MINERALOGY, GEOCHEMISTRY, AND GEOCHRONOLOGY OF THE NORTHERN DANCER TUNGSTEN-MOLYBDENUM DEPOSIT, YUKON AND BRITISH COLUMBIA

by

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Abstract

The Northern Dancer (formerly Logtung) deposit is a low-grade, large-tonnage W-Mo intrusion-hosted porphyry system located on the Yukon-BC border within the central belt of the Yukon-Tanana Terrane. Discovered in 1976, it has an inferred resource estimate of 242 Mt at 0.10% WO₃ and 0.047% MoS₂. Mineralization is developed within late Cretaceous monzonitic granite (109.4 ± 0.9 Ma to 110.5 ± 0.8 Ma), comagmatic crosscutting felsic dikes (111.7 ± 0.7 Ma), and adjacent hornfelsed metasedimentary rocks, which were metamorphosed by early Jurassic diorite plutons (187.7 ± 2.6 Ma) located southwest and northeast of the deposit. The source of the metals is inferred to be the monzonite and felsic dikes. Four spatially overlapping vein types host the majority of mineralization, although minor dissemination occurs in some metasedimentary host rocks. The earliest mineralized veins (Type 1) are quartz-garnet-diopside dominant with accessory molybdoscheelite and fluorite. Crosscutting the Type 1 veins are quartz-feldspar-fluorite veins (Type 2) with accessory scheelite, pyrite, and prominent alteration halos (inner epidote-chlorite and outer hornblende zones). Quartz-epidote veins (Type 3) are generally restricted to the felsic dike system and contain the majority of molybdenite mineralization. Polymetallic sheeted quartz-beryl-scheelite-molybdenite veins (Type 4) which crosscut all earlier veins and most felsite phases can be up to 1 m wide, and continue outside the defined deposit zone. Ore mineral assemblage and scheelite composition varies by vein/host environment; Type 1 veins contain molybdoscheelite only (avg. 4.85 wt.% MoO₃ or 0.09 Mo apfu), Type 2 veins contain purer scheelite (1.13 wt.% MoO₃ or 0.02 Mo apfu), Type 3 veins contain primarily molybdenite ± scheelite (0.73 wt.% MoO₃ or 0.02 Mo apfu), and Type 4 veins contain scheelite ± molybdenite ± beryl (0.92 wt.% MoO₃ or 0.02 Mo apfu). Garnet compositions are intermediate between grossular and andradite end-members in metasedimentary rocks, and are spessartine-rich in felsic intrusive rocks; variations in fluorine content of the fluid may be reflected by F-content in garnet (up to 1.62 wt.% F or 0.39 F apfu). Pyroxene compositions are intermediate between hedenbergite and diopside end-members, and possess temporally evolving Fe²⁺/Fe³⁺ ratios, suggesting changing redox conditions. Whole-rock geochemical and Rietveld analyses suggest that high F content/fluorite abundance correlate with high W content/scheelite abundance.
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1 Introduction

1.1 Location

The Northern Dancer (Logtung) deposit is a low-grade, large-tonnage W-Mo intrusion-hosted porphyry system, located on the Yukon-BC border between Teslin and Watson Lake, near the headwaters of Logjam Creek (UTM coordinates: NAD 83, zone 9, 0355038 E/6654875 N; Fig. 1.1). Northern Dancer has been described as one of the world’s largest tungsten resources, with a historic estimate of 162 million tons grading 0.13% WO₃ and 0.052% MoS₂ (Noble et al. 1984). The deposit corresponds to Yukon MINFILE number 105B 039 (Deklerk and Traynor 2005).

The original mineralized showing found by the Geological Survey of Canada (Canamax 1983, Wengzynowski 2006, Eaton 2007) consisted of blades of wolframite with purple fluorite, tourmaline, cosalite (Pb₂Bi₂S₅), and beryl in a quartz vein cutting quartz monzonite. The main zone found nearby in 1976 was described as scheelite and molybdenite in a multi-stage stockwork vein system developed in a quartz porphyry plug, and disseminated in a vein stockwork cutting garnet-diopside skarn and hornfels peripheral to a fluorite-rich quartz monzonite stock, which intrudes cherty banded argillite and quartzite of Pennsylvanian age (Canamax 1983). Three mineralized zones, called the BC, central and Yukon have been investigated in the past by Noble (1982), Stewart (1983), and Noble et al. (1984, 1986). This study focuses dominantly on the central zone, within the modern resource calculation boundary of the deposit.

W-Mo-Be mineralization (both disseminated and vein-hosted) at Northern Dancer is developed within monzonitic granite, crosscutting felsic dikes, and adjacent hornfelsed country rocks. The latter were thermally metamorphosed by an en echelon set of Early Jurassic diorite plutons that occur southwest and northeast of the Northern Dancer deposit. The source of the metals is thought to be the monzonite and felsic dikes. According to Noble et al. (1984), the mineralization is related to four different quartz vein systems, which vary in their mineralogy, orientation, alteration, and density.

Classification of Northern Dancer has proven problematic since it has characteristics of both W porphyry and Mo skarn deposits. The previous studies suggest that this deposit has
many similarities to classic porphyry Mo deposits and that the skarn minerals are incidental to the W-Mo mineralization, which is almost totally confined to porphyry-style crackle breccia.
1.2 History

Mineralization at the site was first noted by the Geological Survey of Canada in the early 1950's. Early exploration of the area was undertaken by Hudson Bay Exploration and Development Company, Ltd., which concentrated on the Pb-Zn-Ag veins currently known as the Logjam occurrence. Logjam was staked in July 1944 and nine holes were drilled in 1945. Between 1945 and 1967 approximately 2,070 m of drilling and 763 m of underground workings were completed on two levels (Canamax 1983, Wengzynowski 2006). At this time the W-Mo veins to the southwest remained undiscovered. In 1975, Cordilleran Ltd. began active exploration for tungsten in the area, acting for W.M. Bath Investments Ltd., Sicintine Mines Ltd., and several individuals (Abbot 1981c). Tungsten stream sediment anomalies, later traced to scheelite, were located in West Logjam Creek, and the first claims were staked in September 1976. Stream sediment sampling continued, along with geological mapping and rock geochemical surveys, into late 1976. A new company, Logtung Resources Ltd., was created to develop the property.

Amax Potash Ltd. optioned the property in 1977, and subsequently built a road and conducted IP surveys, in addition to continuing with mapping and geochemistry surveys (Harris et al.1981). Fifty-one diamond drill holes (11,628 m) and 496 m of decline and drifts were completed, and a 15,000 tonne bulk sample was collected for preliminary engineering, metallurgical, and environmental studies between 1977 and 1981. Logtung Resources changed its name to Regional Resources Ltd., while W.M. Bath Investments changed to Petromin Resources Corporation in 1982. Amax's interest was transferred to Canamax Resources Inc in 1983 (Eaton 1994).

The Log claims were transferred back to Logtung Resources Ltd. in September 1986, and transferred again in December 1992 to 7188 Yukon Ltd. NDU Resources Ltd entered into an option agreement with Regional Resources Ltd. to obtain a 50% interest in the Yukon portion of the property in June 1993. NDU was required by the agreement to evaluate the gold potential of the deposit and surrounding area over a three year period. Prospecting, soil geochemical surveys, and two diamond drill holes totaling 234 m were completed as part of an exploration program. NDU dropped its option in late 1993 (Eaton 1994).
The claims covering the deposit began to lapse in early 1998. Nordac Resources Ltd. staked the ‘Dansar’ claims, which covered the Yukon side of the deposit, in June 1998. Claims were also staked in British Columbia to cover the southwestern portion of the deposit. Abandoned waste including old fuel drums were removed by the company in 1998 and 2000. Some prospecting was conducted, and in 2000 Nordac evaluated the beryl potential of the property (Eaton 2002).

Additional Dansar claims were staked in March 2001. Nordac Resources Ltd. became Strategic Metals Ltd. in June 2001 after company reorganization. The company began digitizing all previous exploration data, and in September 2001 a brief prospecting program was conducted to verify historical results. At this time more claims were added to the property. Digitizing continued through 2002, and in 2003 the company carried out a small prospecting and hand trenching program (Eaton 2004).

Strategic Metals Ltd. optioned the property to Largo Resources Ltd. in April 2006, with an agreement for Largo to acquire a 100% interest in Northern Dancer with a series of installation payments. A diamond-drill program consisting of 17 twinned and new holes (3,945 m) was completed that summer (Eaton 2007). Largo completed a Mineral Resource estimate for the Northern Dancer deposit, with technical assistance and advice from Snowden Mining Industry Consultants Incorporated (Board & Campbell 2008).

Currently there are 23 contiguous mineral claims in the Yukon and three tenures in British Columbia, for a total area of 1,500 ha. In the summer of 2007, a series of 26 angled drill holes totaling ~8,500 m were added to test higher grade zones within the deposit. On April 2, 2007, Largo announced a NI 43-101 compliant inferred mineral resource of 242.0 million tonnes grading 0.10% WO₃ and 0.047% MoS₂ containing 508.1 million lbs. WO₃ and 151.0 million lbs. Mo confirming Northern Dancer as one of the largest undeveloped W-Mo deposits in the world ((Board & Campbell 2008). This resource includes a higher grade Mo zone of 36.8 million tonnes of 0.085% MoS₂; more drilling is required to define a higher grade W resource.

1.3 Recent field work

Previous field work by the author (prior to undertaking the project as her thesis topic) included a total of five weeks of prospecting, mapping, and surface sampling in 2005 while
working for Archer, Cathro & Associates (1981) Ltd. Field work relating to the thesis began in June 2006; this consisted mostly of core logging in conjunction with Archer, Cathro & Associates (1981) Ltd, for Largo Resources Ltd. Several large samples of related intrusions were collected for purposes of dating and geochemical analysis. A representative sample set of core from the new drill holes was assembled by the author for purposes of geochemical analyses and the mineralogical study. These samples consist of representative lithological units as well as the different vein types. An additional set of samples with inferred high W and Mo content were added to the existing set, which then totaled 52 samples. A follow-up visit to the property took place in August 2007 for final core sampling, and extended mapping of the periphery of the deposit area. Coordination with All-Terrane Mineral Exploration Services for Largo Resources Ltd. took place at this time. In addition, Prof. Robert Linnen of the University of Waterloo visited the property in August 2007, to discuss other applications of the mineralogical study.

1.4 Scope of the thesis

This study examines the timing, geochemistry, and mineral chemistry of the Northern Dancer W-Mo deposit. Questions remain about the age of the mineralizing plutonic rocks, which has been reported as both 117.6 ± 3.5 (Stewart 1983) and 58.0 ± 6.4 Ma (Mihalynuk 2002). Metallurgical issues such as the Mo content of the scheelite, the mineralogical location of fluorine, and distribution of fluorite throughout the deposit will be addressed. This study aims to (1) use modern scientific techniques, such as electron probe microanalysis and quantitative phase analysis using the Rietveld method with X-ray powder diffraction data, to more completely characterize W, Mo, and beryl mineralization at the Northern Dancer deposit, expanding on previous studies that relied largely on petrography; (2) determine the absolute ages of the different intrusive units using more robust U-Pb dating techniques; (3) identify and characterize mineralogical issues affecting the metallurgy and origin of the deposit and (4) classify the different types of mineralization in terms of modern concepts in economic geology. The project is significant because it will lead to a better understanding of this unusual mineral deposit and of the metallogeny of W, Mo, and gem beryl deposits in the Cordillera.
2 Regional Geology

2.1 Regional stratigraphy

The Northern Dancer W-Mo deposit occurs in south-central Yukon at the border with British Columbia, within the Cordilleran Orogen (see Fig. 1.1). The most recent regional bedrock geological mapping for the Yukon map sheet (Dorsey Lake, 105 B/4) was completed in 2004 under the auspices of the Ancient Pacific Margin NATMAP project (YGS Open File 2004-2, Roots et al.; GCS Open File 4630); a project jointly funded by the Geological Survey of Canada, the British Columbia Geological Survey, and the Yukon Geology Program. BCGS open file 2000-6, "Geology of Smart River Area (NTS104O/13)" by Mihalynuk et al. 2000, is the most recent published geological map of the adjoining area on the British Columbian side of the Yukon-BC border, and was completed by Mihalynuk (et al. 2000) of the BCGS. Both maps were completed at a scale of 1:50,000 and were adapted and joined for the purposes of this study, in fig. 2.1. In the last two decades, polydeformed rocks in this region have been analyzed and classification of sedimentary and volcaniclastic rock sequences in the Yukon-Tanana composite terrane has been resolved (Roots et al. 2006). This terrane extends from Alaska to north-central British Columbia, outboard of distal ancestral North America strata and inboard of allochthonous Paleozoic oceanic and Mesozoic island-arc rocks.

The Northern Dancer deposit is located in the central belt of the Yukon-Tanana terrane, which is approximately 40 km wide at the Yukon/BC border, and is bounded on the east by the steeply southwest dipping Hidden Lake fault. On the west the Yukon-Tanana rocks are in contact with the Big Salmon Complex, along what is inferred to be a steep fault as its trace continues for 50 km (Roots et al. 2006). Two main supracrustal assemblages, both with continental characteristics, comprise the majority of the central belt. These are the siliciclastic Devonian-Mississippian Dorsey Complex and the structurally higher Mississippian Swift River Group (SRG) (Roots et al. 2006). These two groups are separated by an ambiguous sheared contact likely caused by competency contrast (Nelson 2001; Roo's et al. 2002), and are unconformably overlain by Permian volcaniclastic rocks of the Klinkit Group (which do not crop out in the vicinity of the Northern Dancer deposit).

Sedimentary host rocks in the Northern Dancer area are part of the carbonaceous and turbiditic SRG (Fig. 2.1). This elastic succession is dominantly basinal in character farther to the
Fig. 2.1. Regional geology of the area around the Northern Dancer deposit (1:50,000), modified from the Yukon Map sheet (Dorsey Lake, 105 B/4) completed in 2004 by the Ancient Pacific Margin NATMAP project (YGS open file 2004-2, Roots et al. 2004; GCS open file 4630) and from BCGS open file 2000-6, Geology of Smart River Area (NTS104O/13) completed by Mihalynuk (et al. 2000) of the BCGS. The Northern Dancer local geology map area is outlined and labeled (see following page for map legend and cross sections).
Fig. 2.1. (cont.). Legend and cross sections accompanying the regional geology map.
east, but suggests proximal sediment sources, or shelf-like conditions are inferred for the package near Northern Dancer (Roots et al. 2006). Regionally, the SRG is characterized by a thick lower unit of chert and argillite punctuated by isolated beds of quartzite, as well as marble and local occurrences of quartz wacke, argillite, and phyllite. The upper Swift River Group near Northern Dancer comprises thicker beds of phyllite, quartz wacke, and quartz-plagioclase grit, with thin limestone layers (Nelson 2001). A lack of distinctive, mappable lithologies within the SRG and the ambiguity of its lower contact with the Dorsey Complex prevent detailed stratigraphical classification; however, the SRG can be generally distinguished from the Dorsey Complex by its lack of strong foliation or ductile fabrics (Roots et al. 2002, 2006).

Results from the NATMAP project show the Northern Dancer area is in places overlain unconformably by the Late Triassic Logjam formation, which consists of thin bedded clastic rocks with minor chert and limestone. One isolated outcrop of dark limestone within the deposit boundary resembles that which yielded Lower Carnian conodonts 4 km to the northwest, however none were found within a 1 kg sample processed recently by C. Roots of the YGS (pers. comm. 2008).

2.2 Regional plutonic rocks

Plutonic rocks of Early to mid-Cretaceous age are widespread in the Cassiar Terrane of the southeastern and south-central Yukon. Most have been assigned to the Cassiar Plutonic Suite (Fig. 2.2; Mortensen et al. 2007) or the Anvil-Hyland-Cassiar Belt (Hart 2004; Hart et al. 2004). These plutons display a range of lithological and geochemical compositions, isotopic ages, and metallogenic signatures which suggest that more than one plutonic suite is present (Liverton and Alderton 1994; Driver et al. 2000; Liverton and Botelho 2001; Liverton et al. 2001, 2005). The most recent geochronological studies employed U-Pb dating of zircons and monazites (Stevens et al. 1993; Liverton et al. 2005; Mortensen et al. 2006) and demonstrated that most plutonic rocks in the area were emplaced between 115 and 97 Ma. Renewed interest in intrusion-hosted mineralization within the Cassiar terrane prompted a recent dating study (Mortensen et al. 2007) which included some intrusions in the Northern Dancer area. That study focused on constraining
the ages, metallogenic associations, and paleotectonic settings of various plutonic rocks of the Cassiar Terrane (geochronological data obtained for the Northern Dancer area intrusives is reviewed and reported in section 5: Geochronology.)

To the north and northwest of the Northern Dancer area are the Thirtymile and Ork Stocks, the Hake Batholith, and the Seagull Batholith, which have been described as a ‘sub-suite’ of Cassiar intrusions. All are post-tectonic, highly fractionated, metaluminous to weakly peraluminous one-mica granites. The Hake Batholith was dated using Rb-Sr methods and found
to be 98.3 ± 2.9 Ma (Liverton et al. 2001). Recent U-Pb dating employing laser ablation ICP-MS methods of a porphyritic section of the Thirtymile Stock produced an age of 102.7 ± 1.1 Ma (Mortensen et al. 2007). Samples of aplitic biotite granite and megacrystic biotite granite from the Seagull Batholith give U-Pb zircon ages of 99.3 ± 2.2 Ma and 95.7 ± 2.1 Ma, respectively, using LA-ICP-MS methods (Mortensen et al. 2006).

It has been suggested that the Seagull batholith is akin to the Tungsten plutonic suite of eastern Yukon and southwestern Northwest Territories (Mortensen et al. 2000; Hart et al. 2004) based on the correlation of their U-Pb ages. Isotopic ages that have been obtained thus far for the Seagull batholith overlap with ages obtained for various intrusions of the Tungsten suite (Mortensen et al. 2000; Hart 2004).

2.3 Regional mineral occurrences

Late Cretaceous and Early Tertiary monzonitic porphyries containing W-Mo, and more commonly Mo ± W mineralization are found in British Columbia and Yukon. Most have been dated using K-Ar techniques, and none but Northern Dancer are known to have been dated by the more robust U-Pb technique (Mihalynuk 2001). Representatives of this type of deposits have an association with intrusions in the 60-87 Ma age range. For example, Red Mountain, 150 km along strike to the northwest of Northern Dancer, is a Mo deposit with calculated resources of 18,270,000 tonnes grading 0.167% MoS₂ (Brown and Kahlert 1995). Minor W mineralization is associated with late mineralized porphyries, and hydrothermal biotite (occurring with molybdenite) was dated using K-Ar methods as 87.3 ± 2.0 Ma according to W.D. Sinclair (Brown and Kahlert 1995).

A polyphase, dominantly porphyritic stock at the Adanac (Ruby Creek) deposit about 100 km southwest of Northern Dancer, contains quartz veins with disseminated molybdenite and occasionally contains traces of scheelite ± fluorite. Ages on four of the quartz monzonite phases range from 70.3 ± 2.4 to 71.6 ± 2.1 Ma (Christopher and Pinsent 1982). At the Glacier Gulch deposit (Hudson Bay Mountain) in northwest-central BC, Mo-W fracture and vein-dominated porphyry mineralization occurs with a quartz monzonite-granodiorite stock and comagmatic radial porphyry dike swarm (Bright and Johnson 1978; Mihalynuk 2001). Biotite from the stock dated using K-Ar has returned ages of 67 ± 5 (Kirkham 1966) and 73.3 ± 3.4 Ma (Carter 1974); with an age of 60 ± 5 (Kirkham 1966) for the porphyry dikes.
At Trout Lake in southeastern BC, Mo ± W mineralization is hosted in the Lower Paleozoic Lardeau Group, which is comprised of pelitic quartzite, marble, calcareous phyllite and quartzite, and metavolcanic rocks. These host rocks are similar to lithologies hosting mineralization near the Logtung monzogranite stock (Mihalynuk 2002). Mineralization at Trout Lake is attributed to the nearby 76 Ma (Boyle and Leitch 1983) granodiorite-tonalite intrusion. Resources are reported as 49 Mt grading 0.19% MoS₂ (Linnen et al. 1995) and tungsten production was recorded in 1942.

Pluto, a Yukon Minfile drilled prospect (116C 134), is another porphyry-Mo occurrence in the Yukon, in the same offset rocks of the Yukon-Tananat terrane which host Northern Dancer’s mineralization, southwest of the Tintina Fault, close to Dawson City. Tungsten mineralization exists in the form of wolframite, found in quartz veins along with pyrite and molybdenite; however the causative intrusion is younger than the Logtung monzogranite, at 59.4 Ma (Yukon MINFILE).

More locally, areas around Southern Wolf Lake (105B), southeastern Teslin (105C), and northern Jennings River (1040) map areas contain a range of mineral occurrences, including carbonate replacement deposits, skarns, greisens and veins, in addition to several apparently stratiform occurrences interpreted to be syngenetic in origin (Mortensen et al. 2002).

It is important to note that Northern Dancer lies on the opposite side of the Tintina strike-slip fault from the large, well-known W-skarn deposits such as Mactung, Cantung, Clea, and Lened (Dawson and Dick 1978). Approximately 430 km of dextral movement occurred along the fault in Late Cretaceous/ early Tertiary time, which post-dates mineralization at these locales (Gabrielse et al. 2006).
3 Local Geology

3.1 Overview

Noble et al. (1984) recognized three main metasedimentary host lithologies at Northern Dancer: biotite quartzite/hornfels, garnet-pyroxene calc-silicate, and wollastonite vesuvianite skarn. These three main host lithologies were expanded for the logging of drill core based on mineralogy, texture, and veining. Logging of new core led to reorganization of lithologies and discarding of some old unit terms for the sake of simplicity. Metasedimentary units described below reflect these changes but retain the three main metasedimentary host rock types from Noble et al. 1984. The three main intrusive units (diorite, monzonite, and felsic dikes) may also host mineralization to a lesser degree, and distinct units within these three rock types are distinguished where significant variation in textural or mineralogical character occurs. Basic geology at surface is shown in Fig 3.1. The outline of the local geology map area is outlined on the regional geology map (Fig. 2.1). The representative sample set compiled for the mineralogical study was chosen based on these lithologies.

The most unaltered metasedimentary units near Northern Dancer were described by Noble et al. (1984) as ~4 to 15 cm wide blocky graphitic quartzite layers alternating with ~5 to 50 cm thick bands of thin-bedded calcareous shale. These rocks are the precursors to the reaction skarns described below, which host the majority of mineralization. Recent mapping found the nearest relatively unaltered host rocks to the northeast of Logtung ridge, slightly east of the Logjam occurrence. These rocks are highly deformed but do not appear to have been subjected to metasomatism or skarnification. They consist of rocks similar to those described by Noble et al. (1984), but also include marble units and gritty carbonate layers, and likely correspond to the marble and quartz-plagioclase grit units of the Swift River group described most recently by Roots et al. (2006).

Unit ‘SDq1’ on the regional geology map (Fig. 2.1) outcrops on two ridges to the southeast of the deposit, and is described as pale-green-grey to white arenite with a calcareous matrix and abundant limey layers; this unit likely corresponds to what Noble et al. (1982) termed ‘marble.’ These units lie on the unmineralized east side of Logjam Creek, at least 2 km from the
Fig. 3.1. Local geology map of the Northern Dancer area. Shown are the geochronology sample sites (purple squares), the original claim boundary (orange solid line), the provincial/territorial border (red dotted line), interpreted faults (red dashed line), the historical deposit boundary (orange dash), and the general limit of mineralization (light blue line). (Modified from Noble et al. 1984)
closest mineralization at surface, and therefore were not sampled for the representative mineralogical sample set.

**3.2 Intrusive rocks at Northern Dancer**

**3.2.1 Diorite**

The oldest intrusion in the Northern Dancer area is a zoned diorite which grades to granodiorite locally, and predates mineralization (Fig. 3.2, a). These rocks correspond to the ‘eJd’ (diorite) and ‘eJg’ (granodiorite) units defined by Roots et al. (2006) on the regional map (see Fig. 2.1). Two elongate diorite limbs trending northwest-southeast, each approximately 0.5 x 1 km, intrude the metasedimentary country rocks to the northeast and southwest of the main monzogranite body and felsic dike complex. The granodiorite unit outcrops further to the northwest, and thus does not interact with the felsic dike complex and mineralizing veins to a significant degree (see Fig. 2.1). Primary mineralogy consists of hornblende and/or clinopyroxene, calcic plagioclase, with minor quartz, Ti-rich biotite, and K-feldspar (Fig. 3.2, b,c). In polished section, plagioclase alters to potassium feldspar, clinopyroxene alters to hornblende, and biotite alters to chlorite and potassium feldspar. In places, textures can become porphyritic with hornblende phenocrysts up to 8 mm, but the main diorite is dominantly heterogeneous and equigranular, with an average grain size of 1-2 mm. Accessory minerals include fine-grainedapatite, which has a higher Cl content than other apatite at Northern Dancer (according to EDS spectra obtained on the SEM – see Apatite section), titanite, garnet, zircon, pyrrhotite and rutile. Titanite occurs at the boundary of intergrown biotite and garnet, as inclusions in potassium feldspar, and also rims apatite inclusions in biotite. Pyrrhotite occurs as rare inclusions in clinopyroxene. Disseminated sulphides (including molybdenite and chalcopyrite) have also been observed within diorite near the contact with metasedimentary host rocks, at surface and in drill core. Diorite dikes have been noted in recent drill core, although they are not prominent at surface. Altered diorite occurs near the contact with metasedimentary rocks, and where wide alteration haloes overlap. These areas are typically higher in chlorite, apatite, titanite, pyrite, chalcopyrite, fluorite and clinopyroxene.

A ‘sporadic aureole’ consisting of early reaction skarns is associated with this unit, which was described as extending up to 30 m from the contacts (Noble et al. 1984), although it is
Fig 3.2. Intrusive Rocks at Northern Dancer. (a) Hand sample of diorite containing hornblende phenocrysts ~0.5-0.8 mm across in a biotite-quartz-feldspar matrix (sample location: AL-06-03, see Fig. 3.1). (b) Polished section scan in plane polarized light of hornblende diorite. (c) Same section of hornblende diorite as ‘b’ in crossed polars. (d) Hand sample of the Logtung monzonite containing quartz phenocrysts up to 4.8 mm, large relict k-feldspar phenocrysts rimmed by fine-grained plagioclase (Na-rich), and biotite (sample location: AL-06-04, see Fig. 3.1). (e) Polished section scan of monzonite in plane polarized light. (f) Same section as ‘e’ in crossed polars. (g) Hand sample of quartz-feldspar porphyry from the felsic dike complex, containing smoky quartz phenocrysts up to 3.5 mm in a fine-grained quartz-feldspar matrix, crosscut by Type 3 ‘quartz-molybdenite’ veins (sample location: AL-06-06, see Fig. 3.1). (h) Polished section scan of quartz-feldspar porphyry in plane polarized light. Molybdenite is visible in the quartz vein crossing the centre of the image. (i) Same section as ‘h’ in crossed polars. (j) Hand sample of ribbon-banded quartz-feldspar porphyry or ‘brain rock.’ (k) Polished section scan of ribbon-banded quartz-feldspar porphyry or ‘brain rock’ in plane polarized light. Some layers contain pyrite, molybdenite, muscovite, and scheelite. (l) Same section as ‘k’ in crossed polars.
possible that much of the calc-silicate rock (reaction skarn) was produced by metasomatism fueled by the diorite. The short time period in which the monzonite, comagmatic felsic dikes, and veins were likely emplaced (see section 5: Geochronology), indicates that there may not have been sufficient time for the large volume of calc-silicate and hornfels, which hosts the deposit, to form. It is reasonable to hypothesize that the two large diorite bodies were responsible for the majority of calc-silicate alteration in the metasedimentary rocks between them, as this would allow sufficient time for skarn development before emplacement of the felsic intrusive and mineralized vein sets. Existing, permeable, brittle (yet low porosity) calc-silicate/hornfels reaction skarn would then provide a reasonable host rock for many overprinting stockwork and sheeted vein sets to occur (as observed at Northern Dancer), versus an initial slow, disseminated skarn-type mineralization phase followed by later vein sets (see Alteration Events, below).

3.2.2 Monzonite

The main intrusive body associated with the felsic dike system and W-Mo mineralization is a biotite monzogranite stock (Fig. 3.2, d). This corresponds to the ‘Logtung stock’, or ‘eEgd’ unit defined by Roots et al. (2006), on the regional map, and is approximately 2 x 0.5 x 1 km in area (see Fig. 2.1). The slightly elongate monzogranite dips ~45° in a northwest direction below the felsic dike system. Dikes connecting to the monzonite are visible at surface on ridges southwest of the main deposit, and are similar mineralogically to the felsic dike complex and associated Type 4 veins. The monzonite was originally characterized by Stewart (1983) who reported high silica content (74.6 – 77.5% SiO₂), 3% modal biotite, a molar Al₂O₃ / (Na₂O + K₂O + CaO) ratio of 1.00, and maximum W and Mo contents of 510 ppm and 235 ppm respectively (see section 6: Whole-rock geochemistry). Dominantly quartz (with less common potassium feldspar) phenocrysts occur within a finer-grained matrix of biotite, Na-K feldspars, and quartz.

Accessory minerals include fluorite, garnet, beryl, apatite, scheelite, ilmenite, pyrite, zircon, allanite and very rare black tourmaline (Fig. 3.2, e,f). Porphyritic textures dominate throughout the body, however there is a fine-grained (1-5 mm) contact phase up to 90 m across, and satellite dikes associated with the intrusion are (rarely) pegmatitic (Noble et al. 1984). Hydrothermal alteration is variable in intensity throughout the monzogranite stock, and consists of feldspar replacement by sericite, calcite and fluorite, and scheelite and biotite replacement by
chlorite. In polished section, fine-grained k-feldspar and albite are intergrown with fluorite. Biotite is Ti-Mn rich and is commonly associated with fine-grained apatite (which can be zoned due to REE content), ilmenite, rutile and zircon. Apatite and ilmenite also occur as inclusions within biotite. Rare monazite and xenotime occur, as well as occasional Nb-rich scheelite intergrown with rutile. These rarer accessory minerals are commonly zoned based on REE content, as seen in backscatter mode on the SEM.

3.2.3 Felsic porphyry dike system

W-Mo mineralization is most intense and centered on the felsic dike system which is inferred to be associated with the monzogranite stock (Fig. 3.2, g). The system consists of an irregularly shaped bi-lobate intrusion approximately 500 m across, which outcrops on both sides of the NE-SW trending Logtung Ridge (a topographical high between the two diorite limbs). Satellite dikes extend out from the main complex, and range in size many metres across down to aplite dikes a few cm wide. Regional mapping (Roots et al. 2006) interprets the felsic dike complex as part of the monzonite (see Fig 2.1). The felsite is porphyritic, with high SiO₂ contents (75.1-76.7 wt. %) as reported by Stewart (1983), and W/Mo values similar to the monzogranite (see Whole-rock geochemistry). Quartz, plagioclase, potassium feldspar, and spessartine garnet phenocrysts (all up to 1.5 mm) are set in a fine-grained felsite groundmass (of the same general mineralogy) of variable grain-size (~0.06-0.09 mm). Porphyritic phases are generally identified as ‘quartz-feldspar porphyry’ or ‘quartz-porphyry’, while felsic intrusive with homogenous texture is referred to as ‘felsite.’ Typically, smoky quartz phenocrysts are dominant; feldspar and garnet phenocrysts are much rarer, with feldspar usually located in the matrix (Fig. 3.2, h,i). Accessory apatite, fluorite, pyrite and rutile are occasionally noted in the felsic dikes.

Ribbon-banded material (or ‘brainrock’) consisting of alternating layers (1-4 mm thick) of quartz, feldspar, apatite needles, and blue beryl occasionally develops in the main felsite body (Fig. 3.2, j). Noble et al. (1984) likened this unit to the ‘crenulate quartz-layered rock’ in the Henderson Deposit (White et al. 1981) These intervals of ‘brain rock’ can be short (a few cm) or comprise large areas up to 15 m in drill core. Ribbon-banded quartz-feldspar porphyry or ‘brain rock’ can also contain layers of pyrite, molybdenite, muscovite and scheelite (Fig. 3.2, k,l). Occasionally these ‘brain rock’ layers appear to grade into thick Type 4 veins, both within the
main felsic dike complex and outboard of it, in metasedimentary rocks. These transitional zones are commonly very silica-rich with occasional large pods of massive sulphide. Where these zones intersect small fractures in the host rock, very thin veins of solid massive blue beryl or of purple fluorite can occur. The existence of these rocks suggests that late felsic dikes are mineralogically and texturally transitional with Type 4 veins, possibly forming under a continuum of magmatic hydrothermal conditions (Candela 1997).

Areas of coarsely crystalline, mono-mineralic massive quartz also occur, especially near zones of 'brain rock', as seen at surface in outcrop along Logtung Ridge; these areas are termed 'quartz flooding' by this study, and may represent silica alteration. The felsic dike system is crosscut by a system of thin (~1-3 mm) quartz-molybdenite (Type 3) veins, as well as the later-stage polymetallic sheeted (Type 4) vein set. In places, the felsite is fractured, with pyrite and molybdenite infilling. A contact aureole ~70 m wide, as described by Noble et al. (1984), affects the reaction skarns intruded by the felsite (see below).

At least two phases of felsite are present, as noted by Noble et al. (1984), and cross-cutting phases are commonly seen in drill core on the scale of cm to many meters. Typically, aplitic or finer-grained phases are crosscut by more coarse-grained or porphyritic phases, but the reverse may also occur, and the massive silica zones described above may crosscut all felsic phases, suggesting late silica alteration. Complex cross-cutting relations of this nature are common at the contact regions of the felsic dike system, especially at the inferred higher levels of the deposit.

Contact zones between felsic dikes and diorite, where they occur, appear to be subject to hydrothermal brecciation, in which angular pieces of diorite are found within fine-grained felsite matrix. In these environments, diorite clasts are almost completely altered to biotite-chlorite assemblages with disseminated pyrrhotite/pyrite. Where diorite clasts comprise the majority of rock, sulphides (dominantly pyrrhotite) may occur as fine-grained masses or blebs between fragments of diorite.

3.3 Alteration events

Alteration events and their affect on the metasedimentary rocks exert influence over the character of mineralization at Northern Dancer, since these are the dominant host lithologies of the mineralized veins. Therefore, their physical and chemical properties are important to
consider when studying the controls on metal deposition. Noble et al. (1984) delineated three major alteration events: (1) hornfels and reaction skarn associated with the intrusion of the diorite; (2) a reaction skarn aureole surrounding the monzogranite stock; and (3) recrystallized reaction skarns associated with the felsic dike complex. A ‘reaction skarn’ is considered to be a metamorphic rock which forms in response to local exchange of chemical components between lithologies with incompatible mineral assemblages in response to thermal metamorphism (Joesten 1977; Einaudi and Burt 1982). Noble et al. (1984) describes these reaction skarns as ‘early, partially obliterated aureoles’ of coarse-grained (0.5-1.0 mm) biotite quartzite containing disseminated sulphides such as pyrrhotite and chalcopyrite, and predate mineralizing events.

Noble et al. (1984) also describes reaction skarns occurring with the intrusion of the monzogranite, in a radius of approximately 1000 m from the contact of the stock. They consist of calc-silicate bands or zones, with garnet-pyroxene as primary minerals, and correspond to the calc-silicate unit described below. Biotite quartzite units of finer-grained texture corresponding to the hornfels unit described below, as well as wollastonite-vesuvianite skarn, was also attributed to alteration associated with the monzogranite. However, as mentioned above, the recent discovery that the monzonite and felsic dike complex (responsible for the vein sets) are comagmatic (see section 5: Geochronology) suggests there may not be sufficient time for this volume of calc-silicate to form and cool to a brittle state before the vein sets could form stockworks within them. The calc-silicate alteration, seen so extensively through the system, may thus be a result of metasomatism initiated by the diorite intrusives. However more study, involving a spatially systematic examination of drill core from all parts of the deposit, would be needed to test this hypothesis, and thus Noble et al.'s (1984) observations of a monzonite aureole are still valid.

As described by Noble et al. (1984), an alteration aureole surrounding the felsic dike complex extends approximately 70 m into the host metasedimentary rocks, superimposing new reaction skarns over existing ones. This alteration event is characterized by massive, recrystallized units with conchoidal fracture, which can be fine-grained and contain no foliation (Noble 1982); this rock corresponds to the ‘silicified calc-silicate,’ observed by this study (see below). An important note is that the earliest mineralized vein set is itself crosscut and recrystallized by this last aureole associated with the felsic dikes. This confirms that the felsic dikes post-date the monzogranite, and also that the earliest mineralization at Northern Dancer is associated with the monzogranite stock (Noble 1982).
3.4 Metasedimentary rocks

The alteration events described above give rise to several types of metasedimentary rocks in the deposit, all of which have been mapped regionally as the Swift River Group (or ‘PSR’ unit defined by Roots et al. 2006; see regional map: Fig. 2.1). The most volumetrically important unit is calc-silicate, which is typically garnet (grossular-andradite, or ‘grandite’)-pyroxene (diopside-hedenbergite)-quartz ± plagioclase, chlorite, epidote, potassium feldspar and fluorite (Fig. 3.3, a-c). Accessory minerals include pyrite, pyrrhotite, scheelite, molybdenite, chalcopyrite, calcite, rutile, apatite, titanite, wollastonite and biotite. Many variations occur in different locations within the deposit, such as garnet-dominant, pyroxene-dominant, garnet + sulphide-rich, fine-grained diopside-rich ‘light green skarn’, and silicified calc-silicate (described above as the product of the aureole around the felsic dike complex; see Fig. 3.3, d-f). Textures vary from coarse to extremely fine-grained, and may include symplectic intergrowth (see section 8.2.16: Garnet). The overprinting nature of the veins, alteration, and dikes make it difficult to easily detect any zonation pattern based on skarn mineralogy.

Hornfels, or ‘biotite quartzite’ as defined by Noble et al. (1984), is also quite variable in lithologic character, and extends far outside the deposit boundaries. It is usually very fine-grained relative to the calc-silicate, and consists of plagioclase, quartz, and potassium feldspar ± biotite, chlorite, fluorite, calcite, titanite, apatite, pyroxene, and garnet (Fig. 3.3, g-i). Usually it also contains fine-grained, disseminated sulphides (usually pyrite or pyrrhotite, but also chalcopyrite in the vicinity of the diorite contact). These disseminations give rise to its rusty appearance at surface. It can be difficult to distinguish hornfels and calc-silicate in outcrop as they are gradational; the two units are separated based on their dominant mineralogy and texture, which is likely influenced by the original protolith composition, especially original Ca-content. Original protoliths, however, are likely gradational, as described in Regional Geology. In some areas, where hornfels is adjacent to felsic dikes or veins, bleaching may occur, giving the rock a grayish-white and sometimes purple appearance. This occurs in particularly fine-grained hornfels lacking sulphide dissemination.

Wollastonite-vesuvianite skarn, as observed by Noble et al. (1984), occurs in minor quantities distal to the deposit core, as is usually the case in skarn systems (Fig. 3.3, j). This fine-grained unit marks the extent of the reaction skarn alteration at Northern Dancer, but not necessarily the limit of mineralization; Type 4 veins extend far beyond this boundary, and Type
Fig. 3.3. Metasedimentary Rocks at Northern Dancer. (a) Hand sample of typical calc-silicate rock (garnet-pyroxene skarn) containing pink-brown grandite garnet and green clinopyroxene (diopside-hedenbergite), minor quartz, feldspar, chlorite, fluorite, and epidote. (b) Polished section scan of calc-silicate in plane-polarized light. A reaction front of epidote-plagioclase altering garnet-pyroxene skarn is visible in the bottom left corner. Original isoclinal fold structure is visible in the top right corner. (c) Same section as ‘b’ in crossed polars. (d) Hand sample of silicified calc-silicate, containing folia (reflecting original bedding) of pink-brown grandite garnet and green diopside between siliceous layers, crosscut by a chlorite-rimmed, feldspar-rich skarn vein. (e) Polished section scan in plane polarized light, showing garnet-pyroxene-quartz layers. (f) Same section as ‘e’ in crossed polars. (g) Hand sample of fine-grained, purple-brown hornfels (biotite-quartzite) crosscut by thin skarn veins which cause local bleaching of the host rock. (h) Polished section scan of the same hornfels in plane-polarized light, showing the extremely fine-grained nature of hornfels within the deposit. (i) Same section as ‘h’ in crossed polars. (j) Hand sample of wollastonite-vesuvianite skarn, containing fine-grained white wollastonite, green diopside, and euhedral grains of vesuvianite. Early, garnet-rich Type 1 ‘molybdochelleite’ stockwork veins are crosscut by a late barren quartz vein which likely follows visible original bedding layers. (k) Polished section scan of fine-grained wollastonite-vesuvianite skarn in plane polarized light. Coarse-grained garnet alteration haloes are visible around earlier skarn veins, which are then crosscut by a later, thicker quartz vein. (l) Same section as ‘k’ in crossed polars.
1 and 2 veins are seen occasionally within this unit (see Vein Types). Mineralogy is primarily wollastonite-vesuvianite-diopside, but small amounts of calcite, quartz, garnet and fluorite were also observed on the SEM (Fig. 3.3, k,l). Representative sections cut from this unit unfortunately did not intersect well-developed vesuvianite, thus no EPMA analyses could be obtained from this mineral, however it was observed in drill core where it displays a brownish-red rectangular morphology in a fine-grained, white-wollastonite + green-diopside matrix (Fig. 3.3, j). Layering is especially prominent in this unit, likely due to its low degree of alteration, allowing original protolith structure to remain intact.

The high calcic contents of these metasedimentary rocks make them good hosts for scheelite mineralization (skarn-hosted or vein-hosted). Layering, if present, can vary from 1 to 20 cm thick, in some areas possibly corresponding to the structure or lithologic variation of the original protolith. Noble et al. (1984) identified foliation in the reaction skarn, defined by aligned lens-shaped quartz and porphyroblast minerals, parallel layering of diopside and garnet (which is sometimes silicified between layers – see Fig. 3.3, d), and biotite flakes in biotite quartzite. Variations in permeability inherent in protolith may give rise to weaker fluid pathways in some layers, as well as resistant layers (see Fig 3.3).

Isoclinal folding of the metasedimentary rocks has been historically noted by Noble (1982) and Noble et al. (1984), and in places structural measurements were reported (relict folding structure is visible in Fig 3.3, b,c). Noble et al. (1984) reported that two sets of folds were identified from the mapping of the decline at Northern Dancer (pers. comm. to Noble et al. 1984, by S. Parry, 1981). Parry suggested that an early set of isoclinal recumbent folds, with axial planar cleavages parallel to bedding, were dominant. Bedding was described as generally striking northeast, with dips of 0-40° southwest and northeast. Open flexures superimposed on the earlier isoclinal folds were also observed. However, an overall trend of NW-SE, similar to the elongation direction of the diorite intrusions, is mapped in several locations around the deposit on the regional map compiled by the NATMAP project (Roots et al. 2006; see Fig. 2.1). The degree to which most rocks have been altered and overprinted by intrusions, alteration haloes, and overlapping veins makes it difficult to accurately and systematically map original folding structure (which itself may be complex). This may explain the lack of consistent original structure data for metasedimentary rocks at Northern Dancer.
4 Vein Sets

4.1 Overview of vein types

Noble et al. (1984) used petrography, hand samples and drill core to define four mineralized vein sets and four unmineralized vein types at Northern Dancer. This study found that this classification is valid and the descriptions below expand and refine the original classification using optical microscopy and the scanning electron microscope (SEM). These descriptions are not limited to the representative sample set obtained for the mineralogical study, but are also based on larger-scale observation via drill core logging, outcrop, and hand sample analysis of new drill core obtained by Largo Resources Ltd. in 2006 and 2007. Vein types are separated into mineralized and unmineralized types, and thereafter arranged temporally. Table 4.1 summarizes mineral components, style, geometry, distribution, paragenesis, and wallrock alteration characteristics of each of the four mineralized vein types, and lists mineral name abbreviations.

4.2 Mineralized vein types

4.2.1 Type 1: quartz-molybdoscheelite veins

Type 1 veins are thin, between 0.5 and 4 mm wide, and occur in a random three-dimensional stockwork (or “crackle breccia”) or as “hairline breaks” connecting discrete molybdoscheelite grains up to 1 mm in diameter (Noble et al. 1984). In well-developed zones of Type 1 veining, they may occur at a frequency of one vein every 1-4 cm (Fig. 4.1, a-d). Type 1 mineralization occurs up to 1.5 km away from the western margin of the Logtung monzogranite, but is most well-developed in calc-silicate host rocks at the north end of the stock, near the felsic dike complex. Type 1 veins are susceptible to reopening and/or overprinting by later veins types, especially Type 2 and 4 veins, which can result in the chemical zonation of some ore and gangue minerals, e.g., scheelite and garnet (Fig. 4.1, e,f; see section 8: Mineralogy).

Principle minerals include quartz, pyroxene (diopside-hedenbergite), and garnet (grossular-andradite, or ‘grandite’), giving rise to a characteristic pink and green colour which
### Table 4.1. Summary of vein characteristics at Northern Dancer. Abbreviations for mineral phases are listed beside their name. (mcsv = muscovite, qtz = quartz, WR = wallrock, y = mineral present, CS = calc-silicate, MS = metasedimentary rocks)

<table>
<thead>
<tr>
<th>Mineralogy</th>
<th>1 (QzMoSch)</th>
<th>2 (QzPySch)</th>
<th>3 (QzMo)</th>
<th>4 (polymet.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenoscheelite (msch)</td>
<td>y</td>
<td>minor</td>
<td>y + rimmed by moly (+ minor WR)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Scheelite (sch)</td>
<td>dominant</td>
<td>sparse</td>
<td>y (along walls, rimming sch, WR)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Molybdenite (moly)</td>
<td>y + WR</td>
<td>y + WR</td>
<td>y + WR (in felsite)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Pyrite (pyr)</td>
<td>y</td>
<td>y + WR</td>
<td>y + WR (in felsite)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Pyrrhotite (po)</td>
<td>y</td>
<td>y + WR</td>
<td>y + WR (in felsite)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Chalcopyrite (cpy)</td>
<td>y</td>
<td>accessory</td>
<td>y + WR (in felsite)</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Sphalerite (sph)</td>
<td>accessory</td>
<td>accessory</td>
<td>access., in felsite</td>
<td>y + WR (in felsite)</td>
</tr>
<tr>
<td>Bismuthinite</td>
<td>accessory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (gal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diopside (diop)</td>
<td>y</td>
<td>accessory</td>
<td>y (in CS.)</td>
<td>WR (in MS)</td>
</tr>
<tr>
<td>Garnet (gar)</td>
<td>y</td>
<td>accessory</td>
<td>y (in CS.)</td>
<td></td>
</tr>
<tr>
<td>Feldspars (ksp/plag)</td>
<td>accessory</td>
<td>y, orthoclase access.</td>
<td>accessory in felsite</td>
<td>y</td>
</tr>
<tr>
<td>Beryl (ber)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hornblende (amph/hbld)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epidote (ep)</td>
<td>accessory</td>
<td>y</td>
<td>y (in MS)</td>
<td>accessory</td>
</tr>
<tr>
<td>Clinozoisite (clz)</td>
<td>y</td>
<td>y</td>
<td>y (in MS)</td>
<td></td>
</tr>
<tr>
<td>Fluorite (fluo)</td>
<td>accessory</td>
<td>anhedral</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>Calcite (cc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biotite (biot)</td>
<td>accessory</td>
<td>y, accessory</td>
<td>y (in CS)</td>
<td>y + WR (in MS)</td>
</tr>
<tr>
<td>Chlorite (chl)</td>
<td>accessory</td>
<td>y + WR</td>
<td>y (in CS)</td>
<td>accessory</td>
</tr>
<tr>
<td>Sericite (sc)</td>
<td>y</td>
<td>mcsv, access.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rutile (rut)</td>
<td></td>
<td></td>
<td></td>
<td>accessory in felsite</td>
</tr>
</tbody>
</table>

### Wallrock Alteration

- Poorly developed; some bleaching
- Best developed @ N-flank of monzonite up to 1.5 km from W-flank
- 70 m wide stockwork annulus around felsite (dominantly within 20m)
- Restricted to stockwork in felsite, locally in country rock up to 5 m from felsite contact
- Extend laterally + vertically beyond deposit limit, fracture system 046°-088°

### Distribution

- Thin, ~0.5-4 mm
- Thin, 1-2 mm wide, prominent alteration haloes
- Fracture (0.1 mm) to vein (avg. 1-3 mm)
- 1 cm - 1 m

### Geometry

- Random, 3D stockwork, 'crackle breccia'
- Random, typical stockwork, can become sheeted near felsite contact
- Felsite crosscut by random veins, can be sheeted (only random in MS)
- Sheeted, 1 per 2-5 m

### Style

- Earliest, coeval with monzonite
- Coeval with monzonite, crosscut by {3}
- Coeval with felsite, crosscuts {2}
- Latest stage, cuts {1},{2},{3}
Fig. 4.1. Examples of Type 1 ‘molybdoscheelite’ veins at Northern Dancer. (a) Hand sample showing frequent, high-density, thin, garnet-rich Type 1 veins crosscut wollastonite-vesuvianite skarn. (b) Hand sample showing a relatively thick Type 1 vein with a garnet and green diopside-hedenbergite core and diopside-chlorite rim crosscuts hornfels, and is offset by later, thin Type 2 quartz-pyrite-scheelite veins with very thin pyroxene alteration envelopes. (c) Polished section scan in plane-polarized light of stockwork Type 1 veins crosscutting fine-grained calc-silicate with siliceous layers. (d) Same section as ‘c’ in crossed polars. (e) Polished section scan in plane-polarized light of Type 1 vein in hornfels, which has likely been reopened by a later vein. (f) Same section as ‘e’ in crossed polars.
aids in identification of this vein type (Fig. 4.1, b). The garnet is occasionally zoned with
anhedral rims (suggesting resorption) and euhedral growth zones in cores. Accessory minerals
include fine-grained epidote, chlorite, fluorite, plagioclase, titanite, calcite, biotite, and K-
feldspar. Minor sulphide minerals include pyrite, which occurs as small anhedral blebs or fine-
grained aggregates, and more rarely, anhedral, fine-grained pyrrhotite and chalcopyrite.
Occasionally, Type 1 veins occur as thin, simple quartz-garnet fractures less than 0.5 mm thick
in wollastonite-vesuvianite skarn, and more rarely in calc-silicate and hornfels. The principal ore
mineral in Type 1 veins is molybdoscheelite, which can occur at vein walls, as discreet grains
less than 1 mm in size, or coating fractures, and is easily identified by its pale yellow
fluorescence under shortwave ultraviolet light. Wallrock alteration is limited to minor bleaching
of host calc-silicate or hornfels.

4.2.2 Type 2: quartz-pyrite-scheelite veins

Type 2 veins are generally 1-2 mm wide, with prominent pale-green inner and dark-green
outer alteration halos 2-4 mm wide; however, Type 2 veins can be as wide as 6 mm with halos
up to 3 cm in width (these larger veins usually occur in calc-silicate rock near the monzogranite
or felsic dikes). Type 2 mineralization is characterized as random, “typical-porphyry style
(three-dimensional stockwork)” veining (Noble et al. 1984). These veins are typically oriented
vertically to sub-vertically, especially in areas where Type 4 veins are also oriented vertically,
usually near the felsite contact. Typically, they have a density of 1 vein per 1-5 cm in those zones
where Type 2 veins are dominant.

In areas further from the intrusions, Type 2 veins can be oriented randomly. Noble et al.
(1984) limited Type 2 distribution to a “70 m wide stockwork irregular annulus” around the
felsite, and characterized it as the dominant vein type within 20 m of the felsite contact.
However, recent observations identify Type 2 veins in the distal wollastonite-vesuvianite skarn
(the most distal skarn zone in the area), based on the original vein classification. The nature of
the host rock in these more distal areas may limit the development of the characteristic double
alteration halo used to identify type 2 veins in the more common hornfels and calc-silicate host
rocks closer to the core of the intrusive deposit (Fig. 4.2, a,b). Generally, Type 2 mineralization
is more highly developed within 70 m of the intrusions, but may extend much further out in a
lower frequency. They reach their highest density near the contact with the felsic dike complex.
Fig. 4.2. Examples of Type 2 ‘quartz-pyrite-scheelite’ veins at Northern Dancer. (a) Hand sample of thick Type 2 vein containing large whitish grains of scheelite in a grey quartz matrix with epidote and pyrite, within calc-silicate. The characteristic double alteration halo used to identify Type 2 veins is prominent (light green inner epidote-chlorite and outer hornblende zones). (b) Hand sample showing very thin Type 2 veins containing pyrite and fine-grained scheelite (which is visible under shortwave ultraviolet light), within fine-grained green skarn. (c) Polished section scan in plane-polarized light showing a high density of overlapping Type 2 veins containing pyrite, scheelite, epidote and chlorite. (d) Same section as ‘c’ in crossed polars. (e) Polished section scan in plane-polarized light showing thin Type 2 veins and one reopened Type 2 vein; fine-grained chlorite and epidote are visible at the new vein selvedge, but were likely part of the original Type 2 vein core. (f) Same section as ‘e’ in crossed polars. (g) Polished section scan in plane-polarized light showing a reopened Type 2 vein in calc-silicate, which has been infilled by quartz on either side of the relict core. Within the core, epidote is altering to clinozoisite, and both are associated with scheelite, fluorite, and pyrite. (h) Same section as ‘g’ in crossed polars.
Occasionally, a Type 2 vein occurs within the felsite itself, suggesting that some phases of the dike complex existed prior to the Type 2 vein event.

