relationship to evolution of the biosphere & biogeochemical element cycling = medium importance for context Mineral evolution and Anthropocene mineralogy = medium importance for context
University of New Brunswick	Also teach mineralogy from the point of view of understanding rocks (10 %) and the thermodynamics of minerals (15 %)
University of Ottawa	use/importance and occurrence of a given mineral - low importance macroscopic identification of minerals in handspecimen - high importance
University of Toronto	Unanswered
University of Winnipeg	Planetary mineralogy - Medium importance
FRANCE	
University of Rennes 1	Unanswered

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
GERMANY	
Freie Universität Berlin	The last lecture is always about the step from mineralogy to petrology - I explain it like thinking of stepping from psychology to sociology
GeoforschungsZe ntrum-Potsdam	Unanswered
Kiel University	Unanswered
University of Freiburg	Systematic mineralogy - remaining 20 %
GREECE	
University of Athens	Applied mineralogy and mineral resources - Medium importance
JORDAN	
University of Jordan	Mineral Growth and related processes: high importance.
ITALY	
University of Messina	Unanswered
University of Parma	Unanswered
NEW ZEALAND	
Victoria University	Unanswered
NORWAY	
University of Oslo	We try not to make it pure mineralogy and therefore links it with actual rocks and phase diagrams
PHILIPPINES	

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
University of the Philippines	Unanswered
U.S.A.	
Appalachian State University	Quartz Deformation and Electron Backscatter Diffraction - Medium-High Importance Phase Diagrams - Medium Importance Mineral Evolution - Medium-Low Importance
Augustana College	I do intend to add a section next year (when we transition to semesters) on gemstone-forming processes (Med. imp.)
Brigham Young University	Instrumental Methods (included in mineral chemistry, maybe) - high importance
Brown University	Point defects; grain boundary structure and chemistry; solution thermodynamics; dislocations; all these subjects I've partitioned above into crystal structure and mineral chemistry
California Institute of Technology	technological use of (synthetic) minerals - medium biominerals medium gem minerals medium
California State University, Chico	lithologies and mineral associations, mineral uses, mineral extraction, hazards associated with minerals (asbestos and other inhallation hazards)
California State University, Fresno	I cover topical aspects with applications to real-world problems: Env. emphasis: asbestiform minerals, clays, zeolites, zirconolite. Geol. emphasis: thermometry, barometry
California State University, Fullerton	Unanswered
Carleton College	Unanswered
Central Washington University	phase diagrams/thermodynamics - high importance XRD, EMP analytical methods - medium importance

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
Colby College	Unanswered
College of William & Mary	Rock and mineral associations (e.g., common igneous minerals, etc.): high importance
Colorado State University	Colorlow, gemslow, mineral environmentsmoderate, formsmod, defectsmod, chemical analytical techniques and other instrumentationmod
Cornell College	Unanswered
Cornell University	Minor amount on ore deposits to cover ore minerals
George Mason University	mineral - rock associations high bonding and other chemistry topics- medium phase diagrams - high earth formation and mineral evolution - high thermodynamics - medium
Grand Valley State University	I think that mineral ID of hand samples if very important and an essential field skill that is being phased out in too many institutions
Hamilton College	Geological Occurrences / Mineral Associations - low importance Applications / Uses - low importance
Indiana University - Purdue University Indianapolis	economic importance/human consumption/use of mineral - medium importance mineral evolution - low importance analytical techniques - medium importance mineral assemblages - medium importance phase diagrams - high importance
Indiana University	Chemical bonding - high importance Health effects of mineral dusts - low importance Phase equilibria - high importance X-ray diffraction - medium importance
Lafayette College	analytical techniques (XRD, SEM), medium importance environment of formation, medium importance

