The Toolstone Formerly Known as Green Andesite: A Geochemical Characterization of Fine-Grained Lithic Materials from the Burrard Inlet Area, Vancouver, B.C. Canada

by

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis/dissertation entitled:

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Abstract

Archaeologists often attempt to identify rock type in the field and laboratory based on generalized visual characteristics. This approach has a great potential to produce incorrect categorizations that would detrimentally impact sourcing studies. This thesis research explores a green toolstone found in the archaeological assemblages of the Burrard Inlet region and surrounding area of North Vancouver, on the southern coast of British Columbia. Previously, this toolstone was called green andesite based solely on visual identification, and the designation has been reproduced in the literature and a handful of circular citations. The goal of this research was to use several geochemical methods, including wavelength dispersive X-ray fluorescence (WD-XRF) and portable energy dispersive X-ray fluorescence (ED-XRF), to answer the question “Is the toolstone known as green andesite actually andesite?” The secondary goal of this project was to compare the toolstone data to publicly available geologic data from the nearby Indian River watershed to see if any locations could be eliminated as geological origins for the toolstone.

The general conclusions of this research are that, based on major element concentrations, the material known as green andesite is not actually andesitic. However, if this research looked at trace element concentrations alone, green andesite dykes of the Indian River Valley could not be excluded. Taking time to establish rock type with standard geological and geochemical techniques before attempting to eliminate potential source affinities using only trace elements is an important step often overlooked in archaeological sourcing studies. The material formerly known as green andesite has been incorrectly labeled, and archaeological reports, collections, and catalogues have been reproducing this miscategorization. Through this research, I identified a possible rock type for the toolstone known as green andesite and using the provenience hypothesis (Wilson and Pollard 2001) I identified several geological contexts within the Indian River watershed that cannot be excluded as possible places of origin.

Lay Summary

The goal of this research was to use several geological and geochemical methods to determine if the archaeological toolstone found in the Burrard Inlet region that researchers call green andesite is actually andesite. The secondary goal was to determine if this material comes from the green andesite dykes in the Indian River watershed from where the name originated. Based on major, minor and trace element composition, the toolstone is not andesitic, and it does not come from the green andesite dykes as previously assumed. This study highlights the reproduction of an incorrect label throughout scholarly literature and archaeological discourse. It showcases the need to verify rock type using appropriate techniques before undertaking sourcing studies.

Preface

This thesis is original, unpublished and the collaborative effort of multiple parties, led by the author, Karen Rose Thomas. Rhy McMillan was instrumental to the development of the research design and methods, and he contributed greatly to data interpretation and thesis edits.

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Acknowledgements

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This is dedicated to the Ancestors.

For holding me up. For standing behind me. For your resistance and resilience.

To Fox Alder Thomas Stenner and Phaedra Jane Mae Thomas, Tomorrow's Ancestors.

May you grow to understand more than I did. I hope you will feel comfortable in these academic institutions because you belong here too, if it is where you want to be. May you look back on these times and remember that I didn't quit, even when it was hard.

For Eileen, everyone's archaeology auntie. I miss your laughter.

Chapter 1: Introductions: To My Work, To Me, To My Ancestors

In this thesis research, I examine a type of toolstone that features heavily in archaeological assemblages located in the Burrard Inlet area of North Vancouver, British Columbia. More broadly speaking, Burrard Inlet is within the Gulf of Georgia region on the Northwest Coast of Canada (see Figure 1.1). In particular, I explore the nature of this toolstone that is relatively undiscussed in archaeological literature. It was classified as green andesite based on visual characteristics in the early 2000s, and it has also been referred to as Anvil Island andesite (Lepofsky and Karpiak 2001).