Principle minerals include quartz, pyrite, feldspar, and fluorite (Fig. 4.2, a-g). Pyrite is ubiquitous and occurs as euhedral crystals as well as anhedral fine-grained aggregates. Feldspar is dominantly white subhedral plagioclase (albite) but occasionally grey anhedral potassium feldspar which occurs in interstices between quartz and other minerals. Noble et al. (1984) observed that orthoclase and microperthite occurred in areas where fluorite was more common. The feldspar minerals can be partially or fully altered to sericite, calcite, and epidote. Fluorite is usually anhedral and grey in colour, fluorescing grey-white or purple-white under shortwave ultraviolet light. Accessory diopside and garnet occur in Type 2 veins, usually in garnet or pyroxene-rich calc-silicate host rocks. Other accessory minerals include epidote, hornblende, chlorite, clinozoisite, and rarely biotite.

The dominant ore mineral of the Type 2 veins is scheelite, which occurs as a minor mineral. The decreasing molybdenum concentration within the scheelite structure is evident from observation of fluorescence; scheelite in Type 2 veins is more white to blue-white in colour than Type 1 molybdoscheelite, which appears yellow-white. (see section 8: Mineralogy (Scheelite); Van Horn 1930; Greenwood 1943; Shoji & Sasaki 1978, Tyson et al. 1988). Scheelite occurs dominantly in the vein cores as sub-anhedral unzoned grains. Rarely, molybdoscheelite occurs as single, small anhedral grains; however, it is possible that these grains were remobilized from earlier Type 1 veins which are occasionally reopened by Type 2 veins (Fig. 4.2, e-h). Rare fine-grained chalcopyrite and very rare sphalerite occur as very fine-grained blebs or aggregates, near pyrite and fluorite.

Type 2 veins have a prominent double alteration halo, identifiable in calc-silicate or green skarn, consisting of a 0.1-0.3 mm pale-green inner zone and a 0.5 mm or less outer dark-green zone (Fig. 4.2, a,b). The inner zone consists of a fine-grained quartz-chlorite-epidote matrix with disseminated pyrite and/or calcite. The outer zone, which sometimes occurs without the inner zone on thinner veins, consists of dark-coloured pleochroic hornblende laths (<0.5 mm) and thin pyrite-filled fractures.

4.2.3 Type 3: quartz-molybdenite veins
This vein set is dominantly characterized by very thin fractures averaging 0.1 mm thick coated with molybdenite, but can occur as thicker, quartz-molybdenite veins up to 8 mm and averaging 3-5 mm, especially outside the felsic dikes (Fig. 4.3, a,b). The veins/coated fractures are randomly oriented in metasedimentary host rocks, but can be sheeted and/or steeply dipping within the felsic dikes (Fig. 4.3, c,d). Type 3 veins are commonly crosscut by later vein sets, but are less typically reopened than the Type 1 and 2 vein sets. Some thicker veins appear to be reopened, but the infill around the relict cores is mono-mineralic quartz, suggesting this may be due to silicic alteration or 'flooding,' rather than reopening by a later Type 4 vein (Fig. 4.3, e,f).

A maximum density of up to one vein per 1-3 cm is found in the quartz-feldspar porphyry, especially garnet-rich quartz-feldspar porphyry, with slightly lower densities in the quartz-rich felsic dike variants. Some very thin Type 3 veins bisect quartz phenocrysts cleanly, suggesting a moderate amount of pressure would have been required to form this vein set within such coherent, silica-rich host rocks (Fig. 4.3, e,f). This high density zone of Type 3 veins is what controls the high-grade molybdenum zone in the core of the deposit (36.8 Mt at 0.085 MoS₂; Board & Campbell 2008). In metasedimentary hosts, the vein density is much lower, and varies geographically through the deposit, possibly based on competency level of silicification of the host rock; the density in these locations is an estimated one vein every 0.5-1.0 m. While Type 3 veins are dominantly restricted to the felsic dike system, some veins can extend into the calc-silicate or hornfels country rock an average of 5 m (Noble et al. 1984), and have recently been observed up to 15 m from the contact.

The Type 3 vein event is responsible for the majority of molybdenite mineralization, and thus the total molybdenum in the system. Principally, Type 3 veins are molybdenite ± quartz within the felsic dikes in metasedimentary hosts; they are dominantly quartz-epidote-clinozoisite-garnet. Quartz in Type 3 veins is characteristically dark-gray to smoky; this unique quartz colour can be useful in identification. Epidote and clinozoisite are rare in Type 3 veins in the felsite. In all host rock types, minor calcite and diopside occur, as well as accessory fluorite, scheelite, and muscovite (these are rare, and very fine-grained, in the felsite). Accessory minerals found only in felsite hosts include pyrrhotite, orthoclase, rutile, and sphalerite; those in calc-silicate hosts include calcite, chlorite, and diopside. Sericite may replace feldspars (plagioclase and orthoclase microperthite), and may be evidence for phyllic-style alteration. In felsite and quartz-porphyry, a 1-2 mm sericite halo may develop, with occasional fine-grained disseminated molybdenite, scheelite, and pyrite up to 5 mm from the vein edge. Molybdenite is the dominant ore mineral in Type 3 veins and in thicker veins it can concentrate along the vein.
Fig. 4.3. Examples of Type 3 'quartz-molybdenite' veins at Northern Dancer. (a) Hand sample showing a thick Type 3 vein within calc-silicate, outboard of the felsic dike complex. Quartz and molybdenite (which forms along the vein walls) are the only two vein minerals. (b) Hand sample showing a thin, molybdenite-coated fracture cross-cutting extremely silicified calc-silicate in a planar fashion. This suggests that the felsic dike contact is close by, and is possibly inducing some of the silicification. (c) Hand sample showing multiple planar, overprinting, molybdenite-rich Type 3 vein fractures crosscutting 'brain rock' layers in ribbon-banded quartz-feldspar porphyry. (d) Hand sample showing relatively thick, planar Type 3 veins crosscutting quartz-feldspar porphyry. Pyrite and pyrrhotite accompany molybdenite and characteristically dark-gray quartz (unique to Type 3 veins) within the veins. (e) Polished section scan in plane-polarized light showing two Type 3 veins crosscutting quartz-feldspar porphyry. Some thicker veins appear to be reopened, but the infill around the relict cores is mono-mineralic quartz, suggesting this may be due to silicic alteration/‘flooding’ rather than reopening by a later Type 4 vein. Even thin Type 3 veins crosscut through quartz phenocrysts, suggesting a moderate amount of pressure would have been required to form this vein set within such coherent, silica-rich host rocks. (f) Same section as ‘e’ in crossed polars.
walls (Fig. 4.3, a). Discrete grains are rare, but where found they are anhedral-subhedral and occur in pods or aggregates. Occasionally, pyrite grains/aggregates can occur in vein cores along with rare chalcopyrite. Some thicker veins appear to be reopened, but the infill around the relict cores is mono-mineralic quartz, suggesting this may be due to silicic alteration/'flooding' rather than reopening by a later Type 4 vein.

4.2.4 Type 4: polymetallic sheeted veins: quartz-beryl-scheelite-molybdenite veins

Type 4 veins are the most prominent and physically conspicuous vein set in the Northern Dancer deposit. They occupy a distinct 046-088° fracture system (documented by Noble 1982) via underground mapping of the adit which becomes most pronounced in metasedimentary host rocks. Type 4 veins are therefore dominantly sheeted, and are typically anywhere between 1 cm and 1 m wide but average 1-5 cm, with sharp contacts (Fig. 4.4, a). Usually these contacts are planar, but near felsic dikes, the contacts can become undulose and some veins grade into small offshoots and extensions of the felsic dikes themselves. Occasionally, Type 4 veins overlap one another, suggesting multiple generations. Density is variable, but averages one vein per 2-5 m.

The Type 4 veins set is part of the most extensive mineralized vein set associated with the deposit; this generation of veins extends both laterally and vertically beyond the deposit boundary. The polymetallic sheeted veins of the Northern Dancer area are separated into three groups (Noble et al. 1984): (1) quartz-beryl-scheelite-molybdenite veins, located within the deposit boundary and centered on the felsic dike complex; (2) quartz-beryl-wolframite veins, located to the southwest of the deposit proper; and (3) Pb-Zn-Ag veins, located to the northwest of Logtung ridge, also known as the Logjam occurrence. Type 4 veins discussed here are those classified as quartz-scheelite-molybdenite veins, located within the deposit proper. However, these three sets may be genetically and spatially linked, and the latter two distal sets approximately follow the same general structural trend as the main deposit set. The more distal sets also become much thicker, and less dense than the Type 4 veins, away from the felsic dike complex. While no traceable surface connection has been made between these sets, more extensive drilling may reveal spatial and chemical associations. Mineral trends appear to suggest a more base-metal rich evolution toward the northwest, in the direction of Logjam (increasing sphalerite and galena content).
Fig. 4.4. Examples of Type 4 'polymetallic sheeted' veins at Northern Dancer. (a) Drill core example of the 'sheeted' nature of Type 4 veins. Sulphides, including pyrite, pyrrhotite, chalcopyrite, and molybdenite congregate as large vein-filling aggregates between quartz, euhedral white-grey scheelite, feldspar, and pyroxene. Bleaching of the calc-silicate rock and an alteration halo containing pyrite/pyrrhotite and biotite are visible. (b) Hand sample showing a Type 4 vein which reopens an earlier (likely Type 2) vein, in fine-grained, diop-rich, calc-silicate. Molybdenite is visible at the new inner vein wall, while pyrite, scheelite, and biotite form the vein core; the original dark-green alteration halo from the Type 2 vein is still visible. A thin layer of quartz between the two veins separates the two veins (it appears to be of a different generation than quartz in the cores of the veins) (c) Hand sample showing a thick, blue beryl and scheelite-rich Type 4 vein hosted within calc-silicate. Sulphides permeate the wallrock, and some euhedral scheelite grains actually occur outside the vein boundary, in the alteration halo. (d) Polished section scan in plane-polarized light showing a thick, planar Type 4 vein in calc-silicate. Scheelite (beige-coloured grains) and sulphides (opaque, therefore they appear black) are the main vein components and appear to infill open space. Beryl crystals are altered in the left side of the image and are intergrown with sericite and calcite. (e) Same section as ‘d’ in crossed polars. (f) Polished section scan in plane-polarized light showing a typical Type 4 vein in altered hornfels. Molybdenite and calcite form aggregates at the vein selvedge, while large, euhedral scheelite crystals (beige-coloured), sulphides (pyrite, pyrrhotite and chalcopyrite, amphibole and euhedral apatite form the majority of the vein core. Needles of amphibole and apatite can be intergrown with scheelite. (g) Same section as ‘f’ in crossed polars.
Type 4 veins occur dominantly within a zone 350 m in strike length on surface, across Logtung Ridge. This zone is centered on the W-Mo anomalies revealed in soil geochemistry (Harris et al. 1981; Wengzynowski 2006). Historically, these veins were found up to 190 m vertically, but recent drilling has revealed Type 4 veins at the bottom of a 350 m diamond drill hole, thus the system currently remains open at depth.

The Type 4 veins, e.g., those in the central area of the deposit, have a principal mineralogy of quartz-beryl-fluorite-scheelite-molybdenite. Scheelite in this vein set is the coarsest in the deposit; grain size overall is very coarse within Type 4 veins. Scheelite can occur in crystals up to 1.5 cm, and are typically subhedral (Fig. 4.4, b,c). Beryl is pale blue, and can be milky at higher levels, but becomes progressively more clear and gemmy at depth. Occasionally, greenish-blue, gemmy beryl occurs within felsite at lower depths in the deposit. Beryl can be up to 3 cm, but averages 3-5 mm, and typically grows in crystals perpendicular to the vein contact. At greater depths within the deposit, thick blue beryl veins up to 1.8 cm wide occur outboard of the felsic dikes, within the calc-silicate and hornfels (Fig. 4.4, c). Where open-space infill is apparent in thick Type 4 veins near surface, beryl can be altered, and intergrown with sericite or calcite (Fig. 4.4, d,e). On rare occasions within ‘brain rock’ textures of quartz-porphyry host rocks, beryl can occur as layers within the ‘brain rock’ itself, and contains associated fine-grained scheelite and fluorite. This texture suggests the Type 4 generation is intimately associated with the ‘brain rock’ texture of the felsic dike complex.

Very rarely, almost pure blue beryl veinlets (quartz absent) can occur as offshoots of larger Type 4 veins, with accessory purple fluorite, scheelite, molybdenite, chalcopyrite, and sphalerite (Fig. 4.4, c). Fluorite is occasionally purple, but can be grey or colourless, occurring as anhedral infill around coarse crystals of beryl and sulphide aggregates, but rarely occurs as subhedral clear purple crystals up to 3 mm in size. Fluorite concentrations increase near the felsite and it can (but not always) fluoresce yellow. Molybdenite is mostly fine-grained, occurring along vein walls, but can occur in vein cores, associated with other metallic minerals (Fig. 4.4, f,g). Minor pyrite, chalcopyrite (increasing away from felsite), pyrrhotite, potassium feldspar, and sphalerite (at lower levels) occur, and can become locally massive, especially close to or within the felsic dikes or diorite. Accessory fluorapatite, titanite, rutile, biotite, muscovite, potassium feldspar near the felsite, galena, bismuthinite, and arsenopyrite distal to the felsite, also occur.

Wallrock alteration associated with Type 4 veins is dependent on the host rock lithology, and alteration halos occur on all veins proximal to the felsic dikes and also on the larger, distal
vein sets. In calc-silicate and hornfels host rocks, the most intense vein margins occur, and these are occasionally zoned. The alteration halos form two zones: an inner quartz-biotite-sulphide zone and an outer quartz-hornblende zone. The inner zone is typically 5-10 cm thick in 1 m thick Type 4 veins, and less than 2 cm in veins less than 5 cm thick. It contains abundant sulphides, including thick aggregate molybdenite, chalcopyrite, and sphalerite. In narrow and distal veins, only the inner halo is present. The outer zone consists primarily of fine-grained quartz and dark green hornblende laths up to 0.8 mm long and minor calcite and diopside. The outer halo only occurs where the inner zone is also present, and can be 3-5 cm wide. Within the felsic dike hosts, alteration halos are not as complex or distinctive, and are typically 1-5 cm wide, consisting of fine-grained disseminated molybdenite and scheelite with minor amphibole, chlorite, biotite, and rare apatite and titanite. Sericite alteration of feldspars, and sometimes beryl (within the veins), is prevalent. In some areas to the south of the main felsic dike complex near the diorite contact, Type 4 veins locally crosscut diorite units, and cause a significant halo very similar to the inner halo found in calc-silicate host rock, up to 8 cm (average 1-4 cm) into the host rock. This halo is biotite rich with quartz, pyrite, chlorite, occasional amphibole, titanite, and apatite.

4.3 Unmineralized vein sets

4.3.1 Quartz veins

Late, barren quartz veins, which post-date W-Mo mineralization and crosscut all mineralized vein sets and felsic dike phases, occur throughout the deposit. Thickness is dependent on host rock, but is generally less than 5 mm.

4.3.2 Calcite veins

Late, barren calcite veins crosscut all vein types including late barren quartz veins, and fill faults and fractures throughout the deposit. Occasionally, fine-grained, bladed chabazite (zeolite) occurs along vein/fracture walls with fine-grained calcite in the cores. These veins occur typically in calc-silicate and hornfels host rocks, and are usually very thin, generally 2 mm or less.
4.3.3 Other vein types

Noble et al. (1984) recognized two other distinct vein sets: "undifferentiated veins" and "skarn-derived dark-grey quartz veins." Undifferentiated veins denote those which defy classification, but are typically minor, unmineralized, and very fine-grained. It is possible these are either early pre-mineralization skarn veins, or late barren quartz veins. Skarn-derived dark-grey quartz veins likely refer to early skarn veins which are quartz-feldspar rich, but are pre-mineralization.

4.4 Cross-cutting vein relationships

The four vein types are labeled numerically based on relative time of emplacement, which was inferred from cross-cutting relationships observed by Noble et al. (1984); these relationships were confirmed and investigated further in this study. Some examples of cross-cutting vein relationships supporting the general temporal classification are shown in Fig 4.5 (a,c,d,e,f,g), and various other examples are periodically referred to in subsequent sections. The influence of host rock on vein alteration halo character is evident in Fig. 4.5 (b), where a Type 2 vein with a prominent pyroxene alteration halo within fine-grained, diopside-rich calc-silicate crosses a felsic aplite dike. Within the dike, there is no alteration halo at all, supporting the idea that the extent of wallrock interaction, and the mineralogy of alteration haloes, depend on host rock as mentioned in individual vein sections above. Fig. 4.5 (f,g) shows the nature of what appears to be silica alteration, represented by large masses of quartz which can 'flood' zones of quartz-feldspar porphyry, felsite, brain rock, or calc-silicate.
Fig. 4.5. Examples of crosscutting vein relationships at Northern Dancer. (a) Hand sample showing the complexity of crosscutting vein relationships within the calc-silicate. Type 2 veins with alteration haloes are crosscut by later Type 3 veins, which are offset the Type 2 veins. (b) Drill core example of the influence of host rock on alteration halo character; A typical Type 2 vein displays a prominent alteration halo within calc-silicate, but shows almost no alteration as it crosses into an aplitic felsic dike phase. (c) Hand sample showing the first three vein sets and their crosscutting relationships, in the same sample. A thick, garnet-rich, Type 1 vein (visible at the centre of the image) is crosscut by a thin Type 2 vein with alteration halo. In the bottom right corner of the image, a Type 3 crosses the Type 2 vein. (d) Polished section scan in plane-polarized light showing a Type 2 vein which crosscut by a Type 3 vein at a high angle, in hornfels. A Type 4 vein has then reopened the Type 2 vein and formed a fsp-fluo-rich alteration halo, within the crosscutting zone of the Type 3 vein only (centre of image). The Type 2 vein has a visible green chlorite alteration halo, and an inner plagioclase-rich zone which is bisected by the Type 4 vein. Scheelite within the qtz-rich Type 3 vein is euhedral (visible in the top left part of the vein). The core of the reopened vein is rich in scheelite (beige), pyrite (black), and fluorite (colourless). (e) Same section as 'd' in crossed polars. (f) Polished section scan in plane-polarized light of quartz-feldspar-porphyry crosscut by planar, parallel, thin Type 3 veins containing mscv and moly, all of which is overprinted by quartz flooding; radial sprays of apatite needles are visible in the quartz zone. (g) Same section as 'f' in crossed polars.
5 Geochronology

5.1 Overview of geochronology

Dating of the intrusive rocks at Northern Dancer has been completed in previous studies by various methods, and has produced several varying ages for some units. Some reported ages are in direct conflict with others and do not appear to correlate with the inferred petrogenesis of the deposit. As part of this study the various intrusive rock units on the property were resampled for dating at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, to elucidate temporal relationships in the deposit. Two dates for the monzonite were obtained using laser ablation ICP-MS (LA-ICP-MS) methods and were published previously by Mortensen et al. (2007); these results are reviewed below. The diorite unit was originally sampled by K. Emon in 1998, and the felsic dike complex was sampled by the author from drill core in 2006. Zircons were separated from both the diorite and the felsic dike and were dated using LA-ICP-MS methods. Results are discussed below. The methodology used for LA-ICP-MS U-Pb dating at the PCIGR is summarized in the Appendix (section 10.1).

5.2 Dating of intrusive rocks

5.2.1 Diorite

The diorite unit at Northern Dancer (which intrudes the north and south flanks of Logtung ridge), was first dated by Stewart (1983) who reported a Rb-Sr age of 245 ± 32 Ma. A sample of massive, medium-grained, equigranular diorite from the “Logtung diorite” body at ~ 0354400 E/6654600 N (Zone 9, NAD 83) yielded abundant zircon. Zircons from the sample comprise clear, colorless fragments derived from square and prismatic to skeletal grains. A total of 12 individual line scans were run on eight zircon grains (Table 5.5). The resulting analyses are all concordant (Fig. 5.1), and a weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages is 187.7 ± 2.6 Ma (MSWD = 0.06; probability of fit = 1.0). This is interpreted as the crystallization age of the diorite. This age is more consistent with regional ages for Early Jurassic intrusions in southern and central Yukon, which includes the Simpson Peak and Nome Lake Batholiths just
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<td>111.5</td>
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<td>0.00011</td>
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<td>110.7</td>
<td>1.75</td>
<td>112.6</td>
<td>0.7</td>
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</table>

1 Errors on calculated ratios given at 1 sigma level; 2 Errors on calculated ages given at 2 sigma level.

Table 5.1. $^{206}$Pb/$^{238}$U analytical data for zircons collected from the ‘Logtung diorite’ and felsic dike complex, analyzed via LA-ICP-MS at PCIGR (Pacific Centre for Isotopic and Geochemical Research), UBC.
Fig. 5.1. U-Pb data for the Logtung diorite sample showing (a) U-Pb concordia plots for zircon analysis (data listed in Table 5.1, data point ellipses are 2σ), ellipses represent the statistical 'concordia age' calculated via ISOPLOT (see Methodology in Appendix A), and the line represents the concordia curve with time (Ma). (b) Weighted average plots (plots, ages and errors were calculated using the ISOPLOT program of Ludwig (2003)).

5.2.2 Monzonite

The main monzogranite body southwest of Logtung Ridge was first dated by Stewart (1983), who obtained an Rb-Sr age of 118 ± 2 Ma (recalculated at 117.6 ± 3.5 Ma using more rigorous regression parameters; Brietsprecher and Mortensen). A K-Ar (muscovite) date of 109 ± 2 Ma for the monzonite was reported by Hunt and Roddick (1987). Mihalynuk and Heaman (2002) produced a U-Pb date on material close to the contact with the felsic porphyry dike system, as well as material from the adit test dumps. Their interpreted age for the monzonite was based on two discordant analyses of zircon that they interpreted to be hydrothermal in origin. The Th/U ratios of the zircons, however, are more typical of igneous, rather than hydrothermal, zircon. The age reported by Mihalynuk and Heaman (2002) for these zircons was 58.6 Ma, which conflicts with the substantially older Rb-Sr and K-Ar dates, as well as an unpublished Re-Os date on molybdenite of 108 Ma (see below).

A sample of coarse-grained intrusive was collected in 2006 from the main monzogranite body, south of the defined deposit boundary (sample Al-06-04; location: UTM coordinates: 0355284 E/ 6653271 N; zone 9, NAD 83; Fig. 3.1). A description of the main monzonite unit is found in Section 3.2.2). A second sample of the monzogranite was also collected; this was from approximately the same location that Mihalynuk and Heaman (2002) obtained their sample (sample Al-06-10; location: UTM coordinates: 0354631 E/ 6655505 N; zone 9, NAD 83; Fig. 3.1). The primary mineralogy of this porphyritic sample consists of quartz-plagioclase, potassium feldspar and biotite, with accessory garnet. Phenocrysts are smaller (~5-8 mm) than that of the previous sample, with an average groundmass grain size of ~0.3-1.0 mm. Both of the two monzogranite samples were analyzed using LA-ICP-MS at PCIGR, and results are reported by Mortensen et al. (2007). Sample Al-06-10 is more intensely altered than AL-06-04, with sericite replacing igneous feldspar (Mortensen et al. 2007).

A moderate amount of zircon was obtained from each of the two samples, which consisted of clear, colourless to pale yellow, stubby prisms with multifaceted terminations, and many of the grains were fractured and contained abundant bubble- and rod-shaped inclusions (Mortensen et al. 2007).
U-Pb zircon analytical results reported by Mortensen et al. (2007) for the two samples are summarized below. A total of 21 individual U-Pb analyses were done on zircons from sample AL-06-04 (main monzogranite body); one of these grains yielded an older age (~125 Ma) that appears to reflect the presence of inherited zircon, and three grains have likely suffered Pb-loss throughout based on their slightly younger ages. A weighted average of the $^{206}\text{Pb}/^{238}\text{U}$ ages of the remaining 17 analyses gives an age of $109.4 \pm 0.9$ Ma, which is interpreted to be the crystallization age of the sample. Twenty analyses from the second sample (AL-06-10) give a weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of $110.5 \pm 0.8$ Ma for a total of 18 individual analyses. Two analyses give slightly older ages, apparently due to the presence of minor inherited zircon. These results overlap well with earlier dating results by K-Ar dating discussed above. The sample obtained from the same outcrop as Mihalynuk and Heaman's sample location did not yield any of the brownish zircons they identified as being hydrothermal in origin (which produced the 58.6 Ma age), therefore their results are difficult to explain.

5.2.3 Felsic dikes

No previous dating of the felsic porphyry dike system has been conducted prior to this study. A sample was obtained from drill core within the main felsic dike complex which outcrops on Logtung Ridge, specifically from historic hole # LT-80-41 at ~50 m depth (sample Al-06-06; drill collar UTM: 354957 E/ 6655061 N, zone 9, NAD 83; Fig. 3.1). The sample consisted of light grey, homogenous, quartz-feldspar porphyry with smoky grey quartz phenocrysts averaging ~3 mm across, with little or no veining (this sample was also used for whole-rock geochemistry). Zircons recovered from this sample form fine to medium grained, stubby, square prismatic grains. The zircons are pale yellow in color, and many were somewhat fractured. No inherited zircon cores were observed. Thirteen line scans were run on a total of 10 grains (Table 5.1). The data show a moderate amount of scatter, as reflected in the higher MSWD and low probability of fit (Fig. 5.2). Two analyses yield relatively young $^{206}\text{Pb}/^{238}\text{U}$ ages, which is interpreted to reflect post-crystallization Pb-loss. A weighted average of the calculated $^{206}\text{Pb}/^{238}\text{U}$ ages for 11 remaining analyses is $111.7 \pm 0.7$ Ma (MSWD = 4.1; probability of fit = 0). This is taken as the best estimate for the crystallization age of the sample. This age is very slightly older than, but essentially overlaps with, the age of the monzonite unit, which has been interpreted to be comagmatic with the felsic dike complex.
Fig. 5.2. U-Pb data for the felsic dike complex sample showing (a) U-Pb concordia plots for zircon analysis (data listed in Table 5.1, data point ellipses are 2σ), ellipses represent the statistical 'concordia age' calculated via ISOPLOT (see Methodology in Appendix A), and the line represents the concordia curve with time (Ma). (b) Weighted average plots (plots, ages and errors were calculated using the ISOPLOT program of Ludwig (2003)).
5.3 Implications for timing of mineralization

A Re-Os age of ~108 Ma was obtained from two molybdenite grains from the Northern Dancer deposit by Drs. Craig Hart of the Yukon Geological Survey and David Selby of Durham University (pers. comm. 2006). The exact geological context of this sample is unknown at present, however. As the Type 3 quartz-molybdenite veins crosscut the felsic dikes, they must be at least slightly younger than the felsic dikes, and therefore Type 3 and 4 vein set mineralization must be 111.7 ± 0.7 Ma or younger. The aforementioned unpublished Re-Os molybdenite date supports the argument that the molybdenite mineralization was approximately coeval with the felsic dike complex emplacement. As well, in many places the Type 4 veins appear texturally and mineralogically transitional to the felsic dikes, which would constrain the emplacement of this final mineralized vein set to the felsic dike complex age.

The three dates obtained from the monzonite and felsic dikes suggest they are comagmatic; hence it is difficult to determine upper and lower time constraints on individual vein sets relating to these two individual intrusive phases. As such, it would be useful to determine specific ore mineral ages for scheelite or molybdenite from each of the vein generations. Additional Re-Os dating on the different generations of molybdenite may be useful, as it has proven to be a highly accurate and precise dating method (e.g., Stein et al., 2001; Selby and Creaser, 2001), although molybdenite does not occur in earlier Type 1 and 2 veins.

Scheelite dating employing Sm-Nd, Rb-Sr, and Pb-Pb methods has been utilized by Eichhorn et al. (1997) at the Felhertaltung tungsten deposit in Austria; however, the four stages of mineralization in this circumstance were spread over 500 m.y. Dating of scheelite using Sm-Nd and Rb-Sr methods was also done by Kempe et al. (2001) at the Au (-W) Muruntaude deposit in Uzbekistan, but again, the two generations of scheelite were ~70 m.y. apart, and therefore these studies do not indicate whether this technique would be as useful as Re-Os dating of molybdenite for dating ore phases from very temporally similar vein sets. In any case, dating the scheelite and/or molybdenite from the Type 4 vein set would provide a lower age constraint for mineralization at Northern Dancer.

In general, it appears the contemporaneous emplacement of the monzonite and felsic dikes and the emplacement of the four overprinting vein sets likely occurred within the span of approximately 2-4 m.y., between 111.7 ± 0.7 Ma and 109.4 ± 0.9 Ma. Future work should focus on obtaining individual mineral ages on either scheelite or molybdenite, or both, using the techniques discussed above.
6 Whole-rock Geochemistry

6.1 Overview of geochemistry

Whole-rock geochemical analyses were obtained for five large samples from the intrusive rocks (north and south flanks of diorite, main body and contact zone of the monzonite, and the felsic dikes); the latter three of these samples (Al-06-04, AL-06-06, and AL-06-10) were also used for U-Pb age dating (see section 5: Geochronology). Analyses were also obtained for the representative sample set investigated in Mineralogy, resulting in a total of 50 whole-rock geochemical analyses from various different vein/host environments. The same vein/host and depth groupings used for analytical purposes here are also used in the Rietveld section below, for consistency. Analytical methods are discussed in Appendix A.

6.2 Geochemistry of intrusive rocks

Whole-rock geochemical analyses for the intrusive units are listed in Table 6.2. The smaller sample size of the representative samples versus the larger intrusive samples likely means that data is relatively more robust for the intrusive samples.

6.2.1 Major element content of the intrusive units

Values of P₂O₅ (0.32 wt.%), TiO₂ (0.68 wt.%), Al₂O₃ (15.92 wt.%), Fe₂O₃ (1.54 wt.%), and LOI (1.70 wt.%) are highest in the northern diorite sample, while MgO (6.06 wt.%), CaO (7.59 wt.%), and FeO (6.75 wt.%) are highest in the southern diorite sample.; overall the two flanks of diorite are geochemically similar. The monzonite contains the highest K₂O (5.43 wt.% and Na₂O (3.72 wt.%) values, while the felsic dikes are highest in silica (78.85 wt.% SiO₂). These two units are also geochemically alike (low Fe/Mg/Ca/Ti, high Si/K values). On an AFM diagram (Fig. 6.1), the monzonite and felsic dikes plot very close to each other near the alkali corner (the diorite samples plot centrally on the AFM diagram), and in general, the two felsic units are fairly similar geochemically (through both major and minor elements). This supports the hypothesis that the felsic dikes are related to, and possibly represent more highly fractionated variations of the monzonite unit. Oxidation state of the intrusive units is plotted in Fig. 6.2, and suggests that the diorite units are very slightly more reduced than the monzonite units; the felsic dikes, and to a lesser extent the monzonite contact zone, are also relatively reduced compared to
Table 6.1. Whole-rock geochemical analyses of intrusive units at the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Diorite (north)</th>
<th>Diorite (south)</th>
<th>Monzonite</th>
<th>Felsic Dyke Complex</th>
<th>Mitch's Monzonite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AL-06-02</td>
<td>AL-06-03</td>
<td>AL-06-04</td>
<td>AL-06-06</td>
<td>AL-06-10</td>
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<tr>
<td>$P_2O_5$ (wt. %)</td>
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<td>&lt;0.01</td>
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<td>78.85</td>
<td>78.25</td>
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<td>0.68</td>
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<td>11.99</td>
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<td>0.03</td>
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<td>0.31</td>
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<td>99.77</td>
<td>99.79</td>
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| Li (ppm)      | <0.1            | <0.1            | <0.1      | <0.1                | <0.1              |
| Be            | 1               | 2               | 16        | 10                  | 138               |
| B             | 41              | 27              | 11        | <10                 | 10                |
| F             | 570             | 1040            | 3500      | 770                 | 780               |
| Cl            | 21              | 57              | 31        | 18                  | 20                |
| Sc            | 16              | 21              | 7         | 9                   | 8                 |
| V             | 145             | 182             | 14        | 5                   | 8                 |
| Co            | 19.5            | 26.3            | 0.9       | 1.3                 | 0.7               |
| Ni            | 34.1            | 36.3            | 1.1       | 1.1                 | 0.5               |
| Cu            | 22              | 52.8            | 2.8       | 33.1                | 18.6              |
| Zn            | 71              | 59              | 13        | 10                  | 7                 |
| Ga            | 16.1            | 15.3            | 17.8      | 19.6                | 19.2              |
| Rb            | 112.9           | 117.1           | 659.7     | 354.7               | 630.1             |
| Sr            | 565.7           | 405.9           | 137.5     | 166                 | 14.9              |
| Y             | 16.9            | 18.5            | 35.2      | 72.6                | 35.1              |
| Zr            | 151.8           | 82.4            | 122.9     | 58.9                | 74.9              |
| Nb            | 6.5             | 5.1             | 43.7      | 62.8                | 89.5              |
| Mo            | 0.6             | 2.5             | 0.6       | 356.1               | 7                 |
| Ag            | 0.1             | 0.1             | <1        | <1                  | <1                |
| Sn            | 3               | 4               | 1         | 3                   | 15                |
| Cs            | 4.8             | 4.2             | 26.1      | 6.3                 | 22.5              |
| Ba            | 1509.7          | 820.5           | 538.5     | 758                 | 47.6              |
| La            | 14.3            | 10.6            | 30.1      | 10                  | 25                |
| Ce            | 29.7            | 23.2            | 63.6      | 25.9                | 51.9              |
| Pr            | 3.52            | 2.85            | 6.57      | 3.57                | 5.27              |
| Nd            | 14.1            | 12.7            | 21.4      | 14.8                | 16.6              |
| Sm            | 2.8             | 2.7             | 4.1       | 6.2                 | 2.9               |

Note: Most major elements were determined using laser ablation (ICP-MS) methods. See Appendix A for full description of analytical methods.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Diorite (north)</th>
<th>Diorite (south)</th>
<th>Monzonite</th>
<th>Felsic Dyke Complex</th>
<th>Mitch's MONzonite</th>
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<td>AL-06-04</td>
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<td>0.9</td>
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<td>&lt;.5</td>
<td>&lt;.5</td>
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<td>H2O⁺</td>
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<td>0.15</td>
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<td>0.14</td>
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<tr>
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<td>1.58</td>
<td>0.61</td>
<td>0.49</td>
<td>0.39</td>
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</table>

Note: Most major elements were determined using laser ablation (ICP-MS) methods. See Appendix A for full description of analytical methods.
AFM plot of intrusions

Fig. 6.1. AFM diagram showing plots of the intrusive units at Northern Dancer deposit.

Oxidation state of Intrusive Units

Fig. 6.2. Plot of $\frac{Fe_2O_3}{(Fe_2O_3 + FeO)}$ versus SiO$_2$ showing relative oxidation states of intrusive units at the Northern Dancer Deposit.
the monzonite, suggesting that the reduced nature of the metasedimentary host rocks may affect the oxidation state of intrusive units in close contact with them. Compared to major W-skarns such as Cantung, intrusive units at the Northern Dancer deposit are closer to neutral, but relatively more oxidized (Meinert et al. 2005).

6.2.2 Minor and trace element content of the intrusive units

While the mobility of many trace elements in hydrothermal systems make it difficult to (Rollinson 1993) determine their petrogenetic source (for example, intrusions sourcing some elements may appear depleted in an element which has mobilized out of it to a large degree), some observations are reasonable. Fluorine is highest in the monzonite at 3500 ppm, and the southern diorite sample shows a much higher F-content (1040 ppm) than the northern diorite sample (570 ppm), likely reflecting the possibility that the source of fluorine was the monzonite, and that fluorine alteration extended, at least, to the southern flank of the diorite. The contact region of the monzonite and the felsic dikes show much lower F contents than the monzonite (770 and 780 ppm, respectively), possibly because F-rich fluids were mobilized out of these zones during mineralizing events, resulting in the fluorite enrichment seen in groundmass of calc-silicate rocks, and higher F content in altered diorite rocks.

The contact region of the monzonite is the most enriched in Be compared to the other units, reaching 138 ppm, which suggests Be congregated near the contact, and possibly, that it was trapped there until the Type 4 vein event. Renders & Anderson (1987) have shown that Be is transported in hydrothermal complexes as hydroxyl-, chloride-, or fluoride- complexes, thus an increasingly higher F activity over time would possibly allow for increased mobility of Be out into the veins. A similar process of transport via fluoride complex may occur for W, which would explain the deposit wide correlation of W/scheelite and F/fluorite/F-rich minerals (see section 7: Rietveld analysis, and section 8: Mineralogy). Mo is elevated only in the felsic dikes, at 356 ppm, which reflects the dominance of the Type 3 quartz-molybdenite veins in this unit over others. The source of the Mo is not clear; the felsic dikes and monzonite are inferred to be coeval; however; there is no Mo enrichment in the monzonite, suggesting that if it was the source of the Mo, then it was mobilized out completely, or that a different source exists. Rb, Nb, Sn, Ta, U, Th, Au, and Bi are also elevated in the monzonite.

W is low in the northern (unmineralized) diorite sample (0.9 ppm), but is elevated (67.3 ppm) in the southern diorite sample. This indicates that W was not likely sourced by the diorite
(unless it was mobilized out of the diorite early on in deposit evolution), and therefore, the hypothesis that the majority of scheelite at Northern Dancer could be dominantly remobilized from disseminated W within early reaction skarn associated with the diorite is less likely. B, Cl, V, Sc, Co, Ni, Cu, Zn, Sr, Ba As, Sb are also elevated in the diorite units. Tungsten is highest in the felsic dikes, at 109.2 ppm, likely indicating that W is sourced here (and the monzonite, by association), and further discounting the hypothesis that scheelite was remobilized from the metasedimentary rocks into the veins. Aside from being enriched in many of the same elements that the monzonite is enriched in, rare earth elements are also elevated in the felsic dikes.

6.3 Whole-rock geochemistry of the representative sample set

Whole-rock geochemical analyses for the representative sample set are shown in Table 6.2, and are averaged by vein/host environment. Analyses for W and Mo were completed using the same procedure as all drill core assay results reported by Largo Resources Ltd. (see Appendix A for a description of analytical methods). The results for each representative sample are shown in Table 6.3, and are compared to an independent calculation of W grade by EPMA and Rietveld methods in section 7.5.

6.3.1 Major element content of the representative sample set

Relative to the intrusive units, the metasedimentary rocks are, in general, more Fe-, Mg-, Mn-, and Ca-rich. The intrusive rocks are more K- and Al-rich; P, Ti, Na, and Na are comparable through the sample set, or at least lack prominent correlation when compared by host environment. Ca content is much lower (15.95 wt.% CaO) in the hornfels than in the calc-silicate rocks (8.23 wt.% CaO), which may explain why earlier vein sets (which probably encountered more fluid-rock interaction than later, larger vein sets) contain more scheelite in calc-silicate than in hornfels. The highest Ca content occurs in wollastonite-vesuvianite skarn (35.41 wt.% CaO). Mg content peaks in light green skarn (5.50 wt.% MgO), a rock type found distal to mineralization, likely due to its high diopside content (see section 7: Rietveld analysis). Manganese also peaks at 1.10 wt.% MnO in the wollastonite-vesuvianite skarn. Ti content peaks in the diorite (1.01 wt.% TiO2), Fe content peaks in garnet-rich calc-silicate rocks (10.17 wt.% Fe2O3), and amongst the metasedimentary rocks, hornfels contains the highest Al content, at 12.23 wt.% Al2O3.
6.3.2 Minor and trace element content of the representative sample set

Tungsten content is plotted versus host rock type in Fig. 6.3. Tungsten content in the intrusive rocks from the sample set appear to show the same trends as those in the larger intrusive samples discussed above. Comparatively, the metasedimentary units have higher W content than the intrusive rocks, likely as a result being hosts to the overlapping vein sets containing the majority of the scheelite in the deposit. Among the metasedimentary rocks in the sample set, calc-silicate contains the highest W-content (1995 ppm), and is also the most W-rich host environment in the deposit, whereas the hornfels contains only 559 ppm W. Wollastonite-vesuvianite skarn contains the lowest W content in the metasedimentary rocks, at 308 ppm.

Fluorine content reaches major peaks in the calc-silicate and hornfels units; for example, the garnet-rich cal-silicate contains 19,482 ppm, while the hornfels unit contains 14,884 ppm and the wollastonite-vesuvianite skarn contains 9,810 ppm. Both F and W contents appear to decrease spatially from the mineralizing source (assuming that the felsic dikes are the source and the rocks closest to the mineralizing source are the calc-silicate, the hornfels, the light green skarn, and the wollastonite vesuvianite skarn, in order of increasing distance). Fluorine content in the representative sample set is correlated to W content (W content is shown in Fig. 6.3). This further supports the hypothesis that W in the Northern Dancer system may be transported by fluoride complexes. Overall, elemental content correlates well with Rietveld data for the representative sample set (see section 7: Rietveld analysis).

Beryllium is enriched to a much greater extent in the hornfels (245 ppm) and calc-silicate (261 ppm), than the felsic intrusive units which are inferred to be its source. Possibly, this indicates that Be was mobilized (likely by fluoride complex in an F-rich fluid) out of the intrusive rocks and into the metasedimentary host rocks, where it was deposited as beryl.

Molybdenum content appears to be very homogenous throughout the various environments (remains between 216 ppm and 484 ppm), aside form the diorite (141 ppm) and the wollastonite-vesuvianite skarn (53 ppm), likely due to their large distance from the core of the molybdenite-rich felsic dike complex.
Table 6.2. Whole-rock geochemical analyses for the representative sample set.

<table>
<thead>
<tr>
<th>Unit</th>
<th>QFP</th>
<th>Silicified QFP</th>
<th>QFP - brain rock</th>
<th>Diorite</th>
</tr>
</thead>
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<td></td>
<td>average</td>
<td>st dev</td>
<td>average</td>
<td>st dev</td>
</tr>
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<td>0.05</td>
<td>0.14</td>
<td>0.13</td>
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<td>5.62</td>
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<td>TiO₂</td>
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<td>0.04</td>
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<td>0.05</td>
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<td>0.00</td>
<td>0.00</td>
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<td>2.55</td>
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<td>0.12</td>
<td>0.18</td>
</tr>
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<p>| Be (ppm) | 10.0 | 4.3 | 29.8 | 35.5 | 4.3 | 4.0 | 7.3 | 4.2 |
| F | 1064.3 | 1222.5 | 3755.0 | 5168.1 | 526.7 | 238.4 | 7993.3 | 5832.0 |
| Sc | 7.1 | 4.9 | 8.3 | 1.9 | 4.0 | 3.0 | 24.3 | 4.8 |
| V | 25.0 | 15.0 | 49.0 | 0.0 | 6.0 | 0.0 | 183.7 | 18.6 |
| Co | 3.9 | 2.7 | 7.7 | 9.7 | 1.4 | 0.6 | 26.6 | 2.1 |
| Ni | 13.0 | 0.6 | 5.5 | 0.5 | 0.0 | 0.0 | 45.0 | 9.3 |
| Cu | 80.2 | 47.0 | 90.0 | 49.3 | 22.3 | 16.1 | 284.8 | 194.7 |
| Zn | 11.7 | 9.8 | 28.3 | 22.3 | 8.3 | 5.6 | 83.0 | 31.6 |
| Ga | 15.4 | 5.5 | 13.8 | 0.7 | 7.9 | 6.3 | 18.6 | 3.3 |
| Rb | 338.2 | 106.3 | 310.3 | 63.8 | 171.0 | 124.2 | 471.5 | 284.4 |
| Sr | 92.3 | 41.7 | 62.5 | 29.9 | 21.3 | 8.2 | 765.0 | 270.5 |
| Y | 57.8 | 14.9 | 53.3 | 23.4 | 43.1 | 19.8 | 33.2 | 11.6 |
| Cs | 8.1 | 4.6 | 9.2 | 4.7 | 4.7 | 4.1 | 27.2 | 22.4 |
| Zr | 48.0 | 18.4 | 50.1 | 13.3 | 27.2 | 20.5 | 154.5 | 49.6 |
| Ba | 511.4 | 97.2 | 471.1 | 296.7 | 130.8 | 65.8 | 1765.2 | 680.5 |
| Nb | 52.9 | 21.9 | 37.0 | 14.0 | 22.7 | 18.5 | 21.1 | 12.3 |
| Mo | 300.4 | 282.7 | 308.9 | 119.3 | 484.2 | 346.1 | 141.3 | 142.5 |
| Ag | 0.3 | 0.2 | 0.5 | 0.4 | 0.2 | 0.1 | 0.4 | 0.1 |
| Sn | 4.9 | 3.9 | 6.5 | 5.7 | 3.3 | 1.7 | 37.0 | 23.5 |
| La | 6.6 | 1.8 | 7.0 | 3.0 | 4.5 | 1.6 | 48.1 | 24.7 |
| Ce | 16.8 | 5.1 | 17.8 | 6.6 | 11.5 | 3.8 | 89.6 | 47.1 |
| Pr | 2.4 | 0.7 | 2.7 | 1.0 | 1.7 | 0.5 | 10.3 | 5.2 |
| Nd | 9.6 | 2.5 | 10.8 | 3.5 | 7.0 | 2.1 | 37.5 | 18.4 |
| Sm | 4.5 | 1.1 | 4.6 | 1.8 | 3.3 | 1.2 | 6.8 | 2.8 |
| Eu | 0.1 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 | 1.7 | 0.7 |
| Gd | 5.9 | 1.4 | 5.5 | 2.3 | 4.1 | 1.7 | 5.8 | 1.9 |
| Tb | 1.4 | 0.3 | 1.2 | 0.5 | 0.9 | 0.4 | 1.0 | 0.3 |
| Dy | 7.5 | 2.2 | 6.6 | 2.9 | 5.0 | 2.6 | 5.0 | 1.4 |
| Ho | 1.5 | 0.4 | 1.2 | 0.5 | 1.0 | 0.6 | 1.0 | 0.2 |
| Er | 4.2 | 1.6 | 3.6 | 1.7 | 3.0 | 1.8 | 2.7 | 0.6 |
| Lu | 0.7 | 0.3 | 0.6 | 0.3 | 0.5 | 0.3 | 0.4 | 0.1 |
| Hf | 3.5 | 1.4 | 3.9 | 0.1 | 2.1 | 1.7 | 3.6 | 1.0 |
| Tm | 0.7 | 0.2 | 0.6 | 0.3 | 0.5 | 0.3 | 0.4 | 0.1 |</p>
<table>
<thead>
<tr>
<th>Unit</th>
<th>QFP</th>
<th>Silicified QFP</th>
<th>QFP - brain rock</th>
<th>Diorite</th>
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<td>average st dev</td>
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Note: Most major elements were determined using laser ablation (ICP-MS) methods. See Appendix A for full description of analytical methods.
Table 6.2. (cont.)

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<td>0.56</td>
<td>98.48</td>
<td>1.07</td>
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</table>

Be (ppm)

| F    | 20.7 | 6.9 | 245.0 | 1070.3 | 281.6 | 487.4 | 12.0 | 13.0 |
| Sc   | 12.7 | 5.2 | 10.8  | 7.4    | 21.0  | 17.9  | 12.0 | 5.0  |
| V    | 274.0 | 164.4 | 170.7 | 121.9 | 125.2 | 28.9  | 85.0 | 119.0 |
| Cr   | 13.1 | 3.5 | 13.3  | 13.3   | 10.2  | 2.9   | 10.6 | 6.1  |
| Ni   | 55.7 | 30.9 | 35.1  | 31.8   | 21.3  | 5.8   | 30.0 | 30.0 |
| Cu   | 223.9 | 196.1 | 296.0 | 478.9 | 201.7 | 102.8 | 151.4 | 8.5  |
| Zn   | 107.3 | 45.4 | 351.3 | 782.9 | 184.8 | 145.7 | 270.0 | 44.0 |
| Ga   | 15.8 | 0.7 | 14.3  | 4.8    | 17.0  | 3.1   | 12.2 | 5.5  |
| Rb   | 45.9 | 25.4 | 140.2 | 171.8 | 371.4 | 225.6 | 31.7 | 1.1  |
| Sr   | 476.4 | 255.1 | 515.2 | 382.9 | 559.5 | 204.8 | 486.0 | 209.9 |
| Y    | 39.0 | 4.7 | 31.9  | 17.9   | 39.2  | 33.4  | 37.6 | 26.9 |
| Cs   | 3.7  | 0.9 | 15.1  | 37.7   | 42.7  | 37.7  | 1.7  | 0.2  |
| Zr   | 83.7 | 5.6 | 78.5  | 34.7   | 86.2  | 10.9  | 67.1 | 41.0 |
| Ba   | 199.7 | 109.7 | 973.7 | 1319.0 | 1063.5 | 775.4 | 448.1 | 9.1  |
| Nb   | 16.2 | 7.4 | 16.5  | 18.2   | 34.1  | 39.3  | 18.8 | 3.1  |
| Mo   | 216.2 | 93.3 | 233.0 | 207.7 | 240.8 | 166.6 | 388.2 | 53.3 |
| Ag   | 0.4  | 0.2 | 1.6   | 1.7    | 0.5   | 0.2   | 0.2  | <1   |
| Sn   | 48.0 | 31.6 | 50.6  | 51.3   | 31.8  | 24.0  | 9.0  | 58.0 |
| La   | 21.2 | 4.0 | 17.0  | 7.6    | 22.0  | 14.8  | 17.0 | 20.6 |
| Ce   | 33.3 | 5.9 | 27.8  | 12.3   | 48.8  | 37.0  | 27.1 | 17.7 |
| Pr   | 5.4  | 0.7 | 4.2   | 1.6    | 6.2   | 4.5   | 4.4  | 3.9  |
| Nd   | 21.4 | 2.1 | 16.5  | 5.8    | 23.1  | 15.2  | 18.1 | 15.2 |
| Sm   | 4.7  | 0.4 | 3.7   | 1.1    | 5.6   | 4.3   | 3.9  | 3.0  |
| Eu   | 1.0  | 0.2 | 0.8   | 0.3    | 1.0   | 0.3   | 0.8  | 0.7  |
| Gd   | 4.6  | 0.4 | 3.8   | 1.6    | 5.5   | 4.5   | 4.0  | 3.0  |
| Tb   | 0.9  | 0.1 | 0.8   | 0.4    | 1.1   | 1.0   | 0.8  | 0.5  |
| Dy   | 4.5  | 0.4 | 3.9   | 2.2    | 5.4   | 4.6   | 4.1  | 2.8  |
| Ho   | 1.0  | 0.1 | 0.8   | 0.5    | 1.1   | 0.9   | 0.8  | 0.6  |
| Er   | 2.7  | 0.4 | 2.2   | 1.3    | 2.8   | 2.2   | 2.4  | 1.8  |
| Tm   | 0.5  | 0.1 | 0.4   | 0.2    | 0.4   | 0.4   | 0.3  | 0.3  |
| Yb   | 2.9  | 0.5 | 2.4   | 1.4    | 2.9   | 2.2   | 2.3  | 1.6  |
Table 6.2. (cont.)

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Note: Most major elements were determined using laser ablation (ICP-MS) methods. See Appendix A for full description of analytical methods.
Table 6.3. Mo- and W-trioxide (wt.%) for the representative sample set.

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<th>WO₃ wt.%</th>
<th>sample</th>
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<td>0.013</td>
<td>QSM-13</td>
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See Appendix A for full description of analytical methods.
Fig. 6.3. W-content (ppm) in the representative sample set, plotted by host environment.
7 Modal analysis using the Rietveld Method

7.1 Sampling and analysis overview

Samples from the representative sample set used for the mineral chemistry study were returned in the form of pulps after whole-rock geochemical analysis (see section 6: Whole-rock geochemistry). The Rietveld method uses X-ray powder diffraction techniques to obtain relative amounts of mineral phases present in a sample; it is akin to modal percentage of a mineral. The purpose of using this technique in this study is to investigate the trends (if any) of the important mineral phases throughout the deposit, both by vein/host environment and by depth; the Rietveld method provides a very accurate, quantitative set of results to facilitate this process, and is much more efficient than mass balance calculations for each phase in every sample. The results will also help to confirm both historical and modern lithological classifications of Northern Dancer rocks, which are commonly extremely fine-grained and difficult to identify, sometimes even in polished section via petrography. In addition, Rietveld analysis combined with EPMA provides a mode of independent calculation of W grade in each sample. Results from those calculations may then be compared to whole-rock geochemical data as a check on accuracy, as assay results can be unreliable due to the fact that the analytical techniques employed may not fully digest certain mineral phases such as scheelite. This independent calculation is conducted below, and compared to whole-rock geochemical assay results for W.

The full analytical method is listed, along with a sample Rietveld refinement plot for one of the samples submitted, in the Appendix (section 10.1). The results of quantitative phase analysis by Rietveld refinement for all samples are given in Table 7.1. Please note that 'actinolite' could actually be amphibole, and possibly hornblende, as their structures are very similar (site occupancies were refined to reflect the phase composition as closely as possible). Clinohlore refers to the variety of chlorite found at Northern Dancer. The presence of two discrete peaks for andradite and grossular suggest the garnets are likely fluctuating between, or close to, the two end-member compositions via oscillatory zoning (see section 8: Mineralogy, Garnet), rather than being a homogenous, intermediate 'grandite' composition. Total garnet percentage equals the sum of the two end-member phase percentages.
Table 7.1. Rietveld results (wt.%), vein/host environment, and depth (m) of the representative sample set.

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7.2 Results from Rietveld analysis

The Rietveld data confirms historical rock description and classification, as observed by Stewart (1983), Noble (1982), and Noble et al. (1984). Data was sorted by vein/host environment and plotted by ore/important gangue mineral phase percentage versus environment to determine if there were any trends based on this variable, and average values are listed in Table 7.2. In Fig. 7.1, all main ore phases are plotted with important gangue mineral phases. For clarity, ore phases are plotted separately in Fig. 7.2, and gangue minerals are plotted separately in Fig. 7.3. While a larger sample set would be useful to make statistically robust statements concerning host environment’s effect on modal percentage of a mineral, some observations can be made.