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
Lawrence University	I also cover thermodynamics, low temperature geochemistry and mineral stability
Michigan State University	Thermodynamics and kinetics - high importance Mineral characterization - high importance Isotopes - medium importance
Montana State University	I'm not sure if you include hand sample identification in the category mineral classes and classification. If not, this is another important part of the course. In addition, I include a major component of instrumentation applied to the analysis and characterization of Earth Materials: powder XRD, SEM/BSE imaging, CL imaging, and EDS elemental analysis. I don't have access to a microprobe, so we work with EDS data. Both these topics are important to my class. Of medium importance is an introduction to the scientific literature. Students are assigned articles from Elements, Am. Mineralogist, etc. to review and report on so the begin to become acquainted with ways in which mineralogy is applied to larger geologic questions.
New Mexico State University	Mineral assemblages in rocks - high Economic mineral deposits - medium
North Dakota State University	X-ray diffraction - High importance Chemical analytical techniques - Medium importance
Ohio State University	Nature of binding- medium imo Environmental miner- medium
Olivet Nazarene University	Mineral occurrence in rock types - Medium importance Mineral chemical reactions - low importance
Oregon State University	Color in minerals, particularly gemstones
Pennsylvania State University	I consider it VITAL to teach about minerals in context. We focus on tectonic environments as key settings for mineral formation.
Pomona College	Mineral associations (e.g. Sulfides group in ores, evaporites as related, incompatibility of elements like B and Li creating suites of pegmatite minerals [medium]; minerals and society [high]. We sometimes read "Barren Lands" in the course as a way of having a novel where minerals are discussed in spades.

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance							
Potsdam State University	Paulings rules, polymorphs							
Princeton University	Biomineralogy, Environmental mineralogy, mineralogy and health, mineral associations and environments							
Purdue University	minerals in large scale earth cycles, for instance silicate weathering and CO2.							
Slippery Rock University	Unanswered							
Smith College	x-ray diffraction, x-ray spectroscopy (EDS), FTIR spectroscopy, mineral synthesis							
	Hand sample identification- high							
Southern Illinois	X-ray diffraction- low							
University	Evolution of minerals- low							
	Phase diagrams- medium							
Stockton University	Thermodynamics and phase diagrams - low to medium importance							
Texas A&M	Ore deposits and economic geology - medium importance							
University-	"Background" chemistry - medium importance.							
Kingsville								
	[x-ray diffraction] - low importance							
Tufts University	[reading primary literature] - medium importance							
	[crystal growth] - medium importance							
University of								
California, Los	Spectroscopy, kinetics							
Angeles								
University of	Hand sample identification - Medium importance							
Chicago	Occurrence (how & where minerals formed) - Medium importance							
University of Dayton	introduction to petrology - medium importance							

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
University of Georgia	mineral uses
University of Illinois at Chicago	X-ray diffraction of mineralsmedium importance
University of Minnesota	Biominerals
University of Missouri - Kansas City	Intro to analytical methods (e.g., XRD, EMPA, SEM/EDS) History of mineralogy
University of North Carolina Wilmington	Chemical distribution of the Earth with respect to potential mineral formation - high importance Mineral association relationships - medium importance Mineral stability - medium importance Mineral formula - medium importance Rock forming versus economic versus strategic mineral classification and importance - medium importance Gemstone and gem varieties - formation, chemistry and uses - medium importance
University of Northern Colorado	Crystal growth-medium importance, mineral associations - medium importance, environments of formation - medium importance
University of Tennessee, Knoxville	Atomic structure, crystal chemistry, phase diagrams
University of Wisconsin– Madison	Analytical techniques - Medium importance Nanophase mineralogy - Medium Minerals in the human environment - low
Virginia Polytechnic Institute and State University	Unanswered