Using several geochemical and spectroscopic methods, I characterize the toolstone and compare the concentrations of major, minor, and trace elements to known geological contexts in the neighbouring Indian River watershed. I will use Indian River watershed to broadly describe the Indian Arm, Indian River Valley, and areas of adjacent Stawamus River Valley, as they share a ridge line in common. I selected the archaeological objects included in the study based on visual assessment, given my familiarity with the material known as green andesite. My goal was to determine if the material known as "green andesite" as identified visually is actually andesite. Through the course of this research, I identified a possible rock type for this toolstone and identified several geological contexts within the Indian River watershed that cannot be excluded as possible places of origin within the theoretical framework of the Provenance Hypothesis (Wilson and Pollard, 2001). The Provenance Hypothesis postulates that "provenancing proceeds by systematic elimination of possible sources rather than by positive attribution" (Wilson and Pollard 2001:510). This framework suggests that it is impossible to identify with certainty the exact source of a material, that one can only exclude possible sources. In this vein, it is much more relevant to exclude potential sources through systematic elimination until only one remains that cannot be rejected. To do this, Wilson and Pollard (2001:510) suggest that simpler bivariate plots coupled with some geologic understanding are more valuable than complex multivariate statistical analysis to determine similarity and difference between samples.

As an Indigenous archaeologist practicing archaeology within the asserted and unceded territories of Tsleil-Waututh Nation, where I am from, I consider myself a steward of our cultural heritage resources. Like other Indigenous archaeologists (see Lippert 2006:437), I have a genetic relationship to the creators of archaeological materials from the region that few other archaeologists can claim. While working in the territory, the acknowledgement and use of traditional place names is important because they provide a link between people and the landscape (Basso 1996; Bierwert 1999; McHalsie 2001). Throughout this text, I utilize place names for archaeological sites where possible, also offering the common name and Borden number (used to identify registered archaeological sites) when available.

My name is Karen Rose Thomas and I come from Tsleil-Waututh Nation, one of many that make up the Coast Salish language family and cultural region. While I do acknowledge my lineages to other nations that my Ancestors have come from, I identify as Tsleil-Waututh both as the community and Nation I was raised in, and also because they claim me. My mother is Lorelei Maureen Thomas. My maternal grandparents were Margaret Thomas (née Charles) of Semiahmoo and Charles Thomas of Tsleil-Waututh. Margaret's parents were Maimie Charles (née Wilcox, of Stó:lō Nation) and Bernard Charles of Semiahmoo. Charles' parents were Hazel Thomas (née Nahanee) of Squamish Nation and Frank Thomas from Tsleil-Waututh.

All of these Nations are a part of the central Coast Salish culture area, as defined by anthropologists and archaeologists, but the Indigenous worldview of many nations in this area sees ourselves as Xwélmexw. Several definitions of Xwélmexw exist; my favorite definition interprets the méxw syllable as "to do with like the dirt," emphasizing the connection to the dirt, read literally as people of the land (McHalsie 2007). I come from a long line of Xwélmexw people. My positionality highlights the connection between past, present and future Xwélmexw generations. I see archaeology as a tool to facilitate this connection. The purpose of asserting my family lineage is to situate myself within my community, and also within the greater Coast Salish continuum.