In general, aside from quartz, calc-silicate rocks are dominantly composed of garnet, pyroxene, plagioclase, fluorite and wollastonite. Hornfels units are primarily composed of plagioclase, potassium feldspar, pyroxene, biotite and andradite. Wollastonite vesuvianite rocks are dominantly composed of wollastonite, pyroxene, andradite and vesuvianite. In calc-silicate, plagioclase content increases along with potassium feldspar and biotite content, with the introduction of Type 3 and 4 veins. In hornfels, plagioclase content decreases and potassium feldspar content increases with the introduction of Type 3 and 4 veins; garnet, pyroxene and pyrrhotite contents also decrease substantially when this occurs.

Muscovite is typically found only in the intrusive rocks; however, two samples of calc-silicate crosscut by Type 1 and 2 (early) veins contain ~3% muscovite and one sample of hornfels contained ~5% muscovite. Biotite averages ~0.2-1.3% in calc-silicate rocks, but within hornfels biotite abundance jumps to 5.7-6.1%. Clinohlore (chlorite) remains fairly constant throughout the units, between ~1 and 3%. Apatite also remains fairly constant, around ~0.5% throughout the calc-silicate rocks, but does not reach significant levels in the other units. Pyrite is highest within garnet-sulphide rich calc-silicate zones, where it averages 29.2% (~0.6-3.0% in other metamorphic units). Pyrrhotite is more abundant in hornfels units (0.4-1.1%) than calc-silicate rocks (0.4-0.6%).

Felsic intrusive rocks vary in their ratio of plagioclase:potassium feldspar:muscovite, which are the most abundant minerals in the felsic units. In general, the higher the silica content, the higher the potassium feldspar content, and the lower the plagioclase and muscovite contents.
Table 7.2. Rietveld results (wt.%) averaged for vein/host environment. Where $n = 1$, no standard deviation is listed.

<table>
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<tr>
<th>Mineral</th>
<th>CS +/- V1, V2</th>
<th>Gar-rich CS +/- V3, V4</th>
<th>Gar-rich CS +/- V2</th>
<th>Silicified CS/HF +/- veins</th>
<th>HF +/- V1, V2</th>
<th>HF +/- V4</th>
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Fig. 7.1. Plot of all important mineral phase (wt.) percentages versus vein/host environment.

Fig. 7.2. Plot of ore mineral phase (wt.) percentages and fluorite percentage versus vein/host environment.
The diorite is also rich in actinolite (amphibole) and biotite, and contains an average of 1.3% titanite. Felsite contains the highest amounts of pyrite in the intrusive rocks, averaging 4.3%, whereas the other units contain ~ 0.3-1.0% pyrite. The altered diorite contains an average of 3.9% pyrrhotite.

Magnetite was significant in three samples, two below 0.3% and one sample at 10.1%; this sample is particularly high in sulphides and represents the garnet-sulphide-rich calc-silicate host environment. The other two samples are quartz-feldspar porphyry. Ilmenite was significant in one sample only, at 0.4% within a calc-silicate rock crosscut by early veins. Stilbite (a zeolite) registered at 3.3% in one sample only; that of a calc-silicate absent of mineralizing veins.

Sphalerite and beryl are abundant only in host rocks containing Type 4 veins.

Scheelite is present in many of the samples at approximately 0.3-0.8%, but is abundant in a few samples (up to 12.0% in sample QSM-12, corresponding to a hornfels sample with large
Type 4 veins; see Fig. 7.2. Molybdenite reaches 1.8% in sample QSM-20, which corresponds to a calc-silicate rock with Type 3 and 4 veins. Molybdenite reaches local maxima in hornfels, garnet + sulphide-rich calc-silicate rocks, and quartz-feldspar porphyry containing Type 3 veins. Beryl shows no obvious trends with other ore minerals or host rock, suggesting its abundance is less affected by vein/host environment. Fluorite is most abundant in garnet and sulphide rich calc-silicate, registering 16.0%; this may indicate that it is the unit with the greatest degree of alteration within the wallrock from F-rich fluids likely sourced by the felsic intrusives. Fluorite is higher in most metasedimentary units containing Type 3 and 4 veins, and is always relatively lower in the same host rocks with only Type 1 and 2 veins. This suggests that fluorite development increases temporally and possibly that fluids are evolving to a more F-rich character. This phenomenon is also seen in mineral chemistry of garnet (see Mineralogy). Fluorite-rich rocks also appear to correspond to scheelite abundance (see below).

In a few instances in Fig 7.1, scheelite local maxima correspond with andradite local minima, but more data would be needed to suggest a possible correlation. In Fig 7.2, scheelite local maxima tend to correspond with fluorite maxima, suggesting that fluorite abundance may accompany scheelite abundance. Molybdenite appears to mildly follow an opposite correlation, reaching slight local maxima where fluorite hits local minima. This is particularly interesting within the metasedimentary hosts, where it is less likely that molybdenite is the only ore mineral phase in the veins, as it is commonly in felsic intrusive hosts.

In Fig. 7.3, garnet and pyroxene gangue minerals are plotted with fluorite. Within metasedimentary host rocks, both garnet end-member phase abundances (grossular and andradite) peak in similar locations. Diopside also appears to be abundant in similar locations as fluorite (and thus, scheelite), whereas andradite appears to hit local minima in the same locations. Therefore it is possible that a scheelite-fluorite-diopside correlation exists, especially in metasedimentary host rocks.

7.3 Effect of depth on mineral phase percentages

Results for both scheelite and fluorite were plotted by depth, and are shown in Figs. 7.4 and 7.5, to identify trends arising from depth within the deposit (samples range from between 8 and 280 m depth). No prominent trends are distinguishable, suggesting that a spatial analysis of mineral phase percentages either requires more detailed sampling, or that depth does not affect
the scheelite or fluorite content of the rock in a significant manner over the relatively small range of depth which is accessible by drilling. The latter assumption, combined with the distributions shown on Fig. 7.4, would imply that scheelite abundance remains fairly consistent within the data range, and that fluorite remains ubiquitous at depth (Fig. 7.5). Garnet and pyroxene phases are plotted versus depth in Fig. 7.6; the plot shows that these phases are ubiquitous at depth. This kind of detailed spatial study of mineral phases could be helpful if trends are found which suggested a mineral zonation pattern.

Skarn mineral zonation has been utilized as an exploration tool; for example, in Au skarns, gold is typically located in distal, lower-T pyroxene-rich skarn, while garnet-rich skarn proximal to the causative intrusion is barren of mineralization, such as at the Nickel Plate Mine in the Hedley District, British Columbia (Ettlinger et al. 1992). At Northern Dancer, spatial zonation (within both the metasedimentary rocks and the felsic dike complex) is likely very complex, but may be important to ore grade, as evidenced by the possible correlation of fluorite abundance and scheelite abundance in metasedimentary host rocks (see above). Sampling of a wider, systematic array of each vein/host type at various depths, instead of only a few representative samples at scattered depths, would give more of an indication if depth had an effect within certain vein/host environment regime.

7.4 Effect of garnet-pyroxene ratios on ore mineral percentage

As mentioned above, garnet and pyroxene ratios can be used as an exploration tool for ore deposits which show a correlation between this ratio and the location of mineralization. In Fig. 7.7, garnet percentage (andradite + grossular) over pyroxene (diopside + ‘actinolite’) percentage is plotted versus scheelite percentage via vein/host environment. The very highest scheelite percentages only occur where low garnet-pyroxene ratios occur, but in the regular range of scheelite values (between ~ 0.1 – 1.0%), the garnet-pyroxene ratio does not seem to correlate with mineralization. The distribution does rule out the possibility that high scheelite percentage corresponds to high garnet content, and the scatter may reflect the possibility of remobilization of W in hydrothermal fluids to other parts of the deposit (see section 8: Mineralogy, Scheelite). While it appears scheelite percentage does not fully depend on the garnet-pyroxene ratio of the host rock based on the scattered distribution in Fig. 7.7 (and evidenced by the fact that scheelite is found in veins within felsite which contains almost garnet or pyroxene), it does not rule out the
Fig. 7.4. Plot of scheelite (wt.) percentage versus depth, via vein/host environment.

Fig. 7.5. Plot of fluorite (wt.) percentage versus depth, via vein/host environment.
Fig. 7.6. Plot of garnet and pyroxene (wt.) percentages versus depth, via vein/host environment.

Fig. 7.7. Plot of garnet (andradite + grossular)/pyroxene (diopside + 'actinolite') ratio versus scheelite (wt.) percentage (via vein/host environment).
possibility that other mineral ratios may affect the scheelite percentage, such as the possible correlation between scheelite-diopside-fluorite observed above.

7.5 Rietveld and EPMA independent calculation: a check on accuracy of W assays

Tungsten grade (WO$_3$ wt.%) is usually calculated based on the sampling of drill core and assaying of tungsten via whole-rock geochemistry; unfortunately based on its high refractory properties, it is difficult to digest during sample preparation and therefore is commonly only partially digested during analysis, giving rise to low apparent W values. To test the accuracy of the geochemical results for W in this study, EPMA and Rietveld Method analysis were utilized in an external control calculation. Pulps used for geochemical assay were returned and submitted for Rietveld Method analysis (see Appendix, section 10.1), which produced a modal percentage of scheelite in each sample. Corresponding polished sections from each sample were then subjected to EPMA analysis, where the average percentage of W in scheelite was calculated for each section. Both techniques are highly accurate and rely on X-ray diffraction techniques, which are not reliant on complete digestion of W. Multiplying modal percentage of scheelite by the average percentage of W in scheelite for each sample gives an average WO$_3$ wt.% value (tungsten grade). This process was repeated for twenty test samples, and results are listed in Table 7.3 and shown in Fig. 7.8. The relative patterns match well; however, for samples with high W content, whole-rock geochemistry values are slightly lower than those calculated via EPMA and Rietveld, suggesting that while precise, whole-rock geochemistry may produce low apparent W grades. The effect is not significant enough to disvalue whole-rock assay results of this study, especially for a largely low-grade deposit such as Northern Dancer, where the grade is generally below 1% WO$_3$. However, for other very high-grade deposits, such as Cantung, this effect may be more pronounced and significantly affect assay results.

These results and conclusions would also generally apply to technical reports completed by Largo Resources, as the same Geochemical Lab and analytical procedure were used for their geochemical assays and subsequent grade calculation. This technique could be used for any tungsten deposit to test overall accuracy of W assay results, or any element which is difficult to analyze accurately by whole-rock analysis, however it is important to note that sample size and coarseness of grains would affect the accuracy of the Rietveld Method and geochemical results. Larger samples are preferable based on their more representative nature, especially where grain size is very coarse.
Table 7.3. Data table for the comparison of EPMA/Rietveld independent calculation of WO$_3$ wt.% (grade) to whole-rock geochemical assay values for WO$_3$ wt.%.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Scheelite % (Rietveld)</th>
<th>Avg. WO$_3$ wt.% (EPMA)</th>
<th>Calculated WO$_3$ wt.%</th>
<th>Grade (WO$_3$ wt.%) from WR</th>
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</thead>
<tbody>
<tr>
<td>Q-1</td>
<td>0.255</td>
<td>78.67</td>
<td>0.20</td>
<td>0.11</td>
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<tr>
<td>Q-2</td>
<td>0.373</td>
<td>79.57</td>
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<td>Q-3</td>
<td>0.703</td>
<td>74.33</td>
<td>0.52</td>
<td>0.60</td>
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<td>Q-5</td>
<td>0.231</td>
<td>74.62</td>
<td>0.17</td>
<td>0.33</td>
</tr>
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<td>Q-7</td>
<td>0.232</td>
<td>77.54</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Q-8</td>
<td>0.146</td>
<td>78.46</td>
<td>0.11</td>
<td>0.14</td>
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<tr>
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<td>0.101</td>
<td>79.02</td>
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<td>Q-10</td>
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<tr>
<td>Q-11</td>
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<td>0.59</td>
<td>0.62</td>
</tr>
<tr>
<td>Q-12</td>
<td>11.991</td>
<td>78.53</td>
<td>9.42</td>
<td>6.01</td>
</tr>
<tr>
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<td>0.19</td>
</tr>
<tr>
<td>Q-23</td>
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<td>Lt-FIS V3B</td>
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<td>76.83</td>
<td>1.62</td>
<td>1.44</td>
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</tbody>
</table>

Fig. 7.8. Plot of whole-rock geochemical W-assay values and Rietveld-EPMA calculated W-content values (WO$_3$ wt.%), for twenty representative samples.
8 Mineralogy

8.1 Mineralogy overview

The mineral chemistry study focuses on the central zone of mineralization defined by Noble et al. (1984), as was completed using the representative sample set selected from recent drill core. The samples were chosen first for representative lithologies and vein set environments, and then for exemplary vein crosscutting relationships. The 52 representative samples are listed with their depths and general vein/host environments in Table 7.1 in section 7.2 (Rietveld analysis).

Polished sections were cut from each sample, as well as selected doubly polished sections (for fluid inclusion analysis). Each section was scanned into a digital image using a Nikon slide scanner and then printed on high-quality photo paper for use as a probe and SEM ‘map’. Petrographic observations were made using optical microscopy and SEM, and qualitative mineralogical information such as texture, approximate composition, grain/crystal size, and revealed alteration and zonation was obtained. Electron microprobe analysis (or EMPA) on ore, vein and gangue minerals was initiated after the 52 samples were petrographically characterized, and results from each mineral analysis are presented and discussed below. Analytical methods for EPMA are discussed in Appendix 12.1.

8.2 Mineral chemistry

8.2.1 Apatite

Apatite is a ubiquitous, if fine-grained, accessory mineral at Northern Dancer. It is never visible in outcrop and crystals are always less than 1 mm in diameter. It can occur in every rock unit, and is found in most vein alteration haloes, but it is most abundant in thick Type 4 veins and in zones of silica alteration or ‘brain rock’. In quartz-feldspar porphyry it can occur as euhedral, zoned intergrowths with potassium feldspar, where the zoning is due to trace amounts of La and Ce (and occasionally Th and Nd; Fig. 8.1). Occasionally, it occurs in radial sprays which originate from the cores of pseudo-phenocrysts in transitional zones between quartz
Fig. 8.1. Backscatter SEM image of zoned apatite in quartz-feldspar porphyry. Compositional zoning is due to variations in trace amounts of REE's such as La and Ce.

Fig. 8.2. Backscatter SEM image of quartz porphyry unit within the felsic dikes. Quartz phenocrysts and fine-grained quartz-feldspar matrix are overprinted by radial sprays of apatite crystals, which appear to originate from zones of silica flooding/alteration. Needles of apatite are occasionally intergrown with rare blebs of pyrite and Ce- and La-rich xenotime.
porphyry and 'brain rock' (Fig. 8.2). Possibly, it is part of the same event as the silica 'flooding'. These radial sprays consist of long, fine needles which can occasionally be intergrown with small blebs of pyrite or La- or Ce-rich xenotime. Commonly, these radial sprays within the quartz phenocrysts extend further than the crystal grain boundaries, into the older felsic porphyry dikes or matrix (Fig. 8.3). Apatite in Type 4 veins is typically euhedral, and can be intergrown with beryl and scheelite, which is also intergrown (Fig. 8.4).

In calc-silicate host rocks which have been silicically altered, fine-grained plagioclase, calcite, and amphibole groundmass appears to be altering into a myrmekitic exsolution of garnet, fluorite, and apatite (Fig. 8.5). This texture is very fine-grained and fairly rare, but suggests that quartz, fluorite, and apatite are part of later alteration events, which are linked to the emplacement of the 'brain rock' and Type 4 veins.

One hundred and fifteen electron microprobe analyses were obtained from 24 apatite crystals/grains in five different polished sections and nine different vein/host environments. The analyses were recalculated on the basis of 13 anions, assuming 1 (OH, F, Cl), per formula unit (apfu). Fluorine content can be difficult to analyze accurately in apatite via EPMA, based on its tendency to migrate out of the apatite crystal when bombarded by an electron beam. To counter this effect, five analysis points (10 μm wide) on each grain were collected at 15 kV and 10nA. For each of the grains, these five points (F % composition) were then plotted versus time (t), and a linear regression trend-line was used to estimate the F content at t = zero. This approach gives the most accurate F content possible. The estimated original F contents were averaged in the same way as other elements analyzed for in apatite (by grain). These were then sorted by host rock/ vein environment. Fluorine content in apatite at Northern Dancer exceeds the maximum possible F content in apatite possible from stoichiometry (1 F apfu, or 3.77 wt.% F), suggesting this approach is not sufficient to render accurate fluorine data in this case. This problem is ubiquitous in the literature, and thus, fluorine results are reported to show relative trends, and do not reflect accurate F contents. The results are given in Table 8.1. Low totals in certain environments, such as the radial apatite occurring within quartz porphyry rocks, are possibly due to alteration such as silicification.

Apatite at Northern Dancer is rich in fluorine, characterizing them as fluorapatite; the deposit-wide average is 4.15 wt.% F (1.120 F apfu). Fluorine contents range from 2.07 wt.% F (0.647 F apfu) in altered diorite, to 5.19 wt.% F (1.246 F apfu) in euhedral apatite in Type 4 veins. A deposit maximum of 5.43 wt.% F (1.374 F apfu) was noted in a euhedral grain
Fig. 8.3. Backscatter SEM image of disseminated apatite overprinting porphyritic texture in a quartz-feldspar porphyry dike.

Fig. 8.4. Polished section QSM-12 in plane-polarized light: coarse-grained, euhedral apatite intergrown with euhedral scheelite near the edge of a thick Type 4 vein, within altered hornfels.
associated with scheelite in a thick Type 4 vein crosscutting altered hornfels (as seen in Fig. 8.4). This suggests that F is highest in the later stages of the deposit, and that fluids responsible for mineral formation within the veins are possibly increasingly F-rich over time. Chlorine is insignificant (below 0.02 wt.% Cl or 0.003 Cl apfu) in all units except the altered diorite. Here, euhedral apatite associated with biotite, plagioclase, and titanite reaches a maximum content of 1.14 wt.% Cl (0.167 Cl apfu), and averages 0.79 wt.% Cl (0.116 Cl apfu). This apatite is also F-rich, averaging 2.07 wt.% F (0.647 F apfu), so it is closer to the fluorapatite end-member, versus chlorapatite. This may be a function of the original Cl content of the diorite, which could have been remobilized during hydrothermal alteration, and reincorporated into apatite.

Iron content is high in euhedral inclusions of apatite in biotite within the monzonite unit and within the altered calc-silicate, averaging 0.21 and 0.27 wt.% FeO (0.015 and 0.019 Fe apfu), respectively. A maximum of 0.42 wt.% FeO (0.03 Fe apfu) occurs in one inclusion in biotite. Iron content is below 0.10 wt.% FeO (Fe apfu) in all other environments. The MnO content in apatite is very low in altered diorite and calc-silicate rocks, averaging 0.05 wt.% MnO (0.004 Mn apfu) and 0.02 wt.% MnO (0.001 Mn apfu) respectively, but is slightly higher in other environments, between 0.23 wt.% MnO (0.018 Mn apfu) and 0.39 wt.% MnO (0.028 Mn apfu).
Table 8.1. Average compositions of apatite samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td></td>
<td>average</td>
<td>st. dev.</td>
<td>average</td>
<td>st. dev.</td>
<td>average</td>
<td>st. dev.</td>
<td>average</td>
<td>st. dev.</td>
</tr>
<tr>
<td>SO₃ (wt. %)</td>
<td>0.02</td>
<td>0.01</td>
<td>0.31</td>
<td>0.16</td>
<td>0.23</td>
<td>0.15</td>
<td>0.04</td>
<td>0.04</td>
</tr>
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<td>P₂O₅</td>
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<td>0.22</td>
<td>39.91</td>
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<td>39.07</td>
<td>1.21</td>
<td>39.43</td>
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<td>Al₂O₃</td>
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<td>0.00</td>
<td>0.01</td>
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<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>MgO</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
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<td>0.01</td>
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<td>Total</td>
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|                   | average | st. dev. | average | st. dev. | average | st. dev. | average | st. dev. |
| S^{6+} (apfu)     | 0.002   | 0.001    | 0.020   | 0.010    | 0.015   | 0.010    | 0.003   | 0.002    |
| P^{5+}           | 2.971   | 0.009    | 2.908   | 0.010    | 2.930   | 0.025    | 2.953   | 0.014    |
| Al^{3+}          | 0.001   | 0.000    | 0.001   | 0.001    | 0.008   | 0.008    | 0.000   | 0.000    |
| Mg^{2+}          | 0.002   | 0.001    | 0.002   | 0.000    | 0.001   | 0.001    | 0.001   | 0.001    |
| Ca^{2+}          | 4.934   | 0.009    | 4.834   | 0.032    | 4.997   | 0.050    | 5.013   | 0.023    |
| Mn^{2+}          | 0.028   | 0.003    | 0.027   | 0.005    | 0.028   | 0.000    | 0.022   | 0.004    |
| Fe^{2+}          | 0.007   | 0.005    | 0.015   | 0.011    | 0.005   | 0.001    | 0.006   | 0.006    |
| Sr^{2+}          | 0.000   | 0.000    | 0.000   | 0.000    | 0.000   | 0.000    | 0.000   | 0.000    |
| F                | 1.179   | 0.048    | 1.359   | 0.099    | 1.159   | 0.057    | 1.132   | 0.016    |
| Cl               | 0.002   | 0.001    | 0.003   | 0.002    | 0.002   | 0.000    | 0.001   | 0.001    |
| H^{+}            | 0.000   | 0.000    | 0.000   | 0.000    | 0.000   | 0.000    | 0.000   | 0.000    |
| O^{2-}           | 11.819  | 0.048    | 11.638  | 0.099    | 11.838  | 0.058    | 11.868  | 0.016    |

Note: The following standards were used: barite (SKα), apatite (PKα, CaKα, FKα), diopside (MgKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), SrTiO₃ (SrLα), albite (NaKα), and scapolite (ClKα).

* Determined by stoichiometry, H₂O calculated assuming 1(OH-, F-, Cl-)

Formula contents recalculated on the basis of 13 anions pfu.
Table 8.1. (cont.)

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<th>Vein/host env.</th>
<th>Radial apatite sprays, in QFP</th>
<th>Radial apatite sprays, in QFP</th>
<th>Apatite assoc. w/ sch in Type 4 vein, in HF</th>
<th>Apatite assoc. w/ sch in Type 4 vein, in HF</th>
<th>Apatite at wall of Type 4 vein, in HF</th>
<th>Apatite at wall of Type 4 vein, in HF</th>
<th>Apatite assoc. w/ biot, plag, titan, in dior.</th>
<th>Apatite assoc. w/ biot, plag, titan, in dior.</th>
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<td>0.02</td>
<td>0.10</td>
<td>0.03</td>
</tr>
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<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>H₂O*</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.41</td>
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</tr>
<tr>
<td>F</td>
<td>3.84</td>
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<td>5.19</td>
<td>0.18</td>
<td>3.91</td>
<td>0.00</td>
<td>2.07</td>
<td>0.17</td>
</tr>
<tr>
<td>Cl</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.79</td>
<td>0.20</td>
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<tr>
<td>O=Cl</td>
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<td>-2.00</td>
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<td>-1.78</td>
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<td>0.51</td>
<td>100.53</td>
<td>0.44</td>
<td>99.89</td>
<td>0.71</td>
<td>98.16</td>
<td>0.25</td>
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| S(S) (apfu)    | 0.002                       | 0.003                       | 0.003                          | 0.001                           | 0.004                          | 0.002                          | 0.007                          | 0.003                          |
| P(V)           | 3.015                       | 0.032                       | 2.963                          | 0.013                           | 2.983                          | 0.023                          | 2.986                          | 0.004                          |
| Al(III)        | 0.001                      | 0.001                      | 0.001                          | 0.000                           | 0.001                          | 0.001                          | 0.001                          | 0.001                          |
| Mg(II)         | 0.001                      | 0.001                      | 0.001                          | 0.001                           | 0.002                          | 0.002                          | 0.001                          | 0.001                          |
| Ca(II)         | 4.822                      | 0.076                      | 4.927                          | 0.041                           | 4.937                          | 0.051                          | 5.000                          | 0.011                          |
| Mn(II)         | 0.018                      | 0.005                      | 0.020                          | 0.004                           | 0.023                          | 0.006                          | 0.004                          | 0.001                          |
| Fe(II)         | 0.003                      | 0.003                      | 0.003                          | 0.001                           | 0.003                          | 0.002                          | 0.007                          | 0.002                          |
| Sr(II)         | 0.000                      | 0.000                      | 0.000                          | 0.000                           | 0.000                          | 0.000                          | 0.000                          | 0.000                          |
| F⁻              | 1.210                      | 0.051                      | 1.246                          | 0.066                           | 1.121                          | 0.038                          | 0.647                          | 0.098                          |
| Cl⁻            | 0.002                      | 0.002                      | 0.001                          | 0.001                           | 0.001                          | 0.002                          | 0.116                          | 0.030                          |
| H⁺              | 0.000                      | 0.000                      | 0.000                          | 0.000                           | 0.000                          | 0.000                          | 0.237                          | 0.074                          |
| O²⁻             | 11.788                     | 0.050                      | 11.752                         | 0.066                           | 11.878                         | 0.038                          | 12.237                         | 0.074                          |

Note: The following standards were used: barite (SKα), apatite (PKα, CaKα, FKα), diopside (MgKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), SrTiO₃ (SrLa), albite (NaKα), and scapolite (ClKα).

* Determined by stoichiometry, H₂O calculated assuming 1(OH-, F-, Cl⁻)
Formula contents recalculated on the basis of 13 anions pfu.
Table 8.1. (cont.)

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>Anhedral apatite in alt./sil. CS</th>
<th>Anhedral apatite in alt./sil. CS</th>
</tr>
</thead>
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<tr>
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<td>st. dev.</td>
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<tr>
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</tr>
<tr>
<td>$\text{SO}_3$ (wt. %)</td>
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<td>0.01</td>
</tr>
<tr>
<td>$\text{P}_2\text{O}_5$</td>
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<td>0.69</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
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<td>0.04</td>
</tr>
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<td>$\text{MgO}$</td>
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<td>0.00</td>
</tr>
<tr>
<td>$\text{CaO}$</td>
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<td>0.50</td>
</tr>
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<td>$\text{MnO}$</td>
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<td></td>
</tr>
<tr>
<td>$\text{FeO}$</td>
<td>0.27</td>
<td>0.16</td>
</tr>
<tr>
<td>$\text{SrO}$</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}^*$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{F}$</td>
<td>4.66</td>
<td>0.03</td>
</tr>
<tr>
<td>$\text{Cl}$</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{O=Cl}$</td>
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<tr>
<td>Total</td>
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<td>1.02</td>
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<tr>
<td>$\text{S}^{6+}$ (apfu)</td>
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<tr>
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<tr>
<td>$\text{Al}^{3+}$</td>
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<td>0.004</td>
</tr>
<tr>
<td>$\text{Mg}^{2+}$</td>
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<td>$\text{Ca}^{2+}$</td>
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<tr>
<td>$\text{Mn}^{2+}$</td>
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<td>0.001</td>
</tr>
<tr>
<td>$\text{Fe}^{2+}$</td>
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<td>0.012</td>
</tr>
<tr>
<td>$\text{Sr}^{2+}$</td>
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<td>0.002</td>
</tr>
<tr>
<td>$\text{F}$</td>
<td>1.177</td>
<td>0.024</td>
</tr>
<tr>
<td>$\text{Cl}^-$</td>
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<td>0.000</td>
</tr>
<tr>
<td>$\text{H}^+$</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$\text{O}^{2-}$</td>
<td>11.822</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Note: The following standards were used: barite (SKα), apatite (PKα, CaKα, FKα), diopside (MgKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), SrTiO₃ (SrLα), albite (NaKα), and scapolite (ClKα).

* Determined by stoichiometry, $\text{H}_2\text{O}$ calculated assuming 1(OH-, F-, Cl-)

Formula contents recalculated on the basis of 13 anions $\text{pfu}$. 
Apatite which appears to be overprinting quartz-feldspar porphyry is very slightly enriched in REE's such as La, Ce, and more rarely Th and Nd.

8.2.2 Beryl

Beryl occurs in Type 4 veins, in both the central zone of polymetallic sheeted veins (quartz-beryl-scheelite-molybdenite veins), and distal beryl-wolframite sheeted veins to the southwest. Type 4 veins in calc-silicate and hornfels host rocks contain more beryl than felsic dike hosted veins; however beryl occurs consistently throughout the deposit and at depth. It is usually blue or rarely blue-green in colour, and averages 1-3 mm wide but euohedral crystals occur up to 4.2 cm wide. Near surface, beryl is fractured and milky-blue, becoming gemmy and less-fractured with increasing depth. (however, no gem beryl from Northern Dancer is known to have been cut). Blue gemmy beryl was noted at a depth of 320 m, at the bottom of drillhole LT-06-61, suggesting beryl mineralization continues at depth (Fig. 8.6). Commonly beryl will occur as euohedral crystals growing into the vein core, perpendicular to and originating at the vein wall. Beryl is typically associated with fluorite, massive sulphide (molybdenite, pyrrhotite, pyrite, sphalerite, galena and chalcopyrite), and occasionally intergrown with scheelite and/or molybdenite (Fig. 8.7). In rare cases, 2 mm-wide pure blue massive beryl veins occur (quartz-free) in felsite, containing accessory purple fluorite and fine-grained muscovite (Fig. 8.8). These thin beryl veins occur parallel to molybdenite fractures (Type 3 veins). Rare magmatic beryl also occurs at the margins of the monzogranite body, near the contact with hornfels and calc-silicate rocks. It is occasionally milky bluish-white in colour and individual crystals can be up to 0.8 cm in width.

Two polished sections from the mineralogical study representative sample set contained beryl in Type 4 sheeted veins. Preliminary investigation by scanning electron microscope (SEM) using backscatter electron imaging mode showed slight compositional zoning based on Fe-content in some euohedral beryl crystals, with slightly higher Fe concentrations in the rims (Fig 8.9). Beryl in the wall of the vein in polished section LT-FIS-V4B has wollastonite and garnet inclusions approximately 15 and 25 µm across, respectively. Very fine-grained Fe-rich garnet appears along euohedral growth zones in beryl in this section. Some beryl in this section is altering extensively to wollastonite (or a Be-Ca-silicate) and contains carbonate inclusions near the rims. Infilling of sulphide minerals (pyrite, chalcopyrite, sphalerite, galena) occurs around
Fig. 8.6. Blue beryl with pyrite and biotite in Type 4 vein, in calc-silicate host. Blue, gemmy beryl was noted at a depth of 320 m, at the bottom of drillhole LT-06-61, suggesting beryl mineralization continues at depth.

Fig. 8.7. Euhedral beryl at Type 4 vein wall, in calc-silicate host. Commonly beryl will occur as euhedral crystals growing into the vein core, perpendicular to and originating at the vein wall. Beryl is typically associated with fluorite, massive sulphide (molybdenite, pyrrhotite, pyrite, sphalerite, galena and chalcopyrite), and occasionally it may be intergrown with scheelite, rutile, chlorite and/or molybdenite.
Fig. 8.8. Massive blue beryl vein in felsite. In rare cases, 2 mm-wide pure blue massive beryl veins occur (quartz-free) in felsite, containing accessory purple fluorite and fine-grained muscovite. These thin beryl veins usually occur parallel to molybdenite fractures (Type 3 veins). Some beryl veins can be up to cm wide in metasedimentary hosts (see Fig. 4.5, c from section 4: Veins).

Fig 8.9. SEM image (in backscatter mode) of zoned, euhedral beryl in Type 4 vein, in calc-silicate host. Compositional zoning in beryl is based on Fe-content in some euhedral beryl crystals, with slightly higher Fe concentrations in the rims. Euhedral beryl grains, possibly where open space existed prior to sulphide deposition. Rarely, small chalcopyrite and pyrite inclusions (less than 10 μm) occur in the beryl. In one area, beryl is associated with a radiating aggregate of calcite, sphalerite, and helvite-danalite [(Mn,Fe,Zn)\(_8\)Be\(_6\)Si\(_6\)O\(_{24}\)S\(_2\)] about 2 mm across (Fig. 8.10). Well-developed liquid-vapour fluid
Inclusions (possibly primary) were identified using a petrographic microscope, in growth zones of euhedral beryl in section QSM-28, along with crosscutting planes of (likely secondary) liquid vapour fluid inclusions (Fig. 8.11). Future work should include analysis of these fluid inclusions for P-T data, as well as fluid compositional information.

Thirty-five electron microprobe analyses were obtained from 16 beryl crystals/grains in two different polished sections containing Type 4 veins. The analyses were recalculated on the basis of 18 O and three Be atoms per formula unit (apfu). This approach gives the maximum possible Be content and ignores possible substitution at the Be site. Water was calculated using the equation of Giuliani et al. (1997): calculated $\text{H}_2\text{O} = (0.84958 \times \text{Na}_2\text{O}) + 0.8373$. Results of the analysis are given in Table 8.2. Iron content, which is likely responsible for the blue colour, averages 1.48 wt.% FeO (or 0.12 Fe apfu) but fluctuates between 0.72 and 2.44 wt.% FeO (or 0.06 and 0.19 Fe apfu, respectively). Chromium content is negligible (less than 0.001 Cr apfu) and vanadium is very low (averaging 0.07 wt.% V$_2$O$_3$, or 0.01 V apfu). MgO content averages 0.61 wt.% with a maximum content of 0.75 wt.% (0.08 and 0.10 Mg apfu, respectively). Beryl also shows average Na$_2$O and Cs$_2$O contents of 0.78 and 0.12 wt. % (0.14 Na and 0.01 Cs apfu).
Fig. 8.12 ('AlvsYsite') shows Al (apfu) versus the sum of other Y-site (octahedral) cations plotted by host/vein environment. Beryl compositions from Northern Dancer show a 1:1 inverse correlation, as expected. No analyses fall above the line, indicating there is no apparent substitution of these cations (Mg, Sc, Mn, Fe, Cr and V) into a different site. Samples with the highest Al content are those intergrown with Type 4 vein scheelite, while altered beryl and those with garnet inclusions along growth planes show the highest degree of cation substitution at the octahedral site. In Fig. 8.13, divalent cations (Mg, Mn and Fe) are plotted versus monovalent cations (Na, K, Cs), most of the analyses fall below the line which indicates that this beryl contains no Li$^{3+}$, but contains some trivalent iron. Altered beryl and garnet-included beryl are displaced furthest from the line, indicating these grains have the highest Fe$^{3+}$ content.

Fig. 8.11. Images of fluid inclusions in beryl. (a) euhedral beryl from a Type 4 vein containing a large, possibly primary fluid inclusion. (b) multiple elongate, euhedral beryl crystals growing perpendicular to a Type 4 vein wall, with some isolated, larger fluid inclusions as well as trails of much smaller, likely secondary fluid inclusions.
Table 8.2. Average compositions of beryl samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>Altered beryl (woll.)</th>
<th>V4 assc. w/ sch</th>
<th>V4 w/ gt incl.</th>
<th>V4 in hornfels</th>
<th>V4 at wall in hornfels</th>
<th>V4 at wall in CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
</tr>
<tr>
<td>SiO_2 (wt.%)</td>
<td>64.51 0.14 4 4</td>
<td>64.73 0.09 3 3</td>
<td>64.31 0.23 5 5</td>
<td>64.53 0.15 7 7</td>
<td>64.53 0.06 2 2</td>
<td>64.45 0.37 15 15</td>
</tr>
<tr>
<td>Al_2O_3</td>
<td>17.07 0.23 2</td>
<td>16.91 0.27 4</td>
<td>16.49 0.24 5</td>
<td>17.04 0.31 7</td>
<td>16.76 0.06 2</td>
<td>16.56 0.62 15</td>
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<td>0.10 0.00 2</td>
<td>0.05 0.02 15</td>
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<tr>
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<td>0.02 0.01 2</td>
<td>0.01 0.01 15</td>
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<td>BeO*</td>
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<td>0.62 0.07 5</td>
<td>0.60 0.03 7</td>
<td>0.56 0.00 2</td>
<td>0.61 0.12 15</td>
</tr>
<tr>
<td>FeO</td>
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<td>1.17 0.22 3</td>
<td>1.58 0.20 5</td>
<td>1.09 0.39 7</td>
<td>1.22 0.28 2</td>
<td>1.87 0.48 15</td>
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<tr>
<td>Na_2O</td>
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<td>0.83 0.02 3</td>
<td>0.81 0.14 5</td>
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<td>0.86 0.04 2</td>
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<tr>
<td>K_2O</td>
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<td>0.06 0.00 3</td>
<td>0.07 0.01 5</td>
<td>0.06 0.01 7</td>
<td>0.05 0.01 2</td>
<td>0.06 0.02 15</td>
</tr>
<tr>
<td>Cs_2O</td>
<td>0.06 0.03 2</td>
<td>0.10 0.02 3</td>
<td>0.10 0.01 5</td>
<td>0.07 0.02 7</td>
<td>0.11 0.00 2</td>
<td>0.17 0.06 15</td>
</tr>
<tr>
<td>H_2O†</td>
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<td>1.55 0.01 3</td>
<td>1.53 0.12 5</td>
<td>1.45 0.03 7</td>
<td>1.56 0.03 2</td>
<td>1.51 0.10 15</td>
</tr>
<tr>
<td>Total</td>
<td>99.08 0.11 4</td>
<td>99.65 0.10 3</td>
<td>99.12 0.14 5</td>
<td>99.19 0.32 7</td>
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<td>99.63 0.42 15</td>
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<th>Si_4+ (apfu)</th>
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<th>V_3+</th>
<th>Cr_3+</th>
<th>Be_2+</th>
<th>Mg_2+</th>
<th>Fe(tot)</th>
<th>Na+</th>
<th>K+</th>
<th>CS+</th>
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<td>0.000 0.000 1</td>
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<td>0.083 0.007 1</td>
<td>0.080 0.027 1</td>
<td>0.131 0.011 1</td>
<td>0.007 0.001 1</td>
<td>0.002 0.001 1</td>
</tr>
</tbody>
</table>

Note: The following standards were used: albite (SiKa, AlKa, NaKa), V metal (VKa), MgCr_2O_4 (CrKa), diopside (MgKa), fayalite (FeKa), orthoclase (KKa), and pollucite (CsLa).

*Determined by stoichiometry.
†Calculated using H_2O = (0.84958 x Na_2O) + 0.8373 (Giuliani et al. 1997).
Fig. 8.12. Al (apfu) versus the sum of other Y-site (octahedral) cations plotted by host/vein environment in beryl. Beryl compositions from Northern Dancer show a 1:1 inverse correlation. No analyses fall above the line, indicating there is no apparent substitution of these cations (Mg, Sc, Mn, Fe, Cr and V) into a different site. Samples with the highest Al content are those intergrown with Type 4 vein scheelite, while altered beryl and those with garnet inclusions along growth planes show the highest degree of cation substitution at the octahedral site.

Fig. 8.13. Divalent cations (Mg, Mn and Fe) are plotted versus monovalent cations (Na, K, Cs) in beryl. Most of the analyses fall below the line which indicates that this beryl contains no Li$^{3+}$, but contains some trivalent iron. Altered beryl and garnet-included beryl are displaced furthest from the line, indicating these grains have the highest Fe$^{3+}$ content.
8.2.3 Epidote, clinozoisite, and allanite

8.2.3.1 Epidote

Epidote is a significant vein mineral and alteration component at Northern Dancer, as it is one of the few hydrous minerals associated with mineralization. It is dominantly found in the Type 2 veins (quartz-pyrite-scheelite veins), but is also found as a minor component in most other veins. In Type 1 veins it is rare, usually fine-grained, and occurs with fine-grained garnet and pyroxene. In Type 2 veins, it typically occurs as sub-anhedral masses up to 5 mm in the cores of veins; however, it can also be found in Type 2 and 4 vein alteration haloes, and rarely, as rims around subhedral pyrite grains within those haloes. In reopened Type 2 veins, there are some zones of massive plagioclase/albite at the vein selvedge; at these locations epidote and pyrite also occur, possibly indicating later sodic alteration (albitization). Type 3 veins contain epidote only when they extend into metasedimentary host rocks, and epidote can be associated with garnet and molybdenite. Type 4 veins typically only contain accessory amounts of epidote, usually occurring as subhedral grains with chlorite and albite. Occasionally, epidote is associated with scheelite and fluorite.

In zones of calc-silicate where there is a high density of cross-cutting Type 2 veins, epidote can be a major component of the groundmass (QSM-30 – points Q30-1 and 2) which is almost completely altered by the overprinting alteration haloes. It can occur as a groundmass component in zones of calc-silicate (and occasionally hornfels – QSM-12) which have been silicified, such as in Fig. 8.14. Here, anhedral, massive epidote occurs with quartz, fluorite, coarse-grained anhedral garnet, calcite and pyrite. A reaction front is visible between a zone of potassium feldspar + plagioclase and epidote + albite + calcite. Although epidote is typically associated with retrograde events in metamorphic rocks, this epidote (along with albite) is more likely alteration product from the breakdown of potassium feldspar during albitization (or sodic alteration). This process might have occurred as late fluids associated with the final felsic dike phases infiltrated brittle reaction skarn along planes of weakness or very thin fractures, rather than defined veins. This may be mineralogically comparable to propylitic (quartz-epidote-chlorite) alteration styles seen in Cu-Mo porphyry deposits (Thompson & Thompson 1996). It is also possible that high F activity may produce ‘retrograde’ mineral assemblages at much higher temperatures (Meinert et al. 2005).
Fig. 8.14. Polished section QSM-23 in plane-polarized light: relict isoclinal folding (pre-skarn) is visible in metasedimentary host rocks. Skarn alteration (to calc-silicate) is visible and consists of a garnet-quartz-pyroxene mineral assemblage. A fine-grained quartz-epidote reaction front is also visible, along with pods of pyrite and pyrrhotite. This may reflect the infiltration of fluids associated with the porphyry veins, following weaknesses in the earlier, more brittle, reaction skarn instead of a defined vein or fracture.

In silicified calc-silicate, especially coarse-grained zones, epidote, fluorite and apatite can account for a major percentage of the groundmass. Garnet-dominant skarn is generally lower in epidote content than pyroxene-rich skarn, however this may simply be a result of the relative locations of the diorite intrusive and resulting mineralogical skarn zones versus the extent of the alteration induced by the monzonite and mineralization events.

Forty-eight electron microprobe analyses were obtained from 27 grains in four different polished sections. The analyses were recalculated on the basis of 13 anions (including 1 OH−) per formula unit. Results of the analysis, grouped by vein/host environment, are given in Table 8.3. Average iron contents vary from 14.47 wt.% Fe₂O₃ or 1.01 Fe³⁺ apfu in the groundmass of calc-silicate skarn crosscut by abundant Type 2 veins, to 17.53 wt.% Fe₂O₃ or 1.07 Fe³⁺ apfu (max. 19.41 wt.% Fe₂O₃ or 1.19 Fe³⁺ apfu) in reopened Type 2 veins, where the epidote is associated with pyrite and chalcopyrite. Epidote inclusions in scheelite within Type 2 veins are also high in iron, averaging 16.36 wt.% Fe₂O₃ or 0.99 Fe³⁺ apfu and reaching a maximum of 18.32 wt.% Fe₂O₃ or 1.12 Fe³⁺ apfu. Epidote is zoned in the cores of reopened Type 2 veins, with grain cores showing higher Fe content and rims showing lower (e.g. in one grain in section QSM-8, the core was 15.60 wt.% Fe₂O₃ or 0.96 Fe³⁺ apfu, mid-grain was 14.31 wt.% Fe₂O₃ or 0.88 Fe³⁺ apfu, and the rim was 13.63 wt.% Fe₂O₃ or 0.83 Fe³⁺ apfu). Overall, epidote
Table 8.3. Average compositions of epidote samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>Reopened Type 2 vein core (calc-sil. host)</th>
<th>Reopened Type 2 vein core, w/ pyr</th>
<th>Reopened Type 2 vein core, near sch.</th>
<th>Ep incl. in sch.(reopened Type 2 vein)</th>
<th>Reopened Type 2 vein selvedge</th>
<th>Type 2 vein alteration halo</th>
<th>Type 2 vein selvedge</th>
<th>Ground-mass of CS, many Type 2 veins</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
<td></td>
<td>36.99</td>
<td>0.30</td>
<td>37.03</td>
<td>0.29</td>
<td>37.05</td>
<td>0.38</td>
<td>37.30</td>
</tr>
<tr>
<td>TiO₂</td>
<td></td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td></td>
<td>21.75</td>
<td>0.62</td>
<td>20.01</td>
<td>1.03</td>
<td>21.00</td>
<td>0.50</td>
<td>20.88</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td></td>
<td>14.67</td>
<td>0.69</td>
<td>17.53</td>
<td>1.35</td>
<td>16.21</td>
<td>0.61</td>
<td>16.36</td>
</tr>
<tr>
<td>MnO</td>
<td></td>
<td>0.63</td>
<td>0.27</td>
<td>0.27</td>
<td>0.12</td>
<td>0.46</td>
<td>0.08</td>
<td>0.21</td>
</tr>
<tr>
<td>MgO</td>
<td></td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
<td>0.01</td>
<td>0.06</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>CaO</td>
<td></td>
<td>22.41</td>
<td>0.44</td>
<td>22.78</td>
<td>0.10</td>
<td>22.38</td>
<td>0.30</td>
<td>22.93</td>
</tr>
<tr>
<td>H₂O*</td>
<td></td>
<td>1.84</td>
<td>0.01</td>
<td>1.85</td>
<td>0.00</td>
<td>1.85</td>
<td>0.01</td>
<td>1.86</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>98.42</td>
<td>0.61</td>
<td>99.61</td>
<td>0.13</td>
<td>99.08</td>
<td>0.30</td>
<td>99.65</td>
</tr>
</tbody>
</table>

| Si⁴⁺ (apfu)    |                                          | 3.008   | 0.010 | 3.006   | 0.019 | 3.006   | 0.021 | 3.011   | 0.009 | 3.003   | 0.007 | 3.001   | 0.012 | 2.998   | 0.009 | 3.113   | 0.037 |
| Al³⁺           |                                          | 2.084   | 0.047 | 1.913   | 0.093 | 2.008   | 0.044 | 1.986   | 0.050 | 2.043   | 0.032 | 1.973   | 0.062 | 1.977   | 0.085 | 2.128   | 0.076 |
| Fe³⁺           |                                          | 0.898   | 0.045 | 1.070   | 0.086 | 0.990   | 0.040 | 0.994   | 0.070 | 0.938   | 0.024 | 1.005   | 0.046 | 1.018   | 0.067 | 1.007   | 0.041 |
| Ti⁴⁺           |                                          | 0.003   | 0.002 | 0.002   | 0.002 | 0.002   | 0.002 | 0.002   | 0.001 | 0.004   | 0.004 | 0.011   | 0.004 | 0.004   | 0.006 | 0.007   | 0.001 |
| Mg²⁺           |                                          | 0.009   | 0.008 | 0.007   | 0.001 | 0.008   | 0.002 | 0.008   | 0.002 | 0.006   | 0.004 | 0.007   | 0.002 | 0.006   | 0.004 | 0.033   | 0.026 |
| Mn²⁺           |                                          | 0.043   | 0.018 | 0.019   | 0.008 | 0.032   | 0.005 | 0.014   | 0.010 | 0.050   | 0.017 | 0.021   | 0.008 | 0.023   | 0.018 | 0.073   | 0.004 |
| Ca²⁺           |                                          | 1.953   | 0.040 | 1.981   | 0.014 | 1.945   | 0.029 | 1.983   | 0.033 | 1.943   | 0.023 | 1.980   | 0.031 | 1.967   | 0.044 | 1.956   | 0.031 |
| H⁺             |                                          | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 | 1.000   | 0.000 |

Note: The following standards were used: albite (NaKα), kyanite (AlKα), MgCr₂O₄ (CrKα), diopside (SiKα, MgKα), fayalite (FeKα), orthoclase (KKα), MnSiO₃ (MnKα), rutile (TiKα), and fluor-phlogopite (FKα). Compositions were recalculated on the basis of 13 apfu (including 1 OH). Na, K, and Cr were sought but not detected. *Determined by stoichiometry.
at Northern Dancer appears to be very iron-rich in a relatively iron-poor host environment; however, epidote is commonly associated with sulphides, especially pyrite. Manganese contents are relatively homogenous in rutile through all host environments, varying between 0.21 wt.% MnO or 0.01 Mn \textit{apfu} and 1.03 wt.% MnO or 0.07 Mn \textit{apfu}. Fluorine was sought but not detected.

8.2.3.2 Clinozoisite

Clinozoisite occurs in veins, and is most likely an alteration product of epidote. This is commonly seen in reopened Type 2 veins (by Type 3 or 4 veins), as seen in Fig. 8.15. As such, it can occur with zoned scheelite. It may occur in thicker Type 3 or Type 4 veins, as anhedral masses with fluorite, scheelite, and pyrite. Clinozoisite can also occur in altered, silicified zones of calc-silicate, as seen in Fig. 8.16. Here again, it is likely the alteration product of earlier epidote.

Nine electron microprobe analyses were obtained from four grains in one polished section. The analyses were recalculated on the basis of 13 anions (including 1 OH) per formula unit. Results of the analysis are given in Table 8.4. Iron content varies from 0.26 wt.% FeO or 0.02 Fe$^{2+}$ \textit{apfu} to 1.01 wt.% FeO or 0.07 Fe$^{2+}$ \textit{apfu}, averaging 0.57 wt.% FeO or 0.04 Fe$^{2+}$ \textit{apfu}. Iron is lower in clinozoisite than in epidote, suggesting iron was mobilized out of the mineral, possibly into accessory pyrite nearby, which is also commonly associated with clinozoisite. Manganese remains very low, averaging 0.07 wt.% MnO or 0.001 Mn \textit{apfu}.

8.2.3.3 Allanite

Allanite is very rare in the Northern Dancer system, and only two examples were found in the representative sample set. A small, fine-grained aggregate mass was found in the groundmass of the felsic porphyry dikes (sample Al-06-06), and another example was found in a thin Type 2 quartz-pyrite-scheelite vein in fine-grained garnet-pyroxene skarn (QSM-27). This second grain contained euahedral growth zones based on varying Ce-La content as seen in Fig. 8.17. EDS analysis via the SEM showed the Ce-La content increases outward from the core/origin. It occurs in an epidote-rich Type 2 vein, and is associated with pyrite, chalcopyrite, fluorite, and clinopyroxene. This kind of oscillatory zoning in allanite and epidote has been noted in high-pressure carbonate rocks (Boundy et al. 2002), and indicates open-system
Fig 8.15. Polished section QSM-8 in plane-polarized light: likely re-opened by a Type 4 vein, an older Type 2 vein contains epidote, clinozoisite, fluorite, scheelite and pyrite with chalcopyrite inclusions. The epidote appears to be altering to clinozoisite.

Fig. 8.16. Backscatter SEM image of epidote and clinozoisite in calc-silicate from section RS-14. Albite and clinozoisite occur together next to epidote and fluorite.
Table 8.4. Average compositions of clinozoisite samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>In Type 2 vein, in CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
</tr>
<tr>
<td></td>
<td>average</td>
</tr>
<tr>
<td>SiO$_2$ (wt.%)</td>
<td>43.79</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>23.68</td>
</tr>
<tr>
<td>MgO</td>
<td>0.03</td>
</tr>
<tr>
<td>MnO</td>
<td>0.07</td>
</tr>
<tr>
<td>FeO</td>
<td>0.57</td>
</tr>
<tr>
<td>CaO</td>
<td>26.72</td>
</tr>
<tr>
<td>BaO</td>
<td>0.01</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.01</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.11</td>
</tr>
<tr>
<td>H$_2$O*</td>
<td>1.90</td>
</tr>
<tr>
<td>Total</td>
<td>96.88</td>
</tr>
<tr>
<td>Si$^{4+}$ (apfu)</td>
<td>3.448</td>
</tr>
<tr>
<td>Al$^{3+}$</td>
<td>2.188</td>
</tr>
<tr>
<td>Mg$^{2+}$</td>
<td>0.003</td>
</tr>
<tr>
<td>Mn$^{2+}$</td>
<td>0.004</td>
</tr>
<tr>
<td>Ca$^{2+}$</td>
<td>2.254</td>
</tr>
<tr>
<td>Fe$^{2+}$</td>
<td>0.037</td>
</tr>
<tr>
<td>Ba$^{2+}$</td>
<td>0.000</td>
</tr>
<tr>
<td>K$^+$</td>
<td>0.001</td>
</tr>
<tr>
<td>Na$^+$</td>
<td>0.016</td>
</tr>
<tr>
<td>H$^+$</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: albite (NaKα), kyanite (AlKα), MgCr$_2$O$_4$ (CrKα), diopside (SiKα, MgKα), fayalite (FeKα), orthoclase (KKα), MnSiO$_3$ (MnKα), rutile (TiKα), and fluor-phlogopite (FKα). Compositions were recalculated on the basis of 13 apfu (including 1 OH$^-$). Ti and Cr were sought but not detected. *Determined by stoichiometry.
Fig. 8.17. Backscatter SEM image of a zoned REE-rich allanite found in a very thin Type 2 vein, hosted by fine-grained garnet-pyroxene skarn. Visible euhedral growth zones are due to varying Ce-La (REE) content. This grain occurs with quartz, pyrite, epidote, fluorite, chalcopyrite and clinopyroxene.