University where instructor teaches introductory mineralogy	Other topics taught in mineralogy course and importance
	Phase diagrams: Medium to high importance
Washington	Geologic occurrence of minerals: low importance
University in St.	Environmental significance of minerals: low to medium importance
Louis	Industrial and residential uses of minerals: medium importance
	Mining and processing of minerals: low importance
West Virginia University	Unanswered
Western Colorado University	SEM/EDS and Xray diffraction - medium importance
Western	Mineral evolution - High importance
Washington University	Analytical methods (SEM-EDS, XRD) - Medium importance
Whitman College	minerals in the nuclear fuel cycle, the course theme because we are located near and downwind of the Hanford reservation, a superfund site with high radioactivity as this was where plutonium was made from the 1940s through the 1970s. Includes radioactive decay, minerals as sources of U and Th, and synthetic minerals that could be made into a ceramic to store waste. High importance X-ray diffractometry - high importance. Possibly you are including this with crystal structure but I wasn't sure. Crystal growth - medium to low importance

	If the instructor would expect their students to be able to answer a question on the MCI correctly								
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
AUSTRALIA									
James Cook University	Yes	Maybe	Yes	No	Yes	No	No	Yes	Maybe
CANADA									
Memorial University of Newfoundland	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Unanswered
Thompson Rivers University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
University of Alberta	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
University of New Brunswick	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
University of Ottawa	Yes	Unanswered	Yes	Yes	Yes	Yes	Yes	Yes	No
University of Toronto	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
University of Winnipeg	No	No	Yes	No	No	Yes	No	Yes	Yes
FRANCE									
University of Rennes 1	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Table B.1. (Continued) Complete results of the expert survey about key topics in introductory mineralogy courses, ordered alphabetically by country.

	If the instructor would expect their students to be able to answer a question on the MCI correctly								
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
GERMANY									
Freie Universität Berlin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
GeoforschungsZe ntrum-Potsdam	Yes	Unanswered	No	Yes	Yes	Yes	Yes	No	No
Kiel University	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
University of Freiburg	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
GREECE									
University of Athens	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No
JORDAN									
University of Jordan	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ITALY									
University of Messina	Yes	Yes	Yes	Yes	Yes	Unanswered	Unanswered	Yes	No
University of Parma	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
NEW ZEALAND									
Victoria University	Yes	No	Yes	Unanswered	Yes	Yes	No	No	Yes
NORWAY									
University of Oslo	Yes	Yes	Yes	Maybe	Yes	Yes	Yes	Yes	No

	If the instructor would expect their students to be able to answer a question on the MCI correctly								
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
PHILIPPINES									
University of the Philippines	Yes	No	Yes	Yes	No	Yes	Yes	No	Yes
U.S.A.									
Appalachian State University	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes
Augustana College	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Brigham Young University	Yes	Yes	Yes	Maybe	Yes	Yes	Yes	No	No
Brown University	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
California Institute of Technology	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
California State University, Chico	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Maybe
California State University, Fresno	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes
California State University, Fullerton	No	Yes							
Carleton College	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	If the instructor would expect their students to be able to answer a question on the MCI correctly								
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
Central Washington University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Yes
Colby College	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
College of William & Mary	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Colorado State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Cornell College	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Cornell University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
George Mason University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Grand Valley State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hamilton College	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered
Indiana University - Purdue University Indianapolis	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Indiana University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Lafayette College	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Lawrence University	Yes	No	No	No	Yes	No	No	Yes	Yes
Michigan State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	If the instructor would expect their students to be able to answer a question on the MCI correctly								
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9
Montana State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
New Mexico State University	Yes	No	Unanswered	No	Yes	Yes	Yes	No	No
North Dakota State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ohio State University	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered
Olivet Nazarene University	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Oregon State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Pennsylvania State University	No	Yes	Yes	Maybe	Yes	Maybe	Unanswered	Yes	Yes
Pomona College	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Potsdam State University	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes
Princeton University	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No
Purdue University	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered
Slippery Rock University	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Smith College	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unanswered
Southern Illinois University	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9	
Stockton University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Texas A&M University- Kingsville	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	
Tufts University	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	
University of California, Los Angeles	Yes	Yes	Yes	Unanswered	Yes	Yes	Yes	No	Yes	
University of Chicago	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
University of Dayton	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	
University of Georgia	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	
University of Illinois at Chicago	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	
University of Minnesota	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
University of Missouri - Kansas City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
University of North Carolina Wilmington	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Question 9	
University of Northern Colorado	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
University of Tennessee, Knoxville	Yes	Yes	Maybe	Yes	Unanswered	Yes	Yes	Yes	Yes	
University of Wisconsin– Madison	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Virginia Polytechnic Institute and State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
Washington University in St. Louis	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
West Virginia University	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	
Western Colorado University	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	
Western Washington University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	
Whitman College	Yes	Yes	No	Unanswered	Yes	Yes	Yes	No	Yes	