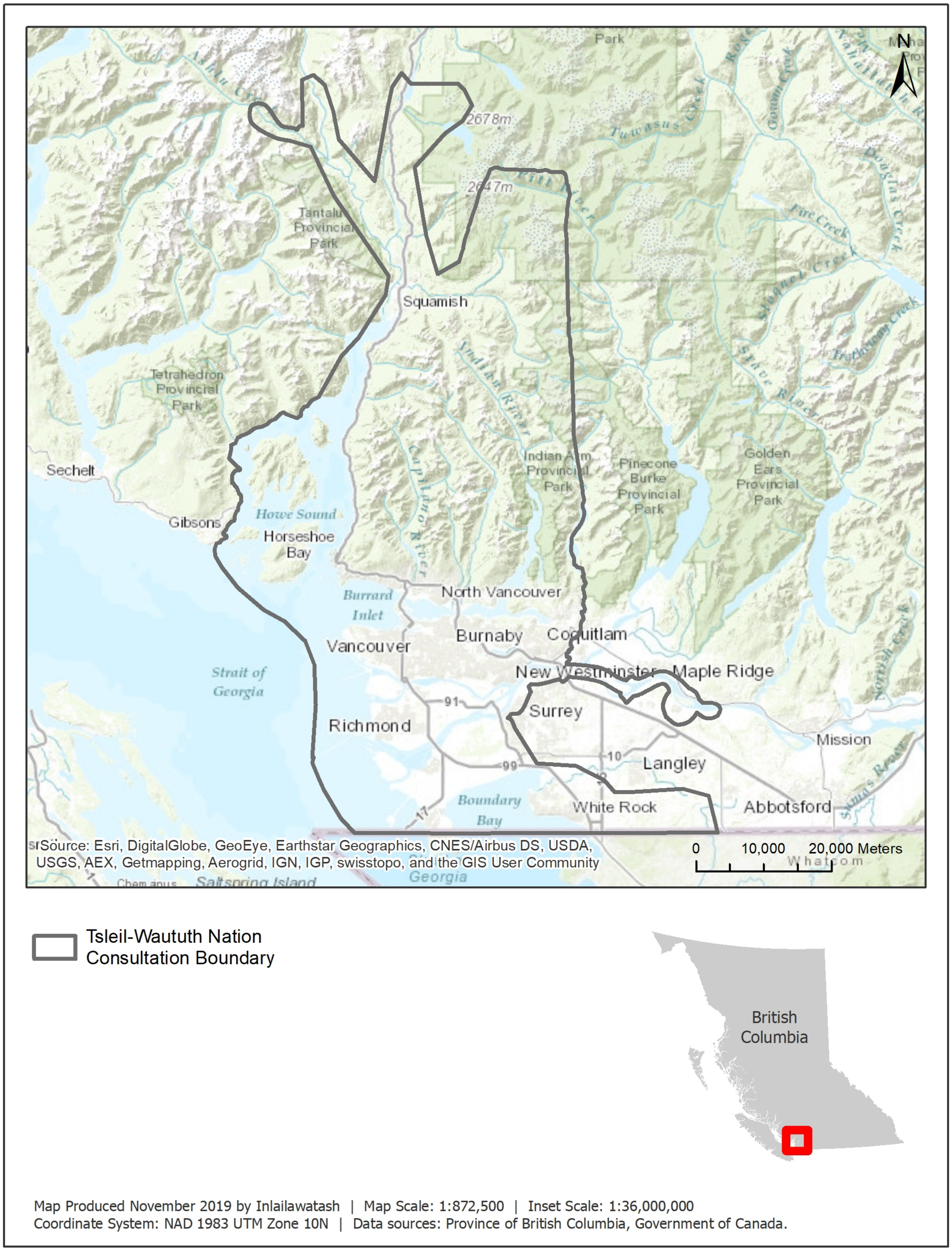


Figure 1.1 Map showing the extent of the Tsleil-Waututh Nation Consultation Boundary in southwestern British Columbia. Map credit: Inlailawatash 2019.

1.1 Guiding Principles of this Thesis Research

Several guiding principles motivate my work. These include:

1) Archaeology as a site of knowledge production inevitably produces an accumulation of things. Once excavated, they are (sometimes) analyzed, then cleaned and sent to their repositories to be stored for perpetuity. The lack of space for an increasing volume of things was acknowledged in archaeology as early as the 1970s (Ford 1977). Known as the "curatorial crisis," it remains unresolved today, nearly 40 years later. This crisis is especially problematic because these are Indigenous ancestral objects and their spirits are locked in the silence of institutions. These objects deserve to be listened to and spoken with (Morin, P. 2014). I strive to use previously excavated assemblages and facilitate relationships between descent communities and their cultural heritage.
2) We are all unfairly affected by colonial compartmentalization (Christie-Peters 2017; Morin, P. 2014). I see this in many facets of my own life, and I seek to soften borders between such things. In response to this principle, I seek to insert my voice into this thesis, as an affront to generations of authoritative third person archaeological reports.
3) The academy needs more disrupters. Following the above point, I see a need to challenge the discourses that have until recently been unquestioned throughout the history of archaeology and anthropology in Indigenous North America. This is a unifying principle of the research questions I ask. Whether small or large disruptions, they chip away at the settler-colonial monopoly within anthropological conversations.