8.2.4 Feldspar

Feldspar is a component of intrusive rocks, metasedimentary host rocks, and veins at Northern Dancer. Both plagioclase and potassium feldspar occur in all intrusive phases, and can be zoned, or show evidence of relict zoning, as in the monzonite (Fig. 8.18). In general, plagioclase is the dominant feldspar in the monzonite, occurring as rims on earlier potassic grains, or as sub-euhedral grains in a coarse-grained matrix. Potassium feldspar dominates the felsic dike phases, especially the ‘brain rock’ unit, occurring as fine-grained, anhedral masses in felsite, as small subhedral grains dispersed through quartz porphyry or as bands in the ‘brain rock’ (between 0.1 mm to several cm wide). Typically, the fine-grained matrix in the felsic dikes is composed of intergrown plagioclase and potassium feldspar. Ca-rich plagioclase and potassium feldspar are both found in the diorite, although the latter is more
Fig. 8.18. Zoned, relict feldspar from monzonite in plane-polarized light (left) and crossed-polars (right). A potassium rich core composition is Or$_{97.44}$Ab$_{2.56}$ (at 606-8) is rimmed by Na-rich plagioclase Ab$_{98.75}$An$_{0.52}$Or$_{0.73}$ (at 606-4). The albite rim may be evidence of sodic alteration. BaO peaks at 0.11 % at 606-6 (in the ksp core).

common. Feldspars, usually potassic, can also occur as very fine-grained, anhedral groundmass components of calc-silicate and hornfels metasedimentary host rocks, or in haloes around veins. Within veins, plagioclase is most occasionally found in vein cores, as fine-grained anhedral masses. Potassium feldspars can occur in the same way, in addition to forming euhedral, compositionally zoned crystals growing perpendicular to Type 4 vein walls. In rare cases, Type 4 veins are composed almost entirely of anhedral massive potassium feldspar.

Sixty-five analyses from six polished sections in 14 different vein/host environments were analyzed via EPMA. Analyses were recalculated on the basis of 8 anions per formula unit. The plagioclase compositions are listed in Table 8.5, and potassium feldspar compositions are shown in Table 8.6. Feldspars in the monzonite are compositionally zoned and/or altered. As mentioned above, in Fig. 8.18 a potassium rich core is rimmed by Na-rich plagioclase (albite). In the core (at 606-7) the composition is Or$_{97.44}$Ab$_{2.56}$ while the rim (at 606-5) it is Ab$_{98.75}$An$_{0.52}$Or$_{0.73}$. The albite rim may be evidence of sodic alteration by later porphyry stages including the felsic dike complex. BaO peaks at 0.11 % at 606-6 (in the potassium feldspar core). Overall, plagioclase in the monzonite averages Ab$_{88.47}$An$_{10.54}$Or$_{0.99}$. Potassium feldspar in the monzonite is close to end-member orthoclase, averaging Ab$_{3.77}$Or$_{96.23}$. Plagioclase in the felsite averages Ab$_{76.64}$An$_{22.26}$Or$_{1.11}$. Potassium feldspar in felsic porphyry dike matrix averages Or$_{94.99}$Ab$_{4.98}$An$_{0.03}$ but becomes more sodic, averaging Or$_{90.95}$Ab$_{8.94}$An$_{0.12}$, near zones of quartz flooding or thick quartz veins. Diorite contains the most calcic plagioclase, averaging Ab$_{55.13}$An$_{43.96}$Or$_{0.91}$. Of potassium feldspars at Northern Dancer, those found in diorite
Table 8.5. Average compositions of plagioclase samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>Monzonite</th>
<th>Felsite groundmass</th>
<th>V4 in hornfels host</th>
<th>Diorite - groundmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>average</td>
<td>st.dev.</td>
<td>average</td>
<td>st.dev.</td>
</tr>
<tr>
<td>SiO$_2$ (wt.%)</td>
<td>66.59</td>
<td>1.91</td>
<td>63.94</td>
<td>0.25</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>21.36</td>
<td>1.28</td>
<td>23.30</td>
<td>0.19</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.04</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>CaO</td>
<td>2.16</td>
<td>1.52</td>
<td>4.58</td>
<td>0.26</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>10.05</td>
<td>0.89</td>
<td>8.71</td>
<td>0.21</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.17</td>
<td>0.08</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td>BaO</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.40</td>
<td>0.34</td>
<td>100.76</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Si$^{4+}$ (apfu) | 2.908 | 0.071 | 2.801 | 0.010 | 2.974 | 0.006 | 2.581 | 0.082 |
Al$^{3+}$ | 1.099 | 0.070 | 1.203 | 0.010 | 1.030 | 0.005 | 1.412 | 0.079 |
Fe$^{3+}$ | 0.001 | 0.001 | 0.001 | 0.001 | 0.006 | 0.002 | 0.004 | 0.001 |
Mg$^{2+}$ | 0.000 | 0.000 | 0.000 | 0.000 | 0.006 | 0.001 | 0.002 | 0.001 |
Mn$^{2+}$ | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 |
Ca$^{2+}$ | 0.102 | 0.072 | 0.215 | 0.012 | 0.047 | 0.000 | 0.438 | 0.082 |
Ba$^{2+}$ | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.000 | 0.000 |
Na$^+$ | 0.851 | 0.073 | 0.739 | 0.017 | 0.888 | 0.004 | 0.545 | 0.075 |
K$^+$ | 0.010 | 0.005 | 0.011 | 0.000 | 0.008 | 0.001 | 0.009 | 0.002 |
Ab | 88.47 | 7.73 | 76.84 | 1.29 | 94.21 | 0.03 | 55.13 | 7.94 |
An | 10.54 | 7.45 | 22.26 | 1.28 | 4.99 | 0.02 | 43.96 | 8.06 |
Or | 0.99 | 0.48 | 1.11 | 0.06 | 0.80 | 0.05 | 0.91 | 0.16 |

Note: The following standards were used: orthoclase (SiKα), anorthite (AlKα, CaKα), Fe$_2$SiO$_4$ (FeKα), albite (NaKα), and orthoclase (KKα). Compositions were recalculated on the basis of 8 O apfu.
Table 8.6. Average compositions of potassium feldspar samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/ host env.</th>
<th>Monzonite</th>
<th>Qtz vein wall in felsite</th>
<th>Felsite groundmass</th>
<th>Fsp-rich V4 in HF</th>
<th>HF groundmass</th>
<th>Diorite groundmass</th>
<th>F-rich V4 in hornfels</th>
<th>Vein wall in hornfels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>average</td>
<td>st.dev</td>
<td>average</td>
<td>st.dev</td>
<td>average</td>
<td>st.dev</td>
<td>average</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
<td>65.06</td>
<td>0.04</td>
<td>63.95</td>
<td>0.84</td>
<td>64.44</td>
<td>0.58</td>
<td>65.20</td>
<td>0.99</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>18.36</td>
<td>0.04</td>
<td>18.85</td>
<td>0.24</td>
<td>18.24</td>
<td>0.29</td>
<td>18.48</td>
<td>0.27</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.01</td>
<td>0.11</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.11</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.11</td>
<td>0.00</td>
<td>1.64</td>
<td>0.95</td>
<td>0.22</td>
<td>0.03</td>
<td>0.95</td>
<td>0.47</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.43</td>
<td>0.14</td>
<td>0.97</td>
<td>0.38</td>
<td>0.56</td>
<td>0.11</td>
<td>1.84</td>
<td>1.80</td>
</tr>
<tr>
<td>BaO</td>
<td>16.72</td>
<td>0.13</td>
<td>15.05</td>
<td>0.79</td>
<td>16.07</td>
<td>0.06</td>
<td>13.94</td>
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<td>94.99</td>
<td>0.94</td>
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Note: The following standards were used: orthoclase (SiK₆), anorthite (AlK₆, CaK₆), Fe₂SiO₄ (FeK₆), albite (NaK₆), and orthoclase (KKα). Compositions were recalculated on the basis of 8 O apfu.
groundmass are the most calcic, averaging \( \text{Or}_{85.80}\text{Ab}_{11.91}\text{An}_{2.29} \). The earlier intrusive phases, e.g., the diorite and monzonite units, show the greatest standard deviation in plagioclase composition, which possibly reflects sodic alteration.

While plagioclase in metasedimentary rocks exists occasionally at Northern Dancer, it is too fine-grained to probe accurately via EPMA. However, some analyses were obtained from potassic feldspars in groundmass of hornfels, which average \( \text{Or}_{89.07}\text{Ab}_{10.57}\text{An}_{0.36} \). Plagioclase found in veins is close to end-member albite in composition, averaging \( \text{Ab}_{94.21}\text{An}_{4.90}\text{Or}_{0.89} \), and is compositionally homogenous, with a standard deviation of \( \pm 0.03 \). Potassium feldspars average \( \text{Or}_{90.61}\text{Ab}_{9.18}\text{An}_{0.20} \) in Type 4 veins, however analyses from massive (likely Type 4) feldspar vein in a hornfels host averaged \( \text{Or}_{83.40}\text{Ab}_{16.41}\text{An}_{0.18} \). Traversing from vein wall to core, this vein was much more sodic in the core (46.36 % albite) than at the rim (only 3.22 % albite). Feldspar from most other vein types was either too altered or fine-grained to analyze.

Ba-rich potassium feldspar tends to be associated with fluorite, and occurs in vein alteration halos within hornfels, at contacts of hornfels and silicified calc-silicate, and within areas of quartz ‘flooding’ within hornfels (Fig. 8.19). It also occurs in the felsic dike phases, at Type 3/4 vein margins. They are usually zoned and show evidence of absorption at the rims, such as in Fig. 8.20, where euhedral, zoned potassium feldspar is growing along a fluorite-rich Type 4 vein. A maximum content of 4.05 % BaO (0.075 Ba apfu) was detected in a grain near a Type 4 vein wall in hornfels. On average, this vein-host environment had the highest barium content, at 2.61 % BaO. According to Roy (1965) and Deer et al. (1996), any feldspar with 2 % BaO or higher is considered a barium feldspar, or “celsian”. Celsian typically occurs in manganese deposits, where the celsian molecule can account for up to 30% of the overall crystal structure.
Fig. 8.19 SEM backscatter image of zoned potassium feldspar with Ba-rich (lighter grey) rims associated with fluorite, occurring within silicified calc-silicate.

Fig. 8.20. SEM backscatter image of zoned, cuhedral potassium feldspar growing perpendicular to the wall of a fluorite-rich Type 4 vein, within a calc-silicate host. Darker cores are 0.26 wt. % BaO (Q18-1) and 0.37 wt % BaO (Q18-3), while lighter rims are relatively Ba-rich, at 1.72 wt% BaO (Q18-2) and 2.76 wt% BaO (QSM-4). The outer rims are resorbed, suggesting fluctuating fluid conditions and/or fluid composition.
8.2.5 Fluorite

Fluorite is a common late accessory mineral in many ore deposits, including tin-tungsten- and REE-enriched granite systems, as it is stable under a wide range of geological conditions. It can occur as infill in open spaces and veins, as disseminated alteration via replacement of wallrock, or form the matrix of a hydrothermal breccia. At Northern Dancer, fluorite is ubiquitous throughout the entire system. Three colours of fluorite have been noted in the deposit: grey-colourless (most common), purple (in Type 4 veins), and green (rare). It occurs in the full range of intrusive rocks, veins, and metasedimentary host rocks, as both a primary and as an alteration mineral. Overall, fluorite is regularly associated with scheelite both in earlier and later stage veins throughout the Northern Dancer deposit.

Fluorite can occur in both unaltered and altered monzonite, usually with muscovite and potassium feldspar, especially near contact zones with the metasedimentary country rocks. Geochemically this is not unexpected as fluorine is elevated in the monzonite (3500 ppm). Occasionally it is present as fine-grained intergrowths with ilmenite between the coarse-grained matrix of feldspars, quartz, and biotite.

Fluorite has been noted in zones of quartz flooding within the felsic dikes, alongside calcite and potassium feldspar; however, in general, fluorite is not overly abundant in the felsic dikes. This is also reflected in the geochemistry by the relatively low F values (averaging 567 ppm) in quartz-feldspar porphyry and felsite (see section 6: Lithogeochemistry). Rarely, disseminated fluorite is encountered within the feldspathic groundmass in quartz porphyry which has been crosscut by Type 4 veins. In this case, it is likely an alteration mineral. In addition, within the associated Type 4 veins themselves, fluorite is slightly enriched in heavy rare earths such as Y and Yb.

Fluorite occurs with quartz and garnet in more siliceous zones of silicified calc-silicate. In these environments, fluorite also comprises a minor amount of the alteration halo (via replacement of the wallrock) around the vein. Fluorite can be a major component in calc-silicate and hornfels groundmass, and can range from very fine-grained to very coarse-grained (the latter in zones of coarse recrystallization or brecciation, see Fig.8.21). In these silicically-altered zones of garnet-pyroxene skarn, fluorite can occasionally occur as coarse-grained crystals up to 5 mm in diameter, alongside coarse potassium feldspar (up to 2 cm masses), and pyrite (up to 2 mm).
Fluorite is associated with Ba-rich, zoned feldspar in silicified garnet-pyroxene skarn, as seen in Fig. 8.19. Occasionally, fluorite alteration may be present as small, disseminated inclusions within zoned garnet in Type 1 veins, which have been altered or reopened by later vein sets (Fig. 8.22).

Fluorite typically appears altered where it occurs as a Type 2 vein component, in those veins which have been reopened by Type 3 or 4 veins (Fig. 8.23). Here, fluorite is associated with scheelite in the earlier Type 2 vein, and both minerals have been altered, likely by fluids arriving via the Type 4 reopening. Fluorite in this environment can also be rich in small inclusions such as garnet, quartz, pyroxene, scheelite, and chlorite. Type 3 veins which extend outboard from the felsic dikes commonly contain fluorite, along with pyrite, potassium feldspar, and occasionally epidote (which is likely hydrothermal and may be locally remobilized from the wallrock). Type 3 veins within the felsic dikes can also occasionally contain fluorite.

In thick Type 4 veins, fluorite is abundant, occurring as large anhedral colourless-grey masses in quartz, or medium- to coarse-grained sub- to euhedral purple crystals. The fluorite tends to congregate at vein junctions, possibly where open space was more available, and it is typically present as a late fracture-filling mineral, along with sphalerite, plagioclase, and rutile. In one case in the representative sample set, fluorite and calcite (and minor galena and molybdenite) fill open space within alteration haloes around Type 4 veins and associated silica.
Fig. 8.22. Backscatter SEM image of Type 1 reopened vein by a later vein. Overprinting fluorite alteration is present as small, disseminated inclusions (outlined in dashed yellow line) within zoned garnet in the Type 1 vein.

Fig. 8.23. Backscatter SEM image of Type 2 reopened vein by a Type 4 vein. Here, the fluorite is associated with scheelite in earlier veins, and both mineral have been altered, likely by fluids arriving via the Type 4 reopening. Fluorite contains inclusions of garnet, quartz, pyroxene, scheelite, and chlorite. The chlorite is found both in the older Type 2 vein “core” and at the vein wall of the new Type 4 vein. Chlorite is higher in F and Mg and contains garnet inclusions in the Type 2 environment, whereas chlorite in the Type 4 environment contains titanite inclusions and is higher in Fe.
flooded zones. Type 4 veins which have no quartz, but are composed almost entirely of massive fluorite, are common where many overprinting felsic dike phases and Type 4 veins occur (and can be up to 2 cm wide); this evidence supports the hypothesis that the major fluorite alteration event is temporally late in the deposit’s evolution. Sometimes, these fluorite veins contain euhedral beryl (Fig. 8.24) or euhedral scheelite (Fig. 8.25), which supports their classification as Type 4 veins. They may be crosscut, and occasionally offset, by later veins or fractures containing molybdenite (Fig. 8.26), which supports the idea of overprinting felsic dike phases and generations of Type 4 veins.

Fluorite is less common in hornfels, in distal calc-silicate crosscut by the Type 1 veining event only, and in wollastonite vesuvianite skarn. Likely this is due to the fact that the fluorine alteration event is late, and centered on the felsic dike complex or around the Type 4 vein system. Host rocks which are more distal or less permeable (such as the wollastonite-vesuvianite skarn and distal, fine-grained, hornfels) are less likely to be affected by this event.

As fluorite is typically 99% CaF₂, it was not analyzed via EPMA for this study; and quantitative checks on selected grains show no significant impurities aside from very minor amounts of SiO₂, which is likely due to minor quartz intergrowth and/or inclusions. Although Y and Ce have been known to substitute for Ca in fluorite in REE-enriched deposits, significant levels of trace elements were not detected by EDS analysis in most environments at Northern Dancer, aside from slightly Yb- and Y-enriched fluorite in feldspathic groundmass in quartz porphyry and associated Type 4 veins. This could indicate that Y- and Yb originate from the same source as the F, which is most likely the felsic dikes.

Fluorite and silica alteration events may play a significant role in the circulation of elements late in the system’s evolution, especially Mo, W, and Be. In sheeted veins which extend outward from the deposit boundaries, especially the beryl-wolframite veins to the south, fluorite and quartz are abundant and fill much of the open space. Based on many examples of quartz-fluorite ‘flooding’ and alteration (for example, in Fig. 8.21 where euhedral zones of relict garnet are replaced by fluorite and silica), these two styles of alteration may occur together temporally.

8.2.6 Topaz

Based on the mineralogy at Northern Dancer, topaz [Al₂(SiO₄)(F,OH)₂] should be expected as a possible accessory mineral. It occurs in areas of granophile (Sn, W, Li, and
Fig. 8.24. Backscatter SEM image of Type 4 ‘fluorite’ vein in a zone of overprinting felsic dike phases. Euhedral beryl and zoned Ba-rich potassium feldspar crystals are intergrown with the fluorite.

Fig. 8.25. Backscatter SEM image of Type 4 ‘fluorite’ vein in a zone of overprinting, fine-grained, felsic dike phases. Euhedral scheelite crystals occur in a massive fluorite vein.
Fig. 8.26. Backscatter SEM image of the same Type 4 ‘fluorite’ vein as in Fig 8.25. Here, it is crosscut, and slightly offset, by a later molybdenite and quartz-filled fracture.

Ta) mineralization and griesen alteration, or in veins, and is associated with fluorite, quartz, chlorite, biotite, muscovite, bismuthinite, molybdenite, and wolframite. However, topaz typically forms at the contact zones of W-Sn-Mo granites and country rocks such as rhyolite, where low pH (and high F activity) conditions intense leaching of aluminum facilitate the hydrolyzing of feldspar and mica to produce topaz (Kooiman et al. 1986). This occurs to a certain extent at the ‘Fire Tower Zone’ of the Mount Pleasant porphyry tungsten-molybdenum deposit in New Brunswick (Kooiman et al. 1986). Since the host rocks at Northern Dancer are particularly Ca-rich and mica-poor, there is probably not enough Al in the protolith or the necessary low pH fluid to form topaz, and in addition there has been no griesen development reported. Likely as a result of this, no topaz has been noted at Northern Dancer, and fluorine is sequestered primarily by fluorite, and to a lesser extent micas and garnet. However, topaz has been noted in the nearby Seagull Batholith (Sinclair & Richardson 1992, Mortensen et al. 2006).
8.2.7 Molybdenite

Molybdenite is the dominant sulphide ore mineral in the Northern Dancer Deposit. The latest (April 2007) NI 43-101-compliant inferred mineral resource estimate at the time of this study was reported to be 242.0 million tonnes grading 0.047% MoS₂, which includes a higher grade Mo zone of 36.8 million tonnes of 0.085% MoS₂. Overall this implies that the deposit contains 151.0 million lbs. of molybdenum (Broad & Campbell 2008). The highest molybdenum grades appear to coincide with area where there is a high density of Type 3 veins (and/or overprinting Type 4 veins). While molybdenite is primarily associated with the felsic dike complex and Type 3 vein set, it is also found in vein alteration haloes, ‘brain rock’ or silica flooding layers in the quartz-feldspar porphyry, Type 4 veins, and less commonly, in Type 2 veins and silicified zones of calc-silicate.

Molybdenite is usually intimately associated with scheelite in the Type 3 and 4 veins (Fig. 8.27), and the two are occasionally intergrown (see scheelite section). The two most common environments in which molybdenite is found are: (1) as fracture-fill or in thin quartz veins crosscutting felsic dikes (see fig. 3.2, g from section 3: Local Geology), and (2), at the vein walls or selvedges of Type 4 veins, where it typically forms radial masses (8.32). In the former case, which includes Type 3 veins, molybdenite and quartz are commonly the only two vein/fracture minerals present. However, when Type 3 veins extend outboard of the felsic dikes, molybdenite can be associated with garnet, scheelite, and epidote, as well. In the latter case, molybdenite can occur with almost any Type 4 vein mineral, and forms at selvedges of Type 4 veins in any host rock environment (intrusive or metasedimentary). Commonly it is associated with other minerals typically found at Type 4 vein selvedges such as chlorite, calcite, plagioclase, biotite, rutile, titanite, apatite, beryl, and scheelite, rather than with other sulphides such as pyrite, pyrrhotite, chalcopyrite, or sphalerite (Fig. 8.28; also Fig. 8.7).

However, it is not limited to vein walls or selvedges; molybdenite can be found in the cores of both Type 3 and 4 veins, and within their alteration haloes in calc-silicate, hornfels, and occasionally altered diorite host rocks. In siliceous brain rock layers, or transitional zones between felsic porphyry and Type 4 veins, potassium feldspar and muscovite “clots” appear to be traps for scheelite, molybdenite, and rutile (Figs. 8.36, 8.37).
Fig. 8.27. Backscatter image of molybdenite and scheelite in a Type 4 vein which crosscuts both an earlier, fluorite-rich Type 4 vein, and the host felsite.

Fig. 8.28. Backscatter image of radial molybdenite at a Type 4 vein wall within altered hornfels. It is intergrown with calcite, and associated with euhedral scheelite, amphibole, plagioclase, apatite and biotite.
Compositionally, molybdenite is essentially pure at Northern Dancer; aside from minor impurities such as Fe where molybdenite and pyrite/pyrrhotite are associated (the molybdenite may contain small pyrite/pyrrhotite inclusions). The molybdenum species is important at Northern Dancer, not only because it is a mineral within the ore itself and directly associated with scheelite in many vein/host environments, but also because it is a possible indicator of temporally changing ore-forming conditions. Likely, as geological conditions evolved within the system, Mo could no longer enter the scheelite structure to form molybdoscheelite, and instead formed the more common molybdenite-scheelite assemblage, giving rise to the purer scheelite we see in Type 3 and 4 veins (see mineralogical discussion). The molybdenite-scheelite (or molybdenite-wolframite) ore mineral assemblage is more common than powellite/molybdoscheelite ore minerals in W-Mo deposits, in general; this topic is discussed below in section 8.2.17: Scheelite (Hsu 1977, Darling 1994).

8.2.8 Xenotime

Xenotime is occasionally found in altered monzonite near the contact with the metasedimentary country rocks. Here it can be zoned, HREE-(Y, Yb, Gd, Er, Dy) and LREE-rich, and is commonly associated with scheelite, monazite, zircon, and apatite (Fig. 8.29). Minor inclusions in xenotime are LREE-, Th and Nd-rich. Rarely, it is found associated with pyrrhotite and small, Mn-rich garnets in quartz-feldspar porphyry rocks (Fig. 8.30). In quartz-feldspar porphyry rocks, it can occasionally form aggregates with fluorite in the matrix. Due to its minor nature and the difficulty in analyzing for heavy rare earth elements via electron microprobe, xenotime was not analyzed for this study.

8.2.9 Tourmaline

Tourmaline is extremely rare within the core of the Northern Dancer deposit; however, black tourmaline can occur within beryl-wolframite sheeted veins extending to the southeast. In one rare example within the deposit, tourmaline occurs in a fine-grained, aggregate mass with
Fig. 8.29. Backscatter SEM image of xenotime associated with scheelite, monazite, zircon, and apatite, in altered monzonite near the contact with the metasedimentary country rocks. Zoning is based on compositional variation of heavy (Y, Yb, Gd, Er, Dy) and light rare-earth elements.

Fig. 8.30. Backscatter SEM image of xenotime associated with pyrrhotite and small, Mn-rich garnets in quartz-feldspar porphyry host rock.
fluorite, magnetite, sphalerite, and plagioclase in myrmekitic quartz porphyry, within the felsic
dike complex. These grains were too fine-grained to analyze quantitatively, but they did register
Mg, Mn, Na, and Fe spectral peaks with EDS analysis (via the SEM). This suggests the species
is likely schorl (Fe and Na-rich tourmaline), or less likely, buergerite (an F-rich tourmaline).

8.2.10 Niobium-tantalum oxides

Very rarely, Nb-Ta oxides can occur within altered monzonite. Small, fine-grained
zones, of what is possibly alteration, form next to equally rare, relict scheelite grains. As these
grains are uncommon and very fine-grained, they could not be analyzed for their composition
except qualitatively by EDS, therefore the exact species could not be determined.

8.2.11 Phyllosilicates

Hydrous minerals, including phyllosilicates, are relatively rare in most calc-silicate host
rocks at Northern Dancer. However, micas do exist in intrusive units, especially the diorite, and
chlorite is a minor accessory mineral in several vein/host environments.

8.2.11.1 Biotite

At Northern Dancer, biotite is usually found as major component in the diorite and
monzonite. Biotite within the diorite is usually enriched in titanium, and can contain inclusions
of apatite, titanite, and may rim relict, euhedral clinopyroxene or amphibole cores (see Fig. 8.52).
Some zones of the diorite become coarse-grained, such as the ‘hornblende porphyry’ unit
identified by Noble and Spooner (1984). Where these zones are exposed to alteration, biotite
alters somewhat to chlorite (Fig 8.31). Occasionally, thin fractures near the fine-grained diorite
contact contain massive biotite and fine-grained clinopyroxene (RS-16), as well as very fine-
grained biotite in the groundmass, which is commonly intergrown with titanite in aggregates.
Biotite in the monzonite is titanium- and manganese-rich, coarse-grained, and contains
inclusions of ilmenite and apatite. As in the diorite, biotite in the monzonite may be partially or
extensively altered (in this case to feldspar), likely depending on its location relative to the
contact with the metasedimentary country rocks.
Fig 8.31. Backscatter SEM image of biotite altering to chlorite, which is intergrown with potassium feldspar. Titanite rims apatite inclusions within the biotite, and occurs as separate inclusions in chlorite.

In altered hornfels, in the alteration haloes of thick Type 4 veins, biotite may form minor intergrown 'clots' or aggregates with titanite, as seen in Fig. 8.32. It can also be a vein mineral, where long biotite crystals are intergrown in the cores of veins with calcite, scheelite, pyrite and quartz, as well as growing perpendicular to the vein contact, at the vein wall with scheelite and molybdenite (also in Fig 8.32). In these vein environments, biotite (±chlorite) are usually rare and the only hydrous minerals present.

Fifty-nine analyses from five polished sections in 10 different vein/host environments were analyzed via EPMA. Analyses were recalculated on the basis of 12 anions assuming 2(OH + F) per formula unit. EPMA results are listed in Table 8.7. Biotite compositions usually reflect the host environment in which they occur, and this appears to be the case at Northern Dancer (Deer et al. 1996). Intrusive-hosted biotite, especially the diorite, contains the highest titanium content, as expected. Biotite in coarse-grained diorite contains an average of 2.92 TiO$_2$ wt.% or 0.17 Ti apfu (max. 3.31 TiO$_2$ wt.% or 0.19 Ti apfu). Monzonite titanium values average 2.24 wt.% TiO$_2$ or 0.13 Ti apfu (max. 2.76 wt.% or 0.16 Ti apfu). By contrast, biotite in hornfels groundmass averages only 0.99 wt.% TiO$_2$ or 0.06 Ti apfu, and in Type 4 veins it is also relatively low at 1.29 wt.% TiO$_2$ or 0.07 Ti apfu. Magnesium contents vary widely: the monzonite averages 7.77 wt.% MgO or 0.89 Mg apfu, the diorite averages 12.04 wt.% MgO or
Fig. 8.32. Polished section QSM-12 in plane-polarized light. Biotite “clots” occur in the alteration haloes of thick Type 4 veins, within altered hornfels host rock. Titanite can be intergrown with biotite grains to form these small aggregates. In cores of Type 4 veins, long biotite grains are intergrown with calcite, and also grow perpendicular (occasionally with scheelite) to the vein wall. Molybdenite congregates in radial masses at the vein wall, which is common in Type 4 veins.

1.37 Mg apfu, hornfels groundmass averages 17.08 wt.% MgO or 1.91 Mg apfu, and Type 4 vein biotite averages 10.74 wt.% MgO or 1.81 Mg apfu. Biotite filling fractures in fine-grained diorite near the contact with the metasedimentary rocks average 19.19 wt.% MgO or 2.12 Mg apfu. Conversely, the monzonite and Type 4 veins contain biotite richest in manganese, averaging 1.16 and 1.62 wt.% MnO, or 0.08 and 0.10 Mn apfu, respectively. Iron content is highest in the intrusive hosts, with the monzonite and diorite containing averages of 18.72 and 20.11 wt.% FeO, or 1.21 and 1.28 Fe$^{2+}$ apfu, respectively. The lowest iron content (average of 10.38 wt.% FeO or 0.67 Fe$^{2+}$ apfu) is found in biotite richest in magnesium, within fractures in fine-grained diorite near its metasedimentary contact.

Fluorine contents in mica from Northern Dancer are plotted by vein/host environment in Fig 8.33. Fluorine content in biotite is much higher in the monzonite, where it averages 3.56 wt.% F or 0.86 F apfu (max. 4.76 wt.% F or 1.12 F apfu), than the diorite where the average is only 0.26 wt.% F or 0.06 F apfu. This supports the idea that the monzonite is the source of F-rich fluids in the system. However, biotite from the fine-grained diorite in the contact zone with adjacent metasedimentary country rocks is also relatively high in fluorine.
Table 8.7. Average compositions of biotite samples from the Northern Dancer deposit.

<table>
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<th>Vein/host environment</th>
<th>Monzonite</th>
<th>Diorite</th>
<th>In diorite; altering to chlorite</th>
<th>Rim on amph in dior., w/ garn/titan incl.</th>
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<td>Cr₂O₃</td>
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<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
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</tr>
<tr>
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</tr>
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<tr>
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<td>20.11</td>
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<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
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<tr>
<td>K₂O</td>
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</tr>
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<tr>
<td>F</td>
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<td>0.56</td>
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<td>-0.05</td>
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<tr>
<td>Total</td>
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<td>0.86</td>
<td>100.13</td>
<td>0.47</td>
<td>100.22</td>
</tr>
</tbody>
</table>

| Sl⁺⁺⁺ (apfu)          | 2.987     | 0.102   | 2.815                           | 0.019                                      | 2.803             |
| Ti⁺⁺⁺                 | 0.130     | 0.033   | 0.167                           | 0.011                                      | 0.171             |
| Al³⁺                  | 1.401     | 0.129   | 1.280                           | 0.005                                      | 1.267             |
| Cr²⁺                  | 0.001     | 0.001   | 0.000                           | 0.001                                      | 0.002             |
| Mg²⁺                  | 0.893     | 0.142   | 1.388                           | 0.009                                      | 1.388             |
| Mn²⁺                  | 0.076     | 0.013   | 0.014                           | 0.001                                      | 0.014             |
| Ca²⁺                  | 0.002     | 0.002   | 0.003                           | 0.002                                      | 0.003             |
| Fe²⁺                  | 1.206     | 0.184   | 1.281                           | 0.029                                      | 1.259             |
| Na⁺                   | 0.012     | 0.004   | 0.025                           | 0.002                                      | 0.018             |
| K⁺                    | 0.962     | 0.017   | 0.930                           | 0.007                                      | 0.946             |
| F⁻                    | 0.864     | 0.129   | 0.063                           | 0.021                                      | 0.033             |
| Cl⁻                   | 0.008     | 0.002   | 0.028                           | 0.003                                      | 0.028             |
| H⁺                    | 1.128     | 0.129   | 1.909                           | 0.023                                      | 1.939             |

Note: The following standards were used: KM₂Si₃O₁₀(OH)₂ (SiKα, MgKα, KKα, FKα), albite (NaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), scapolite (CIKα), and diopside (CaKα). Compositions were recalculated on the basis of 12 anions assuming 2 (OH + F) pfu. *Determined by stoichiometry.
<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Fracture fill in fgr. diorite</th>
<th>Aggr. w/ titan. in HF</th>
<th>V4 core, in HF</th>
<th>Inter-grown w/ sch, in V4, in HF</th>
<th>'Clots' in V4 halo, in HF</th>
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<tr>
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<td>n</td>
<td>average 6</td>
<td>stdev 6</td>
<td>average 3</td>
<td>stdev 3</td>
</tr>
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<td>0.54</td>
<td>6.74</td>
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<td>11.30</td>
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<td>0.01</td>
<td>0.03</td>
<td>0.03</td>
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<tr>
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<td>17.08</td>
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<tr>
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<tr>
<td>Na₂O</td>
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<td>0.03</td>
<td>0.03</td>
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<tr>
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<td>9.49</td>
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<tr>
<td>H₂O⁺</td>
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<td>2.70</td>
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</tr>
<tr>
<td>F</td>
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<td>0.11</td>
<td>2.71</td>
<td>0.21</td>
<td>3.11</td>
</tr>
<tr>
<td>CL</td>
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<td>0.00</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Total</td>
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<td>0.73</td>
<td>99.06</td>
<td>0.39</td>
<td>97.14</td>
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</tbody>
</table>

**Note:** The following standards were used: KMg₃AlSi₃O₁₀(OH)₂ (SiKα, MgKα, KKα, FKα), albite (NaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), scapolite (ClKα), and diopside (CaKα). Compositions were recalculated on the basis of 12 anions assuming 2 (OH + F) pfu. *Determined by stoichiometry."
Fig 8.33. Fluorine contents (F apfu) in mica from Northern Dancer are plotted by vein/host environment.

(average of 2.66 wt.% F or 0.64 F apfu), suggesting that biotite here is forming in different conditions (possibly from F-rich hydrothermal fluids congregating near the contact) than biotite elsewhere in the diorite. Biotite in hornfels groundmass is moderately F-rich, averaging 2.71 wt.% F or 0.64 F apfu. Fluorine is high in fracture-filling biotite in the fine-grained diorite (averaging 3.66 wt.% F or 0.86 F apfu), as well as in Type 4 veins (averaging 3.11 wt.% F or 0.72 F apfu). Biotite intergrown with scheelite reaches an average of 3.70 wt.% F or 0.87 F apfu. The highest average fluorine content in biotite at Northern Dancer occurs in the alteration haloes of thick Type 4 veins in altered hornfels. Here, fluorine averages 3.83 wt.% F or 0.90 F apfu and reaches a maximum of 4.16 wt.% F or 0.98 F apfu. Two modes of analyses from a Type 4 vein core in hornfels show very different F contents: one group is very high (4.26 wt.% F or 1.01 F apfu), similar to that of mica from Type 4 vein haloes, and the other is low (1.14 wt.% F or 0.25 F apfu), similar to F content in muscovite found in quartz-feldspar porphyry. The lower F
content in the latter analysis may support the hypothesis that Type 4 veins are transitional from siliceous quartz-feldspar porphyry.

H₂O content is highest in the diorite, where the system was likely more H₂O rich than the later monzonite/felsic dike system (which was likely low H₂O/high F) at its time of formation. Biotite from the diorite averages 3.76 wt.% H₂O or 1.91 H⁺ apfu, while biotite from the monzonite averages only 2.20 wt.% H₂O or 1.13 H⁺ apfu. Biotite associated with Type 4 veins and their haloes are also relatively low in H₂O and high in fluorine. Fluorine content in biotite generally decreases with temperature and the H₂O/HF content of the fluid in equilibrium with it; either of these can be calculated if the other is known, e.g., H₂O/HF can be obtained from fluid inclusions (Deer et al. 1992).

Chlorine is low in all biotite at Northern Dancer; however, it is relatively elevated in the diorite unit, where it averages 0.22 wt % Cl or 0.028 Cl apfu (max. 0.25 wt.% Cl or 0.032 Cl apfu). Most other vein/host environments do not register chlorine contents above statistical detection limits.

Compositionally, secondary biotite usually has higher Mg/(Mg+Fe) ratios and lower titanium concentrations than igneous biotite (Beane & Titley 1981; Hendry et al. 1985; Jacobs & Parry 1979; Thomson & Thompson 1996). This distinction would therefore be helpful to identify the character of biotite within veins compared to biotite within intrusive units at Northern Dancer. In Fig. 8.34, Mg/(Mg+Fe) ratios are plotted versus Ti⁴⁺ (apfu). Two prominent groups are apparent: one (a) in the top left of the plot, and one (b) in the bottom right. Group (a) consists of biotite found within the monzonite and the diorite, and falls within a field with relatively higher Ti⁴⁺ concentrations and lower Mg/(Mg+Fe) ratios, suggesting this biotite is likely igneous in character. Two outlier points belonging to the monzonite unit suggest that some of the biotite in the monzonite has been altered as they have much lower Ti⁴⁺ concentrations; this hypothesis is supported by the altered morphology of some grains in polished section, described above. The biotite from the diorite host environments has somewhat higher Mg/(Mg+Fe) ratios; this may reflect original magnesium contents of the diorite itself. Some analyses from the diorite which rim amphibole appear to be slightly more 'secondary' in character than the rest, which is reasonable considering it is forming as a rim. Group (b) consists of biotite in veins, fracture fill, diorite contact zones, and alteration haloes and/or groundmass, and falls within a field with relatively lower Ti⁴⁺ concentrations and high Mg/(Mg+Fe) ratios, suggesting this biotite is secondary, or possibly hydrothermal in origin. Therefore, the plot suggests that biotite from Type 4 veins, which are possibly transitory between magmatic and
Fig. 8.34. Mg/(Mg+Fe) ratios are plotted versus Ti\(^{4+}\) (apfu), via vein/host environment. Two prominent groups are apparent: one (a) in the top left of the plot, and one (b) in the bottom right. Group (a) consists of biotite found within the monzonite and the diorite, and falls within a field with relatively higher Ti\(^{4+}\) concentrations and lower Mg/(Mg+Fe) ratios, suggesting this biotite is likely igneous in character. Two outlier points belonging to the monzonite unit suggest that some of the biotite in the monzonite has been altered as they have much lower Ti\(^{4+}\) concentrations. Group (b) consists of biotite in veins, fracture fill, diorite contact zones, and alteration haloes and/or groundmass; these analyses fall within a field of relatively lower Ti\(^{4+}\) concentrations and higher Mg/(Mg+Fe) ratios, suggesting this biotite is secondary, or possibly hydrothermal in origin.

Hydrothermal conditions, is probably not igneous, and is more likely secondary or hydrothermal in character.

The lower content of Ti and Fe in hydrothermal biotite relative to the precursor mineral (in this case primary magmatic hornblende in a Ti-rich intrusion) commonly results in the formation of secondary titanite and rutile, which we see at biotite-hornblende grain boundaries and between hornblende cores and biotite rims in altered diorite (Thomson & Thompson 1996). This kind of biotite alteration in dioritic intrusions may have a temporal and thermal felsic intrusive counterpart in potassic styles of alteration, which may occur to a certain extent in altered monzonite and early phases of the felsic dikes.
8.2.11.2 Muscovite

At Northern Dancer, muscovite is found primarily in the felsic dikes and 'brain rock' units. Muscovite also occurs in altered monzonite, where it is associated with fluorite and potassium feldspar (Fig. 8.35). It may also occur in zones where Type 4 veins appear to grade into 'brain rock' layers or very siliceous zones of porphyry (Fig. 8.36). In these locations, muscovite is associated or intergrown with K-feldspar, either in layers or at what appear to be vein walls or edges of quartz flooding. These muscovite-feldspar layers and "clots" (which can occur as radiating crystals) appear to be traps for scheelite, molybdenite and rutile (Fig. 8.37). Possibly, these 'layers' are discreet zones in the 'brain rock' or silicified quartz-feldspar porphyry where more hydrothermal (vs. magmatic) activity is taking place (in a unit which forms within the magmatic-hydrothermal continuum). In these local environments, F and/or H$_2$O are possibly concentrated at the reaction front, and conditions may be more conducive to the formation of hydrous minerals such as muscovite, and ore minerals such as molybdenite and scheelite.

Fifteen analyses from two polished sections in two different vein/host environments were analyzed via EPMA. Analyses were recalculated on the basis of 12 anions assuming 2(OH + F) per formula unit. Muscovite results are listed in Table 8.8. Both vein/host rock environments show similar results. Silica content averages 46.98 wt.% SiO$_2$ or 3.16 Si $apfu$, aluminum content averages 34.16 wt.% or 2.71 Al $apfu$, and magnesium reaches a maximum of 0.34 wt.% MgO or 0.03 Mg $apfu$. Iron is low, averaging 1.68 wt.% FeO or 0.10 Fe$^{2+}$ $apfu$, whereas fluorine is slightly elevated above zero, averaging 0.38 wt.% F or 0.08 F $apfu$ (see fig. 8.33). Water content averages 4.27 wt.% H$_2$O or 1.92 H$^+$ $apfu$.

8.2.11.3 Chlorite

Chlorite is a relatively common alteration mineral at Northern Dancer. Where chlorite occurs as a component in altered diorite, it is commonly the alteration product of Mg-rich biotite (see Fig. 8.31). Chlorite usually occurs as an alteration around veins in the form of fine-grained haloes (Fig. 8.38), and as a vein mineral (Fig. 8.23). Near Type 1 vein walls, chlorite occurs as a minor intergrowth with hedenbergitic clinopyroxene, and also as an alteration halo component. Chlorite is occasionally found at Type 2 vein selvedges (especially those which have been
Fig. 8.35. Backscatter SEM image of muscovite in altered monzonite, near its contact with the metasedimentary country rocks. Here, muscovite is associated with fluorite and potassium feldspar, and contains very fine-grained Nb- and Ti-rich segregations.

Fig. 8.36. Polished section QSM-9 in plane-polarized light. Muscovite typically occurs in zones where Type 4 veins appear to grade into ‘brain rock’ layers or very siliceous zones of porphyry. Here, it is associated/intergrown with molybdenite, either in layers or at what appear to be vein ‘walls’ or edges of quartz flooding.
Table 8.8. Average compositions of muscovite samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>In QFP w/ molybdenite</th>
<th>In QFP matrix at edge of SiO₂ 'flooding'</th>
</tr>
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<td></td>
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</tr>
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<td>SiO₂ (wt.%)</td>
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<td>46.98 ± 0.57</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.11 ± 0.04</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>34.51 ± 0.43</td>
<td>34.16 ± 0.67</td>
</tr>
<tr>
<td>Cr₂O₃</td>
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<td>0.01 ± 0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>0.13 ± 0.07</td>
<td>0.23 ± 0.08</td>
</tr>
<tr>
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<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>FeO</td>
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<td>1.68 ± 0.40</td>
</tr>
<tr>
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<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.16 ± 0.02</td>
<td>0.12 ± 0.04</td>
</tr>
<tr>
<td>K₂O</td>
<td>10.79 ± 0.19</td>
<td>10.95 ± 0.19</td>
</tr>
<tr>
<td>H₂O*</td>
<td>4.31 ± 0.03</td>
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<td>F</td>
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</tr>
<tr>
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<td>98.83 ± 0.87</td>
</tr>
</tbody>
</table>

| Si⁴⁺ (apfu)           | 3.139 ± 0.011          | 3.162 ± 0.021                          |
| Ti⁴⁺                  | 0.006 ± 0.002          | 0.006 ± 0.002                          |
| Al³⁺                  | 2.743 ± 0.018          | 2.709 ± 0.041                          |
| Cr³⁺                  | 0.001 ± 0.001          | 0.001 ± 0.001                          |
| Mg²⁺                  | 0.013 ± 0.007          | 0.023 ± 0.008                          |
| Mn²⁺                  | 0.006 ± 0.001          | 0.002 ± 0.002                          |
| Ca²⁺                  | 0.005 ± 0.001          | 0.004 ± 0.003                          |
| Fe³⁺                  | 0.095 ± 0.002          | 0.095 ± 0.023                          |
| Na⁺                   | 0.021 ± 0.003          | 0.016 ± 0.006                          |
| K⁺                    | 0.929 ± 0.009          | 0.940 ± 0.019                          |
| F⁻                    | 0.058 ± 0.016          | 0.082 ± 0.023                          |
| Cl⁻                   | 0.002 ± 0.001          | 0.001 ± 0.001                          |
| H⁺                    | 1.940 ± 0.015          | 1.917 ± 0.023                          |

Note: The following standards were used: KMg₃AlSi₃O₁₀(OH)₂ (SiKα, MgKα, KKα, FKα), albite (NaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), scapolite (ClKα), and diopside (CaKα). Compositions were recalculated on the basis of 12 anions assuming 2 (OH + F) pfu. *Determined by stoichiometry.
Fig. 8.37. Backscatter SEM image of muscovite-feldspar “clot” in the ‘brain rock’ unit. These layers/intergrowths may be traps for scheelite, molybdenite, and rutile, as seen in the image.

reopened by Type 4 veins) within fine-grained hornfels/calc-silicate host rocks, along with fine-grained, massive plagioclase (Fig. 8.39).

Most commonly it occurs at the selvedges or in alteration haloes around Type 4 veins in metasedimentary host rocks, or more rarely as a Type 4 vein component. In Type 4 veins with high molybdenite content, chlorite is intergrown with molybdenite at the vein wall/selvedge. In Type 4 veins with abundant beryl, chlorite is commonly found interstitially between euhedral beryl crystals (see Fig. 8.7). Chlorite can be intergrown with scheelite and fluorite in the boundaries between Type 4 veins and the earlier veins they reopened (as in Fig 8.23). It may also occur as an alteration product of biotite in the walls of reopened veins where earlier biotite alteration occurred, indicating overprinting alteration haloes. Rarely, it is present as rims on sulphides, especially pyrite, in thick Type 4 veins. The presence of chlorite and epidote as alteration minerals peripheral to the monzonite is similar to ‘propylitic’ styles of alteration seen in many porphyry systems. Retrograde overprinting alteration (such as chlorite replacing hydrothermal biotite) is also characteristic of porphyry style deposits (Thomson & Thompson 1996).
Fig. 8.38. Polished section QSM-27 in plane-polarized light. Chlorite (green, fine-grained) forms an alteration halo with biotite around a Type 4 vein, and also occurs with pyrite, scheelite, plagioclase, and chalcopyrite within the vein itself.

Fig. 8.39. Polished section LT-FIS-V3B in plane-polarized light. Chlorite and fine-grained massive plagioclase occur at the edge of a reopened Type 2 vein (by a scheelite-bearing Type 4 vein) within fine-grained hornfels/calc-silicate host rocks. A type 3 vein runs ~50° through the reopened vein, post-dating the Type 2 vein, but pre-dating the reopening of the V2 by the Type 4 vein.
Fifty-one analyses from five polished sections in eleven different vein/host environments were analyzed via EPMA. Analyses were recalculated on the basis of 18 anions per formula unit assuming 8(OH + F). Chlorite results are listed in Table 8.9. Iron content varies somewhat from an average of 29.91 wt.% FeO or 2.74 Fe$^{2+}$ apfu in the altered diorite, where it is likely the alteration product of biotite, to an average of 34.26 wt.% FeO or 3.19 Fe$^{2+}$ apfu at the selvedge of a thick Type 4 vein in hornfels where it is intergrown with molybdenite. In the ‘old cores’ of Type 2 reopened veins, however, iron averages only 16.50 wt.% FeO or 1.40 Fe$^{2+}$ apfu, and in this same environment where chlorite is intergrown with scheelite, fluorite, garnet and pyroxene, iron is lowest, averaging only 15.76 wt.% FeO or 1.34 Fe$^{2+}$ apfu. Conversely, magnesium content reaches its peak here, averaging 21.57 wt.% MgO or 3.27 Mg apfu, whereas in the altered diorite, it averages only 12.08 wt.% MgO or 1.91 Mg apfu. Manganese contents are relatively low throughout the deposit, but are relatively higher at an average of 1.51 wt.% MnO or 0.14 Mn apfu where chlorite is intergrown with molybdenite or beryl at the selvedges of Type 4 veins. Chlorite at Northern Dancer does not contain significant amounts of fluorine, however in reopened Type 2 veins, where chlorite is associated with fluorite and scheelite; fluorine contents register above detection at 0.32 wt.% F or 0.10 F apfu average.

Where Type 2 veins have been reopened by Type 4 veins, chlorite composition varies on the local scale (see Fig. 8.23). In Type 2 environments, chlorite is higher in fluorine (avg. 0.38 wt.% F or 0.11 F apfu vs. 0.23 wt.% F or 0.08 F apfu in Type 4 veins), and magnesium (avg. 21.09 wt.% MgO or 3.24 Mg apfu vs. 19.24 wt.% MgO or 2.94 Mg apfu in Type 4 veins). Type 4 vein environment chlorite has higher amounts of iron (avg. 18.06 wt.% FeO or 1.55 Fe$^{2+}$ apfu vs. 16.50 wt.% FeO or 1.40 Fe$^{2+}$ apfu in Type 2 vein environments).
Table 8.9. Average compositions of chlorite samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Chl. altering from biot.</th>
<th>In altered diorite</th>
<th>In altered diorite, assc. w/ pyr, cry, titan, amph</th>
<th>At selvedge in V4, assc. w/ beryl, HF host</th>
<th>At selvedge in V4, assc. w/ moly, HF host</th>
<th>Chl. 'band' at margin btwn reopened V2 and V4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Avg. St dev</td>
<td>Avg. St dev</td>
<td>Avg. St dev</td>
<td>Avg. St dev</td>
<td>Avg. St dev</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
<td>27.20 0.28</td>
<td>29.08 1.66</td>
<td>27.07 0.30</td>
<td>23.75 0.48</td>
<td>23.98 0.23</td>
<td>25.90 0.68</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.10 0.02</td>
<td>0.02 0.03</td>
<td>0.02 0.03</td>
<td>0.58 0.46</td>
<td>0.07 0.01</td>
<td>0.08 0.04</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>18.69 0.33</td>
<td>15.40 3.50</td>
<td>18.34 0.71</td>
<td>21.19 0.27</td>
<td>20.74 0.53</td>
<td>19.56 0.09</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.02 0.03</td>
<td>0.04 0.03</td>
<td>0.02 0.02</td>
<td>0.02 0.02</td>
<td>0.01 0.01</td>
<td>0.03 0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>16.09 0.21</td>
<td>12.08 6.07</td>
<td>15.49 0.17</td>
<td>8.01 1.48</td>
<td>7.47 0.70</td>
<td>10.54 0.89</td>
</tr>
<tr>
<td>MnO</td>
<td>0.31 0.05</td>
<td>0.27 0.11</td>
<td>0.33 0.01</td>
<td>1.35 0.39</td>
<td>1.51 0.14</td>
<td>0.79 0.06</td>
</tr>
<tr>
<td>FeO</td>
<td>25.12 0.09</td>
<td>29.91 7.45</td>
<td>24.78 0.56</td>
<td>33.02 2.17</td>
<td>34.26 1.23</td>
<td>30.27 1.23</td>
</tr>
<tr>
<td>CaO</td>
<td>0.03 0.01</td>
<td>0.55 0.58</td>
<td>0.53 0.46</td>
<td>0.01 0.01</td>
<td>0.01 0.01</td>
<td>0.44 0.04</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.07 0.02</td>
<td>0.15 0.14</td>
<td>0.08 0.03</td>
<td>0.00 0.00</td>
<td>0.01 0.00</td>
<td>0.01 0.01</td>
</tr>
<tr>
<td>H₂O*</td>
<td>11.39 0.02</td>
<td>11.06 0.42</td>
<td>11.28 0.01</td>
<td>10.67 0.11</td>
<td>10.70 0.06</td>
<td>10.99 0.11</td>
</tr>
<tr>
<td>F</td>
<td>0.00 0.00</td>
<td>0.07 0.05</td>
<td>0.10 0.10</td>
<td>0.23 0.06</td>
<td>0.18 0.08</td>
<td>0.05 0.04</td>
</tr>
<tr>
<td>O=F</td>
<td>0.00 0.00</td>
<td>-0.03 0.02</td>
<td>-0.04 0.04</td>
<td>-0.10 0.03</td>
<td>-0.08 0.03</td>
<td>-0.02 0.02</td>
</tr>
<tr>
<td>Total</td>
<td>99.06 0.27</td>
<td>98.69 0.50</td>
<td>98.55 0.15</td>
<td>98.24 0.84</td>
<td>98.88 0.49</td>
<td>98.56 0.79</td>
</tr>
</tbody>
</table>

| St⁴⁺ (apfu)           | 2.863 0.022             | 3.156 0.317        | 2.868 0.025                                      | 2.643 0.025                                    | 2.668 0.026                                    | 2.819 0.053                                    |
| Ti⁴⁺                  | 0.006 0.002             | 0.002 0.003        | 0.047 0.037                                      | 0.006 0.001                                    | 0.007 0.004                                    | 0.000 0.000                                    |
| Al⁴⁺                  | 2.319 0.046             | 1.948 0.379        | 2.290 0.094                                      | 2.779 0.023                                    | 2.719 0.060                                    | 2.510 0.16                                    |
| Cr³⁺                  | 0.002 0.002             | 0.003 0.002        | 0.002 0.002                                      | 0.002 0.002                                    | 0.001 0.001                                    | 0.002 0.002                                    |
| Mg⁡²⁺                 | 2.526 0.029             | 1.912 0.920        | 2.446 0.021                                      | 1.326 0.230                                    | 1.238 0.110                                    | 1.712 0.151                                    |
| Mn⁡²⁺                 | 0.028 0.004             | 0.024 0.009        | 0.030 0.000                                      | 0.128 0.037                                    | 0.143 0.014                                    | 0.073 0.006                                    |
| Ca²⁺                  | 2.212 0.006             | 2.735 0.792        | 2.196 0.054                                      | 3.075 0.231                                    | 3.189 0.128                                    | 2.756 0.121                                    |
| Fe²⁺                  | 0.004 0.001             | 0.066 0.071        | 0.060 0.052                                      | 0.001 0.002                                    | 0.001 0.001                                    | 0.001 0.001                                    |
| K⁺                    | 0.005 0.003             | 0.021 0.021        | 0.011 0.004                                      | 0.000 0.000                                    | 0.000 0.000                                    | 0.000 0.000                                    |
| H⁺                    | 7.996 0.000             | 7.976 0.016        | 7.967 0.031                                      | 7.917 0.023                                    | 7.935 0.022                                    | 7.983 0.012                                    |
| F⁻                    | 0.004 0.000             | 0.000 0.002        | 0.001 0.001                                      | 0.002 0.002                                    | 0.002 0.002                                    | 0.001 0.001                                    |

Note: The following standards were used: KMg₃AlSi₅O₁₂(OH)₂ (SiKα, MgKα, KKα, FKα), albite (NaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), scapolite (ClKα), and diopside (CaKα). Compositions were recalculated on the basis of 18 anions assuming 8 (OH + F) pfu. Cl and Na were sought but not detected. *Determined by stoichiometry.
Table 8.9. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Chl in 'old core' of reopened V2</th>
<th>Chl at V4 selvedge, grows perp. to vein wall</th>
<th>Intergrown w/ sch, fluo, gar, pyx at margin of reopened V2/V4</th>
<th>In V4 assc. w/ sulphide</th>
<th>In V4 alteration halo w/ pyr, sch.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
<td>29.01</td>
<td>0.19</td>
<td></td>
<td>28.39</td>
<td>0.75</td>
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<tr>
<td>TiO₂</td>
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<td>0.02</td>
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<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Al₂O₃</td>
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<td>19.89</td>
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<tr>
<td>Cr₂O₃</td>
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<td>0.01</td>
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<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>21.40</td>
<td>0.39</td>
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<td>19.24</td>
<td>1.63</td>
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<tr>
<td>MnO</td>
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<td>0.05</td>
<td></td>
<td>0.76</td>
<td>0.06</td>
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<tr>
<td>FeO</td>
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<td>0.65</td>
<td></td>
<td>18.06</td>
<td>1.30</td>
</tr>
<tr>
<td>CaO</td>
<td>0.03</td>
<td>0.02</td>
<td></td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>H₂O*</td>
<td>11.65</td>
<td>0.07</td>
<td></td>
<td>11.57</td>
<td>0.09</td>
</tr>
<tr>
<td>F</td>
<td>0.34</td>
<td>0.01</td>
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<td>0.25</td>
<td>0.09</td>
</tr>
<tr>
<td>O=F</td>
<td>-0.14</td>
<td>0.00</td>
<td></td>
<td>-0.10</td>
<td>0.04</td>
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<tr>
<td>Total</td>
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<td>0.63</td>
<td></td>
<td>98.18</td>
<td>0.57</td>
</tr>
<tr>
<td>Si⁴⁺ (apfu)</td>
<td>2.945</td>
<td>0.002</td>
<td></td>
<td>2.911</td>
<td>0.048</td>
</tr>
<tr>
<td>Ti⁴⁺</td>
<td>0.003</td>
<td>0.002</td>
<td></td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Al³⁺</td>
<td>2.266</td>
<td>0.008</td>
<td></td>
<td>2.406</td>
<td>0.110</td>
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<tr>
<td>Cr³⁺</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>3.238</td>
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<td></td>
<td>2.941</td>
<td>0.225</td>
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<tr>
<td>Mn²⁺</td>
<td>0.060</td>
<td>0.004</td>
<td></td>
<td>0.066</td>
<td>0.005</td>
</tr>
<tr>
<td>Ca²⁺</td>
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<td>0.055</td>
<td></td>
<td>1.550</td>
<td>0.126</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.004</td>
<td>0.003</td>
<td></td>
<td>0.008</td>
<td>0.012</td>
</tr>
<tr>
<td>K⁺</td>
<td>0.002</td>
<td>0.002</td>
<td></td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>H⁺</td>
<td>7.891</td>
<td>0.002</td>
<td></td>
<td>7.918</td>
<td>0.030</td>
</tr>
<tr>
<td>F⁻</td>
<td>0.109</td>
<td>0.003</td>
<td></td>
<td>0.090</td>
<td>0.030</td>
</tr>
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</table>

Note: The following standards were used: KMg₃Al₅Si₃O₁₀(OH)₂ (SiKc, MgKc, KKc, FKc), albite (NaKa), rutile (TiKa), kyanite (AIKc), MgCr₂O₄ (CrKc), MnSiO₃ (MnKc), Fe₂SiO₄ (FeKc), scapolite (ClKc), and diopside (CaKc). Compositions were recalculated on the basis of 18 anions assuming 8 (OH + F) pfu. Cl and Na were sought but not detected. *Determined by stoichiometry.
8.2.12 Rutile

Rutile is relatively rare, and tends to occur in local environments where Ca is low (as high Ca would likely promote titanite development), such as areas of quartz flooding, or in thicker quartz veins within the felsite units. As a result, rutile and titanite do not commonly occur together at Northern Dancer, and overall, titanite is the more dominant Ti-mineral in the system. Rutile can occur in fine-grained, rare, aggregate masses in the monzonite, along with apatite, zircon, biotite, ilmenite, and potassium feldspar (Fig 8.40). In altered monzonite rocks, the rutile is Nb-rich, and it occurs near scheelite grains which are also Nb-Ta-rich (Fig. 8.41). It can also form in Type 4 veins intergrown with chlorite, alongside euhedral beryl and molybdenite, (Fig. 8.7).