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
AUSTRALIA										
James Cook University	No	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Yes	
CANADA										
Memorial University of Newfoundland	Yes	No	Yes	Yes	Yes	Unanswered	No	No	No	
Thompson Rivers University	Yes	Yes	Unanswered	Yes	Yes	Unanswered	Yes	Yes	Yes	
University of Alberta	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	
University of New Brunswick	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
University of Ottawa	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	
University of Toronto	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
University of Winnipeg	Yes	Yes	Yes	Yes	Yes	No	No	No	No	
FRANCE										
University of Rennes 1	No	Yes	No	No	Yes	No	Yes	No	No	

Table B.1. (Continued) Complete results of the expert survey about key topics in introductory mineralogy courses, ordered alphabetically by country.

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
GERMANY										
Freie Universität Berlin	Yes	Yes	Maybe	Yes	Yes	No	Yes	Yes	Yes	
GeoforschungsZe ntrum-Potsdam	No	Yes	No	No	No	No	No	Yes	Unanswered	
Kiel University	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
University of Freiburg	Yes	Yes	Yes	Unanswered	No	No	No	Yes	Unanswered	
GREECE										
University of Athens	Yes	Yes	Yes	No	No	No	No	No	No	
JORDAN										
University of Jordan	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	
ITALY										
University of Messina	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	
University of Parma	Yes	Yes	Unanswered	Yes	Yes	Yes	Yes	Yes	Yes	
NEW ZEALAND										
Victoria University	No	Yes	Yes	No	Yes	Yes	No	No	Yes	
NORWAY										
University of Oslo	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	

	If the instructor would expect their students to be able to answer a question on the MCI correctly										
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18		
PHILIPPINES											
University of the Philippines	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes		
U.S.A.											
Appalachian State University	Yes	No	Yes								
Augustana College	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes		
Brigham Young University	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes		
Brown University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
California Institute of Technology	Yes	Yes	Yes	Maybe	Yes	Maybe	Yes	Yes	Yes		
California State University, Chico	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes		
California State University, Fresno	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes		
California State University, Fullerton	No	Yes	Yes	Yes	Yes	Maybe	Yes	Yes	Yes		
Carleton College	Yes	Yes	Yes	Yes	Unanswered	Unanswered	Yes	Yes	Yes		

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
Central Washington University	Yes	Yes	Yes	Yes	Yes	Unanswered	Yes	Yes	Yes	
Colby College	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	
College of William & Mary	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	
Colorado State University	No	Yes	Yes	Yes	No	No	No	Yes	Yes	
Cornell College	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	
Cornell University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unanswered	
George Mason University	No	Yes								
Grand Valley State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	
Hamilton College	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	
Indiana University - Purdue University Indianapolis	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Indiana University	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
Lafayette College	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	
Lawrence University	Yes	Yes	Yes	Yes	Yes	Unanswered	No	Yes	Yes	
Michigan State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
Montana State University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
New Mexico State University	Yes	Yes	Yes	Yes	No	No	No	No	No	
North Dakota State University	No	Yes								
Ohio State University	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	
Olivet Nazarene University	Yes	Yes	Yes	Yes	No	No	No	No	No	
Oregon State University	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	
Pennsylvania State University	No	No	No	Yes	Maybe	Maybe	Yes	No	No	
Pomona College	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	
Potsdam State University	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	
Princeton University	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	
Purdue University	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	Unanswered	
Slippery Rock University	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	
Smith College	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	
Southern Illinois University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
Stockton University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Texas A&M University- Kingsville	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	
Tufts University	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
University of California, Los Angeles	Yes	Yes	Unanswered	Yes	Yes	Yes	Yes	Yes	Yes	
University of Chicago	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	
University of Dayton	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	
University of Georgia	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	
University of Illinois at Chicago	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	
University of Minnesota	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	
University of Missouri - Kansas City	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
University of North Carolina Wilmington	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	