4) Incorporating theories of decolonizing and Indigenous research methodologies (Smith 2012, Kovach 2009, others), I seek to ask and answer community-based questions, as an Indigenous researcher conducting Indigenous research.

5) Tsleil-Waututh traditional law asserts that we are stewards of the land and water. I see this stewardship as an inherited obligation—one that fully includes cultural heritage, and I believe that archaeological objects and data offer a direct connection to the Ancestors. Centering Tsleil-Waututh knowledge of and relationships to the past through this work is one of the unifying goals.

It seems natural and fitting to me to conduct research within the Coast Salish continuum, focused within what is considered to be the core territory of the Tsleil-Waututh Nation on the shores of Burrard Inlet. Having previously undertaken research with community collectors and their assemblages of surface finds (Thomas 2016), as well as having followed my mother around the beach since I was a very small child, I know much about the range of materials and artifact types that can be found in our Inlet. The significant abundance of this toolstone referred to as green andesite in the literature is obvious. That discussions regarding appropriate identification of its material type and geologic origin are missing in the region are problematic.

While the implications for the reproduction of an incorrect title for this toolstone material seem minimal, I must emphasise why I believe it is problematic. I think it speaks to a larger problem whereby settler-colonial archaeology is willing to accept its own conclusions and narratives without substantial proof. While Indigenous epistemology in archaeology is heavily scrutinized and much energy is expended to challenge Indigenous knowledge systems and their ties to the land (i.e. McGhee 2008), perceivably small things like this toolstone label are accepted and reproduced without challenge. I am here to challenge.

Chapter 2: The Coast Salish Continuum

Some Xwélmexw people find the concept of 'Coast Salish' problematic, because it is an anthropological concept, a culture group 'bucket' that our people were dumped into. We do not always consider ourselves to be Coast Salish. I use the term because I study anthropology and this is a term that anthropologists use to describe Xwélmexw people, culture and lifeways. When I conceptualize Coast Salish lands, cultures, and territories, I do not think of a rigid shape with sharp borders and edges. I imagine it as a continuum.

2.1 Ethnography

The Coast Salish continuum is vast and complex; it is modeled by some to be groups of autonomous heterarchies relating to each other (Bierwart 1999:18,203; Barnett 1955:241; Angelbeck and Grier 2012; Angelbeck and McLay 2011). These relationships are created and reinforced via intermarriage, kinship, language, trade, commerce, ceremonies, and stories (Barnett 1955; Suttles 1958, 1960, 1990; Kennedy and Bouchard 1987; Angelbeck and McLay 2011). I see my own Xwélmexw lineage as evidence of this. Archaeologists and anthropologists find it convenient to conceptualize the continuum as an "interaction sphere" (i.e., Lepofsky, Trost and Morin 2007). I like the idea of a continuum, because it could be a colonial conceptualization of a Xwélmexw idea. For this reason, I embrace it in my thoughts and work. The Coast Salish continuum spans from past, to present, and into the future. It is non-linear. It is alive and vibrant today.

Does this idea of decentralized societies of egalitarian heterarchies contradict the current and present idea of distinct local Nations and their territories? Or does this idea re-enforce it? Many individual ethnic divisions of Coast Salish peoples, both ancestral and present day, associate themselves with watersheds or specific river systems (Collins 1980; Carlson 2010, Morin et al. 2018, Ritchie 2010). Even with these watershed affiliations, the various groups of Coast Salish peoples exist together, honour family relationships and recognize ambilateral descent systems. As ethnographer Hill-Tout said of Coast Salish peoples: "Their cousinships are endless and even perplexing to themselves" (1978:33). An expression of continuity, still today families hold rights to economic resources that are inherited or acquired through marriage and the access to resources required for subsistence is gained through kinship relationships.

Tsleil-Waututh Nation asserts the Burrard Inlet, Indian Arm, Port Moody Arm and Indian River watershed amongst our core territory, and we claim and honour a special relationship with the Inlet and the Indian River watershed. Archaeologically and ethnographically, there are multiple lines of evidence used to support this assertion of a distinct ancestral Tsleil-Waututh ethnicity in Burrard Inlet (Lepofsky et al. 2007; Morin 2014, 2015). One of several attributes that Morin notes when asserting a distinct population occupied Burrard Inlet and Indian Arm is the presence of a high frequency of "green andesite" artifacts at Burrard Inlet sites (2016:177).