In zones where earlier, fine-grained, feldspar-rich felsite is overprinted (by quartz porphyry, quartz flooding, or Type 4 veins), rutile is also present. In these environments, rutile can be zoned, and associated with scheelite (Fig 8.42), and beryl. In these grains, the mottling effect seen in backscatter mode on the SEM is due to variations in Nb, Sn, and W content. In the same section as the rutile in Fig 8.42, altered, Nb- and Sn-rich rutile is replaced by calcite and pyrrhotite within a quartz matrix (Fig. 8.43). Zoned rutile also occurs in zones where Type 4 veins appear to grade into ‘brain rock’ within feldspar layers containing scheelite, or very siliceous zones of porphyry dikes. Rutile is also Nb-rich in quartz porphyry that has been cross cut by Type 3 veins (such as in polished section A1-06-06). In this section, Nb-rich rutile appears to be altering to titanite, allanite, monazite and pyrrhotite (Fig. 8.44). This is one of the rare locations where titanite and rutile have been noted together at Northern Dancer.

Very rarely, rutile can form veinlets or fill thin fractures (Fig. 8.45), in coarse-grained calc-silicate rocks which are garnet, fluorite, and pyrite rich. According to Deer et al. (1992), rutile is not unusual in metamorphosed limestones. Overall, rutile content appears to be positively correlated with garnet content in the metasedimentary rocks, possibly because Ca may enter the garnet providing a less calcic local environment for rutile to form.

As rutile is relatively rare and extremely fine-grained at Northern Dancer, only two suitable grains were analyzed from the quartz-feldspar porphyry dikes. These analyses are reported here because of their interesting W content, but should be reanalyzed for Ta, as they have high Nb content, and their totals are slightly lower than 100 wt.%. Rutile analyses were
Fig 8.40. Backscatter SEM image of monzonite: a fine-grained aggregate of inclusions within biotite consisting of rutile, apatite, zircon, biotite, ilmenite, and potassium feldspar, in a coarser-grained matrix of quartz, potassium feldspar, plagioclase, biotite, and occasionally fluorite.

Fig. 8.41. Backscatter SEM image of altered monzonite: a zoned rutile grain in groundmass/matrix, near scheelite. (1) is relatively enriched in Nb and Fe, (2) is moderately enriched in Nb, Fe, and slightly enriched in Sn, and (3) is high in Nb, and relatively enriched in W, Mn and Fe.
Fig. 8.42. Backscatter SEM image of zoned rutile associated with scheelite in a Type 4 vein which crosscuts earlier felsic dikes. Lighter regions are enriched in Nb, Sn and W.

Fig. 8.43. Backscatter SEM image of Nb- and Sn-rich rutile which is being replaced by calcite and pyrrhotite, within a Type 4 vein that crosscuts earlier felsic dikes.
Fig. 8.44. Backscatter SEM image of Nb-rich rutile which appears to be altering to titanite, allanite, monazite and pyrrhotite in felsic porphyry dike crosscut by Type 3 veins.

Fig. 8.45. Polished section RS-13, in plane-polarized light. Very rarely, rutile can form veinlets or fill thin fractures, in coarse-grained calc-silicate rocks which are garnet, fluorite, and pyrite rich.
recalculated on the basis of 2 anions per formula unit, and the results are shown in Table 8.10. F, Mg, Na, Si, Sc, and La were sought but not detected. The titanium content is relatively low, averaging 88.22 wt.% TiO$_2$ or 0.94 Ti apfu, as is usually the case with Nb- or Ta-rich rutile (Deer et al. 1996). Niobium averages 4.36 wt.% Nb$_2$O$_5$ or 0.03 Nb apfu, and iron averages 2.25 wt.% Fe$_2$O$_3$ or 0.02 Fe$_{3+}$ apfu. To allow for the higher valence of the Nb$^{5+}$ (and Ta$^{5+}$) cations in place of Ti$^{4+}$, rutile may take up Fe$^{2+}$ for charge balance via a coupled substitution (Deer et al. 1996), therefore it is likely that some of the Fe$^{3+}$ content is actually Fe$^{2+}$. Calcium is elevated at 0.55 wt.% or 0.01 Ca apfu (avg.), but Al, Mn, Cr, Ce, La and Mo are not significant. Interestingly, tungsten attains significant concentrations in these grains, averaging 0.91 wt.% WO$_3$ or 0.004 W apfu, and one of the grains contains 1.26 wt.% WO$_3$ or 0.005 W apfu. It is possible then, that the transport and/or depositional mechanism responsible for rutile in these environments is related to that of W and W-bearing minerals at Northern Dancer, and therefore, W-content of rutile could act as an exploration indicator for W mineralization elsewhere, and should be investigated more thoroughly (R. Linnen, pers comm., 2006). It is not unusual to find "clots" of rutile, molybdenite, muscovite, and scheelite in the felsic dikes, especially in ‘brain rock’ layers. Tin is also elevated in these grains, averaging 0.49 wt.% SnO$_2$. 
Table 8.10. Average compositions of rutile samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th></th>
<th>Quartz-feldspar porphyry host</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Host env.</td>
</tr>
<tr>
<td>WO&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>MoO&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Nb&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>SnO&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Cr&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Ce&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Fe&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>W&lt;sup&gt;6+&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Mo&lt;sup&gt;6+&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Nb&lt;sup&gt;6+&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Ti&lt;sup&gt;4+&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Sn&lt;sup&gt;4+&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Al&lt;sup&gt;3+&lt;/sup&gt;</td>
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<tr>
<td>Cr&lt;sup&gt;3+&lt;/sup&gt;</td>
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<tr>
<td>Ce&lt;sup&gt;3+&lt;/sup&gt;</td>
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<tr>
<td>Fe&lt;sup&gt;3+&lt;/sup&gt;</td>
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</tr>
<tr>
<td>Mn&lt;sup&gt;2+&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Ca&lt;sup&gt;2+&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

Note: The following standards were used: albite (NaKα), MgCr<sub>2</sub>O<sub>4</sub> (CrKα), fayalite (FeKα), CaSiO<sub>3</sub> (SiKα, CaKα), rutile (TiKα), Mo (MoLα), W (W Lα), kyanite (AlKα), Sc (ScKα), Topaz (FKα), Nb (NbLα), Sn (SnLα), Y/La/Ce/Pr (LaLα, CeLα), and MnSiO<sub>3</sub> (MnKα). Compositions were recalculated on basis of 2 O pfu. F, Mg, Na, Si, Sc, and La were sought but not detected.
8.2.13 Sulphides

Aside from molybdenite, other sulphides occurring as accessory, minor, and (locally) major minerals in the metasedimentary host rocks, veins, and alteration haloes include pyrite, pyrrhotite, chalcopyrite, sphalerite, galena, and bismuthinite. Most sulphides are pure in composition, with the exception of those which contain fine-grained inclusions of other sulphides (as detected on EDS via the SEM).

8.2.13.1 Pyrite and pyrrhotite

Pyrite, and to a lesser extent pyrrhotite, are the most abundant sulphides (with the exception of molybdenite) at Northern Dancer. Pyrite occurs in most rock units and vein environments; however, typically it is only an accessory mineral, although it can be a major mineral in localized, massive sulphide-rich Type 4 vein environments. Both pyrrhotite and pyrite can be found as an extremely fine-grained component of hornfels rocks, and usually near overprinting veins (the former being less common). Both are rare in more distal units such as wollastonite-vesuvianite skarn.

Pyrite in Type 2 veins can be euhedral but typically altered, with a slight to moderate appearance of resorption (Fig. 8.46), and it is also occasionally associated with scheelite. Type 4 vein pyrite is less homogenous, sub-anhedral, but much coarser-grained and largely unaltered aside from minor crosscutting, late-stage quartz veins (Fig. 8.47). It seems that while pyrite and pyrrhotite occur together as vein (and alteration halo) constituents in earlier Type 1 and 2 veins, pyrite and chalcopyrite occur together in later Type 3 and 4 veins, with pyrrhotite seen mostly in vein alteration haloes around Type 4 veins, within biotite hornfels or diorite host rocks.

Occasionally, where pyrite and pyrrhotite are disseminated within calc-silicate near veins, they can contain titanite inclusions (Fig. 8.48). Disseminated pyrite occurs in haloes around Type 3 veins. In general, the sulphide most associated with the Type 3 veins and the felsic dikes is pyrite (excluding molybdenite). Both pyrite and pyrrhotite occur next to each other in calc-silicate zones within hornfels, as aggregate masses (Fig. 8.49). Pyrite occurring in calc-silicate zones which have been silicified is altered and anhedral. Most pyrite and pyrrhotite at Northern Dancer appears altered and some possibly remobilized, with the exception of massive pyrite in
Fig. 8.46. Polished section QSM-30 in plane-polarized light: pyrite-rich Type 2 stockwork veins in calc-silicate. Pyrite appears altered and possibly resorbed where veins have been reopened by later fluids.

Fig. 8.47. Polished section QSM-1 in plane-polarized light: Type 4 veins contain mostly unaltered, massive pyrite and pyrrhotite.
Fig. 8.48. Polished section QSM-2 in plane-polarized light: disseminated pyrite (appearing black, euhedral) and minor pyrrhotite in calc-silicate, near overprinting Type 2, 3, and 4 veins.

Fig. 8.49. Polished section QSM-13 in reflected light. Aggregate masses of pyrite, pyrrhotite, and chalcopyrite occur within calc-silicate and are associated with scheelite, fluorite, and garnet.
thick, late sheeted Type 4 veins. This could also be evidence for changing fluid composition and/or geological conditions including the oxidation state of the overall system.

8.2.13.2 Chalcopyrite

Chalcopyrite dominantly occurs as an accessory mineral in Type 4 veins, usually with other sulphides, especially pyrite. It may also be present in fractures within altered diorite host rocks, and it is seen disseminated in rusty hornfels (in outcrop) along Logtung Ridge, near the diorite contact with the metasedimentary country rocks. In Type 4 veins, chalcopyrite can occur as separate subhedral grains up to 8 mm across, as blebby inclusions in large pyrite crystals, or as blebs within sphalerite inclusions (also known as ‘chalcopyrite disease’) in pyrite (Fig. 8.50). Occasionally, chalcopyrite is rimmed by fine-grained, massive aggregate of calcite and rutile, within pyrite. Chalcopyrite can also occur as inclusions in pyrite in Type 2 vein cores. In some porphyry Cu systems, especially those associated with quartz monzonites or quartz diorites (such as Bingham Canyon, Utah, Butte, Montana, and Bisbee, Arizona), chalcopyrite formed by precipitation from high-salinity, late-stage fluids. It is possible that chalcopyrite at Northern Dancer formed from similarly saline, late-stage fluids associated with the felsic porphyry dikes.

8.2.13.3 Sphalerite and galena

Sphalerite is a common accessory sulphide in Type 4 veins, and may indicate a genetic connection to the Pb-Zn-Ag sheeted veins of the Logjam occurrence to the northwest of the deposit. Galena is less common, and seems to occur in Type 4 veins at deeper levels of the deposit. Commonly, they both occur as subhedral grains in Type 4 vein cores, or as blebby inclusions within pyrite (Fig. 8.50). Sphalerite appears to be late-stage, open-space infill within thick quartz veins, in zones where Type 4 veins appear to grade into brain rock layers, or very siliceous zones of porphyry dikes (Fig. 8.51). Temporally, sphalerite first appears in Type 2 veins as a rare, fine-grained accessory, typically associated with galena, pyrite, epidote, and fluorite. Sphalerite can also occur as inclusions in titanite, as mentioned in the titanite section.
Fig. 8.50. Backscatter SEM image of sulphides in a Type 4 vein within altered hornfels. The sphalerite is massive and coarse-grained, up to 4 mm wide, and contains chalcopyrite inclusions ("chalcopyrite disease"). Pyrite (euhedral), chalcopyrite, pyrrhotite and fine-grained galena are intergrown at the edge of the massive sphalerite, near open space in the vein core.

Fig. 8.51. Backscatter SEM image of sulphide infill within thick quartz veins in polished section QSM-10. Sphalerite, chalcopyrite, andradite garnet, and fluorite are intergrown between massive quartz.
8.2.13.4 Bismuthinite

Bismuthinite occurs as an accessory mineral in beryl-wolframate sheeted veins which occur to the southeast, outside the Northern Dancer deposit boundary. However, it has been occasionally noted in drill core from the deposit itself. In one case, it occurs in anhedral masses, associated with calcite, garnet and minor sphalerite, at the wall of a Type 3 vein. It has also been noted as a rare accessory in deeper Type 4 veins, associated with massive chalcopyrite, pyrite, and sphalerite.

8.2.13.5 Magnetite

Magnetite was detected in three samples via X-ray powder diffraction analysis; however, magnetite was not identified in polished section. Sulphide-garnet-rich calc-silicate, quartz feldspar porphyry, and silicified quartz-feldspar porphyry registered magnetite values (10.1 %, 0.07 %, and 0.06 %, respectively). As hematite and magnetite are useful phases in constraining approximate $fO_2$ and $fS_2$ conditions (see section 8: Scheelite), it may be useful to investigate in more detail which environments contain magnetite, especially those which also contain scheelite.

8.2.14 Titanite

Titanite occurs dominantly as fine-grained, sub- to euhedral grains in vein alteration halos in all host rocks. This is usually the case in the diorite, where it occurs as small inclusions or rim apatite inclusions within biotite, in grain boundary zones between biotite/chlorite, biotite/amphibole and garnet/apatite, or within alteration zones around veins (Fig. 8.52). When amphibole alters to biotite during hydrothermal alteration, secondary titanite and rutile commonly form (as seen in Fig 8.52), as hydrothermal biotite has lower Ti and Fe contents relative to the precursor mineral; in this case primary magmatic hornblende in a Ti-rich intrusion (Thompson & Thompson, 1996). Several episodes of this nature may have occurred; in Fig. 8.52, titanite rims not only the inner relict amphibole core, but also the surrounding biotite.

Occasionally, titanite is intergrown with potassium feldspar, hornblende, and pyrite or chalcopyrite. In areas of more pervasively altered diorite, titanite can form a significant accessory component of the feldspar-rich groundmass occurring as fine-grained, subhedral
Fig. 8.52. SEM backscatter image of titanite inclusions in biotite, within altered diorite. Here, titanite rims a euhedral, zoned amphibole grain (darker core is Al-poor) which is itself an inclusion within a larger biotite grain. Small apatite inclusions within biotite are also rimmed by titanite. Titanite also rims the outer edge of the biotite.

Grains, occasionally alongside apatite and fluorite. The relatively higher concentration of titanite in the diorite unit and surrounding metasediments is reflected in whole-rock geochemistry (0.68 wt% TiO₂ in the diorite and between 0.25-0.44 wt.% TiO₂ in the metasedimentary rocks versus 0.17 wt.% TiO₂ in the monzonite and ).

In calc-silicate rocks, disseminated pyrite and/or pyrrhotite occasionally contain titanite inclusions, and titanite can occur as a very minor accessory within highly altered calc-silicate groundmass near the diorite contact. This may be evidence of hydrothermal alteration which has released titanium from Ti-rich minerals in the diorite (such as hornblende and biotite), and remobilized it along fluid pathways into calc-silicate near the diorite contact, where calcium activity is still high enough for titanite to form.

It also occurs as anhedral masses with molybdenite in Type 3 and 4 vein walls within hornfels. As with the diorite, titanite can occur as fine-grained sub- to euhedral grains in vein alteration haloes in hornfels, and again, it is notably associated with apatite (± fluorite) in these alteration environments. Sometimes it may be intergrown with chlorite or garnet at vein walls.
Fig. 8.53. Titanite intergrown with chlorite near garnet, at Type 2 reopened vein core and Type 4 vein wall, within hornfels. Titanite is found at vein wall margins, between the new opening and the older vein core (which becomes the new vein wall).

especially in re-opened veins, or at vein junctions (Fig. 8.53). In this kind of environment, one zoned, euhedral grain intergrown with garnet was found in a Type 3 vein core near the junction with a Type 2 vein (Fig. 8.54). The core is more pure CaTiSiO$_5$, while the rim is enriched in Mg, Nb, and Fe, and depleted in Al and Ti. This suggests a change in fluid chemistry and/or available substituents between the Type 2 and 3 vein generations. This grain also contained anhedral sphalerite, pyrite, and rutile inclusions.

Overall, titanite is much less common in the felsic units and veins. Occasionally it occurs as altered, euhedral grains in aggregates of clinopyroxene, garnet, fluorite, and calcite within Type 4 veins (Fig. 8.55). These grains can be zoned, with the grain cores showing enrichment in Sn, Mn, Fe, Nb, and W and rims showing enrichment in F and Al. These grains appear altered in comparison to the garnet and carbonate minerals occurring alongside in these aggregate masses, suggesting the fluid they formed from was not in equilibrium with the titanite, and post-dates the primary titanite formation. However, in spite of these examples, rutile is typically the dominant, albeit rare, Ti mineral in these locally felsic, Ca-poor environments.

Fifty-eight analyses from 52 grains in six polished sections were analyzed with the electron microprobe for 17 elements, including W and Mo, and the results are listed in Table 8.11. Data were recalculated on the basis of five anions (O + F = 5).
Fig. 8.54. Zoned, euhedral titanite intergrown with garnet in a Type 3 vein core near the junction with a Type 2 vein, within hornfels. The core is almost pure CaTiSiO₅, while the rim is enriched in Mg, Nb, and Fe, and depleted in Al and Ti. This grain also contains anhedral sphalerite, pyrite, and rutile inclusions. Rutile inclusions suggest that it may be the primary titanium phase. This suggests a change in fluid chemistry and/or available chemical substituents, including Ca, between the Type 2 and 3 vein generations.

Fig. 8.55. Altered, zoned, euhedral titanite within an aggregate of clinopyroxene, garnet, fluorite, and calcite, in a Type 4 vein (calc-silicate host). These grains can be zoned, grain cores are enriched in Sn, Mn, Fe, Nb, and W and the rims are enriched in F and Al. These grains appear altered compared to garnet and calcite occurring alongside, suggesting the fluid these minerals formed from was not in equilibrium with the titanite, and post-dates the primary titanite formation.
Table 8.11. Average compositions of titanite samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host env.</th>
<th>At qtz vein margin, in hornfels host</th>
<th>In V2, in CS host</th>
<th>Inclusion in K-feldspar, in diorite host</th>
<th>In V3, in felsite host</th>
<th>Inclusion in cpx, in diorite host</th>
<th>In fracture, in QFP host</th>
<th>In QFP groundmass</th>
<th>In CS groundmass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>avg.</td>
<td>stdev</td>
<td>avg.</td>
<td>stdev</td>
<td>avg.</td>
<td>stdev</td>
<td>avg.</td>
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<td>0.04</td>
<td>0.05</td>
<td>0.01</td>
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<td>0.10</td>
<td>30.20</td>
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<tr>
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<td>29.04</td>
<td>0.51</td>
<td>27.79</td>
<td>0.42</td>
<td>28.28</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>1.94</td>
<td>0.48</td>
<td>3.52</td>
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<td>0.17</td>
<td>0.03</td>
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</tr>
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<td>-0.07</td>
<td>0.01</td>
<td>-0.72</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>97.35</td>
<td>0.31</td>
<td>97.71</td>
<td>0.48</td>
<td>97.93</td>
<td>0.32</td>
<td>96.72</td>
</tr>
</tbody>
</table>

Note: The following standards were used: albite (NaKα), MgCr2O4 (CrKα), fayalite (FeKα), CaSiO3 (SiKα, CaKα), rutile (TiKα), Mo (MoLα), W (W Lα), kyanite (AlKα), Sc (ScKα), Topaz (FKα), Nb (NbLα), Sn (SnLα), Y/La/Ce/Pr (LaLα, CeLα), and MnSiO3 (MnKα). Compositions were recalculated on basis of 5 anions (O + F = 5) pfu. Na, Cr, Ce, La, W, Mo, and Sc were sought but not detected.
Some of the cations analyzed show insignificant concentrations in titanite, including Mo, W, Sc, Cr, and Mn. The main substituent at the Ti site is Al (followed by Fe, Nb, and Mg), and there is approximately eight times as much Al as Fe. The highest aluminum content occurs in Type 2 veins in calc-silicate rocks (9.02 wt.% Al₂O₃ or 0.35 Al apfu), while the highest iron content occurs in quartz-feldspar porphyry (1.83 wt.% Fe₂O₃ or 0.05 Fe³⁺ apfu). Niobium contents are highest in the quartz feldspar porphyry, where the average is 3.88 wt.% Nb₂O₅ or 0.06 Nb apfu, but Nb is also relatively high in Type 3 veins within felsite. Figure 8.56, a plot of Ti versus substituents, suggests that most to all of the iron is ferric, as most analyses plot along the 1:1 line. The lowest degree of substitution occurs in grains occurring as inclusions within potassium feldspar or clinopyroxene in the diorite host rocks, suggesting that this titanite was early, possibly associated with the diorite intrusive event. There is no evidence for any substitution at the Si site. Very minor substitution at the Ca site is likely due to Na, Ce and La, as these substituents are slightly elevated. Tin is slightly elevated in titanite within Type 2 veins in calc-silicate rocks (0.61 wt.% SnO₂ or 0.01 Sn apfu), as well as the quartz-feldspar porphyry (0.38 wt.% SnO₂ or 0.01 Sn apfu). In general, analytical totals are low, possibly reflecting adsorbed water content and volume expansion due to metamictization. U, Th and other REE’s (which were not analyzed) are therefore possibly present in minor quantities. This could be confirmed using X-ray diffraction techniques (beyond the scope of the study).

The Al and F contents in titanite appear to have a good correlation (see Fig. 8.57). Therefore most of the charge imbalance associated with replacing Ti⁴⁺ with Al³⁺ is relieved by replacing O²⁻ with F⁻. This association can be substantiated mineralogically with the example of the zoned grain described above in Fig 8.54, where the Al-rich rims are also enriched in F. Maximum average F content in titanite at Northern Dancer occurs in at a vein margin, within hornfels (1.94 wt.% F or 0.20 F apfu). The low F⁻ in grains occurring as inclusions in clinopyroxene (0.13 wt.% F or 0.01 F apfu) and potassium feldspar (0.17 wt.% F or 0.02 F apfu) in diorite likely reflects a lower degree of Al substitution at the Ti site; therefore there is no need for charge balance via F⁻ replacement of O²⁻.
Fig 8.56. A plot of Ti versus Ti-site substituents via vein/host environment. Most analyses plot along the 1:1 line suggesting that most to all of the iron is ferric.

Fig 8.57. A plot of aluminum versus fluorine content (apfu) in titanite, via vein/host environment. The Al and F contents in titanite appear to have a good correlation, therefore most of the charge imbalance associated with replacing Ti\(^{4+}\) with Al\(^{3+}\) is relieved by replacing O\(^{2-}\) with F\(^{-}\).
8.2.14 Amphibole

As mentioned above in the phyllosilicates section, hydrous minerals are relatively uncommon at Northern Dancer. Amphibole is found primarily in diorite intrusive units and even more rarely, in silicified/altered hornfels or calc-silicate rocks; however, varying vein/host environments give rise to a range of amphibole compositions.

In the groundmass of the diorite unit, amphibole can be both a primary mineral in the form of individual subhedral grains, as relict cores (which can be zoned and/or rimmed by biotite or clinopyroxene – see Fig. 8.58), and it can be associated with alteration. Commonly, relict cores of amphibole (usually euhedral and less than 0.5 mm) are rimmed first by fine-grained titanite, and then by biotite containing inclusions of apatite and titanite (Fig. 8.52). In zones of altered diorite, amphibole occurs both with secondary titanite and apatite, and with chlorite, pyrite and chalcopyrite (Fig. 8.59). In this environment amphibole occasionally contains apatite and sulphide inclusions. In metasedimentary rocks, amphibole can be found in Type 1 vein haloes within altered hornfels, where it occurs as randomly oriented, medium-grained, altered laths (occasionally containing chalcopyrite and pyrite inclusions). It also occurs in altered/silicified calc-silicate, where myrmekitic garnet, fluorite and scheelite form intergrowths with skeletal hornblende and plagioclase, on the edges of a silicified zone (Fig. 8.60). Rarely, amphibole can form small (less than 50 μm), anhedral masses at contact of Type 4 veins (especially those rich in F) and fine-grained hornfels, but these grains were too small to obtain a microprobe analysis.

Forty-one analyses from four polished sections in nine different vein/host environments were analyzed via EPMA. Analyses were recalculated on the basis of 24 anions assuming 2 (OH, F, Cl) per formula unit. Amphibole results are listed in Table 8.12. General classification of amphiboles was determined using the I.M.A. commission on nomenclature for amphiboles (Leake et al. 1997). (Ca+Na) is always > 1.00, and Na is always < 0.50 for all compositions, suggesting that amphibole at Northern Dancer is 'calcic' in all environments. Calcium contents average 11.86 wt.% CaO or 1.82 Ca apfu in the diorite but spike to a maximum average of 20.59 wt.% CaO or 3.15 Ca apfu (and max. overall 21.30 wt.% CaO or 3.26 Ca apfu) in the inner cores of relict hornblende grains in altered diorite. Aluminum content varies widely, from a minimum of 1.52 wt.% Al₂O₃ or 0.26 Al apfu in the inner cores of relict amphibole cores in altered diorite, to 16.60 wt.% Al₂O₃ or 2.61 Al apfu in altered calc-silicate. Relict amphibole cores in diorite
Fig. 8.58. Polished section RS-9 in plane-polarized light. Relict amphibole cores are rimmed by biotite/clinopyroxene in diorite.

Fig. 8.59. Backscatter SEM image of amphibole associated with chlorite, potassium feldspar, titanite and euhedral apatite, within altered diorite. Likely, titanite occurring at the boundary of the hornblende grain formed during hydrothermal alteration, which scavenges Ti from the amphibole and produces hydrothermal biotite (which has then likely altered to chlorite).
Fig. 8.60. Backscatter SEM image of altered amphibole laths intergrown with fluorite and scheelite, in altered/silicified calc-silicate. In this environment, myrmekitic garnet and fluorite form intergrowths with skeletal hornblende and plagioclase, on the edges of a silicified zone. Apatite alteration (related to 'potassic' styles of alteration seen in porphyry systems) is likely.

and altered diorite contain much higher titanium contents than any other amphibole at Northern Dancer. With the exception of the inner cores of zoned relict grains in diorite, cores average between 0.99 and 1.07 wt.% TiO$_2$ or 0.11 and 0.18 Ti apfu. Other amphiboles in the altered diorite unit or metasedimentary host rocks average between 0.08 and 0.27 wt.% TiO$_2$ or 0.01 and 0.03 Ti apfu. This data may support the idea that biotite alteration of more Ti-rich, primary hornblende produced hydrothermal biotite (lower in Ti and Fe than igneous biotite) and titanite around relict hornblende cores (see biotite section).

The magnesium content is relatively constant, between 11.16 wt.% MgO or 2.45 Mg apfu (avg.) and 15.27 wt.% MgO or 3.26 Mg apfu (avg.) in diorite environments (max. 16.04 wt.% MgO or 3.39 Mg apfu in zoned hornblende associated with sulphides in altered diorite).

Metasedimentary units contain slightly lower average Mg contents between 11.16 wt.% MgO or 2.45 Mg apfu and 12.54 wt.% MgO or 2.74 Mg apfu. In the diorite environments, manganese content remains fairly constant, between 0.33 wt.% MnO or 0.04 Mn apfu (avg.) and 0.50 wt.% MnO or 0.06 Mn apfu (avg.). The manganese content is higher in metasedimentary (altered calc-silicate and hornfels) environments, where it falls between 0.83 wt.% MnO or 0.10 Mn apfu (avg.) and 1.44 wt.% MnO or 0.18 Mn apfu (avg.). Iron contents also vary widely, averaging
Table 8.12. Average compositions of amphibole samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Assc. w/ + sulph, in altered diorite</th>
<th>Assc. w/ titan + cpy + pyr + chl, in altered diorite</th>
<th>Zoned, w/ sulph incl., in altered diorite</th>
<th>Relict core, biot rim, in diorite</th>
<th>in altered diorite groundmass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n 3</td>
<td>4</td>
<td>4</td>
<td>3</td>
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</tr>
<tr>
<td></td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
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<td>51.61</td>
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<td>0.14</td>
<td>0.02</td>
<td>0.08</td>
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<td>0.28</td>
<td>3.13</td>
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<td>18.65</td>
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<tr>
<td>F</td>
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<tr>
<td>Cl⁻</td>
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<td>-0.13</td>
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<tr>
<td>Total</td>
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<td>0.33</td>
<td>98.70</td>
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Note: The following standards were used: diopside (SiKα, MgKα, CaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), albite (NaKα), orthoclase (KKα), and KMg₃AlSi₃O₁₀(OH)₂ (FKα). * Determined by stoichiometry. H₂O calc. assuming 2(OH⁻, F⁻, Cl⁻). Compositions recalculated on the basis of 24 anions pfu.
Table 8.12. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Inner relict cores, in diorite</th>
<th>Outer relict cores, in diorite</th>
<th>Altered calc-silicate w/ garnet exsolution</th>
<th>Skeletal w/ cpy, pyr incl. in altered hornfels groundmass</th>
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<th>average</th>
<th>stddev</th>
<th>average</th>
<th>stddev</th>
<th>average</th>
<th>stddev</th>
<th>average</th>
<th>stddev</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂ (wt.%)</td>
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<td>46.02</td>
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<td>47.77</td>
<td>4.94</td>
<td>45.54</td>
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<td>TiO₂</td>
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<td>0.99</td>
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<td>0.05</td>
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<tr>
<td>Al₂O₃</td>
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<td>6.94</td>
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<td>7.86</td>
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<td>7.40</td>
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<td>3.84</td>
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<td>0.01</td>
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<td>0.05</td>
<td>0.05</td>
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<td>MgO</td>
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<td>0.28</td>
<td>11.16</td>
<td>2.94</td>
<td>12.53</td>
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<tr>
<td>MnO</td>
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<td>0.03</td>
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<td>0.38</td>
<td>0.83</td>
<td>0.06</td>
<td></td>
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</tr>
<tr>
<td>Na₂O</td>
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<td>0.04</td>
<td>1.14</td>
<td>0.06</td>
<td>1.85</td>
<td>2.25</td>
<td>1.51</td>
<td>0.10</td>
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<td></td>
</tr>
<tr>
<td>K₂O</td>
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<td>0.77</td>
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<td>1.09</td>
<td>0.08</td>
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</tr>
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<td>0.00</td>
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<tr>
<td>Fe</td>
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<td>0.23</td>
<td>0.05</td>
<td>0.85</td>
<td>0.39</td>
<td>1.54</td>
<td>0.12</td>
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</tr>
<tr>
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<td>0.02</td>
<td>0.18</td>
<td>0.02</td>
<td>0.02</td>
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<td>0.04</td>
<td>0.01</td>
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</tr>
<tr>
<td>O=Cl</td>
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<td>0.01</td>
<td>-0.10</td>
<td>0.02</td>
<td>-0.40</td>
<td>0.16</td>
<td>-0.85</td>
<td>0.05</td>
<td></td>
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</tr>
<tr>
<td>Total</td>
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<td>0.31</td>
<td>98.90</td>
<td>0.06</td>
<td>98.52</td>
<td>0.73</td>
<td>98.79</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Si⁴⁺ (apfu)     | 7.350   | 0.038  | 6.734   | 0.013  | 6.953   | 0.483  | 6.699   | 0.083  |
| Ti⁴⁺           | 0.035   | 0.008  | 0.109   | 0.003  | 0.010   | 0.006  | 0.030   | 0.002  |
| Al³⁺           | 0.325   | 0.068  | 1.197   | 0.040  | 1.304   | 0.554  | 1.283   | 0.093  |
| Fe³⁺           | 0.003   | 0.021  | 1.805   | 0.011  | 1.631   | 0.442  | 1.709   | 0.053  |
| Cr³⁺           | 2.900   | 0.000  | 0.007   | 0.001  | 0.005   | 0.006  | 0.006   | 0.004  |
| Mg²⁺           | 3.154   | 0.017  | 2.672   | 0.061  | 2.445   | 0.657  | 2.747   | 0.072  |
| Ca²⁺           | 0.053   | 0.101  | 1.854   | 0.005  | 1.728   | 0.411  | 1.881   | 0.013  |
| Mn²⁺           | 1.040   | 0.003  | 0.046   | 0.004  | 0.179   | 0.049  | 0.103   | 0.008  |
| Na⁺            | 0.126   | 0.010  | 0.322   | 0.018  | 0.508   | 0.575  | 0.430   | 0.031  |
| K⁺             | 0.020   | 0.004  | 0.144   | 0.009  | 0.121   | 0.057  | 0.204   | 0.016  |
| H⁺             | 1.947   | 0.003  | 1.851   | 0.026  | 1.553   | 0.183  | 1.276   | 0.059  |
| O²⁻            | 23.947  | 0.003  | 23.851  | 0.026  | 23.553  | 0.183  | 23.276  | 0.059  |
| F⁻             | 0.048   | 0.007  | 0.104   | 0.021  | 0.443   | 0.183  | 0.716   | 0.059  |
| Cl⁻            | 0.006   | 0.004  | 0.045   | 0.005  | 0.004   | 0.003  | 0.009   | 0.002  |

Note: The following standards were used: diopside (SiKα, MgKα, CaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), albite (NaKα), orthoclase (KKα), and KMg₃AlSi₃O₁₀(OH)₂ (FKα). * Determined by stoichiometry. H₂O calc. assuming 2(OH⁻, F⁻, Cl⁻). Compositions recalculated on the basis of 24 anions pfu.
between 9.66 wt.% Fe₂O₃ or 1.04 Fe³⁺ apfu in relict hornblende cores in diorite, to 18.65 wt% Fe₂O₃ or 2.08 Fe³⁺ apfu in zoned hornblende associated with sulphides in the altered diorite.

Fluorine is elevated in most amphibole at Northern Dancer, with a maximum value of 1.74 wt.% F or 0.82 F apfu (avg. 1.54 wt.% F or 0.72 F apfu) occurring in altered calc-silicate rocks, and a minimum of 0.09 wt.% F or 0.04 F apfu (avg. 0.11 wt.% F or 0.05 F apfu) in the inner cores of relict hornblendes in the altered diorite. Hornblende associated with apatite and titanite in altered diorite averages 0.46 wt.% F or 0.21 F apfu and 0.35 wt.% F or 0.16 F apfu, respectively. This supports the hypothesis that fluorine was indeed a volatile which was introduced late in the development of the deposit, and was likely a component in mineralizing and/or altering fluids (as relict, primary hornblende cores are low in fluorine).

While amphiboles are more difficult to portray graphically due to their compositional variations, an attempt has been made here to classify the Northern Dancer amphiboles (Meinert et al. 2005). Calcic amphibole compositions are classified via their Mg/(Mg + Fe) ratio versus their silica (apfu) content, which is shown in Fig. 8.61. Aside from two outliers, Mg/(Mg + Fe) follows a slight linear trend (note that the x-axis is reversed), within the magnesio-hornblende field. This composition is expected for a tungsten deposit; amphiboles from W-skarns (as well as Au and Sn skarns) typically fall within the compositional range of actinolite-hastingsite-hornblende (Meinert et al. 2005). As silica content increases, the Mg/(Mg + Fe) ratio also increases. Inner, relict cores of hornblende grain and grains associated with apatite, titanite, and sulphides, all within the altered diorite, have the highest relative Si and Mg content. Outer cores of relict hornblende grains, cores rimmed by biotite, homogenous grains within the diorite groundmass, and 'skeletal'/altered grains in altered hornfels groundmass all have comparatively lower Si and Mg contents. Hornblende found within the calc-silicate however, has a broad range of compositions across the magnesio-hornblende field, but this is based on Si content as Mg/(Mg + Fe) ratio remains relatively constant in this environment. This may reflect locally variable silica contents in fluids altering the calc-silicate, which may in turn reflect silica alteration of the original reaction skarn. The section from which these amphiboles were analyzed appears to be silicified, and also contains fluorite in the groundmass.
Fig. 8.61. Plot of amphibole compositions via Mg/(Mg+Fe) versus Si (apfu). Most of the amphibole from Northern Dancer falls within the magnesio-hornblende field.
8.2.15 Pyroxene and pyroxenoids

8.2.15.1 Pyroxene

Pyroxene is dominantly fine-grained, anhedral, and associated with garnet and quartz in the calc-silicate groundmass (Fig. 8.62). In higher levels of the deposit, interstitial space between garnet and pyroxene may be filled by massive calcite (Fig. 8.63). It may also occur in any range of altered metasedimentary units, including those which have been silicically altered, and may be associated with other accessory minerals such as fluorite, molybdenite, and scheelite, in the groundmass (Fig. 8.64). It can occur in the matrix of diorite rocks, in the cores and selvedges of Type 1 veins, and as fine-grained masses within potassium-feldspar rich Type 4 veins in altered hornfels or calc-silicate. It is an integral mineral within the metasedimentary host rocks at Northern Dancer, and variations of the ferric/ferrous iron ratio may possibly help indicate the local oxidation state of each individual vein/host environment.

One hundred fourteen electron microprobe analyses were obtained from eight different polished sections and 14 different vein/host rock environments. Electron microprobe compositional data was recalculated by valence calculation on the basis of 4 cations and 6 anions per formula unit. The results are listed in Table 8.13. Pyroxene analyses from the diorite tend toward an augite composition; this is not unexpected as it is probably magmatic within the diorite, whereas it is likely the product of calc-silicate alteration within the metasedimentary rocks (reaction skarn). Pyroxene within the diorite contains the highest average amounts of Al (3.21 wt.% Al₂O₃ or 0.146 Al apfu), Fe²⁺ (11.40 wt.% FeO or 0.365 Fe²⁺ apfu), Na (0.43 wt.% Na₂O or 0.032 Na apfu), and Ti (0.39 wt.% TiO₂ or 0.011 Ti apfu). Conversely, it contains the lowest average amount of Ca (16.08 wt.% CaO or 0.654 Ca apfu), Mn (0.31 wt.% MnO or 0.01 Mn apfu), and Fe³⁺ (0.78 wt.% Fe₂O₃ or 0.022 Fe³⁺ apfu). Aside from pyroxene in the diorite, the majority of analyses are calcic, and are found within the groundmass of various metasedimentary rocks. Calcic pyroxenes can be plotted on a ternary to distinguish compositions between Mg-, Mn-, and Fe-rich end-members (see Fig. 8.65). These end-members are johannsenite (CaMnSi₂O₆), diopside (CaMgSi₂O₆), and hedenbergite (CaFeSi₂O₆).

Most calcic pyroxene in the deposit is Mn-poor, and falls between the diopside and hedenbergite end-members. The most diopside-rich pyroxene end-members at Northern Dancer include: (1) massive pyroxene which occurs in thick, potassium-rich Type 4 veins in hornfels, and (2) in altered/silicified calc-silicate groundmass, associated with fluorite and molybdenite.
Fig. 8.62. Backscatter SEM image of calc-silicate groundmass: garnet and pyroxene are intergrown; in between, open space creates permeability.

Fig. 8.63. Backscatter SEM image of garnet-rich calc-silicate groundmass: zoned garnet is intergrown with anhedral masses of pyroxene. Intergranular space, likely created via volume change during calc-silicate alteration, is filled by massive calcite (but may also be filled with quartz elsewhere).
Table 8.13. Average compositions of pyroxene samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environ.</th>
<th>In diorite matrix</th>
<th>In V1, in CS</th>
<th>V1 selvedge, in CS</th>
<th>In V1 in CS, wlsch</th>
<th>CS groundmass</th>
<th>Garnet-rich CS groundmass</th>
<th>In garnet core of CS-hosted garnet vein</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
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<td>51.23</td>
<td>2.90</td>
<td>51.25</td>
<td>0.43</td>
<td>51.06</td>
<td>1.00</td>
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<tr>
<td>TiO₂</td>
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<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
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<td>2.62</td>
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<td>0.23</td>
<td>0.34</td>
<td>0.06</td>
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<td>Cr₂O₃</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe₂O₃*</td>
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<td>0.03</td>
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<td>0.77</td>
<td>98.86</td>
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<td>98.40</td>
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**Note:** The following standards were used: diopside (SiKα, MgKα, CaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), albite (NaKα), orthoclase (KKα), and KMg₃AlSi₃O₁₀(OH)₂ (FKα). *Determined by stoichiometry. Compositions were recalculated on the basis of 4 cations and 6 anions pfu. Diopside (Dp), hedenbergite (Hd), and johannsenite(Jo) end-member compositions are listed, along with Fe²⁺/Fe³⁺ ratio.
Table 8.13. (cont.)

<table>
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<tr>
<th>Vein/host environ.</th>
<th>In garnet rim of CS-hosted garnet vein</th>
<th>Silicified CS groundmass</th>
<th>Silicified CS w/ fluo + moly</th>
<th>Silicified CS groundmass w/ sch</th>
<th>HF groundmass</th>
<th>In older, pyx skarn vein in HF</th>
<th>Massive pyx in thick Type 4 ksp vein, in HF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
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<td></td>
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</tr>
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<td>stdev</td>
<td>average 9</td>
<td>stdev</td>
<td>average 13</td>
<td>stdev</td>
<td>average 5</td>
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<td>51.29 0.56</td>
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<td>52.67 0.59</td>
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<td>45.44 7.49</td>
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<td>0.00 0.01</td>
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<td>0.25 0.26</td>
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<td>0.05 0.06</td>
</tr>
<tr>
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<td>0.23 0.07</td>
<td></td>
<td>1.70 0.53</td>
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<td>0.02 0.02</td>
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<td>0.01 0.02</td>
</tr>
<tr>
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<td>1.98 0.69</td>
<td></td>
<td>1.04 0.65</td>
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<td>8.62 8.77</td>
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<td>3.76 1.01</td>
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<td>0.60 0.15</td>
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<td>14.70 0.60</td>
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<td>24.38 0.16</td>
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<td>24.60 0.27</td>
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<td>27.55 4.43</td>
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<td>0.24 0.13</td>
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<td>99.58 0.45</td>
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<td>99.68 0.47</td>
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<tr>
<td>Si⁴⁺ (apfu)</td>
<td>1.976 0.011</td>
<td></td>
<td>1.971 0.010</td>
<td></td>
<td>1.950 0.019</td>
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<td>1.781 0.243</td>
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<td></td>
<td>0.000 0.000</td>
<td></td>
<td>0.007 0.007</td>
<td></td>
<td>0.002 0.002</td>
</tr>
<tr>
<td>Al³⁺</td>
<td>0.013 0.002</td>
<td></td>
<td>0.010 0.003</td>
<td></td>
<td>0.074 0.023</td>
<td></td>
<td>0.169 0.198</td>
</tr>
<tr>
<td>Cr³⁺</td>
<td>0.001 0.000</td>
<td></td>
<td>0.001 0.001</td>
<td></td>
<td>0.000 0.000</td>
<td></td>
<td>0.000 0.001</td>
</tr>
<tr>
<td>Fe³⁺</td>
<td>0.046 0.023</td>
<td></td>
<td>0.057 0.020</td>
<td></td>
<td>0.029 0.018</td>
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<td>0.264 0.272</td>
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<td>0.316 0.025</td>
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<td>0.284 0.050</td>
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<td>0.116 0.032</td>
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<td>0.188 0.150</td>
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<tr>
<td>Mn²⁺</td>
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<td></td>
<td>0.019 0.005</td>
<td></td>
<td>0.065 0.019</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>0.579 0.015</td>
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<td>0.596 0.053</td>
<td></td>
<td>0.811 0.031</td>
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<td>0.360 0.281</td>
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<tr>
<td>Ca²⁺</td>
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<td>1.003 0.007</td>
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<td>0.976 0.010</td>
<td></td>
<td>1.169 0.226</td>
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<td>0.011 0.002</td>
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<td>0.017 0.009</td>
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</tr>
<tr>
<td>Fe²⁺/Fe³⁺</td>
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<td>5.87 2.80</td>
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<td>8.54 10.53</td>
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<td>0.71 0.55</td>
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<tr>
<td>Dp</td>
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<td>63.03 5.79</td>
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<td>85.74 3.64</td>
<td></td>
<td>40.52 25.56</td>
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<tr>
<td>Hd</td>
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<td>29.97 5.26</td>
<td></td>
<td>12.28 3.22</td>
<td></td>
<td>19.51 15.59</td>
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<tr>
<td>Jo</td>
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<td>7.00 1.86</td>
<td></td>
<td>39.97 40.92</td>
<td></td>
<td>4.03 4.03</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside (SiKα, MgKα, CaKα), rutile (TiKα), kyanite (AlKα), MgCr₂O₄ (CrKα), MnSiO₃ (MnKα), Fe₂SiO₄ (FeKα), albite (NaKα), orthoclase (KKα), and KMg₃Al₃Si₃O₁₀(OH)₂ (FKα). * Determined by stoichiometry. Compositions were recalculated on the basis of 4 cations and 6 anions pfu. Diopside (Dp), hedenbergite (Hd), and johannsenite (Jo) end-member compositions are listed, along with Fe²⁺/Fe³⁺ ratios.
These two environments are likely inherently lower in iron; therefore, it is not surprising they would contain the most diopside-rich pyroxene. The latter contains the highest Mg content in the system (averaging 14.70 wt.% MgO or 0.811 Mg apfu), and the lowest Fe$^{2+}$ content (averaging 3.76 wt.% FeO or 0.116 Fe$^{2+}$ apfu). Altered/silicified calc-silicate groundmass associated with scheelite contains the highest Al (averaging 3.51 wt.% Al$_2$O$_3$ or 0.169 Al apfu) and Ca contents (27.55 wt.% CaO or 1.169 Ca apfu). In contrast, this environment also contains the lowest Mg content (averaging 6.29 wt.% MgO or 0.360 Mg apfu).

Five analyses from polished section QSM-4 have end-member compositions averaging 91.67% johannsenite; these are low iron (outlined in dashed orange circle in Fig 8.65). These pyroxenes occur as the dominant groundmass component, within silicified calc-silicate host rock located close to surface (i.e., at a high-level in the deposit), which has been oxidized. However, garnets in this section have relatively Ca- and Mg-rich compositions, and occur in more garnet rich calc-silicate zones, and do not host scheelite. Scheelite hosted by johannsenite-rich pyroxene is high in Mo (6.62-11.65 wt.% MoO$_3$).

The range of calcic pyroxene compositions at Northern Dancer is characteristic for tungsten skarns (Meinert et al. 2005), but is slightly more diopside-rich than the typical range for Mo-skarns, based on worldwide data from Meinert (1983, 1989) and Einaudi et al. (1981).
Fig. 8.65. Ternary plot of pyroxene end-member compositions, as analyzed via EPMA: Jo = johannsenite (CaMnSi$_2$O$_6$), Dp = diopside (CaMgSi$_2$O$_6$), and Hd = hedenbergite (CaFeSi$_2$O$_6$). Analyses outlined by the orange circle indicate those with particularly low iron, johannsenite-tending compositions which occur in altered calc-silicate (see pyroxene section). The majority of analyses lie between the diopside or hedenbergite end-members, and are shown in the enlarged portion of the ternary.
Skarn type is influenced by prevailing redox conditions during deposit evolution. These redox conditions can be inferred from the determination of relative ferric/ferrous iron ratios in certain skarn minerals, as mentioned in section 8.2.16 (Garnet) (Sato 1980). Specifically, reduced systems show relatively high Fe\(^{2+}/\text{Fe}^{3+}\) where oxidized systems show relatively low Fe\(^{2+}/\text{Fe}^{3+}\). While Northern Dancer is not a traditional ‘skarn’, these conditions are likely still important in deposit evolution. Garnet at Northern Dancer is not a reliable mineral to use due to its ‘hydrous’ nature, as mentioned above; however, as pyroxene is anhydrous, it may provide more reliable information. In Fig. 8.66, (Fe\(^{2+}/\text{Fe}^{3+}\)) ratios in pyroxene are plotted versus vein/host environment, which is arranged approximately temporally.

According to Fig 8.66, the environment forming pyroxene is relatively oxidized in the diorite, more reduced within the calc-silicate and Type 1 vein environments, and again relatively oxidized in hornfels. Silicified calc-silicate and Type 4 vein environments plot close to the mean (grey dashed line), between the two extremes of the unaltered calc-silicate and hornfels host environments. Hornfels is less reduced, perhaps due to its lower degree of alteration (possibly only heat, with no accompanying metasomatism). The reduced nature of pyroxene in the calc-silicate units, and especially within veins, suggest that early in the deposit evolution, vein minerals were influenced by the redox state of the host rocks. However, the ratios within these units have the greatest standard deviation, suggesting that a wide range of local redox conditions exist within calc-silicate rocks at Northern Dancer. The intermediate iron ratios of the pyroxene associated with the silicified calc-silicate and Type 4 veins suggest that this environment may be less influenced by the conditions of the host rocks and more influenced by the fluids forming pyroxene, indicating less wallrock interaction, and possibly mixing with a more oxidized fluid. A closer inspection of redox trends, indicated by iron ratios of pyroxene in calc-silicate environments where scheelite also occurs, would reveal any correlations between redox state and mineralization.