	If the instructor would expect their students to be able to answer a question on the MCI correctly									
University where instructor teaches introductory mineralogy	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16	Question 17	Question 18	
University of Northern Colorado	Yes	Yes	Yes	Yes	Yes	Unanswered	Yes	Yes	Yes	
University of Tennessee, Knoxville	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Unanswered	
University of Wisconsin– Madison	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Virginia Polytechnic Institute and State University	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	
Washington University in St. Louis	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	
West Virginia University	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
Western Colorado University	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	
Western Washington University	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	
Whitman College	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	
B.2 The Mineralogy Concept Inventory

Please answer the questions below to the best of your abilities. Please bubble in all of your answers on the bubble sheet that is included as the final page of this document.

Completing the assessment counts toward in-class participation, but otherwise it is not graded. There is no penalty for not knowing the correct answer, just do your best.

1. Given the ionic radii and charges of the following elements, choose which element is <u>least</u> likely to substitute for Zn (zinc) in sphalerite (chemical formula: ZnS).

Element	Ionic radius (Å)	Charge
Zn (zinc)	0.74	2+

	Element	Ionic radius (Å)	Charge
A.	Fe (iron)	0.645	2+
В.	Cd (cadmium)	0.97	2+
C.	Li (lithium)	0.76	1+
D.	K (potassium)	1.38	1+

- E. I do not know
- 2. Imagine that a crystal of quartz starts at the earth's surface and is moved progressively deeper into the earth until it reaches the lower mantle (about 660 kilometers deep). How would the structure of that crystal of quartz change as it moves progressively deeper into the earth?
 - A. The crystal wouldn't change
 - B. The bonds in the crystal would become more random
 - C. The crystal would melt
 - D. The structure of the crystal would become more dense
 - E. I do not know

- 3. Why can certain minerals be a variety of different colours? For example, quartz can be colourless, purple, pink, yellow, etc.
 - A. Colour is due to small inclusions of other minerals within the main mineral
 - B. Colour is produced by electrons that jump from higher to lower energy levels and release waves
 - C. The colour of a mineral is related to the environment that it formed in
 - D. Colour is caused by elements that occur in trace amounts in the mineral
 - E. I do not know
- 4. In which layer of the Earth would you be **most likely** to find a mineral with the chemical composition (Mg,Fe)₂SiO₄?
 - A. Crust
 - B. Upper mantle
 - C. Lower mantle
 - D. Outer core
 - E. I do not know
- 5. The diagram below shows the variation in composition between Fe, Al, and Cr. The labels indicate the end-member compositions (i.e. 100% of that element). What is the composition of point 'X'?
 - A. 10% Fe, 10% Al, 80% Cr
 - B. 40% Fe, 30% Al, 30% Cr
 - C. 60% Fe, 20% Al, 20% Cr
 - D. 80% Fe, 10% Al, 10% Cr
 - E. I do not know



- 6. Examine the (3-dimensional) **square-based** prism below. Imagine that you are asked to draw a 2-dimensional plane through the object to create a mirror image on both sides of the dividing plane. How many different planes could you draw to do this?
 - A. 1 plane
 - B. 2 planes
 - C. 3 planes
 - D. 4 planes
 - E. 5 planes
 - F. I do not know