2.2 Present day Tsleil-Waututh People, Surface Collection and Stewardship

"Tsleil-Waututh Nation has a sacred, legal obligation to protect, defend, and steward the water, land, air, and resources in their territory. Tsleil-Waututh Nation's stewardship obligation includes the responsibility to maintain or restore conditions that provide the environmental, cultural, spiritual, and economic foundation for the community to thrive." (Tsleil-Waututh Nation 2009). The broad area that Tsleil-Waututh considers within our realm of stewardship obligation based on traditional use and occupancy can be seen above in Figure 1.1.

The Tsleil-Waututh population was decimated by contact and colonial policy. However, we work hard to establish and maintain our presence on the land. Co-management is one example of Tsleil-Waututh exercising our stewardship obligations. Within our territory we maintain agreements with municipal and provincial governments to co-manage parklands that exist on the land where ancient villages once stood. The co-management of parks allows for Tsleil-Waututh influence over development and planning. In this way, our ideas influence policy, process and procedures allowing for a level of control over parcels of our territory that would not otherwise be possible. Say Nuth Khaw Yum Provincial Park, located in the Indian River watershed and Whey-ah-Wichen (Cates Park), on the north shore of Burrard Inlet both include archaeological sites that establish use and occupation by ancestral Tsleil-Waututh. These parks are significant to this project because my research suggests that the geological context for this toolstone is likely in the Indian River watershed, possibly within Say Nuth Khaw Yum itself, and because this material features in the assemblage at Whey-ah-Wichen.

In my undergraduate honours thesis (Thomas 2016), I made the argument that, in the case of Tsleil-Waututh and Burrard Inlet, descent community surface collection behaviours are an example of stewardship. I highlighted archaeology's prioritization of data associated with systematically excavated artifacts over real human interactions with and relationships to objects. In archaeological circles, surface collecting behaviours are seen as problematic, lumped in with nefarious looting behaviors (Thomas 2016; Hart and Chilton 2014:319). Community surface collectors are never compared to the avocational archaeologist. Some archaeologists have more recently begun to address it (ie. Schaepe et al. 2017), but historically there has been no space in academic conversations for the idea of Indigenous descent communities connecting with their Ancestors through objects.

Chapter 3: The Mystery Material

Archaeologists regularly make a visual assessment and identification of stone type in the field and laboratory based on generalized characteristics of common toolstone types. This type of assessment can be efficient when the assessor is experienced and knowledgeable about toolstone materials specific to an area. However, visual assessment can produce incorrect categorizations, especially when a material is never verified by geochemical analysis, as many rock type categories (e.g., andesite) are based on chemical and mineralogical, not visual, characteristics. It must be noted that there possibly exists a certain amount of heterogeneity, both within material type (i.e. objects of a visually similar material type may be geochemically variable) and also within geological source (i.e. geochemically similar materials from the same place may look different). This makes most visual assessments risky.

3.1 Existing Studies, Origin of the Label "Green Andesite"

The toolstone I have chosen to focus on is one such example. At some point in archaeological discourses of Burrard Inlet and Indian Arm, this raw material was labelled "green andesite," likely based on a description of green andesite dykes in a 30-year-old geology MSc thesis (Reddy 1989). The designation has been reproduced in the region's literature and in archaeological databases over and over again, and yet the material itself remains largely ignored.

Reddy's 1989 MSc thesis in geology provides a broad overview of the geology of the Indian River area in Southwestern British Columbia. Reddy's work focusses on the eastern portion of the Britannia - Indian River pendant within the Coast Plutonic Complex, which he describes as a metamorphosed assemblage of marine pyroclastics, flows and sedimentary units (1989). His work looks at the major and trace element compositions, structure, geochronology and mineralization of the seven north to northwest trending strips of the eastern side of the Britannia Indian River pendant (1989:48). Reddy collected 31 samples and 10 duplicates to classify them geochemically, explore alterations and compare the volcanic suite to established trends. The thesis defined the green andesite dykes which influenced the label of green andesite for this material found in the archaeological deposits of the Burrard Inlet area.