8.2.15.2 Pyroxcnoids: wollastonite

Wollastonite occurs dominantly at the periphery of the reaction skarn, and likely marks the limit of the earlier skarn development. Wollastonite-vesuvianite skarn was noted by Noble et al. (1984), but no vesuvianite was identified within the representative sample set used for the mineralogy study in this project. As such, vesuvianite is not considered to be an integral mineral.
Iron ratios ($\text{Fe}^{2+}/\text{Fe}^{3+}$, apfu) in pyroxene versus vein/host environment

Fig. 8.66. Plot of ($\text{Fe}^{2+}/\text{Fe}^{3+}$, apfu) ratios in pyroxene versus vein/host environment, which is arranged approximately temporally; the solid grey line corresponds to the neutral constant $= 1$, and the dashed grey line corresponds to the deposit-wide mean. The plot indicates the environment forming pyroxene is relatively oxidized in the diorite, more reduced within the calc-silicate and Type 1 vein environments, and again relatively oxidized in hornfels. Silicified calc-silicate and Type 4 vein environments plot close to the mean (grey dashed line), between the two extremes of the unaltered calc-silicate and hornfels host environments.
in the core of the Northern Dancer deposit, but is likely present distally. The most common vein set to cross-cut the wollastonite-vesuvianite skarn are the Type 1 veins (see Fig. 3.3, j). It is occasionally found in the groundmass of unaltered, fine-grained diopside skarn as well; however, these units do not contain high W or Mo grades, as they rarely occur in areas where a high density of overlapping vein sets exists, and are also distal to mineralization.

8.2.16 Garnet

8.2.16.1 Garnet composition

Electron microprobe compositions were renormalized on the basis of Na$^+$ + Mg$^{2+}$ + Al$^{3+}$ + Ca$^{2+}$ + Ti$^{4+}$ + Mn$^{2+}$ + Fe$^{2+}$ = 5 (e.g. cation renormalization). OH$^-$ was calculated as OH = 4(3-Si-F/4) following Visser (1993). Fe$^{2+}$ and Fe$^{3+}$ proportions were calculated based on the general garnet formula $X_3Y_2(ZO_4)_3M(OH,F)_4M$, where the X-site contains Ca, Fe$^{2+}$, Mg, Mn, and Na, and the Y-site contains Al, Ti, and Fe$^{3+}$ (X+Y = 5). A total of 144 analyses were obtained from eleven representative vein and host rock environments in eight different polished sections. Average compositions are listed in Table 8.14. Cr, Ti, Mg, and Na contents are low in all garnet analyses from Northern Dancer. Cl$^-$ was sought but not detected. The average deposit-wide end-member composition is Py$_{0.52}$ Alm$_{5.54}$ Gro$_{37.95}$ And$_{41.08}$ Uv$_{0.06}$ Sp$_{14.71}$.

Garnets at Northern Dancer are split into two compositional groups. Within felsic intrusive phases, they fall between spessartine and almandine end-member compositions, whereas in the calcareous metasedimentary rocks, they are ‘grandites’ (between grossular and andradite end-members). End-member compositions are plotted in Fig. 8.67 on a ternary of grossular (Gro), andradite (And), and ‘pyralspite’ (Pyr = pyrope + almandine + spessartine). The two compositional groups are clearly distinguished. Based on their host environment, these compositions agree with average end-member proportions reported in the literature; according to Wright (1938), granites/pegmatites are typically spessartine-almandine rich, while calcareous contact rocks are grossular-andradite rich (or ‘grandite’ - there is a complete solid solution between grossular and andradite).

Subcalcic garnets from the felsic intrusive host rocks are plotted in Fig. 8.68 on a ternary of spessartine (Sp), almandine (Alm), and andradite (And), based on the dominant three
Table 8.14. Average compositions of garnet samples from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>In brain rock in QFP rock matrix</th>
<th>Felsite matrix</th>
<th>CS groundmass</th>
<th>CS groundmass, assoc. w/ sch</th>
<th>n</th>
<th>11</th>
<th>10</th>
<th>7</th>
<th>8</th>
</tr>
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<tbody>
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<td></td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
</tr>
<tr>
<td>SiO₂ (wt.%)</td>
<td>35.21</td>
<td>0.33</td>
<td>34.71</td>
<td>0.37</td>
<td>35.72</td>
<td>0.32</td>
<td>39.05</td>
<td>8.69</td>
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<td>0.24</td>
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<td>0.22</td>
<td>0.19</td>
<td>0.61</td>
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<tr>
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<td>0.61</td>
<td>19.27</td>
<td>0.43</td>
<td>10.02</td>
<td>1.41</td>
<td>11.55</td>
<td>2.79</td>
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<tr>
<td>Cr₂O₃</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
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<tr>
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<td>0.08</td>
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<td>0.17</td>
<td>0.04</td>
<td>0.66</td>
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<td>0.02</td>
<td>-0.28</td>
<td>0.13</td>
<td>-0.33</td>
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<td>Total</td>
<td>98.47</td>
<td>0.55</td>
<td>96.72</td>
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<td>99.07</td>
<td>0.38</td>
<td>97.85</td>
<td>1.25</td>
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| Si⁴⁺ (apfu)           | 2.905    | 0.024  | 2.925    | 0.022  | 2.793    | 0.026  | 3.544    | 1.911  |
| Al³⁺                  | 1.863    | 0.051  | 1.914    | 0.033  | 0.923    | 0.126  | 1.140    | 0.214  |
| Cr³⁺                  | 0.001    | 0.001  | 0.001    | 0.001  | 0.001    | 0.001  | 0.001    | 0.001  |
| Ti⁴⁺                  | 0.017    | 0.009  | 0.015    | 0.005  | 0.013    | 0.011  | 0.039    | 0.019  |
| Fe²⁺ (tot)            | 0.733    | 0.036  | 0.834    | 0.056  | 1.178    | 0.132  | 0.912    | 0.269  |
| Mg²⁺                  | 0.066    | 0.010  | 0.047    | 0.004  | 0.004    | 0.001  | 0.009    | 0.002  |
| Mn²⁺                  | 2.134    | 0.032  | 2.042    | 0.068  | 0.066    | 0.023  | 0.183    | 0.115  |
| Na⁺                   | 0.011    | 0.004  | 0.013    | 0.003  | 0.001    | 0.001  | 0.013    | 0.025  |
| Ca²⁺                  | 0.174    | 0.038  | 0.134    | 0.016  | 2.784    | 0.038  | 2.704    | 0.179  |
| F                     | 0.029    | 0.013  | 0.045    | 0.011  | 0.164    | 0.074  | 0.209    | 0.095  |
| O²⁻                   | 11.739   | 0.052  | 11.794   | 0.051  | 10.979   | 0.082  | 12.587   | 3.831  |

| x-site total          | 3.119    | 0.042  | 3.070    | 0.028  | 4.063    | 0.129  | 3.820    | 0.231  |
| y-site total          | 2.000    | 0.001  | 1.999    | 0.001  | 2.000    | 0.001  | 1.999    | 0.000  |
| M = (OH+F)/4          | 0.985    | 0.024  | 0.075    | 0.022  | 0.207    | 0.026  | -0.544   | 1.911  |

| pyrope                | 2.21     | 0.35   | 1.57     | 0.15   | 0.14     | 0.04   | 0.28     | 0.08   |
| almandine             | 20.48    | 1.50   | 25.47    | 2.73   | 3.83     | 0.68   | 3.05     | 2.10   |
| spessartine           | 71.14    | 1.08   | 68.06    | 2.28   | 3.19     | 0.78   | 6.10     | 3.82   |
| andradite             | 5.96     | 2.10   | 3.51     | 1.42   | 53.18    | 6.44   | 41.03    | 11.55  |
| uvarovite             | 0.03     | 0.03   | 0.04     | 0.03   | 0.04     | 0.03   | 0.03     | 0.04   |
| grossular             | -0.19    | 1.40   | -0.93    | 1.05   | 39.58    | 6.53   | 49.07    | 12.67  |

Note: The following standards were used: almandine- Fe₃Al₂Si₅O₁₄ (SiKa, AlKα, FeKα), KMg₃AlSi₅O₁₀(OH)₂ (FKα), albite (NaKα), rutile (TiKα), grossular- Ca₃Al₂Si₅O₁₂ (CaKα), MgCr₂O₄ (CrKα), diopside- Mg₃Al₂Si₅O₁₂ (MgKα), and MnSiO₄ (MnKα). * Determined by stoichiometry. Compositions were recalculated on the basis of 5 cations (Na⁺, Mg²⁺, Al³⁺, Ca²⁺, Ti⁴⁺, Mn²⁺, Fe²⁺) pfu. OH⁻ was calculated as OH⁻ = 4(3-Si-F/4) as adapted from Visser (1993). Fe²⁺ and Fe³⁺ proportions were calculated based on the general garnet formula X₃Y₂(ZC₄)M(OH,F)₄M, where the X-site contains Ca, Fe²⁺, Mg, Mn, Na and the Y-site contains Al, Ti, and Fe³⁺ (X+Y = 5).
Table 8.14. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Garnet-rich CS groundmass</th>
<th>Type 1 vein selvedge, in CS</th>
<th>Type 1 vein, in CS</th>
<th>Type 2 vein selvedge, in CS</th>
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<td>n</td>
<td>3</td>
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<td>SiO₂ (wt.%)</td>
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<td>0.33</td>
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<td>0.54</td>
<td>97.79</td>
<td>0.93</td>
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</tbody>
</table>

| Si⁴⁺ (apfu)           | 2.883    | 0.051  | 2.879  | 0.049  | 2.812   | 0.057  | 2.820   | 0.017  |
| Al³⁺                  | 1.002    | 0.265  | 1.024  | 0.184  | 0.956   | 0.185  | 0.992   | 0.170  |
| Cr³⁺                  | 0.001    | 0.001  | 0.001  | 0.002  | 0.001   | 0.001  | 0.001   | 0.001  |
| Ti⁴⁺                  | 0.006    | 0.004  | 0.025  | 0.020  | 0.021   | 0.015  | 0.008   | 0.004  |
| Fe²⁺ (tot)            | 1.011    | 0.240  | 1.025  | 0.211  | 1.123   | 0.193  | 1.113   | 0.165  |
| Mg²⁺                  | 0.007    | 0.001  | 0.008  | 0.004  | 0.010   | 0.012  | 0.006   | 0.001  |
| Mn²⁺                  | 0.045    | 0.012  | 0.200  | 0.132  | 0.082   | 0.020  | 0.125   | 0.098  |
| Na⁺                   | 0.002    | 0.002  | 0.002  | 0.002  | 0.002   | 0.002  | 0.001   | 0.001  |
| Ca²⁺                  | 2.297    | 0.042  | 2.176  | 0.162  | 2.606   | 0.031  | 2.755   | 0.128  |
| F⁻                    | 0.135    | 0.042  | 0.138  | 0.046  | 0.164   | 0.076  | 0.139   | 0.055  |
| O²⁻                   | 11.206   | 0.050  | 11.228 | 0.092  | 11.041  | 0.155  | 11.073  | 0.075  |

| Fe²⁺                  | 0.992    | 0.268  | 0.960  | 0.186  | 1.022   | 0.193  | 1.001   | 0.171  |
| Fe³⁺                  | 0.019    | 0.028  | 0.074  | 0.043  | 0.101   | 0.020  | 0.112   | 0.032  |
| Fe(Tot)               | 1.011    | 0.240  | 1.025  | 0.211  | 1.123   | 0.193  | 1.113   | 0.165  |
| OH⁻ (apfu)            | 0.331    | 0.165  | 0.348  | 0.192  | 0.587   | 0.210  | 0.579   | 0.050  |

| x-site total         | 1.999    | 0.001  | 1.999  | 0.002  | 1.999   | 0.001  | 1.999   | 0.001  |
| y-site total         | 0.117    | 0.051  | 0.121  | 0.049  | 0.188   | 0.057  | 0.180   | 0.017  |

| pyrope               | 0.23     | 0.03   | 0.26   | 0.13   | 0.33    | 0.40   | 0.19    | 0.05   |
| almandine            | 0.63     | 0.94   | 2.48   | 1.43   | 3.35    | 0.66   | 3.74    | 1.07   |
| spessartine          | 1.50     | 0.40   | 6.66   | 4.39   | 2.73    | 0.56   | 4.18    | 3.21   |
| andradite            | 49.60    | 13.39  | 47.54  | 9.30   | 51.14   | 9.84   | 50.06   | 8.57   |
| uvarovite            | 0.07     | 0.06   | 0.06   | 0.10   | 0.07    | 0.07   | 0.05    | 0.04   |
| grossular            | 47.89    | 11.97  | 42.92  | 13.60  | 42.31   | 9.29   | 41.72   | 7.48   |


Note: The following standards were used: almandine-Fe₃Al₂Si₃O₁₂ (SiKα, AlKα, FeKα), KMg₃Al₃SiO₁₀(OH)₂ (FKα), albite (NaKα), rutile (TiKα), grossular-Ca₃Al₂Si₃O₁₂ (CaKα), MgCr₂O₄ (CrKα), diopside- Mg₃Al₂Si₃O₁₂ (MgKα), and MnSiO₃ (MnKα). * Determined by stoichiometry. Compositions were recalculated on the basis of 5 cations (Na⁺, Mg²⁺, Al³⁺, Ca²⁺, Ti⁴⁺) apfu. OH⁻ was calculated as OH⁻ = 4(3-Si-F/4) as adapted from Visser (1993). Fe²⁺ and Fe³⁺ proportions were calculated based on the general garnet formula X₃Y₂(ZO₄)M(OH,F)₄M, where the X-site contains Ca, Fe²⁺, Mg, Mn, Na and the Y-site contains Al, Ti, and Fe³⁺ (X+Y = 5).
Table 8.14. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>in Type 1 vein, in silicified CS</th>
<th>in Type 4 vein in CS</th>
<th>n</th>
<th>average</th>
<th>stddev</th>
<th>average</th>
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<th>average</th>
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<td>23</td>
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<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt; (wt.%)</td>
<td>35.80 ± 0.10</td>
<td>35.57 ± 0.45</td>
<td>35.96 ± 0.64</td>
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<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.46 ± 0.16</td>
<td>0.86 ± 0.11</td>
<td>0.49 ± 0.26</td>
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<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>10.78 ± 0.36</td>
<td>10.21 ± 1.94</td>
<td>12.05 ± 2.29</td>
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<tr>
<td>Cr&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.04 ± 0.02</td>
<td>0.02 ± 0.02</td>
<td>0.03 ± 0.04</td>
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<tr>
<td>FeO</td>
<td>14.85 ± 0.48</td>
<td>15.43 ± 2.49</td>
<td>13.78 ± 3.11</td>
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<tr>
<td>MgO</td>
<td>0.07 ± 0.02</td>
<td>0.08 ± 0.02</td>
<td>0.08 ± 0.02</td>
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<tr>
<td>MnO</td>
<td>1.57 ± 0.36</td>
<td>2.21 ± 0.74</td>
<td>2.45 ± 1.39</td>
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<tr>
<td>Na&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>0.01 ± 0.01</td>
<td>0.01 ± 0.02</td>
<td>0.02 ± 0.03</td>
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<tr>
<td>CaO</td>
<td>33.36 ± 0.28</td>
<td>32.58 ± 1.27</td>
<td>32.73 ± 1.70</td>
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<tr>
<td>F</td>
<td>0.66 ± 0.11</td>
<td>0.61 ± 0.12</td>
<td>0.79 ± 0.22</td>
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<tr>
<td>O=F</td>
<td>-0.28 ± 0.05</td>
<td>-0.26 ± 0.05</td>
<td>-0.33 ± 0.09</td>
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<tr>
<td>Total</td>
<td>97.33 ± 0.18</td>
<td>97.11 ± 0.57</td>
<td>98.04 ± 0.69</td>
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Si<sup>4+</sup> (apfu) 2.855 ± 0.015 | 2.853 ± 0.021 | 2.836 ± 0.047 | |
Al<sup>3+</sup> 1.013 ± 0.031 | 0.962 ± 0.186 | 1.118 ± 0.199 | |
Cr<sup>3+</sup> 0.002 ± 0.001 | 0.001 ± 0.001 | 0.002 ± 0.002 | |
Ti<sup>4+</sup> 0.028 ± 0.010 | 0.039 ± 0.007 | 0.029 ± 0.015 | |
Fe<sup>2+</sup> (tot) 0.990 ± 0.035 | 1.037 ± 0.180 | 0.912 ± 0.218 | |
Mg<sup>2+</sup> 0.009 ± 0.002 | 0.009 ± 0.003 | 0.009 ± 0.003 | |
Mn<sup>2+</sup> 0.106 ± 0.024 | 0.150 ± 0.052 | 0.164 ± 0.094 | |
Na<sup>+</sup> 0.002 ± 0.002 | 0.002 ± 0.002 | 0.002 ± 0.004 | |
Ca<sup>2+</sup> 2.850 ± 0.025 | 2.799 ± 0.076 | 2.764 ± 0.119 | |
F<sup>-</sup> 0.166 ± 0.027 | 0.155 ± 0.028 | 0.196 ± 0.052 | |
O<sup>2-</sup> 11.161 ± 0.031 | 11.149 ± 0.065 | 11.162 ± 0.118 | |

Fe<sup>3+</sup> 0.957 ± 0.031 | 0.997 ± 0.167 | 0.851 ± 0.206 | |
Fe<sup>2+</sup> 0.033 ± 0.009 | 0.040 ± 0.027 | 0.060 ± 0.032 | |
Fe<sub>total</sub> 0.990 ± 0.035 | 1.037 ± 0.180 | 0.912 ± 0.218 | |
OH<sup>-</sup> (apfu) 0.415 ± 0.060 | 0.433 ± 0.071 | 0.459 ± 0.183 | |

x-site total 3.957 ± 0.031 | 3.997 ± 0.167 | 3.851 ± 0.206 | |
y-site total 1.998 ± 0.002 | 1.999 ± 0.001 | 1.998 ± 0.002 | |
M = (OH+F)/4 0.145 ± 0.015 | 0.147 ± 0.021 | 0.164 ± 0.047 | |

pyrope 0.29 ± 0.07 | 0.30 ± 0.09 | 0.30 ± 0.10 | |
amdantine 1.11 ± 0.30 | 1.33 ± 0.90 | 2.01 ± 1.08 | |
spessartine 3.53 ± 0.80 | 5.02 ± 1.73 | 5.47 ± 3.14 | |
andradite 47.89 ± 1.57 | 49.90 ± 8.36 | 42.62 ± 10.31 | |
uvarovite 0.11 ± 0.07 | 0.06 ± 0.06 | 0.10 ± 0.12 | |
grossular 47.00 ± 1.95 | 43.34 ± 9.84 | 49.42 ± 11.65 | |

Total 99.93 ± 4.76 | 99.94 ± 20.98 | 99.92 ± 26.40 | |

Note: The following standards were used: almandine-Fe<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub> (SiKα, AlKα, FeKα), KMg<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>10</sub>(OH)<sub>2</sub> (FKα), albite (NaKα), rutile (TiKα), grossular-Ca<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub> (CaKα), MgCr<sub>2</sub>O<sub>4</sub> (CrKα), diopside-Mg<sub>3</sub>Al<sub>2</sub>Si<sub>3</sub>O<sub>12</sub> (MgKα), and MnSiO<sub>3</sub> (MnKα). * Determined by stoichiometry. Compositions were recalculated on the basis of 5 cations (Na<sup>+</sup>, Mg<sup>2+</sup>, Al<sup>3+</sup>, Ca<sup>2+</sup>, Ti<sup>4+</sup>, Mn<sup>2+</sup>, Fe<sup>2+</sup>) pfu. OH<sup>-</sup> was calculated as OH = 4(3-Si-F)/4 as adapted from Visser (1993). Fe<sup>2+</sup> and Fe<sup>3+</sup> proportions were calculated based on the general garnet formula X<sub>3</sub>Y<sub>2</sub>(ZO<sub>4</sub>)<sub>3</sub>M(OH,F)<sub>4</sub>M, where the X-site contains Ca, Fe<sup>2+</sup>, Mg, Mn, Na and the Y-site contains Al, Ti, and Fe<sup>3+</sup> (X+Y = 5).
Garnet end-member compositions: all

Fig. 8.67. Ternary plot of all end-member compositions of garnet by vein/host environment. Grossular = Gr, andradite = Ad, and 'pyralspite' = Pyr = pyrope + almandine + spessartine.

Garnet end-member compositions:
**felsic intrusive** host rocks

Fig. 8.68. Ternary plot of all end-member compositions of garnet in felsic intrusive environments. Spessartine = Sp, almandine = Alm, and andradite = Ad.
end-member compositions calculated from the electron microprobe analyses. They plot nearest to spessartine, but are at least 20-25% almandine in composition. These are the most Mn-rich garnets at Northern Dancer, averaging 20.86 - 30.54 wt.% MnO (2.042 - 2.134 Mn apfu), and they are most likely magmatic. In addition to being the poorest in Ca of the Northern Dancer garnets, they are also the most F- and Fe-poor, and the most Al-rich. They occur as occasional pinkish-red unzoned, subhedral grains ~0.5-1.5 mm across, in the matrices of felsic dike units such as felsite, quartz-porphyry and quartz-feldspar porphyry, including ‘brain rock’. In these host rocks, garnet is typically the only ferromagnesian mineral present.

Granditic garnets at Northern Dancer occur in a range of environments. In calc-silicate groundmass, they occur as anhedral masses, subhedral grains (in a matrix with pyroxene, ± plagioclase, ± quartz, ± epidote, ± fluorite, ± calcite), or euhedral, zoned grains, such as those associated with pyroxene in Fig 8.63. They are occasionally intergrown with other minerals, such as those listed above, and can contain a range of inclusions (usually quartz, pyroxene, apatite, fluorite, or sulphide minerals). In one case, a symplectite intergrowth of garnet and quartz occurs next to what appears to be an altered zone of plagioclase and hornblende. This is typically thought of as an alteration texture indicating a solid-state reaction, and therefore in this case it likely represents the original calc-silicate alteration, and (Fig. 8.5; Vernon 2004). Garnet and pyroxene are commonly associated with scheelite in silicified calc-silicate groundmass (see fig. 8.64). Some zones of calc-silicate are extremely garnet-rich and pyroxene-poor; these zones contain the most grandite-rich garnets (highest calcium) in the deposit, with average compositions of And$_{49.7}$Gro$_{47.9}$Py$_{2.4}$ (see Fig. 8.69). In this study, garnet-pyroxene ratios were not analyzed spatially to find correlation with mineralization (i.e., as seen in some mineralized Au skarns), due to the fact that the calc-silicate alteration was induced mainly by the diorite, which pre-dates the mineralization.

Oscillatory zoning is usually rare or poorly developed in metamorphic minerals with the exception of occasional major-element or yttrium zoning in garnet porphyroblasts within metapelites (Schumacher et al. 1999; Stallard & Hickey 2002) and in the case of grandite in Fe-rich calc-silicate rocks. In the latter case, oscillatory zones are much sharper, narrower and more numerous, and garnet in many skarns may form vein-like aggregates which fill or project into cavities, suggesting growth within a fluid (Deer et al. 1992; Rice 1993; Lessing & Standish 1973; Schutkenberg et al. 2001). Garnet within groundmass at Northern Dancer shows this kind of texture, as well as oscillatory zoning of end-member compositions (see Fig. 8.70). Cores of calc-silicate hosted garnet at Northern Dancer range from
Fig. 8.69. Ternary plot of average end-member compositions of garnet by vein/host environment. Grossular = Gr, andradite = Ad, and 'pyralspite' = Pyr = pyrope + almandine + spessartine.

Fig. 8.70. Ternary plot of all end-member compositions of garnet cores and rims, in metasedimentary groundmass environments. Grossular = Gr, andradite = Ad, and 'pyralspite' = Pyr = pyrope + almandine + spessartine.
46-63% And and 31-46% Gro; however, the compositional range narrows towards the rims, to a range of 46-68% And and 35-44% Gro. Even more pronounced is the zonation pattern of garnets in silicified calc-silicate, i.e., calc-silicate which has been siliceously altered by fluids associated with the felsic dikes. The cores of garnets in this environment are notably andraditic (54-60% And, 32-36% Gro), evolving toward more grossular-rich rims (29-46% And, 49-62% Gro). The cores are homogenous and altered or resorbed, and rimmed by euhedral, cyclic growth zones. This suggests that original calc-silicate garnet formed in a different environment than the rimming garnet which is likely associated with later, possibly mineralizing, aqueous fluids. Zoning in grandites is representative of rapid changes in the chemistry of the hydrothermal solution or the oxidation state of the iron (Deer et al. 1997). Andradite cores and grossular rims have been noted at the King Island deposit in Tasmania (Hing & Kwak 1979) in the aureole of the Grassy granodiorite. Oscillatory zoning can also be seen in epidote and allanite, where zones vary by REE (La and Ce) content (see Fig. 8.17 of allanite REE zoning), and in the literature this has been noted in high-pressure carbonate rocks (Boundy et al. 2002). Iron-rich mica with oscillatory Mg-Ti zoning in skarn was noted by Kwak (1981). This kind of oscillatory zoning in metamorphic minerals is usually attributed to open-system growth conditions involving changes in fluid composition (Jamtveit 1991; Jamveit & Anderson 1992; Jamveit et al. 1993; Clechenko & Valley 2003).

In veins, granditic garnet is typically either found as anhedral masses (associated with pyroxene or fluorite), or as zoned, euhedral grains (Fig. 8.71). In Type 1 veins, it is a major vein component with pyroxene, and is present in alteration haloes in higher concentrations than the surrounding groundmass. In Type 2 veins, it is less common, and is typically a fine-grained accessory mineral. Type 3 veins, especially those extending outbound of the felsic dike complex, can contain major amounts of garnet, which is associated with epidote. Type 4 veins also contain garnet, usually associated with fluorite, although never in more than accessory amounts. Type 4 veins and calc-silicate with scheelite contain the most grossular-rich garnet (49.92 and 49.07 % Gro, respectively). In Type 1 and 2 veins which have been reopened by later vein sets, garnet sometimes displays homogenous, partially resorbed grandite cores rimmed by more subcalcic, zoned garnet, which is rimmed by more grandite rich garnet (see Fig. 8.72). This suggests that instead of simple compositional zoning based on fluctuating fluid chemistry or oxidation state of a single aqueous fluid, these garnets were altered or resorbed first, and subsequently rimmed by a later fluid of a different character.
Fig. 8.71. Ternary plot of all end-member compositions of garnet cores and rims, in vein environments. Grossular = Gr, andradite = Ad, and 'pyralspite' = Pyr = pyrope + almandine + spessartine.

Fig. 8.72. Backscatter SEM images of zoned garnet in a reopened Type 1 vein in hornfels. (a) Anhedral fluorite and pyroxene are intergrown with the euhedral growth zones of granulate garnet. Altered garnet cores are Fe-rich and closer to andraditic end-member composition than unaltered, euhedral Fe-poor rims, which are more grossular in composition. Fluorite appears to be infilling space where original garnet has been resorbed. (b) Altered, euhedral, zoned garnet with fluorite inclusions, intergrown with pyrite. Fluid inclusions (possibly primary, outlined with red dashed line) occur along euhedral growth zones in garnet.
For a more detailed examination of the character of zonation in the garnet, one section displaying typical zonation and textural characteristics was examined in detail. In Fig. 8.73, zoned garnet is intergrown with pyroxene and scheelite within an older Type 1 vein. This vein has been altered and likely infiltrated by fluids from a nearby (less than 10 mm) Type 4 vein. Pyroxene and cores of garnet appear altered and slightly resorbed, whereas rims are euhedral and unaltered. Scheelite appears to infill space around the resorbed garnet and pyroxene; however it is subhedral and is intergrown with the pyroxene. Pyroxene in Fig. 8.73 has an average, homogenous composition of $D_p 63.3 H_d 29.4 J_o 7.1$, while scheelite has a molybdenum component of 7.06 wt.% $MoO_3$ (or 0.14 Mo $apfu$). In the anhedral, massive cores of the garnet, the initial composition averages $G_{ro} 54.3 A_{nd} 41.5 P_{y} 4.2$. This is followed by a darker, cyclically-zoned mid-zone with an average composition of $A_{nd} 58.8 G_{ro} 22.4 P_{y} 18.8$. A second mid-zone rims this, with a composition of $G_{ro} 47.1 A_{nd} 45.4 P_{y} 7.4$, and finally, the outer rim which is also dark, averages a composition of $A_{nd} 55.5 G_{ro} 19.8 P_{y} 15.2$. The mid-zones and rim are much more subcalcic than the core garnet, which is likely original Type 1 vein garnet. Its composition is itself less andraditic than what is likely original reaction skarn garnet formed by initial calc-silicate alteration (an average composition of the cores of garnet in calc-silicate groundmass is $A_{nd} 56.3 G_{ro} 35.3 P_{y} 8.1$).

### 8.2.16.2 Fluorine content

The presence of fluorine as a trace component in hydrogarnets and garnets has not been studied in detail, in spite of a report of 0.63 wt.% F by Eckermann in 1922. Only a limited number of occurrences have been described (Visser 1993; Gunow et al. 1980; Valley et al. 1983; van Marcke de Lumen 1986; Flohr & Ross 1989; Smyth et al. 1990). According to Smyth et al. (1990), garnet may preserve a record of the variations in the F activity of aqueous fluids during metamorphism or hydrothermal alteration, due to the fact that F is incorporated into the crystal structure much the same as OH$^-$ in hydrogrossular, and not simply as submicroscopic inclusions or exsolution-derived grains of other F-bearing minerals such as fluorite. Substantial amounts of fluorine have been detected in garnet at Northern Dancer, and are documented below. Maximum fluorine content found is 1.62 wt.% F (0.392 F $apfu$), with an average deposit-wide value of 0.57 wt.% F (0.144 F $apfu$).

Fluorine content does not seem to be correlated with garnet end-member composition. Rather, F content of garnet is influenced by vein/host environment and timing, in a general sense, and is highest where mineralization is known to occur. In felsic intrusive hosts, average F
Fig. 8.73. Backscatter image of a zoned garnet in a Type 1 vein in calc-silicate, near a Type 4 sheeted vein. Garnet, pyroxene, and scheelite are intergrown. Garnet compositions range from Gr$_{54.3}$Ad$_{41.5}$Py$_{4.2}$ in the massive core zone ('core zone'), to Ad$_{58.8}$Gr$_{22.4}$Py$_{18.8}$ in a cyclically-zoned mid-zone ('mid-zone a'), to Gr$_{47.1}$Ad$_{45.4}$Py$_{7.4}$ in a second mid-zone ('mid-zone b'), and finally, to Ad$_{65.6}$Gr$_{19.8}$Py$_{15.2}$ in the outer rim ('rim' zone).

content is between 0.11 and 0.17 wt.% F (or 0.029 and 0.045 F apfu). In calc-silicate host rocks and earlier vein sets, average F content falls between 0.54 and 0.66 wt.% F (or 0.135 and 0.166 F apfu). In calc-silicate which has been silicified, or where garnet is associated with scheelite in calc-silicate, average F content is higher, between 0.61 and 0.77 wt.% F (or 0.155 and 0.209 F apfu), respectively. In Type 4 veins in calc-silicate (which contain the coarsest, purest scheelite in the deposit), garnet contains a peak average F content of 0.79 wt.% F (or 0.196 F apfu). The maximum F content detected in garnet anywhere in the Northern Dancer deposit (at 1.62 wt.% F or 0.392 F apfu as mentioned above), was found in a Type 1 vein reopened by a later Type 4 vein, in calc-silicate host rocks.

In the example of zoned garnet mentioned above in the discussion of end-member compositions, F content also varies over a local scale. Type 1 vein garnet cores contain an average F content of only 0.27 wt.% F, or 0.07 F apfu. Mid-zones, which display a high degree of compositional oscillatory zoning, average 0.48 and 0.49 wt.% F (0.12 and 0.13 F apfu). The rims, which are possibly forming from fluid emanating from nearby Type 4 veins, are 0.80 wt.% F (0.20 F apfu) on average, and can be up to 0.92 wt.% F (0.23 F apfu - this is over double the
average F content of 0.43 wt.% F or 0.11 F apfu in garnet within relatively unaltered calc-silicate groundmass).

Major element (wt.%) compositions of F-rich garnet from Northern Dancer are similar to those listed in the literature as hydrogrossular (Deer et al. 1992); this further supports the notion that F-rich garnet is structurally and compositionally similar to hydrogrossular, as stated by Smyth et al. (1990). Specifically, those listed as occurring in the garnet-clinopyroxene skarn at the Kagata Mine in Japan (Shimazaki 1977) are proportionally similar to those of Northern Dancer, if slightly less Fe-rich, and slightly more aluminous. Zones which contain garnet and fluorite are common. Generally, fluorite appears to be a later, possible ‘alteration’ event, filling open space between grains, and in fractures. The correlation of the occurrence of higher-grade scheelite mineralization and high F content in grandite garnet at Northern Dancer, on both a local/microscopic and deposit-wide scale, indicates that the F-content of garnet may be a good mineral chemistry exploration indicator for W mineralization of a similar nature. It also lends support to the hypothesis that F may be an assisting volatile to W mineralization, or perhaps even the ion (or one of the ions) responsible for W transport/speciation.

As mentioned above, high fluorine activity can promote the development mineral assemblages which mimic ‘retrograde’ metamorphic mineral assemblages (including epidote and chlorite), at higher temperatures (Meinert et al. 2005). It is also possible that a high fluorine activity in the fluid could promote ‘hydrogrossular-like’ F-rich grandites, in the same way; since ‘retrograde’ conditions can produce hydrogrossular rims on regular grossular (Yoder 1950; Hutton 1943; Pabst 1942). This hypothesis would explain how F-rich ‘hydrogarnet’ occurs alongside epidote, pyroxene, and potassium feldspar in the same local environment without alteration (and would not require lower temperature and higher H2O activity of which there is no evidence in these locales).

8.2.16.3 Iron ratios

The high F content of the garnet suggest that they could also contain a significant amount of OH⁻ because of their probable ‘hydrogarnet’ crystal structure. While Fe²⁺/Fe³⁺ ratios can reveal information relating to oxidation state, in this case it is not possible to calculate meaningful Fe²⁺/Fe³⁺ ratios in garnet at Northern Dancer because the OH⁻ content of the garnets
via hydrogarnet substitution is unknown. As such, pyroxene, being non-hydrous, likely acts as a better indicator of local oxidation state than garnet (L. Groat pers. comm. 2008).

8.2.17 Scheelite and molybdoscheelite

8.2.17.1 Scheelite overview

Scheelite is the dominant ore mineral at Northern Dancer, and is responsible for the entire W grade which has most recently been assessed to be 242 million tonnes grading 0.10% WO₃, implying the deposit contains 508.1 million lbs. of tungsten trioxide (Broad & Campbell 2008). Scheelite (CaWO₄) is tetragonal (it forms simple dipyramids) and has an unusually high specific gravity (5.9-6.1). Molybdoscheelite is the intermediate composition between scheelite, CaWO₄ and powellite, CaMoO₄. Tungsten has a greater atomic mass than Mo (184 vs. 96), however, they belong to same family in the periodic table, and due to lanthanide contraction they have approximately the same ionic radius. They freely substitute at the coordinating cation site in the warped tetrahedral grouping (AO₄ ion), which are linked together by cations (such as Ca²⁺ or Pb²⁺) in octahedral coordination. However, geochemical differentiation separates W and Mo, so pure primary end-members are possible. This gives rise to the scheelite-powellite solid solution. Consequently, where high Mo content occurs in scheelite, lower W content must compensate, resulting in less W in a scheelite concentrate.

Scheelite also experiences solid solution with stolzite (CaPbO₄) whereas powellite experiences solid solution with wulfenite (PbMoO₄), which also shares solid solution with stolzite. Only scheelite and molybdoscheelite are found at Northern Dancer. The degree to which Mo substitutes for W in the scheelite crystal structure can affect the metallurgical process of extracting tungsten from an economic deposit, as well as alter the overall calculated grade and tonnage. As tungsten and molybdenum have very different industrial applications (tungsten acts as a strengthening agent for steel alloys, whereas molybdenum is used as a lubricant), their mutual ‘contamination’ is not ideal in comparison to pure tungsten or molybdenum ore. An example of another deposit in which this occurs is the Nui Phao mine in Vietnam, where special milling and smelting processes have been developed in attempt to overcome this problem (Davie & Heymann 2005).

Fluorescence is the primary characteristic used to identify scheelite, and has been used as a diagnostic property since the work of Van Horn (1930). Pure scheelite fluoresces blue (425
nm), but the addition of Mo into the crystal structure results in the emission of longer-wavelength light (530 nm), which can appear progressively more yellow-white as the Mo content increases (see Figs. 8.74 through 8.77; Greenwood 1943; Shoji & Sasaki 1978, Tyson et al. 1988). This property can be used qualitatively to estimate Mo content of scheelite in the field, and all Northern Dancer core was passed through a dark room and analyzed with a shortwave UV lamp as part of core logging (see Methodology). A range of Mo contents in the scheelite at Northern Dancer gives rise to a range of fluorescence colours.

8.2.17.2 Scheelite at Northern Dancer

Scheelite and/or molybdoscheelite are found in all four mineralized vein types at Northern Dancer, and in various metasedimentary/groundmass environments. Minor dissemination also occurs proximal to the veins, i.e. in their alteration halos. Scheelite morphology, grain size, abundance and composition change by vein/host environment. Electron microprobe and scanning electron microscopy (SEM) were used to determine morphological, grain size, and compositional changes, while X-ray diffraction (the Rietveld method) and lithogeochemistry were used to determine abundance. To maximize W counts and decrease dead-time, 40 nA current and longer counting times were used for scheelite analysis (see analytical procedures in Appendix A). Scheelite compositions were recalculated using the Formula program, on a basis of 4 anions pfu.

A total of 1024 compositions representing fifty-one different vein/host environments, were obtained from 43 of the representative samples. Compositions were renormalized on the basis of 4 anions. Average results for overall vein and groundmass environments are shown in Table 8.15, while analyses for individual vein/host environments are displayed in below. Adequate representation of each vein type and host rock combination was sought and achieved: Type 1, 2, 3, and 4 veins account for 202, 134, 139, and 371 of the total analyses, respectively (see Fig. 8.78, below for a graphical representation). The remaining 178 analyses are from grains found in host-rock groundmass or the alteration haloes of veins. Large average grain size (see discussion of grain size below), higher average abundance within this vein set, and the extensive, overprinting nature of the Type 4 vein set all contribute to this natural abundance of Type 4 vein scheelite at Northern Dancer, which is reflected in the data of Fig. 8.78.
Fig. 8.74. Image of calc-silicate groundmass which contains both blue-white fluorescing scheelite and yellow-white fluorescing molybdocheelite under shortwave ultraviolet light.

Fig. 8.75. Image of a Type 4 vein containing molybdenite and scheelite at a vein wall, in daylight (*left*), and in shortwave ultraviolet light (*right*). This sample contains both blue-white fluorescing scheelite at the vein wall, pale-purple-fluorescing fluorite within the vein core, and yellow-white fluorescing molybdocheelite disseminated throughout the groundmass of the calc-silicate host rock.
Fig. 8.76. Image of a Type 4 vein with coarse scheelite in the vein core and fine-grained scheelite disseminated at the vein selvedge, in daylight (*top*), and shortwave ultraviolet light (*bottom*).

Fig. 8.77. Image of a Type 4 vein in calc-silicate, with anhedral scheelite elongated perpendicular to the vein wall, in daylight (*left*), and shortwave ultraviolet light (*right*). Massive pods of pyrrhotite and pyrite occur as accessory minerals. Thin Type 3 veins are visible in the left side of the image, where they are crosscut by the much larger Type 4 vein.
Table 8.15. Average compositions of scheelite samples in general environments from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Type 1 vein</th>
<th>Type 2 vein</th>
<th>Type 3 vein</th>
<th>Type 4 vein</th>
<th>Groundmass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>avg</td>
<td>st dev</td>
<td>avg</td>
<td>st dev</td>
</tr>
<tr>
<td>WO$_3$ (wt.%)</td>
<td>202</td>
<td>74.34</td>
<td>4.33</td>
<td>78.38</td>
<td>2.69</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td></td>
<td>4.85</td>
<td>4.03</td>
<td>1.13</td>
<td>1.51</td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td></td>
<td>0.04</td>
<td>0.07</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>FeO</td>
<td></td>
<td>0.13</td>
<td>0.17</td>
<td>0.17</td>
<td>0.38</td>
</tr>
<tr>
<td>MgO</td>
<td></td>
<td>0.01</td>
<td>0.01</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>MnO</td>
<td></td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
<td></td>
<td>19.88</td>
<td>0.54</td>
<td>19.50</td>
<td>0.44</td>
</tr>
<tr>
<td>PbO</td>
<td></td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>99.33</td>
<td>0.72</td>
<td>99.35</td>
<td>1.77</td>
</tr>
</tbody>
</table>

W$^{6+}$ (apfu) 0.904 0.073 0.973 0.032 0.976 0.021 0.975 0.059 0.968 0.036
Mo$^{5+}$ 0.093 0.073 0.022 0.029 0.015 0.015 0.018 0.029 0.028 0.036
Nb$^{5+}$ 0.001 0.001 0.001 0.001 0.004 0.002 0.003 0.002 0.003 0.011
Ta$^{5+}$ 0.001 0.001 0.001 0.001 0.000 0.001 0.000 0.001 0.001 0.001
Fe$^{2+}$ 0.005 0.007 0.007 0.017 0.003 0.011 0.002 0.005 0.007 0.011
Mg$^{2+}$ 0.001 0.001 0.003 0.014 0.004 0.012 0.002 0.002 0.002 0.003
Mn$^{2+}$ 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.001 0.006
Ca$^{2+}$ 0.998 0.014 1.000 0.017 1.010 0.026 1.006 0.156 0.999 0.024
Pb$^{2+}$ 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000

Note: The following standards were used: diopside- Mg$_2$Al$_2$Si$_3$O$_{12}$ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO$_3$ (MnKα), Nb (NbLα), Mo (MoKα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Fig 8.78. Plot showing distribution of Mo content (MoO$_3$ wt.%) in scheelite versus total number of analyses, for each general environment (Type 1, 2, 3, 4 veins and groundmass). Adequate representation of each vein type and host rock combination was sought: Type 1, 2, 3, and 4 veins and the groundmass account for 202, 134, 139, 371, and 178 of the total analyses, respectively.

However, it is probable that scheelite in other vein/host environments also contribute greatly to the overall W grade of the deposit.

8.2.17.3 Scheelite in Type 1 veins

In Type 1 veins, molybdoscheelite dominates as small, subhedral crystals averaging 0.02 mm, and can be found in both the core and the wall of the main vein, as well as in the alteration halo. Occasionally it occurs as clusters of crystals or anhedral aggregates up to 1 cm across, and can be intergrown with garnet and pyroxene (see Fig. 8.73). Type 1 molybdoscheelite is occasionally associated with anhedral/subhedral zoned garnet, and may fill interstices between garnet, quartz, plagioclase and clinopyroxene. Where Type 1 veins have been reopened by later
vein generations, molybdoscheelite can be zoned (e.g., QSM-6, see Zoned Scheelite, below), or have overgrowth of a later, purer phase, which is visible in backscatter mode on the SEM. The highest concentrations of molybdoscheelite in Type 1 veins occur at the intersection of multiple veins, perhaps due to the increased available space created by brecciation/stockwork processes. Some Type 1 veins appear to be crack-seal, and in this case the molybdoscheelite is located between opening boundaries; for example, in Fig. 8.79, a Type 1 vein has a quartz-garnet-clinopyroxene outer zone which has been reopened by a later, garnet-rich phase, and the molybdoscheelite is found mostly in the boundary between the garnet vein ‘core’ and the outer, older quartz-garnet-clinopyroxene vein. Inclusions in Type 1 molybdoscheelite are rare, possibly due to their small average grain size; however, some small anhedral quartz inclusions were observed. The majority of Type 1 molybdoscheelite grains are fractured and/or show evidence for dissolution or resorption at their grain boundaries. This may indicate that later generations of fluids of a different character altered and possibly remobilized scheelite from earlier veins.

A total of 202 EPMA analyses representing nine different vein/host environments were collected from seven different polished sections, and the results are shown in Table 8.15. General cation trends and Mo content trends are discussed below.

8.2.17.4 Scheelite in Type 2 veins

Type 2 veins contain scheelite with a lower Mo content, which is evident in compositional data but also in the colour of fluorescence; Type 2 scheelite fluorescence is much bluer in colour compared to the pale yellow fluorescence of the Type 1 molybdoscheelite. Most grains are small subhedral crystals less than 0.5 mm in diameter, but some grains in wider Type 2 veins can be up to 2.5 mm across (see Grain Size, below). Typically associated with pyrite, epidote, clinozoisite, or plagioclase, Type 2 vein scheelite is most abundant in Type 2 veins within calc-silicate host rocks or calcium-rich hornfels rocks (Fig. 4.2), but was also found in Type 2 veins crosscutting altered diorite rocks. Some grains occur as small inclusions in larger pyrite grains (see ‘Incl. in pyr., in light green skarn’ in Table 8.17). In this case, scheelite inside pyrite has lower Mo-contents and higher Nb-contents than scheelite outside, in the vein. Where Type 2 veins have been reopened by Type 3 or 4 veins, older Type 2 vein scheelite appears altered (see Fig. 8.23).
Fig. 8.79. Backscatter SEM image of Type 1 vein in calc-silicate. Some Type 1 veins appear to be crack-seal in nature, or possibly reopened by later veins. In this case, the molybdocheline is located along the boundaries of an older quartz-garnet-clinopyroxene ‘outer zone’ and a younger, garnet-rich vein ‘core’.

A total of 134 EPMA analyses representing ten different vein/host environments in ten different polished sections were collected, and results are shown in Table 8.17. General cation trends and Mo content trends are discussed below.

8.2.17.5 Scheelite in Type 3 veins

Type 3 vein scheelite is the purest at Northern Dancer, averaging only 0.73 wt% MoO₃ or 0.02 Mo apfu (see below), and fluoresces an intense blue-white. Scheelite in Type 3 veins is slightly more abundant in those veins which extend outboard of the felsic dike complex (most Type 3 veins are restricted to the dikes themselves), although fine-grained scheelite occasionally occurs in thicker Type 3 veins and their alteration haloes, within the dike complex. In Type 3 veins hosted by metasedimentary units, scheelite can be associated with the most common accessory minerals in this vein environment: molybdenite, garnet and epidote. Type 3 veins (and Type 4 veins as well) in metasedimentary host rocks occasionally contain abundant molybdenite
Table 8.16. Average compositions of scheelite samples in Type 1 veins from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>In CS, assc. w/ moly</th>
<th>Near Type 4 vein, in CS</th>
<th>Gar-rich Type 1 vein solvofide, in silicified CS</th>
<th>Type 1 vein halo, in gar-rich CS</th>
<th>Type 1 vein edge, in gar-rich CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>13</td>
<td>14</td>
<td>43</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>stddev</td>
<td>average</td>
<td>stddev</td>
<td>average</td>
</tr>
<tr>
<td>WO$_3$ (wt.%)</td>
<td>75.97</td>
<td>2.70</td>
<td>74.43</td>
<td>3.43</td>
<td>74.33</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td>3.83</td>
<td>2.83</td>
<td>3.95</td>
<td>3.11</td>
<td>5.21</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>FeO</td>
<td>0.08</td>
<td>0.08</td>
<td>0.38</td>
<td>0.35</td>
<td>0.11</td>
</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
<td>0.02</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>MgO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>19.61</td>
<td>0.36</td>
<td>19.82</td>
<td>0.36</td>
<td>19.79</td>
</tr>
<tr>
<td>PbO</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Total</td>
<td>99.62</td>
<td>0.75</td>
<td>98.73</td>
<td>0.88</td>
<td>99.58</td>
</tr>
<tr>
<td>W$_6^{2+}$ (apfu)</td>
<td>0.927</td>
<td>0.051</td>
<td>0.914</td>
<td>0.056</td>
<td>0.900</td>
</tr>
<tr>
<td>Mo$_6^{2+}$</td>
<td>0.074</td>
<td>0.053</td>
<td>0.077</td>
<td>0.060</td>
<td>0.101</td>
</tr>
<tr>
<td>Nb$_5^{2+}$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Ta$_5^{2+}$</td>
<td>0.003</td>
<td>0.003</td>
<td>0.015</td>
<td>0.015</td>
<td>0.004</td>
</tr>
<tr>
<td>Fe$_2^{2+}$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
</tr>
<tr>
<td>Mn$_2^{2+}$</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg$_2^{2+}$</td>
<td>0.988</td>
<td>0.008</td>
<td>1.006</td>
<td>0.018</td>
<td>0.990</td>
</tr>
<tr>
<td>Ca$_2^{2+}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_2^{2+}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside- Mg$_3$Al$_2$Si$_3$O$_12$ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO$_3$ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Table 8.16. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>In CS</th>
<th>Type 1 vein layer, in hornfels</th>
<th>In light green skarn</th>
<th>In wollastinite-vesuvianite skarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
</tr>
<tr>
<td>WO₃ (wt.%)</td>
<td>75.91</td>
<td>3.46</td>
<td>66.63</td>
<td>7.44</td>
</tr>
<tr>
<td>MoO₃</td>
<td>3.88</td>
<td>3.40</td>
<td>11.89</td>
<td>6.86</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>0.06</td>
<td>0.08</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>FeO</td>
<td>0.07</td>
<td>0.09</td>
<td>0.39</td>
<td>0.10</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>CaO</td>
<td>19.65</td>
<td>0.44</td>
<td>20.77</td>
<td>0.72</td>
</tr>
<tr>
<td>PbO</td>
<td>0.02</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>99.64</td>
<td>0.63</td>
<td>99.79</td>
<td>0.51</td>
</tr>
<tr>
<td>W⁶⁺ (apfu)</td>
<td>0.926</td>
<td>0.061</td>
<td>0.778</td>
<td>0.119</td>
</tr>
<tr>
<td>Mo⁶⁺</td>
<td>0.075</td>
<td>0.063</td>
<td>0.217</td>
<td>0.121</td>
</tr>
<tr>
<td>Nb⁵⁺</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Ta⁵⁺</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.003</td>
<td>0.003</td>
<td>0.014</td>
<td>0.004</td>
</tr>
<tr>
<td>Mn²⁺</td>
<td>0.000</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>0.990</td>
<td>0.010</td>
<td>0.996</td>
<td>0.009</td>
</tr>
<tr>
<td>Pb²⁺</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside- Mg₃Al₂Si₃O₁₂ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO₃ (MnKα), Nb (NbLα), Mo (MoKα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Table 8.17. Average compositions of scheelite samples in Type 2 veins from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>Altered diorite dike</th>
<th>Garnet-rich CS</th>
<th>Silicified CS</th>
<th>Altered hornfels</th>
<th>Near Type 4 vein, in CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>average</td>
<td>stdev</td>
<td>average</td>
<td>stdev</td>
</tr>
<tr>
<td>WO₃ (wt.%)</td>
<td>79.29 (0.86)</td>
<td>80.23 (1.51)</td>
<td>80.19 (0.46)</td>
<td>78.40 (1.18)</td>
<td>78.90 (0.55)</td>
</tr>
<tr>
<td>MoO₃</td>
<td>0.54 (0.64)</td>
<td>0.70 (1.24)</td>
<td>0.13 (0.10)</td>
<td>0.44 (0.32)</td>
<td>1.17 (0.38)</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.05 (0.06)</td>
<td>0.04 (0.04)</td>
<td>0.08 (0.05)</td>
<td>0.06 (0.05)</td>
<td>0.07 (0.05)</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>0.01 (0.02)</td>
<td>0.02 (0.03)</td>
<td>0.04 (0.05)</td>
<td>0.05 (0.07)</td>
<td>0.05 (0.05)</td>
</tr>
<tr>
<td>FeO</td>
<td>0.12 (0.11)</td>
<td>0.07 (0.10)</td>
<td>0.06 (0.08)</td>
<td>0.21 (0.24)</td>
<td>0.32 (0.65)</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01 (0.02)</td>
<td>0.01 (0.01)</td>
<td>0.02 (0.02)</td>
<td>0.01 (0.02)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>MgO</td>
<td>0.02 (0.00)</td>
<td>0.04 (0.07)</td>
<td>0.02 (0.01)</td>
<td>0.02 (0.01)</td>
<td>0.03 (0.02)</td>
</tr>
<tr>
<td>CaO</td>
<td>19.63 (0.19)</td>
<td>19.28 (0.23)</td>
<td>19.60 (0.18)</td>
<td>19.63 (0.66)</td>
<td>19.36 (0.07)</td>
</tr>
<tr>
<td>PbO</td>
<td>0.01 (0.03)</td>
<td>0.02 (0.03)</td>
<td>0.01 (0.03)</td>
<td>0.00 (0.01)</td>
<td>0.02 (0.02)</td>
</tr>
<tr>
<td>Total</td>
<td>99.69 (0.44)</td>
<td>100.41 (0.58)</td>
<td>100.16 (0.58)</td>
<td>98.82 (0.66)</td>
<td>99.93 (0.74)</td>
</tr>
</tbody>
</table>

W⁶⁺ (apfu) | 0.984 (0.013) | 0.989 (0.024) | 0.993 (0.003) | 0.981 (0.013) | 0.974 (0.007) |
Mo⁶⁺      | 0.011 (0.013) | 0.014 (0.024) | 0.003 (0.002) | 0.009 (0.006) | 0.023 (0.007) |
Nb⁵⁺      | 0.001 (0.001) | 0.001 (0.001) | 0.002 (0.001) | 0.001 (0.001) | 0.001 (0.001) |
Ta⁵⁺      | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.001 (0.001) | 0.001 (0.001) |
Fe⁴⁺      | 0.005 (0.004) | 0.003 (0.004) | 0.002 (0.003) | 0.008 (0.010) | 0.013 (0.026) |
Mn⁴⁺      | 0.001 (0.001) | 0.001 (0.001) | 0.001 (0.001) | 0.000 (0.000) | 0.000 (0.000) |
Mg²⁺      | 0.001 (0.000) | 0.003 (0.005) | 0.001 (0.001) | 0.001 (0.001) | 0.002 (0.001) |
Ca²⁺      | 1.007 (0.011) | 0.982 (0.007) | 1.003 (0.006) | 1.016 (0.038) | 0.988 (0.006) |
Pb²⁺      | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) | 0.000 (0.000) |

Note: The following standards were used: diopside- Mg₃Al₂Si₃O₁₂ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO₃ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Table 8.17. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>CS</th>
<th>Hornfels</th>
<th>Light green skarn</th>
<th>Incl. in pyr, in light green skarn</th>
<th>Intersecting Type 1 vein, in light green skarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( n )</td>
<td>25</td>
<td>11</td>
<td>20</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>( n )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{average} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{stdev} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{average} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{stdev} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{average} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{stdev} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{average} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{stdev} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( WO_3 ) (wt.%)</td>
<td>79.04</td>
<td>0.56</td>
<td>78.16</td>
<td>2.38</td>
<td>75.10</td>
</tr>
<tr>
<td>( MoO_3 )</td>
<td>0.45</td>
<td>0.42</td>
<td>1.12</td>
<td>1.70</td>
<td>2.93</td>
</tr>
<tr>
<td>( Nb_2O_5 )</td>
<td>0.06</td>
<td>0.08</td>
<td>0.10</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>( Ta_2O_5 )</td>
<td>0.04</td>
<td>0.07</td>
<td>0.04</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>( FeO )</td>
<td>0.05</td>
<td>0.07</td>
<td>0.10</td>
<td>0.08</td>
<td>0.43</td>
</tr>
<tr>
<td>( MnO )</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>( MgO )</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.13</td>
</tr>
<tr>
<td>( CaO )</td>
<td>19.33</td>
<td>0.18</td>
<td>19.54</td>
<td>0.31</td>
<td>19.57</td>
</tr>
<tr>
<td>( PbO )</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>( \text{Total} )</td>
<td>99.03</td>
<td>0.58</td>
<td>99.12</td>
<td>0.72</td>
<td>98.30</td>
</tr>
</tbody>
</table>

| \( W^6+ \) (epfu)      | 0.988 | 0.007 | 0.972 | 0.035 | 0.930 | 0.041 | 0.968 | 0.023 | 0.937 | 0.014 |
| \( Mo^6+ \)            | 0.009 | 0.008 | 0.022 | 0.033 | 0.058 | 0.038 | 0.023 | 0.024 | 0.059 | 0.015 |
| \( Nb^5+ \)            | 0.001 | 0.002 | 0.002 | 0.002 | 0.002 | 0.001 | 0.003 | 0.002 | 0.002 | 0.001 |
| \( Ta^5+ \)            | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| \( Fe^{2+} \)          | 0.002 | 0.003 | 0.004 | 0.003 | 0.018 | 0.037 | 0.016 | 0.009 | 0.004 | 0.003 |
| \( Mn^{2+} \)          | 0.000 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| \( Mg^{2+} \)          | 0.000 | 0.001 | 0.002 | 0.001 | 0.010 | 0.035 | 0.003 | 0.001 | 0.001 | 0.001 |
| \( Ca^{2+} \)          | 0.999 | 0.008 | 1.004 | 0.010 | 1.002 | 0.013 | 0.996 | 0.009 | 1.000 | 0.011 |
| \( Pb^{2+} \)          | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Note: The following standards were used: diopside- \( \text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12} \) (\( \text{MgK}\alpha \)), scheelite (\( \text{CaK}\alpha, \text{WM}\alpha \)), fayalite (\( \text{FeK}\alpha \)), \( \text{MnSiO}_3 \) (\( \text{MnK}\alpha \)), \( \text{Nb} \) (\( \text{NbL}\alpha \)), \( \text{Mo} \) (\( \text{MoM}\alpha \)), galena (\( \text{PbM}\alpha \)), and \( \text{Ta} \) (\( \text{TaL}\alpha \)). Compositions were recalculated on basis of 4 anions pfu.
at the vein walls/selvedges (Fig. 4.3); these environments are usually more scheelite-rich than those which lack molybdenite. Scheelite may form long anhedral masses parallel to the vein wall, or it can form aggregates with pinkish-brown garnet and/or epidote. Occasionally, Type 3 vein scheelite may even be euhedral, especially in quartz-rich, thicker Type 3 veins, near other vein intersections (see Fig. 8.32). Besides molybdenite, other sulphide minerals such as pyrite and chalcopyrite may be present in Type 3 veins, and are occasionally associated with fine-grained scheelite. Rarely, these sulphides contain small scheelite inclusions.