- 7. Examine the (3-dimensional) **rectangular-based** prism below. Imagine that you are asked to draw a 2-dimensional plane through the object to create a mirror image on both sides of the dividing plane. How many different planes could you draw to do this?
 - A. 1 plane
 - B. 2 planes
 - C. 3 planes
 - D. 4 planes
 - E. 5 planes
 - F. I do not know



- 8. In what type of environment would you expect to form the mineral aragonite (chemical formula: CaCO₃)?
 - A. Volcano
 - B. River bed
 - C. Lake
 - D. Ocean
 - E. I do not know

- 9. Examine the (3-dimensional) crystal shown below. Light is shined through the crystal at several different orientations, as indicated by the arrows. The light always enters the crystal perpendicular to one of its faces. Will the light travel at the same speed regardless of the orientation at which it travels through the crystal?
 - A. Yes, all of the beams of light will travel at the same speed
 - B. No, <u>one</u> of the beams of light will travel at a different speed than the other beams
 - C. No, all of the beams of light will travel at different speeds
 - D. I do not know



- 10. Sodium (Na) and potassium (K) are both cations with a +1 charge. Na has an ionic radius of 1.02 Å and K has an ionic radius of 1.38 Å. Which of these two cations would you expect to have the largest number of negatively charged anions surrounding it?
 - A. Na because a smaller ionic radius can fit more negatively charged anions around it
 - B. Na because a smaller ionic radius has a stronger nucleus and can pull more negatively charged anions towards it
 - C. K because a larger ionic radius can fit more negatively charged anions around it
 - D. K because a larger ionic radius has a stronger nucleus and can pull more negatively charged anions towards it
 - E. I do not know
- 11. What is the most common element in the Earth's crust?
 - A. Oxygen
 - B. Carbon
 - C. Iron
 - D. Silicon
 - E. I do not know

12. Below are photos of two minerals. What would be the **<u>best way</u>** to tell if the two minerals are the **<u>same</u>** mineral?



- A. Pour acid on them to see if they fizz
- B. Powder each mineral and see what colour the powder is
- C. Test their hardness
- D. Hold a magnet near them to see if they're magnetic
- E. I do not know

13. Why are some minerals harder than others?

- A. Hardness is related to the environment that the mineral was formed in
- B. Hardness is related to the type of bonds between the atoms
- C. Hardness is related to the composition of the mineral
- D. Hardness is related to the angle of the bonds between atoms
- E. I do not know

14. You are observing a very thin slice of a rock (called a "thin section") under the microscope using light that is polarized (vibrating in one direction). There are two polarized rays of light that are vibrating perpendicular to one another. They both enter the same side of the crystal. As you slowly spin the thin section in the light under the microscope, which of the following crystal shapes is most likely to stay black, regardless of which side you look through under the microscope? For similar shapes, side lengths have been described.



E. I do not know

- 15. Refer again to the crystal shapes above. Which of the shapes will never stay black, regardless of its orientation under the microscope?
 - A. Shape A
 - B. Shape B
 - C. Shape C
 - D. Shape D
 - E. I do not know

16. The mineral olivine can vary in composition in between 100% Mg2SiO4 and 100% Fe2SiO4. Imagine there is some liquid olivine at point 'X' on the figure, that has a composition of 70% Fe2SiO4 (30% Mg2SiO4) and a temperature of 2000°C. What will be the composition of the liquid olivine and, if present, any solid olivine, when it is cooled to 1500°C? Report the composition in terms of %Fe2SiO4.



True or False Questions

For each of the following questions there are the formulae of two minerals listed. Decide whether or not a mineralogist would group those two minerals together if they were classifying them. Bubble in "T" on your bubble sheet to indicate true, and "F" on your bubble sheet to indicate false. Bubble in "X" if you do not know.

17. A mineralogist would group the minerals PbSO4 and Cu₅FeS4 together.

- T. True
- F. False
- X. I do not know
- 18. A mineralogist would group the minerals CaF₂ and NaCl together.
 - T. True
 - F. False
 - X. I do not know