This toolstone was mentioned most recently in a paper (Toffolo et al. 2019) on a 1300-year-old Coast Salish rock shelter. During an overview of the Indian River watershed, where this rock shelter (DjRr-4) is situated, they discuss “a green andesite that occurs at archaeological sites in Burrard Inlet” (p.648) and mention cobbles of a similar material seen in the gravel bars of the Indian River. This is where I first learned of the connection to Reddy’s 1989 MSc thesis, as they cite his description of basalt and andesite dykes which crisscross the Indian River Valley. They also note that the location of these dykes is not recorded (2019:648); however, Reddy’s thesis (1989:121) does include the latitude and longitude for at least one of these andesite dykes.

Before this, Morin (2016) conducted a Burrard Inlet projectile point pilot study and observed trends in variability, including concentrations of a toolstone he identified as “green andesite” in several of the Burrard Inlet sites. He also noted that there was an east to west trend across the Inlet in both toolstone materials and formed tool type. Given the small-scale nature of a pilot study, it would be useful to expand the scope of this study to include more assemblages.

In his PhD dissertation, Reimer (2012) explored the lithic resources and landscapes of Skwxwú7mesh Úxwumixw (Squamish Nation) territories. Utilizing portable X-ray Fluorescence (pXRF) analysis, Reimer compared archaeological assemblages to known toolstone quarries and interpreted the results with his knowledge of Skwxwú7mesh Úxwumixw worldview. One of the lithic quarries he characterized was Lhaxwm (Anvil Island) which is the source of the toolstone known as Lhaxwm Smant (Anvil Island andesite) (Reimer 2012:85). While Reimer included objects from Say-umiton (n=3) and Tsleil-Waututh Indian Reserve #3 (IR#3)(n=3) in his dissertation work, he does not investigate concentrations of major (e.g., Si) and minor (e.g., K, Na) elements useful for identifying material (rock) type (e.g., andesite, dacite, rhyolite). In addition, it is unclear whether the material type of the objects thought to be made of Lhaxwm Smant found at Say-umiton and IR#3 sites were geochemically verified or only visually assessed. Finally, the lack of Si concentrations in Reimer's results prevent me from incorporating the data in my own research.

The toolstone at Say-umiton which Reimer calls Lhaxwm Smant, other researchers have called green andesite (see Lepofsky et al. 2007, and the summary below). Because of the inability of researchers to identify material (rock) type visually in cryptocrystalline fine-grained materials (especially from a weathered surface), this method of analysis involving visual assessment and investigations of trace element concentrations is problematic, as my results below will support.

Lepofsky and others (2007) compare three sites in the Inlet locality: Whey-ah-Wichen (Cates Park), Say-umiton (Strathcona Park) and Tum-tu-mey-Whueton (Belcarra Park). They note that the Say-umiton assemblage is heavily dominated by a green andesite material similar in appearance to the "green 'Anvil island' type" (Lepofsky et al. 2007:209). Based on the predominance of local lithic and faunal resources observed in this study, Lepofsky and others (2007:215) concluded that the people who occupied the Inlet locality in the past comprised a smaller regional social network nested within and linked to the broader Coast-Salish socio-economic networks. This conclusion speaks to the idea that the ancestral Tsleil-Waututh peoples maintained their own smaller social network nested within and linked to the rest of the Coast Salish continuum.

Lepofsky and Karpiak (2001) documented the results of SFU's 2000 Field School at Say-umiton and their archaeological investigations at IR #3. Initially, they made reference to a green andesite found throughout the course of their research. Part way through the report, they named the green andesite material as "Anvil Island andesite" (2001:54), even though this has never been geochemically or petrographically confirmed. They noted that the green andesite/Anvil Island Andesite material is common at IR #3 sites and Say-umiton, as well as the sites in the surrounding locality.