A total of 139 EPMA analyses representing nine different vein/host environments in twelve different polished sections were collected, and results are shown in Table 8.18. General cation trends and Mo content trends are discussed below.

8.2.17.6 Scheelite in Type 4 veins

Type 4 vein scheelite at Northern Dancer can occur in many different morphologies, ranging from fine-grained anhedral masses, to clusters of subhedral grains, to large euhedral grains up to 9.4 mm across (see fig. 8.82 below, and Fig. 8.4). Sometimes it may occur as anhedral or subhedral masses elongated perpendicular to the vein wall, which is occasionally planar, especially in very wide veins (Fig 8.74). Scheelite occasionally occurs in Type 4 vein haloes, most occasionally in hornfels or diorite host rocks; here, it may be associated with other Type 4 vein halo minerals such as biotite, molybdenite, chlorite, amphibole, titanite, or apatite. In some cases it appears as coarse, subhedral to euhedral crystals in thick Type 4 veins, and also as fine-grained disseminations at the vein selvedge which can extend several centimetres into surrounding calc-silicate, as part of the alteration halo (see Fig. 8.76). Scheelite is not abundant in most other vein alteration haloes.

Type 4 veins which crosscut quartz-feldspar porphyry rocks and felsic dikes are occasionally fluorite or beryl rich, and can contain vein-filling scheelite with euhedral morphology (Fig. 8.24). In felsic host environments, especially altered monzonite rocks, scheelite is occasionally associated with rutile, which is usually zoned based on Nb-content (Fig. 8.41). As mentioned above, Type 4 veins in metasedimentary rocks which contain abundant molybdenite at the vein walls/selvedges are occasionally rich in scheelite, which may also grow near vein walls and can be intergrown with biotite
Table 8.18. Average compositions of scheelite samples in Type 3 veins from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>In veins, in silicified QFP 'brain rock'</th>
<th>Vein wall, in silicified QFP 'brain rock'</th>
<th>In fractures, in silicified QFP 'brain rock'</th>
<th>Silicified QFP</th>
<th>In vein core, in QFP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>average</td>
<td>st dev</td>
<td>average</td>
<td>st dev</td>
</tr>
<tr>
<td>WO$_3$ (wt.%)</td>
<td></td>
<td>78.31</td>
<td>2.27</td>
<td>75.50</td>
<td>7.67</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td></td>
<td>0.37</td>
<td>0.29</td>
<td>0.40</td>
<td>0.23</td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td></td>
<td>0.17</td>
<td>0.10</td>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td></td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>FeO</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.16</td>
<td>0.36</td>
</tr>
<tr>
<td>MnO</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>MgO</td>
<td></td>
<td>0.03</td>
<td>0.02</td>
<td>0.12</td>
<td>0.22</td>
</tr>
<tr>
<td>CaO</td>
<td></td>
<td>19.39</td>
<td>0.66</td>
<td>19.20</td>
<td>0.92</td>
</tr>
<tr>
<td>PbO</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>98.36</td>
<td>2.70</td>
<td>95.68</td>
<td>8.03</td>
</tr>
</tbody>
</table>

| W$^{6+}$ (apfu)        |     | 0.985   | 0.011  | 0.971   | 0.029  | 0.979   | 0.009  | 0.981   | 0.013  | 0.984   | 0.013  |
| Mo$^{6+}$              |     | 0.008   | 0.006  | 0.008   | 0.005  | 0.016   | 0.009  | 0.015   | 0.014  | 0.010   | 0.013  |
| Nb$^{5+}$              |     | 0.004   | 0.002  | 0.005   | 0.002  | 0.006   | 0.002  | 0.006   | 0.002  | 0.003   | 0.001  |
| Ta$^{5+}$              |     | 0.000   | 0.000  | 0.001   | 0.001  | 0.000   | 0.000  | 0.000   | 0.001  | 0.001   | 0.001  |
| Fe$^{2+}$              |     | 0.001   | 0.001  | 0.008   | 0.020  | 0.004   | 0.007  | 0.000   | 0.000  | 0.000   | 0.001  |
| Mn$^{2+}$              |     | 0.001   | 0.001  | 0.001   | 0.001  | 0.001   | 0.001  | 0.001   | 0.001  | 0.001   | 0.001  |
| Mg$^{2+}$              |     | 0.002   | 0.001  | 0.011   | 0.022  | 0.003   | 0.001  | 0.003   | 0.001  | 0.003   | 0.001  |
| Ca$^{2+}$              |     | 1.008   | 0.015  | 1.027   | 0.043  | 0.994   | 0.005  | 0.992   | 0.009  | 1.002   | 0.009  |
| Pb$^{2+}$              |     | 0.000   | 0.001  | 0.000   | 0.000  | 0.000   | 0.000  | 0.000   | 0.000  | 0.000   | 0.000  |

Note: The following standards were used: diopside- Mg$_3$Al$_2$Si$_3$O$_{12}$ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO$_3$ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMoα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions ptu.
Table 8.18. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>At vein wall, in QFP</th>
<th>In fractures, in felsite</th>
<th>CS</th>
<th>Hornfels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>st dev</td>
<td>average</td>
<td>st dev</td>
</tr>
<tr>
<td>WO$_3$ (wt.%)</td>
<td>79.67</td>
<td>0.35</td>
<td>78.63</td>
<td>0.65</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td>0.13</td>
<td>0.07</td>
<td>0.36</td>
<td>0.23</td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td>0.17</td>
<td>0.10</td>
<td>0.24</td>
<td>0.12</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>0.05</td>
<td>0.06</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>FeO</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>0.04</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
<td>19.35</td>
<td>0.27</td>
<td>19.72</td>
<td>0.21</td>
</tr>
<tr>
<td>PbO</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>99.51</td>
<td>0.20</td>
<td>99.05</td>
<td>0.41</td>
</tr>
</tbody>
</table>

| W$_{6+}^{+}$ (apfu)   | 0.993   | 0.005  | 0.981   | 0.008  | 0.960   | 0.017  | 0.941   | 0.009  |
| Mo$_{6+}$             | 0.003   | 0.001  | 0.007   | 0.005  | 0.034   | 0.017  | 0.053   | 0.009  |
| Nb$_{5+}$             | 0.004   | 0.002  | 0.005   | 0.003  | 0.002   | 0.001  | 0.001   | 0.001  |
| Ta$_{5+}$             | 0.001   | 0.001  | 0.000   | 0.001  | 0.000   | 0.000  | 0.000   | 0.000  |
| Fe$_{2+}$             | 0.002   | 0.002  | 0.001   | 0.001  | 0.000   | 0.001  | 0.001   | 0.001  |
| Mn$_{2+}$             | 0.001   | 0.000  | 0.000   | 0.001  | 0.000   | 0.001  | 0.000   | 0.000  |
| Mg$_{2+}$             | 0.003   | 0.001  | 0.002   | 0.001  | 0.001   | 0.000  | 0.001   | 0.000  |
| Ca$_{2+}$             | 0.997   | 0.014  | 1.017   | 0.009  | 1.010   | 0.008  | 1.010   | 0.004  |
| Pb$_{2+}$             | 0.000   | 0.000  | 0.000   | 0.000  | 0.000   | 0.000  | 0.000   | 0.000  |

Note: The following standards were used: diopside- Mg$_3$Al$_2$Si$_3$O$_{12}$ (MgK$_α$), scheelite (CaK$_α$, WM$_α$), fayalite (FeK$_α$), MnSiO$_3$ (MnK$_α$), Nb (NbL$_α$), Mo (MoM$_α$), galena (PbM$_α$), and Ta (TaL$_α$). Compositions were recalculated on basis of 4 anions pfu.
or amphibole, and associated fluorite and apatite (see Fig. 8.75; Fig. 8.28, and Fig. 8.32). Type 4 vein scheelite is occasionally zoned based on compositional variation of Nb, Ta, and Mo (see Zoned Scheelite, below).

Type 4 vein scheelite can contain subhedral-euhedral quartz and beryl inclusions up to 3 mm, as well as apatite inclusions up to 2.7 mm wide, especially in thick Type 4 veins in altered hornfels or diorite which contain abundant beryl. Occasionally, microscopic garnet, pyrite, rutile, biotite, pyrrhotite, and calcite inclusions are also found in Type 4 scheelite (see fig. 8.82 below).

Molybdenite is the mineral most occasionally seen associated with scheelite, both in Type 4 veins and elsewhere in the deposit (see Fig. 8.27). Molybdenite does not occasionally accompany scheelite in earlier veins; this is likely due to the fact that Mo is incorporated into the scheelite structure at this point in time, giving rise to molybdo-scheelite, rather than the scheelite + molybdenite assemblage. Certain geological conditions, such as $f_O^2$, govern whether we see molybdo-scheelite versus scheelite + molybdenite in a deposit setting; this issue is discussed below (Hsu 1977; Darling 1994). In the King Island deposit in Tasmania, earlier Mo-rich scheelite ‘armoured’ in garnet was ‘dissolved, redistributed, and redeposited as Mo-poor scheelite and molybdenite (Kwak & Tan 1981); a similar process may have happened at Northern Dancer, and would explain the compositional trends observed.

Fluorite is also occasionally seen nearby or alongside scheelite, in Type 4 veins and many environments; it is possible that F may act as a complexing ion in the transport of W, or at least facilitate the transport and/or depositional mechanisms of scheelite. Where scheelite occurs alongside epidote, as in Fig. 8.15, fluorite is also present and the F-content of the epidote is high, suggesting high F activity. A high F activity in the fluid may explain why a ‘retrograde’ mineral such as epidote (or amphibole/chlorite) can occur alongside an anhydrous, typically higher-T ore mineral such as scheelite (or beryl): high F activity can facilitate the precipitation of ‘hydrous’ minerals, which may appear to be retrograde but actually precipitate at much higher temperatures (Meinert et al. 2005; Dick & Hodgson 1982). This phenomenon has been noted in some tin-tungsten (-fluorine) skarn systems (e.g., Lost River, Alaska; Dobson, 1982). Stable isotope studies could determine if there was a magmatic component to any ‘retrograde’ minerals such as epidote, amphibole, chlorite or hydrogarnet, at Northern Dancer (Meinert et al. 1999; Meinert 2000).
A total of 371 EPMA analyses representing 17 different vein/host environments in 19
different polished sections were collected, and results are shown in Table 8.19. General cation
trends and Mo content trends are discussed below.

8.2.17.7 Groundmass environments

Approximately 5-10% of scheelite occurs in the groundmass or matrix of the hosting
intrusive or metasedimentary rocks, at Northern Dancer. Scheelite can occur in the groundmass
of a range of host rocks, but the two main environments are calc-silicate rocks and siliceous
quartz-feldspar porphyry, including ‘brain rock’. In calc-silicate, it occasionally occurs as fine,
anhedral grains disseminated amongst pyroxene, garnet, and quartz (see Fig. 8.74, Fig. 8.64),
especially in areas which appear to have been silicically altered. Various types of calc-silicate
groundmass contain scheelite, such as garnet-rich, pyroxene-rich, sulphide-rich, and siliceous
versions, as well as original, largely unaltered, calc-silicate.

The second major environment is within felsic intrusive host rocks. Type 4 veins
occasionally appear to grade into ‘brain rock’ layers or very siliceous zones of porphyry dikes; in
these locations, muscovite is intergrown with potassium feldspar, molybdenite and rutile, either
in layers or at what appear to be vein walls or edges of quartz flooding. These muscovite-
feldspar “clots” and layers are the second common environment for scheelite to occur in
groundmass, although occasionally, scheelite may occur along ‘brain rock’ layers without the
aforementioned accessory minerals (see Fig. 8.36).

Hornfels, fine-grained light-green skarn and wollastonite vesuvianite skarn also contain
scheelite, although in these cases it is less common. Occasionally, scheelite is found
disseminated in altered monzonite or altered diorite (usually a dike in the latter case), although
scheelite can be abundant in veins which crosscut the main diorite body. In the former case,
scheelite is associated with rare zoned, Nb-rich rutile, and appears altered. EPMA analyses from
scheelite in this environment register low totals (indicating possible alteration), are very low in
Mo, and are extremely rich in Nb and Fe. It is possible this may be a transitional phase between
scheelite and another Ti-rich mineral.

Scheelite may also occur in wide alteration haloes around veins, and thus may appear to
be part of the groundmass. As such, scheelite which has been classified as ‘groundmass’ in this
study was carefully chosen to avoid this, although it is still possible that some grains may be
<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>At vein wall, in silicified QFP</th>
<th>QFP</th>
<th>Zoned, in silicified QFP</th>
<th>Assc. w/ moly, in QFP 'brain rock'</th>
<th>Altered diorite</th>
<th>Transitional Type 4 vein (~QFP), in CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>31</td>
<td>19</td>
<td>20</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>WO$_3$ (wt.%)</td>
<td>80.24</td>
<td>0.56</td>
<td>78.89</td>
<td>1.45</td>
<td>79.82</td>
<td>0.51</td>
</tr>
<tr>
<td>MoO$_3$</td>
<td>0.27</td>
<td>0.25</td>
<td>0.57</td>
<td>1.04</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Nb$_2$O$_5$</td>
<td>0.24</td>
<td>0.12</td>
<td>0.21</td>
<td>0.07</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>Ta$_2$O$_5$</td>
<td>0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>FeO</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>19.48</td>
<td>0.27</td>
<td>19.44</td>
<td>0.26</td>
<td>19.15</td>
<td>0.44</td>
</tr>
<tr>
<td>PbO</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>100.34</td>
<td>0.43</td>
<td>99.24</td>
<td>0.63</td>
<td>99.29</td>
<td>0.77</td>
</tr>
<tr>
<td>W$_6^+$ (apfu)</td>
<td>0.991</td>
<td>0.007</td>
<td>0.982</td>
<td>0.022</td>
<td>0.998</td>
<td>0.006</td>
</tr>
<tr>
<td>Mo$_5^+$</td>
<td>0.005</td>
<td>0.005</td>
<td>0.011</td>
<td>0.020</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Nb$_5^+$</td>
<td>0.005</td>
<td>0.003</td>
<td>0.005</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Ta$_5^+$</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Fe$_2^+$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Mn$_2^+$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Mg$_2^+$</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>Ca$_2^+$</td>
<td>0.994</td>
<td>0.011</td>
<td>1.001</td>
<td>0.010</td>
<td>0.990</td>
<td>0.016</td>
</tr>
<tr>
<td>Pb$_2^+$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside (Mg$_3$Al$_2$Si$_3$O$_12$ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO$_3$ (MnKα), Nb (NbKα), Mo (MoKα), galena (PbKα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Table 8.19. (cont.)

<table>
<thead>
<tr>
<th>Vein/host</th>
<th>In altered hornfels</th>
<th>Crosscut by felsic dikes</th>
<th>In vein core, in Gar-rich CS</th>
<th>Intersects Type 2 vein, in Gar-rich CS</th>
<th>In all halo at vein wall, in Gar-rich CS</th>
<th>In vein core, in Gar-rich CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>20</td>
<td>51</td>
<td>14</td>
</tr>
<tr>
<td>WO₃ (wt.%)</td>
<td>79.04 ± 0.18</td>
<td>79.52 ± 0.67</td>
<td>77.99 ± 1.08</td>
<td>78.81 ± 0.89</td>
<td>79.19 ± 0.77</td>
<td>79.45 ± 0.77</td>
</tr>
<tr>
<td>MoO₃</td>
<td>0.30 ± 0.05</td>
<td>0.07 ± 0.03</td>
<td>0.16 ± 0.09</td>
<td>0.18 ± 0.08</td>
<td>0.11 ± 0.06</td>
<td>0.11 ± 0.05</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.11 ± 0.03</td>
<td>0.14 ± 0.05</td>
<td>0.12 ± 0.09</td>
<td>0.10 ± 0.04</td>
<td>0.05 ± 0.02</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>0.03 ± 0.02</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.03</td>
<td>0.02 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>FeO</td>
<td>0.02 ± 0.02</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.03</td>
<td>0.02 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>0.05 ± 0.01</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.04</td>
<td>0.02 ± 0.03</td>
<td>0.02 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
<tr>
<td>CaO</td>
<td>0.97 ± 0.01</td>
<td>0.00 ± 0.02</td>
<td>0.00 ± 0.02</td>
<td>0.00 ± 0.01</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>PbO</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Total</td>
<td>98.30 ± 0.34</td>
<td>99.04 ± 0.51</td>
<td>99.00 ± 0.94</td>
<td>98.89 ± 0.51</td>
<td>99.67 ± 0.27</td>
<td>99.29 ± 0.84</td>
</tr>
</tbody>
</table>

W₆⁺ (apfu) 0.998 ± 0.005 0.962 ± 0.004 0.962 ± 0.004 0.962 ± 0.004 0.962 ± 0.004
Mo₆⁺ 0.001 ± 0.001 0.002 ± 0.002 0.002 ± 0.002 0.002 ± 0.002 0.002 ± 0.002
Nb⁵⁺ 0.001 ± 0.001 0.001 ± 0.001 0.001 ± 0.001 0.001 ± 0.001 0.001 ± 0.001
Ta⁵⁺ 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000
Fe²⁺ 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000
Mn²⁺ 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000
Ca²⁺ 0.976 ± 0.005 1.005 ± 0.009 1.005 ± 0.009 1.005 ± 0.009 1.005 ± 0.009
Pb²⁺ 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000 0.000 ± 0.000
Note: The following standards were used: diopside (Mg₃Al₂Si₃O₁₂, MgKα), scheelite (CaWO₄, WMa), fayalite (Fe₂SiO₄, FeMα), Nb (NbLo), Mo (MoKα), galena (PbMα, PbC), and Ta (TaLo). Compositions were recalculated on basis of 4 anions apfu.
Table 8.19. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>At vein wall, in CS</th>
<th>In vein core, in hornfels</th>
<th>At vein wall, in hornfels</th>
<th>At vein wall, in light green skarn</th>
<th>Wollastinite-vesuvianite skarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
<td>average stdev</td>
</tr>
<tr>
<td><strong>WO₃ (wt.%)</strong></td>
<td></td>
<td>38 7 63 11 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>78.07</td>
<td>2.07</td>
<td>78.51</td>
<td>0.65</td>
<td>78.60</td>
</tr>
<tr>
<td>MnO</td>
<td>1.49</td>
<td>1.86</td>
<td>0.36</td>
<td>0.07</td>
<td>0.38</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.11</td>
<td>0.09</td>
<td>0.18</td>
<td>0.07</td>
<td>0.13</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>FeO</td>
<td>0.10</td>
<td>0.12</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>0.02</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>19.33</td>
<td>0.36</td>
<td>18.96</td>
<td>0.27</td>
<td>19.44</td>
</tr>
<tr>
<td>PbO</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>99.17</td>
<td>0.76</td>
<td>98.16</td>
<td>0.89</td>
<td>98.69</td>
</tr>
<tr>
<td><strong>W⁶⁺ (apfu)</strong></td>
<td></td>
<td>0.969</td>
<td>0.035</td>
<td>0.991</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Mo⁶⁺</strong></td>
<td></td>
<td>0.029</td>
<td>0.036</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Nb⁵⁺</strong></td>
<td></td>
<td>0.002</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Ta⁵⁺</strong></td>
<td></td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Fe²⁺</strong></td>
<td></td>
<td>0.004</td>
<td>0.005</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Mn²⁺</strong></td>
<td></td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Mg²⁺</strong></td>
<td></td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Ca²⁺</strong></td>
<td></td>
<td>0.992</td>
<td>0.016</td>
<td>0.989</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Pb²⁺</strong></td>
<td></td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside- Mg₃Al₂Si₃O₁₂ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO₃ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
associated with a nearby vein which was not visible in the sample. Scheelite which could be associated with certain vein alteration haloes was grouped with the vein type, and not into the 'groundmass' category.

A total of 178 EPMA analyses representing 13 different vein/host environments in 18 different polished sections were collected, and results are shown in Table 8.20. General cation trends and Mo content trends are discussed below.

8.2.17.8 Zoned scheelite

Zoned grains comprise less than 10% of those analyzed, and most occur in calc-silicate host rocks where Type 1 veins were reopened by Type 4 veins or where Type 1 grains were proximal to, or were intersected by, large Type 4 veins. The cores of scheelite grains in Type 1 veins, which were reopened by Type 4 veins, show cyclic (oscillatory) zoning, with an overall trend toward the more pure scheelite end-member. For example, in polished section QSM-6 (Fig. 8.80; Fig. 8.81 and EMPA analyses in Table 8.21), WO₃ content increases from 70.25 wt.% in the core to 78.62 wt.% in the rim, while CaO shows a slight decrease from 20.44 wt.% to 19.17 wt.% Most prominent is the change in molybdenum content; MoO₃ drops from 8.36 wt.% in the core to 0.58 wt.% at the rim. A similar pattern is seen in the King Island (Dolphin) Mine (Kwak & Tan 1981).

In backscatter mode on the SEM, this zoning is apparent: cores are darker overall, with minor cycling as fine as 10 μm, while rims are very bright. This kind of sharp, narrow, frequent zoning is also seen in garnet and allanite at Northern Dancer, where it likely represents open-system growth conditions involving a changing fluid composition. Here, it may also represent other changing geological conditions which affect the Mo-content of scheelite, such as $\text{fO}_2$, the availability of Mo in the fluid, or temperature (see below).

Some resorption is inferred to have occurred between the Type 1 and Type 4 phases, due to the inhomogeneous boundary between the older Type 1 core and the Type 4 rim. It is possible that intermediate vein sets may have contributed to the zonation, based on the changing orientations of the grain morphology apparent in the zone layers. Zoned scheelite also exists in earlier veins reopened by Type 2 and 3 veins.

In addition, Nb and Ta contents can vary from core to rim, as seen in one large scheelite grain (9.4 mm across) in polished section QSM-12 (see Fig. 8.82). Eleven analyses traversing
Table 8.20. Average compositions of scheelite samples in groundmass from the Northern Dancer deposit.

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>altered monzonite</th>
<th>Silicified QFP</th>
<th>Altered diorite dike</th>
<th>Gar-rich CS</th>
<th>CS w/ dissem. sulphide</th>
<th>Gar. + sulph.-rich CS</th>
<th>Pyx-rich CS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( n )</td>
<td>average</td>
<td>stddev</td>
<td>average</td>
<td>stddev</td>
<td>average</td>
<td>stddev</td>
</tr>
<tr>
<td>( WO_3 ) (wt.%)</td>
<td>6</td>
<td>78.19</td>
<td>2.89</td>
<td>79.43</td>
<td>0.69</td>
<td>78.35</td>
<td>1.61</td>
</tr>
<tr>
<td>( MoO_3 )</td>
<td>17</td>
<td>0.00</td>
<td>0.00</td>
<td>0.40</td>
<td>0.24</td>
<td>0.73</td>
<td>1.07</td>
</tr>
<tr>
<td>( Nb_2O_5 )</td>
<td>6</td>
<td>1.37</td>
<td>2.32</td>
<td>2.62</td>
<td>0.14</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>( Ta_2O_5 )</td>
<td>6</td>
<td>0.08</td>
<td>0.12</td>
<td>0.04</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>( FeO )</td>
<td>8</td>
<td>0.70</td>
<td>0.99</td>
<td>0.01</td>
<td>0.01</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>( MnO )</td>
<td>25</td>
<td>0.37</td>
<td>0.73</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>( MgO )</td>
<td>24</td>
<td>0.01</td>
<td>0.00</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>( CaO )</td>
<td>18.34</td>
<td>1.23</td>
<td>19.43</td>
<td>0.27</td>
<td>19.72</td>
<td>0.12</td>
<td>19.72</td>
</tr>
<tr>
<td>( PbO )</td>
<td>0.05</td>
<td>0.09</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>99.11</td>
<td>0.53</td>
<td>99.66</td>
<td>0.54</td>
<td>99.00</td>
<td>0.63</td>
</tr>
</tbody>
</table>

\[ W^6+ \text{(apfu)} \] = 0.977, \( \text{Mo}^6+ \) = 0.000, \( \text{Nb}^5+ \) = 0.030, \( \text{Ta}^5+ \) = 0.001, \( \text{Fe}^{2+} \) = 0.028, \( \text{Mn}^{2+} \) = 0.015, \( \text{Mg}^{2+} \) = 0.001, \( \text{Ca}^{2+} \) = 0.948, \( \text{Pb}^{2+} \) = 0.001.

Note: The following standards were used: diopside- \( \text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12} \) (MgK\( \alpha \)), scheelite (CaK\( \alpha \), WM\( \alpha \)), fayalite (FeK\( \alpha \)), MnSiO\( 3 \) (MnK\( \alpha \)), Nb (NbL\( \alpha \)), Mo (MoM\( \alpha \)), galena (PbM\( \alpha \)), and Ta (TaL\( \alpha \)). Compositions were recalculated on basis of 4 anions \( \text{pfu} \).
Table 8.20. (cont.)

<table>
<thead>
<tr>
<th>Vein/host environment</th>
<th>CS</th>
<th>Hornfels</th>
<th>Altered hornfels</th>
<th>Light green skarn</th>
<th>Near Type 2 vein, in light green skarn</th>
<th>Wollastinite-vesuvianite skarn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<td>stddev</td>
<td>average</td>
<td>stddev</td>
<td>average</td>
<td>stddev</td>
</tr>
<tr>
<td>WO₃ (wt.%)</td>
<td>77.02</td>
<td>3.57</td>
<td>78.52</td>
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<td>78.32</td>
<td>1.63</td>
</tr>
<tr>
<td>MoO₃</td>
<td>2.34</td>
<td>3.81</td>
<td>1.11</td>
<td>1.53</td>
<td>0.88</td>
<td>1.20</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.11</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.07</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>FeO</td>
<td>0.16</td>
<td>0.12</td>
<td>0.18</td>
<td>0.24</td>
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</tr>
<tr>
<td>MnO</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>MgO</td>
<td>0.03</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>CaO</td>
<td>19.71</td>
<td>0.40</td>
<td>19.88</td>
<td>0.19</td>
<td>18.95</td>
<td>0.52</td>
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<tr>
<td>PbO</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>99.45</td>
<td>0.62</td>
<td>99.82</td>
<td>0.86</td>
<td>98.40</td>
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</tr>
<tr>
<td>W⁺⁺⁺⁺⁺(apfu)</td>
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<td>0.067</td>
<td>0.969</td>
<td>0.030</td>
<td>0.984</td>
<td>0.027</td>
</tr>
<tr>
<td>Mo⁺⁺⁺⁺⁺⁺</td>
<td>0.044</td>
<td>0.071</td>
<td>0.022</td>
<td>0.030</td>
<td>0.018</td>
<td>0.024</td>
</tr>
<tr>
<td>Nb⁺⁺⁺⁺⁺⁺</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Ta⁺⁺⁺⁺⁺⁺</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
</tr>
<tr>
<td>Fe⁺⁺⁺⁺⁺⁺⁺⁺⁺</td>
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<td>0.005</td>
<td>0.007</td>
<td>0.010</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Mn⁺⁺⁺⁺⁺⁺</td>
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<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
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</tr>
<tr>
<td>Mg⁺⁺⁺⁺⁺⁺⁺⁺</td>
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<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Ca⁺⁺⁺⁺⁺⁺⁺⁺</td>
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<td>0.010</td>
<td>1.014</td>
<td>0.009</td>
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</tr>
<tr>
<td>Pb⁺⁺⁺⁺⁺⁺⁺⁺</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: The following standards were used: diopside- Mg₃Al₂Si₃O₁₂ (MgKα), scheelite (CaKα, WMb), fayalite (FeKα), MnSiO₃ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.
Fig. 8.80. Backscatter SEM image of a zoned, altered scheelite grain in a wide Type 4 vein, which likely reopened an earlier Type 1 vein, within calc-silicate, from polished section QSM-6. Cyclic (oscillatory) zoning, with an overall trend toward the more pure scheelite end-member, is visible. Nine EPMA analyses (corresponding to points 34-42) traversing from core to rim are plotted in fig. 8.81 and results are listed in Table 8.21.

Table 8.21. EPMA analyses from zoned scheelite (QSM-6). Note: The following standards were used: diopside- $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), $\text{MnSiO}_3$ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.

<table>
<thead>
<tr>
<th>EPMA point</th>
<th>Q6-34</th>
<th>Q6-35</th>
<th>Q6-36</th>
<th>Q6-37</th>
<th>Q6-38</th>
<th>Q6-39</th>
<th>Q6-40</th>
<th>Q6-41</th>
<th>Q6-42</th>
</tr>
</thead>
<tbody>
<tr>
<td>core/rim</td>
<td>dark c</td>
<td>light m</td>
<td>grey m</td>
<td>dark m</td>
<td>lt. m</td>
<td>light r</td>
<td>light r</td>
<td>light r</td>
<td>lt band</td>
</tr>
<tr>
<td>$\text{WO}_3$ (wt.%)</td>
<td>71.63</td>
<td>70.25</td>
<td>73.70</td>
<td>70.71</td>
<td>71.81</td>
<td>78.62</td>
<td>78.26</td>
<td>76.43</td>
<td>77.71</td>
</tr>
<tr>
<td>$\text{MoO}_3$</td>
<td>7.55</td>
<td>8.36</td>
<td>4.62</td>
<td>8.14</td>
<td>6.46</td>
<td>0.58</td>
<td>0.92</td>
<td>2.91</td>
<td>1.15</td>
</tr>
<tr>
<td>$\text{Nb}_2\text{O}_5$</td>
<td>0.07</td>
<td>0.05</td>
<td>0.12</td>
<td>0.03</td>
<td>0.00</td>
<td>0.04</td>
<td>0.07</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{Ta}_2\text{O}_5$</td>
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<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.18</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{CaO}$</td>
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<td>20.11</td>
<td>19.50</td>
<td>20.44</td>
<td>20.09</td>
<td>19.33</td>
<td>19.22</td>
<td>19.61</td>
<td>19.17</td>
</tr>
<tr>
<td>$\text{FeO}$</td>
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<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$\text{MgO}$</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{MnO}$</td>
<td>0.06</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$\text{PbO}$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.06</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>99.60</td>
<td>98.82</td>
<td>98.08</td>
<td>99.35</td>
<td>98.46</td>
<td>98.85</td>
<td>98.53</td>
<td>99.06</td>
<td>98.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EPMA point</th>
<th>Q6-34</th>
<th>Q6-35</th>
<th>Q6-36</th>
<th>Q6-37</th>
<th>Q6-38</th>
<th>Q6-39</th>
<th>Q6-40</th>
<th>Q6-41</th>
<th>Q6-42</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{W}^{6+}$ (apfu)</td>
<td>0.853</td>
<td>0.840</td>
<td>0.907</td>
<td>0.841</td>
<td>0.871</td>
<td>0.984</td>
<td>0.981</td>
<td>0.941</td>
<td>0.977</td>
</tr>
<tr>
<td>$\text{Mo}^{6+}$</td>
<td>0.145</td>
<td>0.161</td>
<td>0.092</td>
<td>0.156</td>
<td>0.126</td>
<td>0.012</td>
<td>0.019</td>
<td>0.058</td>
<td>0.023</td>
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<tr>
<td>$\text{Nb}^{5+}$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>$\text{Ta}^{4+}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$\text{Ca}^{2+}$</td>
<td>0.999</td>
<td>0.994</td>
<td>0.992</td>
<td>1.005</td>
<td>1.007</td>
<td>1.000</td>
<td>0.996</td>
<td>0.999</td>
<td>0.997</td>
</tr>
<tr>
<td>$\text{Fe}^{2+}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.004</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$\text{Mg}^{2+}$</td>
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<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
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</tr>
<tr>
<td>$\text{Mn}^{2+}$</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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</tr>
<tr>
<td>$\text{Pb}^{2+}$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Fig. 8.81. Plot of cation content in zoned scheelite, from nine EPMA analyses traversing from core to rim, which are shown in fig. 8.80— and results (corresponding points 34–42) are listed in Table 8.21. WO₃ content increases from 70.25 wt.% in the core to 78.62 wt.% the rim, while CaO shows a slight decrease from 20.44 wt.% to 19.17 wt.% Most prominent is the change in molybdenum content: MoO₃ drops from 8.36 wt.% in the core to 0.58 wt.% at the rim.
Fig. 8.82. Image of a large (9.4 mm across), zoned, euhedral scheelite grain in a wide Type 4 vein in altered hornfels, from polished section QSM-12, in plane-polarized light. Eleven EPMA analyses (corresponding to points 19-30) traversing from rim to rim are plotted in Fig. 8.83 (below) and the results are listed in Table 8.22.

Fig. 8.83. Eleven EPMA analyses traversing from rim to rim are shown in fig. 8.82 (above) and results (corresponding red points 19-30) are listed in Table 8.22. MoO₃, Nb₂O₅ and Ta₂O₅ show oscillatory zoning with Mo and Ta peaking at the rim (0.46 wt.% MoO₃ or 0.01 Mo apfu and 0.21 wt.% Nb₂O₅ or 0.005 Nb apfu, respectively) and in the core (0.49 wt.% MoO₃ or 0.01 Mo apfu and 0.23 wt.% Nb₂O₅ or 0.005 Nb apfu, respectively), and Ta showing relatively opposite trends (peaking in mid-grain zones) at 0.12 wt.% Ta₂O₅ or 0.002 Ta apfu. Fe, Mg and Pb show little or no significant change from core to rim in zoned grains.
Table 8.22. EPMA analyses from zoned scheelite (QSM-12).

<table>
<thead>
<tr>
<th>EPMA point</th>
<th>Q12-19</th>
<th>Q12-20</th>
<th>Q12-21</th>
<th>Q12-22</th>
<th>Q12-23</th>
<th>Q12-24</th>
<th>Q12-25</th>
<th>Q12-26</th>
<th>Q12-27</th>
<th>Q12-28</th>
<th>Q12-29</th>
<th>Q12-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>core/rim</td>
<td>r</td>
<td>r</td>
<td>m</td>
<td>m</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>m</td>
<td>m</td>
<td>r</td>
<td>r</td>
</tr>
<tr>
<td>WO₃ (wt.%)</td>
<td>78.69</td>
<td>78.56</td>
<td>79.44</td>
<td>78.95</td>
<td>78.55</td>
<td>79.15</td>
<td>80.28</td>
<td>79.10</td>
<td>79.53</td>
<td>78.92</td>
<td>80.22</td>
<td>79.01</td>
</tr>
<tr>
<td>MoO₃</td>
<td>0.39</td>
<td>0.47</td>
<td>0.25</td>
<td>0.35</td>
<td>0.39</td>
<td>0.44</td>
<td>0.49</td>
<td>0.37</td>
<td>0.22</td>
<td>0.46</td>
<td>0.31</td>
<td>0.39</td>
</tr>
<tr>
<td>Nb₂O₅</td>
<td>0.26</td>
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<td>0.15</td>
<td>0.09</td>
<td>0.13</td>
<td>0.11</td>
<td>0.23</td>
<td>0.11</td>
<td>0.10</td>
<td>0.15</td>
<td>0.21</td>
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<tr>
<td>Ta₂O₅</td>
<td>0.19</td>
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<td>0.09</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>FeO</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>MgO</td>
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<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
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<td>0.05</td>
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</tr>
<tr>
<td>MnO</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
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</tr>
<tr>
<td>PbO</td>
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<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
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<td>0.00</td>
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<td>98.79</td>
<td>98.44</td>
<td>99.30</td>
<td>100.7</td>
<td>99.33</td>
<td>99.29</td>
<td>99.08</td>
<td>100.1</td>
<td>99.09</td>
</tr>
</tbody>
</table>

W₆⁺ (apfu) | 0.982  | 0.984  | 0.993  | 0.989  | 0.988  | 0.986  | 0.987  | 0.985  | 0.994  | 0.985  | 0.993  | 0.986  |
| Mo⁺      | 0.008  | 0.009  | 0.005  | 0.007  | 0.008  | 0.009  | 0.010  | 0.007  | 0.004  | 0.009  | 0.006  | 0.008  |
| Nb⁵⁺     | 0.006  | 0.003  | 0.000  | 0.003  | 0.002  | 0.003  | 0.002  | 0.005  | 0.002  | 0.002  | 0.003  | 0.005  |
| Ta⁵⁺     | 0.002  | 0.000  | 0.001  | 0.000  | 0.001  | 0.000  | 0.002  | 0.000  | 0.003  | 0.000  | 0.000  | 0.000  |
| Ca²⁺     | 1.005  | 1.009  | 0.997  | 0.998  | 1.004  | 1.007  | 0.996  | 1.005  | 0.990  | 1.008  | 0.992  | 1.004  |
| Fe²⁺     | 0.001  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.003  | 0.003  | 0.000  | 0.000  | 0.000  |
| Mg²⁺     | 0.004  | 0.004  | 0.002  | 0.003  | 0.002  | 0.001  | 0.003  | 0.002  | 0.004  | 0.004  | 0.002  | 0.002  |
| Mn²⁺     | 0.001  | 0.000  | 0.002  | 0.001  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  |
| Pb²⁺     | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  | 0.000  |

Note: The following standards were used: diopside- Mg₃Al₂Si₃O₁₂ (MgKα), scheelite (CaKα, WMα), fayalite (FeKα), MnSiO₃ (MnKα), Nb (NbLα), Mo (MoMα), galena (PbMα), and Ta (TaLα). Compositions were recalculated on basis of 4 anions pfu.

from rim to rim are plotted in Fig. 8.83 (EMPA analyses are shown in Table 8.22). MoO₃, Nb₂O₅ and Ta₂O₅ show oscillatory zoning with Mo and Tb peaking at the rim (0.46 wt.% MoO₃ or 0.01 Mo apfu and 0.21 wt.% Nb₂O₅ or 0.005 Nb apfu, respectively) and in the core (0.49 wt.% MoO₃ or 0.01 Mo apfu and 0.23 wt.% Nb₂O₅ or 0.005 Nb apfu, respectively), and Ta showing relatively opposite trends (peaking in mid-grain zones) at 0.12 wt.% Ta₂O₅ or 0.002 Ta apfu.

Fe, Mg, and Pb show little or no significant change from core to rim in zoned grains.

8.2.17.9 Grain size and morphology

The overall average grain size for scheelite in all vein/host environments is 0.57 mm.

This average is based on the physical measurement of 1025 scheelite grains from 43 of the 50 representative mineralogical samples. Table 8.23 represents average grain sizes by vein type.
Table 8.23. Average grain size by vein type.

<table>
<thead>
<tr>
<th>Vein Type / GM</th>
<th>Average grain size (mm)</th>
<th># of grains measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>0.17</td>
<td>200</td>
</tr>
<tr>
<td>Type 2</td>
<td>0.21</td>
<td>134</td>
</tr>
<tr>
<td>Type 3</td>
<td>0.32</td>
<td>139</td>
</tr>
<tr>
<td>Type 4</td>
<td>1.21</td>
<td>374</td>
</tr>
<tr>
<td>Groundmass</td>
<td>0.07</td>
<td>170</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td><strong>0.57</strong></td>
<td><strong>1025</strong></td>
</tr>
</tbody>
</table>

Table 8.24 Average grain size (mm) by vein and host rock type.

<table>
<thead>
<tr>
<th></th>
<th>Monzonite</th>
<th>silicified QFP - brain rock</th>
<th>silicified QFP</th>
<th>felsite</th>
<th>apelite</th>
<th>altered diorite</th>
<th>silicified CS</th>
<th>light green skarn</th>
<th>CS</th>
<th>CS, garnet-rich</th>
<th>CS, gab. sulf-rich</th>
<th>hornfels</th>
<th>wollastonite - vesuvianite skarn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.122</td>
<td>0.081</td>
<td>0.262</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Type 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.058</td>
<td>0.225</td>
<td>0.088</td>
<td>0.747</td>
<td>0.365</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td><strong>Type 3</strong></td>
<td></td>
<td></td>
<td>0.804</td>
<td>0.198</td>
<td>0.476</td>
<td>0.200</td>
<td>0.040</td>
<td></td>
<td></td>
<td>0.357</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Type 4</strong></td>
<td></td>
<td></td>
<td>0.254</td>
<td>0.717</td>
<td>0.558</td>
<td>0.068</td>
<td>0.150</td>
<td>0.965</td>
<td>0.624</td>
<td>3.321</td>
<td>0.076</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Groundmass</strong></td>
<td>0.050</td>
<td></td>
<td>0.106</td>
<td></td>
<td></td>
<td>0.030</td>
<td>0.046</td>
<td>0.087</td>
<td>0.043</td>
<td>0.050</td>
<td>0.082</td>
<td>0.050</td>
<td></td>
</tr>
</tbody>
</table>

Grain size is also dependent on the host lithology, as shown in Table 8.24 and Figures 8.84 through 8.88. Note that blank cells in the tables denote host rock environments where the corresponding vein-type scheelite does not occur; full tables listing minimum, maximum and standard deviation for scheelite grain size are found in Appendix B. Also, note that the y-axes (grain size in mm) change scale in each figure.

Overall, grain size increases temporally (with successive vein type). Calc-silicate host rocks contain the coarsest Type 1 and 2 vein scheelite (avg. 0.26 and 0.75 mm). Silicified quartz-feldspar porphyry with ‘brain rock’ texture contains the coarsest Type 3 vein scheelite (avg. 0.80 mm), while hornfels located near the felsic dike system contains the coarsest Type 4 vein scheelite (avg. 3.32 mm). Groundmass scheelite is much finer-grained, with the coarsest grains located in silicified quartz-feldspar porphyry and calc-silicate host rocks (avg. 0.11 and 0.09 mm, respectively).
Fig. 8.84. Plot of grain size (mm) versus host rock type for scheelite in Type 1 veins. The coarsest scheelite occurs in Type 1 veins within calc-silicate, which average 0.26 mm in diameter.

Fig. 8.85. Plot of grain size (mm) versus host rock type for scheelite in Type 2 veins. The coarsest scheelite occurs in Type 2 veins within calc-silicate, which average 0.75 mm. Altered diorite contains the finest scheelite in Type 2 veins (avg. 0.058 mm).
Type 3 vein scheelite:
Grain size by host rock

Fig. 8.86. Plot of grain size (mm) versus host rock type for scheelite in Type 3 veins. Silicified quartz-feldspar porphyry with 'brain rock' texture contains the coarsest Type 3 vein scheelite, averaging 0.80 mm in diameter. Aplite contains the finest-grained scheelite within Type 3 veins (avg. 0.04 mm).

Type 4 vein scheelite -
Grain size by host rock

Fig. 8.87. Plot of grain size (mm) versus host rock type for scheelite in Type 4 veins. Hornfels host rocks located near the felsic dike system contains the coarsest Type 4 vein scheelite (avg. 3.32 mm). Altered diorite dikes contain the finest scheelite in Type 4 veins (avg. 0.068 mm).
Fig. 8.88. Plot of grain size (mm) versus host rock type for scheelite in groundmass. Groundmass scheelite is much finer-grained than vein scheelite, with the coarsest grains located in silicified quartz-feldspar porphyry and calc-silicate host rocks (avg. 0.11 and 0.09 mm, respectively). Once again, altered diorite contains the finest scheelite in groundmass (avg. 0.03 mm).

8.2.17.10 Scheelite chemical trends through vein/host type: molybdenum content

Electron microprobe compositions of scheelite (see Table 8.15 and Fig. 8.78 for general environment average EPMA compositions of scheelite) show deposit-wide average Mo concentrations of 1.90 wt% MoO₃ (0.038 Mo apfu), and a maximum of 22.49 wt% MoO₃ (0.40 Mo apfu). Individual vein/host environment EPMA analyses are grouped by general environment: Type 1 through 4 veins and groundmass, and are shown above in corresponding Tables 8.16 – 8.20, as mentioned in their individual sections.

Type 1 veins average 4.85 wt.% MoO₃ or 0.09 Mo apfu (the deposit maximum mentioned above is found in Type 1 vein scheelite), Type 2 veins average 1.13 wt.% MoO₃ or 0.02 Mo apfu (max. 7.03 wt.% MoO₃ or 0.14 Mo apfu), and Type 3 veins average 0.73 wt.% MoO₃ or 0.02 Mo apfu (max. 4.95 wt.% MoO₃ or 0.10 Mo apfu). Type 4 veins average 0.92 wt.% MoO₃ or 0.02 Mo apfu (max. 11.83 wt.% MoO₃ or 0.22 Mo apfu), while groundmass
scheelite averages 1.27 wt.% MoO₃ or 0.03 Mo apfu (max. 11.19 wt.% MoO₃ or 0.21 Mo apfu). The average Mo content in scheelite is plotted with other substituting cations in Fig. 8.89.

Molybdenum content in scheelite varies by vein/host environment. Mo content (Mo⁶⁺, apfu) in scheelite in five general environments, including Type 1-4 veins and groundmass, are plotted by individual host rock environments in Figs 8.90 – 8.94. Type 1 veins have the highest MoO₃ wt.% in scheelite (molybdoscheelite) in the deposit, reaching a maximum, as mentioned above, of 22.49 wt.% MoO₃ (or 0.40 Mo apfu), and also display the widest range of values (see Table 8.16 and Fig. 8.90). In spite of this, vein/host environment averages all lie fairly close to the mean, and only Type 1 veins in hornfels deviate to any significant degree. Light green skarn and wollastonite vesuvianite skarn appear to contain the lowest Mo-content in scheelite relative to other host rock environments (averaging 3.09 and 3.17 wt.% MoO₃, or 0.061 and 0.062 Mo apfu, respectively), while Type 1 veins in hornfels and garnet-rich calc-silicate average the highest, at 11.89 and 5.21 wt.% MoO₃ (or 0.217 and 0.101 Mo apfu), respectively.

Type 2 veins show a marked decrease in the Mo content of the scheelite compared to Type 1 veins, and also display a lower range of values (see Table 8.17 and Fig. 8.91). Possibly, fluid-rock interaction is less intense for this vein generation, based on decreased permeability caused by the earlier emplacement of Type 1 veins. It may also be due to other factors, such as decreased fO₂, which are discussed below. Light green skarn contains the same approximate average of Mo content, but is now the highest amongst the Type 2 veins, averaging 2.93 wt.% MoO₃ (or 0.058 Mo apfu). Where Type 2 veins intersect Type 2 veins in light green skarn, the Mo content is even higher than isolated Type 2 veins, at 3.01 wt.% MoO₃ (or 0.059 Mo apfu). Siliceous zones of calc-silicate and hornfels host more pure scheelite in Type 2 veins (0.13 wt.% MoO₃ and 0.003 Mo apfu); again, possibly due to a lower degree of permeability and fluid-rock interaction within silicic host rocks.

Type 3 veins show two trends; felsic intrusive host phases are lower grade but host purer scheelite (for example, quartz-feldspar porphyry averages 0.52 wt.% MoO₃ or 0.01 Mo apfu), whereas calc-silicate and hornfels host rocks are the most impure and average well above the mean, at 1.71 wt.% MoO₃ or 0.03 Mo apfu and 2.71 wt.% MoO₃ or 0.05 Mo apfu, respectively (see Table 8.18 and Fig. 8.92). It is important to note that scheelite is lower grade in Type 3 veins in general, and Type 3 veins which extend outboard of the felsic dike complex are the rarest Type 3 vein style. Type 3 veins within silicic felsic phases are slightly higher in Mo than less silicic phases.
Average cation contents in scheelite by general vein/host type

Fig. 8.89. Average Mo content in scheelite (MoO₃ wt.%) is plotted with other substituting cations, including Mn, Fe, Mg, and Nb. The other cations remain fairly low compared to Mo, which dramatically drops after the Type 1 vein generation, and is lowest in Type 3 veins. Other cations are plotted on a smaller scale without Mo in Fig. 8.97, where their trends are easier to observe.