I contacted Doug Reddy whose 1989 geology thesis is where the green andesite label originated. I wanted to let him know that archaeologists in the region were using his thesis and ask for his thoughts about this material type. He replied very promptly and enthusiastically to my request for information, suggesting I look to the major and minor trace element data in his thesis. When I sent photos of the toolstone, his reply was "I would not have called those specimens "andesite". Too much silica," (Reddy personal communication, 2019). Thanks to our correspondence, I had some leads to explore when I undertook the analysis searching for a geological origin for this green toolstone.

3.2 Description of the Material

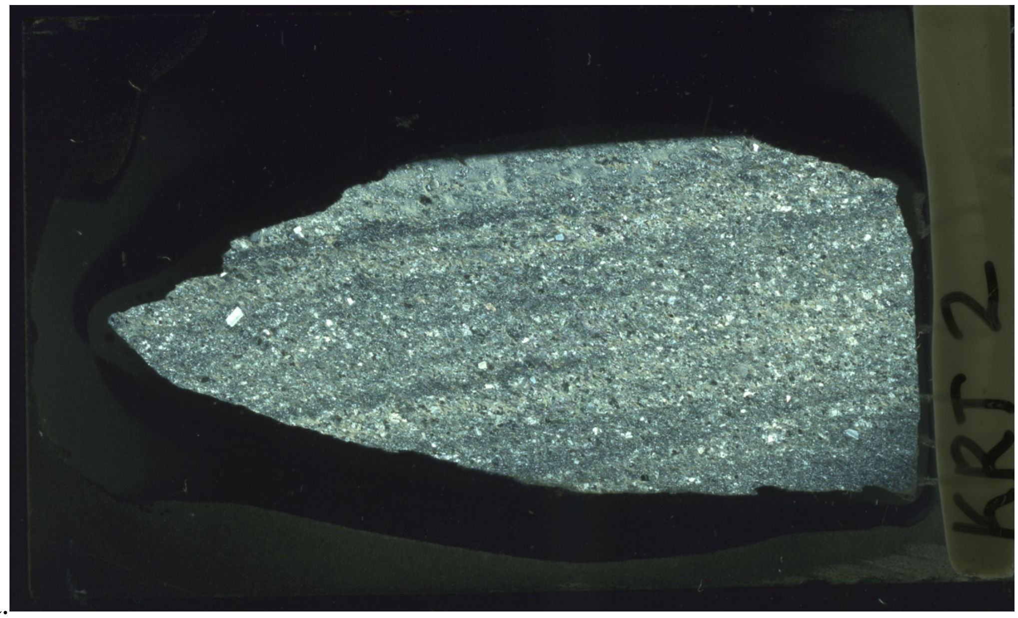
The toolstone material of interest is currently underrepresented in the literature. The toolstone varies in colour from a vibrant green to a subdued brown and there are many distinctive white crystals, called phenocrysts, in some specimens. The texture is waxy, not unlike a chert, and there is occasional banding or patina (Figure 3.1).

Figure 3.1 Object Krt-2, prior to submission for thin section preparation and WD-XRF analysis. (Scale is 1 mm^2 for fine grid and 1cm^2 for coarse grid).

To begin analysis, study object Krt-1 from Whey-ah-Wichen, was selected for exploratory Raman spectroscopic investigations (see McMillan et al., 2019 for method and instrumental set-up). This showed that the small white phenocrysts in Krt-1 are a plagioclase/oligoclase and that the green groundmass material produces both quartz and carbonaceous material spectra. No mineral grains or any other indicators of rock type were visible with 100x magnification.

A thin section of study object Krt-2 was analyzed with a cross-polarizing microscope and the results showed layering of mineral grains with various degrees of maturity and sorting, as well as possible fiamme structures (glass shards) and imbrication textures. These characteristics suggest that it is most likely of pyroclastic or sedimentary origin, and the presence of fiamme structures and imbrication textures are indicative of an ash-flow tuff (Ross and Smith 1961).