Perhaps, since silicic phases are those which appear closer to the magmatic-hydrothermal transition and occur at the periphery of the dike complex, it is possible that some mixing of fluids near contact zones with metasedimentary rocks could remobilize earlier, Mo-rich scheelite back into the new fluid. Occasionally, scheelite is found in ‘traps’ of muscovite, potassium feldspar and molybdenite, in layers of ‘brain rock’. ‘Brain rock’, or ‘UST’s’ (unidirectional solidification textures) form based on saturation and depletion of elements along a reaction front which progresses perpendicularly to the layers (Candela 1997). If the local crystallization front was forming in mixed magmatic-hydrothermal fluids which had remobilized scheelite from the nearby country rocks, it is reasonable that relatively Mo-rich scheelite could reform along these layers as the front moved forward, giving rise to the textures seen at Northern Dancer. Textures of the metasedimentary rocks near ‘brain rock’ and silicic porphyry are very convoluted and variable, and appear themselves silicified and altered.
Fig. 8.90. Plot of Mo content (Mo\(^{6+}\) apfu) in Type 1 vein scheelite (via EPMA analysis) versus vein/host environment. Type 1 veins have the highest MoO\(_3\) wt.% in scheelite (molybdoscheelite) in the deposit, and also display the widest range of values (see Table 8.16). Light green skarn and wollastonite vesuvianite skarn appear to contain the lowest Mo-content in Type 1 vein scheelite relative to other host rock environments (averaging 3.09 and 3.17 wt.% MoO\(_3\), or 0.061 and 0.062 Mo apfu, respectively), while Type 1 veins in hornfels and garnet-rich calc-silicate average the highest, at 11.89 and 5.21 wt.% MoO\(_3\), (or 0.217 and 0.101 Mo apfu), respectively.
Mo (apfu) content in scheelite in Type 2 veins

![Graph showing Mo content in scheelite in Type 2 veins](image)

Fig. 8.91. Plot of Mo content (Mo$^{6+}$ apfu) in Type 2 vein scheelite (via EPMA analysis) versus vein/host environment. Type 2 veins show a marked decrease in the Mo content of scheelite from Type 1 veins, and also display a lower range of values (see Table 8.17). Light green skarn contains the highest average of Mo content in the Type 2 veins, averaging 2.93 wt.% MoO$_3$ (or 0.058 Mo apfu). Where Type 2 veins intersect Type 2 veins in light green skarn, the Mo content is even higher than isolated Type 2 veins, at 3.01 wt.% MoO$_3$ (or 0.059 Mo apfu). Siliceous zones of calc-silicate and hornfels host more pure scheelite in Type 2 veins (0.13 wt.% MoO$_3$ and 0.003 Mo apfu).
Fig. 8.92. Plot of Mo content (Mo\textsuperscript{6+} apfu) in Type 3 vein scheelite (via EPMA analysis) versus vein/host environment. Type 3 veins show two trends; felsic intrusive host phases are lower grade but host purer scheelite (for example, quartz-feldspar porphyry averages 0.52 wt.% MoO\textsubscript{3} or 0.01 Mo apfu), whereas calc-silicate and hornfels host rocks are the most impure and average well above the mean, at 1.71 wt.% MoO\textsubscript{3} or 0.03 Mo apfu and 2.71 wt.% MoO\textsubscript{3} or 0.05 Mo apfu, respectively (see Table 8.18).
Mo (apfu) content in scheelite in Type 4 veins

Fig. 8.93. Plot of Mo content (Mo⁶⁺ apfu) in Type 4 vein scheelite (via EPMA analysis) versus vein/host environment. Type 4 veins have the largest range of any vein set, and therefore occur in the widest range of host environments (see Table 8.19). The same bimodal distribution is seen in Type 4 vein scheelite as in Type 3 veins: felsic intrusive hosts are low Mo (for example, quartz-feldspar porphyry averages 0.57 wt.% MoO₃ or 0.01 Mo apfu), while metasedimentary hosts are high Mo (Garnet-rich calc-silicate averages 1.61 wt.% MoO₃ or 0.03 Mo apfu). Scheelite in the cores of thick Type 4 veins in calc-silicate are lower in Mo-content (0.70 wt.% MoO₃ or 0.02 Mo apfu) than those near vein walls (1.49 wt.% MoO₃ or 0.03 Mo apfu).
Mo content in scheelite in groundmass

Fig. 8.94. Plot of Mo content (Mo\(^{6+}\) apfu) in groundmass scheelite (via EPMA analysis) versus vein/host environment. Groundmass environments also host scheelite with a large range of Mo contents (see Table 8.20). Original, less-altered calc-silicate (pyroxene-rich) and hornfels are low in Mo-content (0.88 wt% MoO\(_3\) or 0.02 Mo apfu, and 1.11 wt% MoO\(_3\) or 0.02 Mo apfu, respectively). Felsic intrusive matrix-hosted scheelite Mo-content is also very low (e.g., silicic quartz-feldspar porphyry averages 0.40 wt% MoO\(_3\) or 0.01 Mo apfu), and is actually below detection limits in scheelite within altered monzonite. The scheelite in the altered monzonite is also very high in Nb (avg. 1.37 wt.% Nb\(_2\)O\(_5\) or 0.03 Nb apfu, max. 6.45 wt.% Nb\(_2\)O\(_5\) or 0.14 Nb apfu), and occurs intergrown with Nb-rich zoned rutile. Low EPMA analysis totals from scheelite in zones of intense quartz ‘flooding’ suggest it has been altered. Higher average Mo-content occurs in altered diorite-hosted scheelite (avg. 0.73 wt.% MoO\(_3\) or 0.02 Mo apfu) than felsic intrusive (as mentioned above). Wollastonite-vesuvianite skarn hosts scheelite which is high in Mo-content (1.25 wt.% MoO\(_3\) or 0.03 Mo apfu).
Type 4 veins have the largest range of any vein set, and therefore occur in the widest range of host environments (see Table 8.19 and Fig. 8.93). The same bimodal distribution is seen in Type 4 vein scheelite as in Type 3 veins: felsic intrusive hosts are low in Mo (for example, quartz-feldspar porphyry averages 0.57 wt.% MoO$_3$ or 0.01 Mo apfu), while metasedimentary hosts are high in Mo (Garnet-rich calc-silicate averages 1.61 wt.% MoO$_3$ or 0.03 Mo apfu). Again, the higher grade outside the felsic dike complex is likely due to remobilization of earlier, more Mo-rich scheelite back into the vein fluid (see below for discussion of this topic). Scheelite in the cores of thick Type 4 veins in calc-silicate are lower in Mo-content (0.70 wt.% MoO$_3$ or 0.02 Mo apfu) than those near vein walls (1.49 wt.% MoO$_3$ or 0.03 Mo apfu), suggesting that at least in calc-silicate host environments, wall-rock interaction has some effect on scheelite composition.

Groundmass environments also host scheelite with a large range of Mo contents (see Table 8.20 and Fig. 8.94). While in general it has relatively high average Mo content within groundmass, scheelite in these settings is still lower in Mo-content than Type 1 vein scheelite (averaging 1.27 wt.% MoO$_3$ or 0.03 Mo apfu), likely due to the influence of some or all four previous overprinting vein sets (some of which are more pure than others and would thus affect the average). Original, less-altered calc-silicate (pyroxene-rich) and hornfels are lower in Mo-content (0.88 wt.% MoO$_3$ or 0.02 Mo apfu, and 1.11 wt.% MoO$_3$ or 0.02 Mo apfu, respectively), possibly because they occur in distal regions of the deposit and are only affected by farther-reaching veins (such as Type 4 veins) which coincidentally precipitate lower Mo-content scheelite. Felsic intrusive matrix-hosted scheelite Mo-content is very low (e.g., silicic quartz-feldspar porphyry averages 0.40 wt.% MoO$_3$ or 0.01 Mo apfu), and is actually below detection limits in scheelite within altered monzonite. The scheelite in the altered monzonite is also very high in Nb (avg. 1.37 wt.% Nb$_2$O$_5$ or 0.03 Nb apfu, max. 6.45 wt.% Nb$_2$O$_5$ or 0.14 Nb apfu), and occurs intergrown with Nb-rich zoned rutile. Low EPMA analysis totals from scheelite in zones of intense quartz ‘flooding’ suggest it has been altered. Higher average Mo-content occurs in altered diorite-hosted scheelite (avg. 0.73 wt.% MoO$_3$ or 0.02 Mo apfu) than felsic intrusive (as mentioned above), likely because fluids which manage to reach the diorite have already passed through metasedimentary rocks and many earlier veins, and remobilized scheelite with higher Mo-content. Wollastonite-vesuvianite skarn hosts scheelite which is high in Mo-content (1.25 wt.% MoO$_3$ or 0.03 Mo apfu). Possibly, as Type 2 and 3 veins do not reach this far out of the core of the deposit, only earlier Type 1 veins have a major influence.
Based on the overall deposit averages and the individual environment averages investigated above, some general system-wide trends are apparent (see Fig. 8.89). Mo content in scheelite begins fairly high in Type 1 veins, after which it decreases sharply in Type 2 veins, and molybdenite makes its first (if rare) appearance. Groundmass scheelite is approximately as pure as Type 2 vein scheelite. Type 3 vein scheelite is the most pure in the deposit, although it is lower grade than scheelite from the other general environments. Scheelite from Type 4 veins is only slightly less pure than Type 3 scheelite (and of much higher grade), likely due to the possible remobilization of earlier, less pure scheelite into the newer veins by Type 4 vein-associated fluids. Therefore, the overall ore mineral assemblage in the Northern Dancer system evolves temporally, from molybdischeelite to scheelite + molybdenite. While the Mo content of the scheelite varies based on vein/host environment (spatial and temporal characteristics), it is not necessarily varying directly as a result of these characteristics. However, vein/host environment may indicate varying geological conditions, such as $f_2O_2$, temperature, fluid composition, pressure, $f_{S_2}$, or other less intuitive factors. One of these factors, or a combination of them, is likely the driving force behind the Mo content of the scheelite. Indications of which of these factors are more important than others will take more investigation, although evidence from other parts of this study suggest that changing fluid composition, and possibly $f_2O_2$, are correlated with ore mineral trends (for example, iron ratios in pyroxene in pyroxene and beryl suggest possible temporally variable redox conditions).

While Type 1 and 2 veins display fairly homogenous ranges of Mo content in scheelite, the later Type 3 and 4 vein sets show a prominent bimodal distribution. In these two cases, felsic hosts of scheelite have low Mo contents, while metasedimentary hosts have high Mo contents. As Type 1 and 2 veins do not occur in felsic intrusive host rocks, we cannot discern a similar bimodal distribution of Mo-content in their scheelite. Several factors (such as those mentioned above) may influence the pattern seen in Type 3 and 4 veins; these factors are likely either directly or indirectly associated with the local environment in which the scheelite is forming. The evolution of the vein fluid chemistry and character may be a dominant influence on the factors affecting Mo content in scheelite. Similarly, the host rock composition and character (permeability, oxidation state, etc.) may be a major influence. However, since late
fluids precipitating Type 4 vein scheelite still produce relatively pure scheelite within felsic host rocks, and only precipitate Mo-rich scheelite outside intrusive hosts, it is not intuitive that the fluid character itself is evolving to a large extent, but rather that the local environment of the host rock (and relative chemical gradient influencing fluid-rock interaction) is more important.

These two possible influences (fluid and host rock character) on local geochemical environment are not necessarily mutually exclusive, and both may play a part in determining the local conditions affecting scheelite composition. In this case, the relative chemical (or T/J02 etc.) gradient may be much higher outside the felsic intrusive hosts than within them, where a vein fluid may have equilibrated before being released (possibly by fluctuating fluid pressure), which would lead to more fluid-host rock interaction. This could lead to the remobilization of earlier, Mo-rich scheelite back into the fluid. Hydrothermal remobilization of scheelite can occur at fairly low temperatures in many different hydrothermal environments (Meinert et al. 2005). Equilibration of a magmatic-hydrothermal fluid in the felsic dike complex is not unlikely based on the evidence that the felsic dikes themselves are transitional between magmatic and hydrothermal origins, evidenced by 'brain rock' textures and the transitional nature (textural and mineralogical) of some Type 4 veins.

8.2.17.12 Factors affecting W-Mo ore assemblages

Studies have been conducted on the role of fO2 and fS2 in the stability of powellite, molybdenite and scheelite (Hsu, 1977; Darling, 1994). The experiments described in Hsu (1977, see Fig. 8.95) were conducted at a fixed pressure of 1 kb and temperature of 577 °C, which is probably slightly higher than the temperature of ore mineral deposition at Northern Dancer, inferred to be between 275 and 400 °C (based on preliminary primary fluid inclusion data from beryl and scheelite). Hsu found that the occurrence of powellite phases requires higher fO2 at a given, occasionally low fS2, and that for the most common geological conditions (including 'hypogene' environments), scheelite + molybdenite are stable, coexisting, and occupy a large stability field. To apply these curves, Hsu used sulphide and oxide mineral assemblages, such as pyrite + hematite + magnetite; however, the nature of the overprinting vein sets make it difficult to discern sulphide mineral assemblage data at Northern Dancer in a conclusive manner, especially considering there is almost no tungstenite, hematite or magnetite present in the veins.
Darling (1994; see Fig. 8.96) utilized data from Hsu (1977) in his study of the Cannivan Gulch molybdenum deposit in Montana, U.S.A., where reaction curves were recalculated for CaMoO₄ and CaCO₃ + MoS₂, at 300 °C and 1.5 kb (based on thermodynamic equations 14 and 25 from Helgeson et al., 1978). The purpose of the study was to determine why powellite was not present in the deposit, despite abundant carbonate host rocks and relatively high fO₂ conditions. Darling raises the point that “fluid composition variables are likely to change when a Mo-bearing fluid passes from a host rock of granitic composition to one that is dominated by carbonate minerals.” The study found that even small amounts of CO₂ (X_CO₂ = 0.05) in an ore fluid can greatly extend the stability of molybdenite to higher oxygen fugacities. Therefore,
Fig. 8.96. Log $f_{O_2}$ - Log $f_{S_2}$ plot calculated at 300 °C and 1.5 kb showing instability of powellite with pyrite-magnetite at even low values of $fC_{O_2}$, adapted from Darling (1994). Stability fields for pyrite, pyrrhotite, magnetite and hematite are shown, and were used to estimate volatile fugacities in Darling (1994). This figure shows that as $fC_{O_2}$ increases, the molybdenite stability field increases while powellite stability field decreases in size. PPM = pyrite-pyrrhotite-magnetite-buffer, PMH = pyrite-magnetite-hematite buffer.

CO$_2$ present in the mineralizing fluid may influence which ore assemblage forms (molybdscheelite vs. molybdenite + scheelite) at Northern Dancer.

However, while the local geology and vein mineral assemblages are very similar to Northern Dancer, no scheelite is present at Cannivan Gulch, and therefore W phases were not considered in the calculation of the reaction curves. Thus, empirical conclusions on the influence of $f_{O_2}$, $f_{S_2}$, and CO$_2$ are not realistic until more experimental work is conducted on the stability curves of powellite, scheelite, and molybdenite. While the reaction curves calculated in Hsu (1977) and Darling (1994) may not be applicable at different P and T, it is reasonable that general trends would be upheld, such as the relationship between higher $f_{O_2}$ conditions and powellite formation, versus lower $f_{O_2}$ conditions and the presence of CO$_2$ in the ore fluid for a scheelite + molybdenite ore assemblage.

Therefore, while it is likely that more than one influence drives the Mo-W assemblage in each local environment, the reaction curves in Hsu (1977) show that a decrease in $f_{O_2}$ (or similarly, an increase in $f_{S_2}$) can cause molybdscheelite to split into a dual mineral assemblage of scheelite + molybdenite. Temporally decreasing and locally variable $f_{O_2}$ conditions within vein sets are indicated by other minerals (such as pyroxene and beryl) in the Northern Dancer system. Fluid inclusions would also help indicate the role (if any) CO$_2$ plays in scheelite.
formation, and it is important to note that in preliminary fluid inclusion studies initiated during the course of this study, CO₂-rich fluid inclusions were observed in beryl, scheelite and quartz in Type 3 and 4 veins.

In conclusion, the fact that the scheelite within the felsic intrusive is very pure and occasionally occurs with molybdenite indicates it is possible that the fluid in this setting has a lower \( f_O^2 \) (and/or higher \( f_S^2 \)) than outside the felsic hosts. Whether the \( f_O^2 \) of the fluid is based on an internally evolving fluid character (magmatic-hydrothermal influence), or based on fluid mixing with hydrothermal/meteoric/dehydration fluids existing outboard of the dike complex, is unclear. Stable isotope and fluid inclusion investigation would likely help reveal some information on these topics. Mineral chemistry (i.e., iron oxidation state) of other vein and host rock minerals at Northern Dancer may also be useful in estimating local redox conditions; for example, \( Fe^{3+}/Fe^{2+} \) ratios in pyroxene (see section 8.2.15: pyroxene).

8.2.17.13 Other cation substitution

The average Mn, Fe, Mg, and Nb contents in scheelite are relatively constant in comparison to Mo substitution, over the five general environments (see Fig. 8.89, as mentioned above). When examined on a more detailed scale in Fig. 8.97, some trends are apparent. The Mn content in scheelite remains fairly constant, even over this narrow scale range. The maximum Mn content in scheelite occurs in grains within altered monzonite, where it reaches 1.99 wt.% MnO (or 0.08 Mn \textit{apfu}); it is important to note that the most Mn-rich (spessartine-rich) garnet also occurs in felsic intrusive host rocks (see Garnet section).

The Mg content of the scheelite also remains fairly constant, but peaks slightly in Type 3 veins, where it averages 0.03 wt.% MgO (or 0.002 Mg \textit{apfu}). A maximum content of 0.34 wt.% MgO or 0.03 Mg \textit{apfu} is reached in this environment.

The Fe content of the scheelite peaks in Type 2 veins at 0.17 avg. wt.% FeO or 0.01 Fe \textit{apfu}, and is also elevated in the groundmass, where it averages the same: 0.17 wt.% FeO or 0.01 Fe \textit{apfu}. This suggests that iron-rich calc-silicate host rocks (and possibly pyrite-rich vein settings) may influence the Fe substitution in scheelite. A maximum Fe content in scheelite of 3.64 wt.% FeO or 0.17 Fe \textit{apfu} was found in a Type 2 vein setting.
Fig. 8.97. Average Mn, Fe, Mg, and Nb contents in scheelite are plotted by wt.%. Mn content in scheelite remains fairly constant, even over this narrow scale range; a maximum Mn content in scheelite occurs in altered monzonite. Mg content in scheelite also remains fairly constant, but peaks slightly in Type 3 veins. Fe content in scheelite peaks in Type 2 veins, and is also elevated in the groundmass. Nb content in scheelite peaks in the Type 3 veins. Maximum Nb content in scheelite is found in the groundmass of altered monzonite where it occurs near Nb-rich rutile. Tantalum and Pb were also sought, but occur in insignificant amounts and do not display any systematic trends based on vein/host environment.

The Nb content of the scheelite peaks in the Type 3 veins where it averages 0.19 wt.% Nb$_2$O$_5$ or 0.004 Nb apfu; perhaps the fluid precipitating the scheelite has a magmatic influence and/or is mixing with fluids that have scavenged Nb from surrounding sedimentary host rocks containing Nb. Maximum Nb$_2$O$_5$ content of the scheelite is found in the groundmass of altered monzonite where it occurs near Nb-rich rutile. Here, it reaches 6.45 wt.% Nb$_2$O$_5$ or 0.14 Nb apfu. Tantalum and Pb were also sought, but occur in insignificant amounts and do not display any systematic trends based on vein/host environment.
9 Conclusions

9.1 Geochronology

Geochronology data obtained in this study allows for more clarity on the ages of intrusive units in the Northern Dancer area. A previous study published two dates for the monzonite, 109.4 ± 0.9 Ma and 110.5 ± 0.8 Ma, which overlap with earlier K-Ar dating (Mortensen et al. 2007). The monzonite and felsic dike ages essentially overlap indicating they are coeval. Crystallization ages of 187.7 ± 2.6 Ma for the diorite, and 111.7 ± 0.7 Ma for the felsic dike complex, were obtained as part of this study. This diorite age is consistent with regional ages for Early Jurassic intrusions in southern and central Yukon, which includes the Simpson Peak and Nome Lake Batholiths just south of the Yukon/BC border, and Lokken Batholith to the Northwest of Northern Dancer (J.K. Mortensen, pers. comm. 2008).

The similar ages of the monzonite and the felsic dike complex make it difficult to determine upper and lower time constraints on individual vein sets relating to these two individual intrusive phases. Therefore, it would be useful to determine specific ore mineral ages for scheelite or molybdenite from each of the vein generations (see section 10: Suggestions for future work). The data suggests that the emplacement of the monzonite and felsic dikes and the emplacement of the four overprinting vein sets likely occurred within the span of approximately 2-4 m.y., between 111.7 ± 0.7 Ma and 109.4 ± 0.9 Ma.

The contemporaneous emplacement of the monzonite, felsic dike complex, and mineralization suggest that ground preparation in the form of calc-silicate alteration of metasedimentary rocks may have been caused by the intrusion of the diorite, rather than the monzonite. This hypothesis would allow sufficient time for the large volume of reaction skarn to form; however, additional calc-silicate alteration associated with the monzonite and felsic dike emplacement would allow for fluid pressure build-up and release in the form of vein stockworks and fracturing (Type 1 and 2 vein sets).

9.2 Whole-rock geochemistry

The monzonite and felsic dike units at the Northern Dancer deposit are geochemically alike (low Fe/Mg/Ca/Ti, high Si/K values, similar minor and trace element trends), and plot very
close to each other on an AFM diagram, near the alkali corner. This supports the hypothesis that the felsic dikes are related to the monzonite, and possibly represent more highly fractionated variations of it. In general, the two flanks of diorite are geochemically similar in major elements but vary amongst minor and trace elements, likely reflecting the fact that mineralization and alteration appear to have only affected the southern diorite flank.

The contact region of the monzonite is the most enriched in Be compared to the other units, suggesting Be congregated near the contact, and possibly, that it was trapped there until the Type 4 vein event. Renders & Anderson (1987) have shown that Be is transported in hydrothermal complexes as hydroxyl-, chloride-, or fluoride- complexes, thus an increasingly higher F activity over time would possibly allow for increased mobility of Be out into the veins. A similar process of transport by fluoride complex may occur for W, which would explain the deposit wide correlation of W/scheelite and F/fluorite/F-rich minerals. Mo content is only elevated in the felsic dikes, which reflects the dominance of the Type 3 quartz-molybdenite in this unit over others. The source of the Mo is not clear, as the felsic dikes and monzonite are inferred to be coeval; however, there is no Mo enrichment in the monzonite. This suggests that if the monzonite was the original source of the Mo, it must have been mobilized out, leaving the intrusive rocks depleted.

Tungsten content is low in the northern (unmineralized) diorite sample, but is elevated in the southern (mineralized) diorite sample. This indicates that W was not likely sourced by the diorite, and therefore, the hypothesis that the majority of scheelite at Northern Dancer could be dominantly remobilized from disseminated W in early reaction skarn associated with the diorite is less likely. Additionally, W content is highest in the felsic dikes, likely indicating that W is sourced by the felsic dikes (and the monzonite, by association), which further discounts the hypothesis that scheelite was remobilized into veins from the metasedimentary rocks. Both fluorine and W contents appear to decrease spatially from the mineralizing source (assuming that the felsic dikes are the source and the rocks closest to the mineralizing source are the calc-silicate, the hornfels, the light green skarn, and the wollastonite vesuvianite skarn, in order of increasing distance). In general, fluorine content correlates with W content in the intrusive rocks and the representative sample set, giving more support to the hypothesis that W may be transported via fluoride complexes.
9.3 Rietveld analysis and mineral zonation trends

Rietveld data confirms historical rock description and classification, as observed by Stewart (1983), Noble (1982), and Noble et al. (1984). The very highest scheelite percentages only occur where low garnet-pyroxene ratios occur, but in the regular range of scheelite values, the garnet-pyroxene ratio does not seem to correlate with mineralization. However, scheelite local maxima tend to correspond with fluorite maxima, suggesting that fluorite abundance may occasionally accompany scheelite abundance, possibly because both minerals favour similar calcic environments, or because W could be transported by fluoride complexes in an F-rich fluid. Molybdenite reaches local maxima in hornfels, garnet + sulphide-rich calc-silicate rocks, and quartz-feldspar porphyry containing Type 3 veins, and appears to follow an opposite correlation to that of fluorite, reaching local maxima where fluorite hits local minima. Fluorite is higher in most metasedimentary units containing Type 3 and 4 veins, and is always relatively lower in the same host rocks with only Type 1 and 2 veins. This suggests that fluorite development increases temporally and possibly that fluids are evolving to a more F-rich character. Diopside also appears to be abundant in similar locations as fluorite (and thus, scheelite); further investigation into this mineral correlation would be useful.

Multiplying modal percentage of scheelite by the average percentage of W in scheelite for each sample gave an average WO\textsubscript{3} wt.% value (tungsten grade), and the resulting plot of this calculated value versus W grade from whole-rock geochemical showed that where samples are high in W content, whole-rock geochemistry values are slightly lower than those calculated via EPMA and Rietveld. This suggests that whole-rock geochemistry may produce low apparent W grades. This effect is not as significant in lower grade deposits such as Northern Dancer, but it may affect assay results for tungsten in higher-grade W deposits.

9.4 Vein development

With continued crystallization of the reaction skarn, sections of the hydrological system may have become 'clogged' by calc-silicate alteration leading to lowered permeability. This would give rise to periodic fluid pressure build-up and release, perhaps via hydrofracturing and subsequent stockwork vein emplacement (Type 1 and 2 vein sets). Type 3 veins may have formed within the felsic dikes in a similar way, as volatiles (such as F) built up within the dike
complex as it cooled, causing pressure buildup and fracturing, followed by veining. Sheeted Type 4 veins likely formed similarly but on a larger scale, and may reflect emplacement along a preferential structural weakness inherent in the rock (e.g., a prominent joint system), based on their planar character. Similar processes are inferred to occur at the King Island (Dolphin) Mine in Tasmania (Kwak & Tan 1981).

High fluorine activity increases volatility and decreases silicate polymerization, therefore lowering viscosity (Meinert et al. 2005). This mechanism may allow the Type 4 veins, which are very high in fluorine, to extend far outside the deposit and the other vein networks (which are lower in fluorine content, as evidenced by the lower F-content in vein minerals and lower abundances of fluorite). The fact that Type 4 veins extend so far outside deposit boundaries indicates that the system is likely below hydrostatic pressure at this point; if the system did access the surface, volatiles would be released and viscosity would be greatly reduced, limiting further extension of the veins. The abundance of fluorite in beryl-wolframite sheeted veins to the southwest of the deposit supports this hypothesis. Late fluids are likely high in F, Si, and P, indicated by the presence of fluorite and apatite needles in zones of silica ‘flooding’ which crosscut brain rock phases and some Type 4 veins.

9.5 Vein minerals and fluorine

The presence of anhedral, altered, subcalcic garnet rimmed by euhedral zones of grandite garnet suggests that instead of simple compositional zoning based on fluctuating fluid chemistry or oxidation state of a single aqueous fluid, these garnets were altered or resorbed first, and subsequently rimmed by a later fluid of a different character (i.e., that original calc-silicate garnet formed in a different environment than the rimming garnet which is likely associated with later, possibly mineralizing, aqueous fluids). Zoning in grandites is usually representative of rapid changes in the chemistry and/or oxidation state of the hydrothermal solution; oscillatory compositional zoning seen in allanite, epidote, and garnet suggests that open-system growth conditions involving changes in fluid character such as those described above occurred at Northern Dancer.

Fluorine content of garnet is influenced by vein/host environment and timing, rather than by garnet end-member composition. Thus, garnet at Northern Dancer likely preserves a record of the variations in the F activity of aqueous fluids during metamorphism or hydrothermal
alteration, due to the fact that F is incorporated into the crystal structure much the same as OH⁻ in hydrogrossular, and not simply as submicroscopic inclusions or exsolution-derived grains of other F-bearing minerals such as fluorite. The highest F-content in garnet occurs where mineralization is known to occur. The correlation of the occurrence of higher-grade scheelite mineralization and high F content in grandite garnet at Northern Dancer, on both a local/microscopic and deposit-wide scale, indicates that the F-content of garnet may be a good mineral chemistry exploration indicator for W mineralization of a similar nature. It also lends support to the hypothesis that F may be an assisting volatile to W mineralization, or perhaps even the ion (or one of the ions) responsible for W transport/speciation.

As mentioned previously, high fluorine activity can promote the development of mineral assemblages which mimic ‘retrograde’ metamorphic mineral assemblages (including epidote, amphibole, and chlorite), at higher temperatures (Meinert et al. 2005). This may explain how minerals typically stable at higher temperatures (such as potassium feldspar and pyrrhotite) can occur next to lower temperature ‘retrograde’ minerals (such as epidote and chlorite) without altering. It is also possible that a high fluorine activity in the fluid could promote ‘hydrogrossular-like’ F-rich grandites, in the same way; since ‘retrograde’ conditions occasionally produce hydrogrossular rims on regular grossular (Yoder 1950; Hutton 1943; Pabst 1942). This hypothesis would explain how F-rich ‘hydrogarnet’ occurs alongside epidote, pyroxene, and potassium feldspar in the same local environment without alteration.

9.6 Redox conditions

Skarn type is influenced by prevailing redox conditions during deposit evolution (Meinert et al. 2005). These redox conditions can be inferred from the determination of relative iron ratios in certain skarn minerals (Sato 1980). Specifically, reduced systems show relatively high Fe²⁺/Fe³⁺ where oxidized systems show relatively low Fe²⁺/Fe³⁺. Based on their Fe²⁺/Fe³⁺ ratios, most Northern Dancer skarn minerals indicate variable redox conditions within different vein/host environments. Pyroxene shows relatively reduced conditions in calc-silicate rocks, and more oxidized conditions in diorite and hornfels environments.

Pyroxene associated with Type 4 veins, however, are intermediate between these two extremes, and beryl contains more ferric (Fe³⁺) iron in later veins than earlier phases, suggesting that within Type 4 veins, redox conditions are evolving toward more oxidized conditions. This
could be due to the mixing of magmatic, hydrothermal, and/or meteoric fluids, or it may reflect an increase in the buffering capability of the fluid, leading to a lower degree of fluid-rock interaction, especially in more reduced calc-silicate environments. The changing redox conditions may also reflect evolving $fO_2$, which can influence the ore assemblage to form in a given formation, e.g., molybdo scheelite versus molybdenite and scheelite (see below). Isotope and fluid inclusion data would provide useful information on this topic (see section 10: Suggestions for future work). The variable redox conditions at Northern Dancer contrast those of major tungsten skarn deposits in the area, such as Cantung, which is a dominantly reduced system (Meinert et al. 2005).

9.7 Scheelite deposition mechanisms

The basic mechanism for scheelite deposition in vein-hosted tungsten deposits is usually attributed to the vein providing an avenue for W dissolved in a fluid to encounter Ca-rich host rocks, at which point W comes out of solution and is precipitated as scheelite. In some tungsten deposits, scheelite can be remobilized from skarn-type disseminated mineralization into hydrothermal fluids following fracture networks or veins (retrograde solubility conditions, similar to quartz at lower temperature; Meinert et al. 2005), and thus, does not necessarily require a previously W-enriched fluid.

Remobilization of scheelite from earlier veins may explain its presence in locations which are not necessarily high Ca activity. One example is the silicic magmatic-hydrothermal transition zones of the quartz-feldspar porphyry ‘brain rock’ into Type 4 veins, where layers of scheelite, fluorite, blue beryl, molybdenite, pyrite, rutile, and muscovite occur between ‘brain rock’ layers. This may possibly reflect a ‘mixing zone’ where siliceous fluids of mixed magmatic-hydrothermal character strip adjacent calc-silicate wallrock of the scheelite within its crosscutting Type 1, 2 and/or 3 veins and remobilize it back into the system. These fluids can then form layers containing the minerals described above, via saturation and depletion of mineralizing elements (such as Fe, Mo, Be, Ti, Ca, and W) at the unidirectional reaction front. However, it is likely that additional tungsten was being added to the system as it evolved and not solely sourced from remobilized scheelite from earlier Type 1 and 2 veins; this is evidenced by the presence of coarse scheelite in Type 3 and 4 veins within the felsic dike complex. In this magmatic-hydrothermal system it may also be important that there is a continuum between
metasomatic and metamorphic processes, as sometimes the mineralizing fluid may be cooler than the host rock causing increased variation on a local scale, including small-scale metasomatic transfer.

9.8 Conditions affecting scheelite mineral chemistry

As mentioned previously, 95% of mineralization at Northern Dancer occurs within veins; the ore assemblage consists of molybdo-scheelite, scheelite, or molybdnite + scheelite. This ore mineral assemblage and molybdenite content in scheelite at Northern Dancer changes with vein type, and thus, evolves temporally. The dominant cation substituting into the scheelite is Mo; other minor cations include Mn, Mg, Fe, Ta. However, all of these occur in insignificant concentration relative to Mo. Mo content in scheelite begins fairly high in Type 1 veins, after which it decreases sharply in Type 2 veins, and molybdenite makes its first (if rare) appearance. Groundmass scheelite is approximately as pure as Type 2 vein scheelite. Type 3 vein scheelite is the most pure in the deposit, although it is lower grade than scheelite from the other general environments. Scheelite from Type 4 veins is only slightly less pure than Type 3 scheelite (and of much higher grade), likely due to the possible remobilization of earlier, less pure scheelite into the newer veins by Type 4 vein-associated fluids.

Thus, the Mo content of the scheelite varies based on vein/host environment (spatial and temporal characteristics), although it is not necessarily varying directly as a result of these characteristics. Vein/host environment may indicate varying geological conditions, however, such as $fO_2$, temperature, fluid composition (e.g., Mo-content), redox conditions, pressure, $fS_2$, or other less intuitive factors. One of these factors, or a combination of them, is likely the driving force behind the Mo content of the scheelite. The relative chemical (or $T/fO_2$ etc.) gradient is likely higher outside the felsic intrusive hosts than within them, where a vein fluid may have equilibrated before being released (possibly by fluctuating fluid pressure), which would lead to increased fluid-host rock interaction (isotope studies could help determine the degree of fluid buffering or mixing occurring in these environments; see section 10: Suggestions for future work).

Studies have been conducted on the role of $fO_2$ and $fS_2$ in the stability of powellite, molybdenite and scheelite which essentially concluded that the occurrence of powellite phases requires higher $fO_2$ at a given, occasionally low $fS_2$, and that for the most common geological
conditions scheelite + molybdenite are stable, coexisting, and occupy a large stability field (Hsu 1977; Darling, 1994). These studies also found that even small amounts of CO₂ in an ore fluid can greatly extend the stability of molybdenite to higher oxygen fugacities, thus, CO₂ present in the mineralizing fluid may influence which ore assemblage forms (molybdscheelite vs. molybdenite + scheelite) at Northern Dancer. It is important to note that these studies were not necessarily conducted at similar pressures and temperatures of mineralization at Northern Dancer (as that information is unknown at present).

Therefore, while it is likely that more than one influence drives the Mo-W assemblage in each local environment at Northern Dancer, these studies show that a decrease in fO₂ (or similarly, an increase in fS₂) can cause molybdscheelite to split into a dual mineral assemblage of scheelite + molybdenite. Temporally decreasing and locally variable fO₂ conditions within vein sets are indicated by other minerals (such as pyroxene and beryl). Fluid inclusions would also help indicate the role (if any) CO₂ plays in scheelite formation, and would provide temperature and fluid composition data (see section 10: Suggestions for future work).

In conclusion, the fact that the scheelite within the felsic intrusive is very pure and occasionally occurs with molybdenite indicates it is possible that the fluid in this setting has a lower fO₂ (and/or higher fS₂) than outside the felsic hosts. Whether the fO₂ of the fluid is based on an internally evolving fluid character (magmatic-hydrothermal influence), or based on fluid mixing with hydrothermal/meteoric/dehydration fluids existing outboard of the dike complex, is unclear at present. Stable isotope and fluid inclusion investigation would likely help reveal some information on these topics (see section 10: Suggestions for future work).
10 Suggestions for Future Work

10.1 Geochronology

As the exact geological context of the Re-Os age of ~108 Ma obtained by Drs. Craig Hart and David Selby is unknown at present, additional Re-Os dating of molybdenite, specifically from individual vein sets, would be useful to distinguish different mineralization events. However, molybdenite does not occur within all vein sets, therefore, as scheelite occurs in all mineralized veins, it would be the ideal ore mineral to date. Sm-Nd, Rb-Sr, and Pb-Pb methods have been used to date scheelite by Eichhorn et al. (1997) and Kempe et al. (2001), although these methods were not used for dating of mineralization of events as temporally close together as at Northern Dancer. Dating of scheelite from a Type 4 vein would at least provide a lower age constraint for mineralization at Northern Dancer. Thus, future work should focus on obtaining individual mineral ages from scheelite and/or molybdenite.

10.2 Rietveld analysis

The 52 representative samples did not statistically provide enough information for detailed spatial analysis of mineral trends throughout the Northern Dancer deposit. Systematic sampling of a wide range of deposit positions within similar vein/host environments would allow for more detailed analysis of mineral zonation, if any exists. Specifically, garnet/pyroxene ratios tend to be correlated with mineralization in some mineralized skarns (e.g., low garnet/pyroxene ratios correlate with Au mineralization at the Nickel Plate Mine in the Hedley District, British Columbia; Ettlinger et al. 1992), thus a detailed study of the change in this ratio versus locations of abundant scheelite/high W grade may provide a useful exploration tool for locating mineralization in other similar deposits. Other minerals may also show correlation with mineralization with additional sampling and analysis; additional data could be tied into a 3-D model of drill hole assay data, allowing for three-dimensional analysis of mineral trends.

10.3 Mineralogy
Analysis of scheelite by laser ablation ICP-MS methods could be used to identify variation in trace-element composition. Sylvester and Ghaderi (1997) found that scheelites associated with different lode-gold deposits in Western Australia had varying REE patterns, indicating that hydrothermal fluids which formed the scheelite did not have a common composition and or source. This technique could compliment fluid composition data obtained from fluid inclusion analysis. The geochemical analysis of hydrothermal apatite and scheelite pairs from various vein/host environments could provide insight into REE partitioning between the two minerals, as both minerals concentrate REE (Raimbault 1993). The behavior of Eu in these minerals can be related to redox conditions, thus combining this data with iron ratios in pyroxene would reveal more information about the oxidation state of the mineralizing environments. Determination of REE in coexisting scheelite and apatite is an efficient tool for identification of successive ore-bearing fluids (Raimbault 1993).

Trace element compositions of minerals such as apatite and rutile or titanite in the Northern Dancer deposit could reveal vectors for W-Mo mineralization that are not apparent in whole-rock geochemistry due to the nature of elements such as W and Mo which substitute into these minerals. The nature of this mineral 'vector' could appear in the form of something like an As-W-Mo halo defined by hydrothermal apatite (R. Linnen, pers. comm. 2007). If correlations were found to exist in this deposit and other W-Mo occurrences, heavy mineral stream sediment sampling for these minerals followed by composition analysis could be used to explore for new targets.

The mineral pair hedenbergite-andradite limits the $f_\text{O}_2$ range possible for their joint production under equilibrium conditions (Gustafson 1974; Kalinin 1967b). If temperatures obtained from fluid inclusion data could be determined for these minerals, $f_\text{O}_2$ could be estimated in their local environment, and therefore $f_\text{O}_2$ could be documented at different locations where the two minerals coexist throughout the deposit. This information could reveal any patterns or trends in $f_\text{O}_2$ through the deposit, and possibly help explain the evolution of the ore mineral assemblage shift from molybdochseelitel to scheelite + molybdenite (see section 9: Conclusions).

10.4 Fluid inclusion studies

Preliminary fluid inclusion petrography and microthermometric analysis from four samples indicate that in general, fluid inclusion populations are complex and numerous at
Northern Dancer. However, possible primary liquid-vapour (±carbonic) inclusions were identified in growth zones of garnet, beryl, and quartz, and large, likely primary fluid inclusions were found within scheelite. Thus a detailed study of these inclusions could reveal information such as temperature and composition of fluid in the mineralizing environment (for example, primary fluid inclusions located in different growth zones in vein garnet could reveal evolving fluid composition/temperature). Fluid inclusion analysis could also help determine if any scheelite at Northern Dancer has been dissolved, remobilized by later fluids, and redeposited at lower temperatures, or if any boiling has occurred within the system. Fluid inclusions would also help indicate the role (if any) CO₂ plays in scheelite + molybdenite or molybdoscheelite formation, and it is important to note that in preliminary fluid inclusion studies initiated during the course of this study, CO₂-rich fluid inclusions were observed in beryl, scheelite and quartz in Type 3 and 4 veins. Fluid inclusions could indicate a temperature of formation for ‘retrograde’ minerals such as epidote, amphibole, chlorite or hydrogarnet, which do not appear to represent actual retrograde conditions as they occasionally occur with higher temperature prograde minerals and ore minerals within the vein sets.

10.5 Isotope studies

As the Northern Dancer system appears to be transitional between magmatic and hydrothermal conditions, stable isotope studies of vein ore minerals could be helpful in determining fluid source/character in different environments, as well as help to constrain temperatures of vein formation. For example, an oxygen isotope study of quartz from each vein set, the felsic dikes and quartz-feldspar-porphyry ‘brain rock’, and from ‘silica flooded zones’ would reveal the evolution, if any, in source of fluid and possibly indicate if any fluid mixing with other (meteoric) fluids occurred in different vein/host environments. Cathodoluminescence could be used to confirm quartz generations and association with scheelite and molybdenite. The degree of variation in oxygen isotope values obtained from vein minerals would also indicate if the fluids were buffered during fluid-rock interaction, and thus indicate whether vein mineral formation is more dependent on fluid character alone or if it is affected by wall-rock interaction

Other minerals associated with mineralization, including scheelite, fluorite, beryl, and garnet would also be good candidates for isotopic study to determine fluid source, if quartz could not be associated with mineralization in certain environments. Stable isotope studies may also
help to determine if there was a magmatic fluid component to any ‘retrograde’ minerals such as epidote, amphibole, chlorite or hydrogarnet, which do not appear to represent actual retrograde conditions, as discussed in their individual sections. Obtaining isotope data from garnet (or another typical groundmass mineral component) in skarn unaffected by the vein sets and comparing it to garnet in groundmass affected by veining could reveal if fluids associated with veins (inferred to be coming from the monzonite) are the same or similar to those involved in calc-silicate alteration of early, pre-vein skarn. This would help determine if the monzonite or the diorite was responsible for the majority of the calc-silicate alteration at Northern Dancer.
References


Eckermann, H. von, 1922. The rocks and contact minerals of the Mansjo Mountain. Geologiska Föreningen i Stockholm Forhandlingar, 44, 203-410


Greenwood, R., 1943. Effect of chemical impurities on scheelite fluorescence, Economic Geology, 38-1, 56-64.


Kwak, T.A.P., 1981. Sector-zoned annite<sub>85</sub>phlogopite<sub>15</sub> micas from the Mt. Lindsay Sn-W-F-(Be) deposit, Tasmania, Australia. Canadian Mineralogist, 19, 643-650.


Schumacher, 1999. Subtle oscillatory zoning in garnet from regional metamorphic phyllites and mica schists, western Erzgebirge, Germany. Canadian Mineralogist, 37, 381-402.


Appendix A – Analytical Methods

Geochronology

The methodology used for LA-ICP-MS U-Pb dating at the PCiGR has been described by Mortensen et al. (2006). Minor modifications of the method that was employed in this study include using the Plešovice zircon (Sláma et al. 2007) as the main external zircon standard and a 197 Ma in-house zircon monitor for all analyses and collecting data in mixed analog and ion counting mode, with the strongest isotopic peaks (for $^{238}$U and $^{232}$Th) being counted in analog mode and the other weaker peaks in ion counting mode. These changes have resulted in substantially stronger ion beams and much improved counting statistics, leading to better precision and accuracy for individual analyses. In this study a total of 12-16 line scans were collected for each sample. The time resolved signal from each analysis was carefully examined and portions of the signal that reflect the effects of post-crystallization Pb-loss and/or the presence of older inherited zircon cores were excluded from calculation of the final isotopic ratios. Interpreted crystallization ages are based on a weighted average of the calculated $^{206}$Pb/$^{238}$U ages for 12-15 individual analyses from each sample. Errors for the calculated ages are given at the 2σ level using the method of Ludwig (2003).

Whole-rock geochemistry

Whole-rock analyses were completed by ACME Analytical Laboratories of Vancouver, BC. The samples were first dried at 60 °C and jaw crushed (up to 1 kg) to 70% passing 10 mesh (2 mm); a 250 g riffle split was then pulverized to 95% passing 150 mesh (106 microns) in a mild-steel ring-and-puck mill. Pulp splits of 0.25 g were weighed into Teflon test tubes. Fluorine was determined by fusion and electrochemistry, and Cl by both specific ion electrode and neutron activation analysis (detection levels of 10 ppm). Inorganic C was determined by direct CO₂ evolution and Leco analysis, while Boron was determined by NaOH fusion and induction-coupled plasma methods. Aside from Mo, Nb, Ta, U, and W (methods determining these elements are described below), precious metals and base metals were determined from an aqua regia digestion; all other elements were determined by induction-coupled plasma mass
spectrometry (ICP-MS) with a LiBO$_2$ fusion (H$_2$O$^-$: moisture, 110 °C, H$_2$O$^+$: lattice water, 1500 °C).

Mo, Nb, Ta, U, and W were analyzed by phosphoric acid digestion and induction-coupled plasma mass spectrometry (ICP-MS) methods (via the same procedure utilized by Largo Resource Ltd. for W assays). The specific procedure involves digesting an aliquot of the acid solution (H$_3$PO$_4$-HF-HNO$_3$) on a hot plate for approximately one hour. A 25% HCl is added to redissolve the salts and the solutions are transferred to 100 mL volumetric flasks and made to volume. Solutions are then aspirated into a Jarrel Ash Atomcomp model 800 or 975 or Spectro Ciros Vision ICP atomic-emission spectrometer. QA/QC protocol incorporates a sample-prep blank (SI or G-1) carried through all stages of preparation and analysis as the first sample, a pulp duplicate to monitor analytical precision, a -10 mesh rejects duplicate to monitor sub-sampling variation (drill core only), two reagent blanks to measure background, and aliquots of in-house Standard Reference Materials to monitor accuracy.

**X-ray diffraction methods: Rietveld analysis**

Samples were reduced into fine powder to the optimum grain-size range for X-ray analysis (<10 μm) grinding under ethanol in a vibratory McCrone Micronising Mill for seven minutes. Step-scan X-ray powder-diffraction data were collected over a range 3-80° 2θ with CoK$\alpha$ radiation on a standard Siemens (Bruker) D5000 Bragg-Brentano diffractometer equipped with an Fe monochromator foil, 0.6 mm (0.3°) divergence slit, incident- and diffracted-beam Soller slits and a Vantec-1 strip detector. The long fine-focus Co X-ray tube was operated at 35 kV and 40 mA, using a take-off angle of 6°.

The X-ray diffractograms were analyzed using the International Centre for Diffraction Database PDF-4 using Search-Match software by Siemens (Bruker). X-ray powder-diffraction data were refined with Rietveld program Topas 3 (Bruker AXS). The results of quantitative phase analysis by Rietveld refinement represent the relative amounts of crystalline phases normalized to 100%. An example of a Rietveld refinement plot is shown in Fig. A.
Figure A. Rietveld refinement plot of sample QSM-1 (blue line - observed intensity at each step; red line - calculated pattern; solid grey line below – difference between observed and calculated intensities; vertical bars, positions of all Bragg reflections). Coloured lines are individual diffraction patterns of all phases.
**SEM and EPMA methods**

The Philips XL30 scanning electron microscope (SEM) at the University of British Columbia, which is equipped with an energy-dispersion X-ray spectrometer (EDS), was used for preliminary examination of the electron-microprobe mounts. Electron-probe micro-analyses were obtained with a fully automated CAMECA SX-50 instrument, operating in the wavelength-dispersion mode.

Samples were analyzed with the following operating conditions: excitation voltage, 15 kV; beam current, 10 nA (20 nA for amphiboles, 40 nA for scheelite); peak count time, 20 s (40 s for F and Cl, except for apatite, see below); background count time, 10 s (20 s for F and Cl, except for apatite); and spot diameter, 5 μm (2 μm for scheelite). Data reduction was done using the “PAP” φ(pZ) method (Pouchou & Pichoïr 1991).

For apatite data, F and Cl were collected from an adjacent spot with the following parameters: excitation voltage 10 kV; beam current, 5 nA; peak count time, 60 s; background count time, 30 s; spot diameter, 10 μm. Five analyses for each ‘point’ were collected this way, plotted versus time, and analyzed via linear regression to obtain an F value at theoretical time = zero; this technique maximizes accuracy of F in apatite which has a tendency to migrate out of the apatite crystal when bombarded by an electron beam.
Appendix B – Additional Grain Size Data for Scheelite

Additional grain size (mm) data for vein type grain size summary table:

<table>
<thead>
<tr>
<th>Type</th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>0.174</td>
<td>0.600</td>
<td>0.020</td>
<td>0.1347</td>
</tr>
<tr>
<td>Type 2</td>
<td>0.289</td>
<td>0.020</td>
<td>2.500</td>
<td>0.6109</td>
</tr>
<tr>
<td>Type 3</td>
<td>0.316</td>
<td>0.020</td>
<td>1.200</td>
<td>0.3239</td>
</tr>
<tr>
<td>Type 4</td>
<td>1.206</td>
<td>0.030</td>
<td>9.400</td>
<td>1.9018</td>
</tr>
<tr>
<td>groundmass</td>
<td>0.072</td>
<td>0.030</td>
<td>0.250</td>
<td>0.0451</td>
</tr>
</tbody>
</table>

Additional grain size (mm) data for Type 1-4 vein scheelite:

<table>
<thead>
<tr>
<th>Type 1</th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>silicified CS</td>
<td>0.122</td>
<td>0.200</td>
<td>0.075</td>
<td>0.0380</td>
</tr>
<tr>
<td>light green skarn</td>
<td>0.081</td>
<td>0.100</td>
<td>0.070</td>
<td>0.0141</td>
</tr>
<tr>
<td>CS</td>
<td>0.262</td>
<td>0.600</td>
<td>0.080</td>
<td>0.1390</td>
</tr>
<tr>
<td>hornfels</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.0000</td>
</tr>
<tr>
<td>wollastonite-vesuvianite skarn</td>
<td>0.055</td>
<td>0.080</td>
<td>0.020</td>
<td>0.0309</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type 2</th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>altered diorite</td>
<td>0.058</td>
<td>0.080</td>
<td>0.020</td>
<td>0.0303</td>
</tr>
<tr>
<td>silicified CS</td>
<td>0.225</td>
<td>0.080</td>
<td>0.020</td>
<td>0.0303</td>
</tr>
<tr>
<td>light green skarn</td>
<td>0.088</td>
<td>0.080</td>
<td>0.020</td>
<td>0.0303</td>
</tr>
<tr>
<td>CS</td>
<td>0.747</td>
<td>2.500</td>
<td>0.020</td>
<td>1.1141</td>
</tr>
<tr>
<td>CS, gar-rich</td>
<td>0.365</td>
<td>0.800</td>
<td>0.100</td>
<td>0.2777</td>
</tr>
<tr>
<td>hornfels</td>
<td>0.065</td>
<td>0.080</td>
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<td>0.0198</td>
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</table>

<table>
<thead>
<tr>
<th>Type 3</th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>silicified QFP - brain rock</td>
<td>0.804</td>
<td>1.000</td>
<td>0.020</td>
<td>0.4132</td>
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<tr>
<td>silicified QFP</td>
<td>0.198</td>
<td>0.450</td>
<td>0.040</td>
<td>0.1717</td>
</tr>
<tr>
<td>QFP</td>
<td>0.476</td>
<td>0.850</td>
<td>0.080</td>
<td>0.2968</td>
</tr>
<tr>
<td>felsite</td>
<td>0.200</td>
<td>0.200</td>
<td>0.200</td>
<td>0.0000</td>
</tr>
<tr>
<td>aplite</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td>0.0000</td>
</tr>
<tr>
<td>CS</td>
<td>0.357</td>
<td>0.950</td>
<td>0.140</td>
<td>0.3022</td>
</tr>
<tr>
<td>hornfels</td>
<td>0.204</td>
<td>0.300</td>
<td>0.140</td>
<td>0.0876</td>
</tr>
</tbody>
</table>

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### Type 4

<table>
<thead>
<tr>
<th></th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>silicified QFP - brain rock</td>
<td>0.254</td>
<td>0.800</td>
<td>0.100</td>
<td>0.1330</td>
</tr>
<tr>
<td>silicified QFP</td>
<td>0.717</td>
<td>2.000</td>
<td>0.040</td>
<td>0.8412</td>
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<tr>
<td>QFP</td>
<td>0.558</td>
<td>1.900</td>
<td>0.060</td>
<td>0.6851</td>
</tr>
<tr>
<td>altered diorite</td>
<td>0.068</td>
<td>0.090</td>
<td>0.030</td>
<td>0.0254</td>
</tr>
<tr>
<td>light green skarn</td>
<td>0.150</td>
<td>0.150</td>
<td>0.150</td>
<td>0.0000</td>
</tr>
<tr>
<td>CS</td>
<td>0.965</td>
<td>3.100</td>
<td>0.030</td>
<td>1.0685</td>
</tr>
<tr>
<td>CS, gar-rich</td>
<td>0.624</td>
<td>1.000</td>
<td>0.250</td>
<td>0.2781</td>
</tr>
<tr>
<td>hornfels</td>
<td>3.321</td>
<td>9.400</td>
<td>0.750</td>
<td>3.0451</td>
</tr>
<tr>
<td>wollastonite-vesuvianite skarn</td>
<td>0.076</td>
<td>0.150</td>
<td>0.050</td>
<td>0.0452</td>
</tr>
</tbody>
</table>

Additional grain size (mm) data for groundmass scheelite:

<table>
<thead>
<tr>
<th>Groundmass</th>
<th>avg. (mm)</th>
<th>max.</th>
<th>min.</th>
<th>st. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>monzonite</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.0000</td>
</tr>
<tr>
<td>silicified QFP</td>
<td>0.106</td>
<td>0.250</td>
<td>0.040</td>
<td>0.0820</td>
</tr>
<tr>
<td>altered diorite</td>
<td>0.030</td>
<td>0.030</td>
<td>0.030</td>
<td>0.0000</td>
</tr>
<tr>
<td>light green skarn</td>
<td>0.046</td>
<td>0.050</td>
<td>0.040</td>
<td>0.0051</td>
</tr>
<tr>
<td>CS</td>
<td>0.087</td>
<td>0.200</td>
<td>0.050</td>
<td>0.0403</td>
</tr>
<tr>
<td>CS, gar-rich</td>
<td>0.043</td>
<td>0.050</td>
<td>0.040</td>
<td>0.0052</td>
</tr>
<tr>
<td>CS - gar, sulf-rich</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.0000</td>
</tr>
<tr>
<td>hornfels</td>
<td>0.082</td>
<td>0.150</td>
<td>0.030</td>
<td>0.0442</td>
</tr>
<tr>
<td>wollastonite-vesuvianite skarn</td>
<td>0.050</td>
<td>0.050</td>
<td>0.050</td>
<td>0.0000</td>
</tr>
</tbody>
</table>