Figure 3.2 shows an overview of the thin section of object Krt-2, first in cross polarized light (a), and next in plane polarized light (b). Further analysis of the thin section under high magnification confirmed the presence of plagioclase and quartz crystals as identified by Raman spectroscopy (Figure 3.3).

a.


b.


Figure 3.2 Thin section sample of Krt-2: a. Cross polarized light and b. Plane polarized light (Scale: Slide is 27x46 mm).

a. 

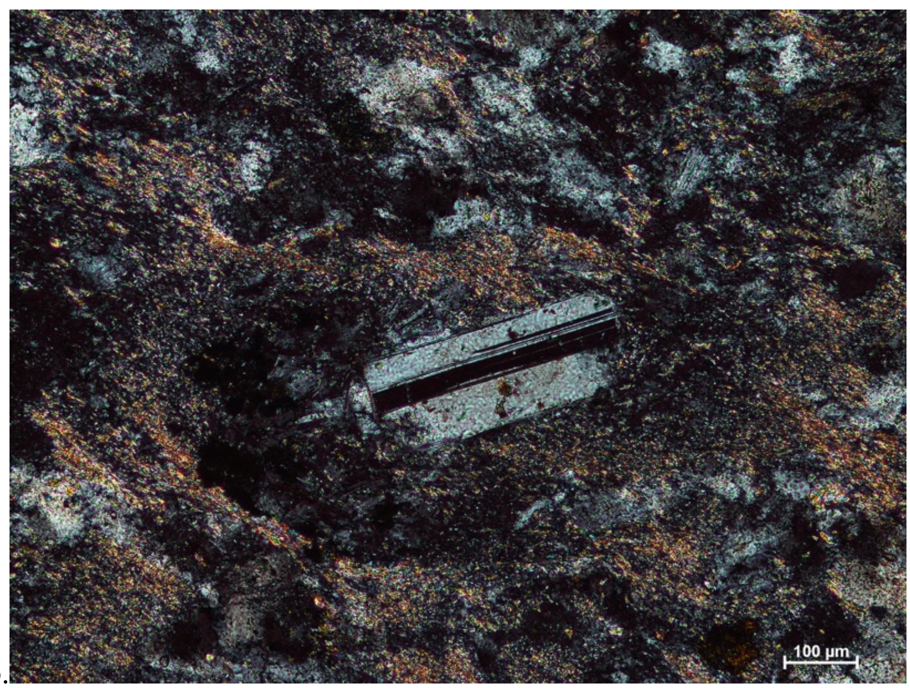
b. 

Figure 3.3 Thin section details: a. cluster of plagioclase and quartz crystals b. Plagioclase crystal.

Chapter 4: Research Context and Methods of Analysis

Here, I will detail my research context. Because this material is mostly overlooked in the literature of the greater Gulf of Georgia region, it seemed that its usage and distribution was isolated to the eastern Burrard Inlet area. However, research into collections shows that there are materials from other locations that visually appear to be a similar stone type. Several of these pieces were included in the study. After I briefly describe the sampled collections and existing studies, I will outline my object selection criteria and methods of analysis.

4.1 Sampled Sites, Their Repositories and Community Assemblages

Most of the sites chosen for inclusion in this study are located in Burrard Inlet. This is because of Tsleil-Waututh ties to the lands and waters and my own familiarity with the materials of the Inlet. Prior to undertaking this research project, this toolstone was observed to be heavily favoured by ancient inhabitants of the Burrard Inlet locality—enough to permit distinguishing these assemblages from those located elsewhere in the Gulf of Georgia and Lower Fraser River locales (Morin 2015:117). The sites where study objects were found can be seen in Figure 4.1.

4.1.1 Whey-ah-Wichen, Cates Park DhRr-8

Tsleil-Waututh oral history recounts that Whey-ah-Wichen was a village with a fortified palisade and had been the location of several battles. Whey-ah-Wichen is strategic for its sightlines, Chief Dan George has said that Whey-ah-Wichen means “looks both ways” (BC Archaeological Site Inventory Form for DhRr-8, 1972). Indeed, there is a small peninsula that faces the wind in both directions, where one could conceivably look east up the Inlet and also west towards Second Narrows.

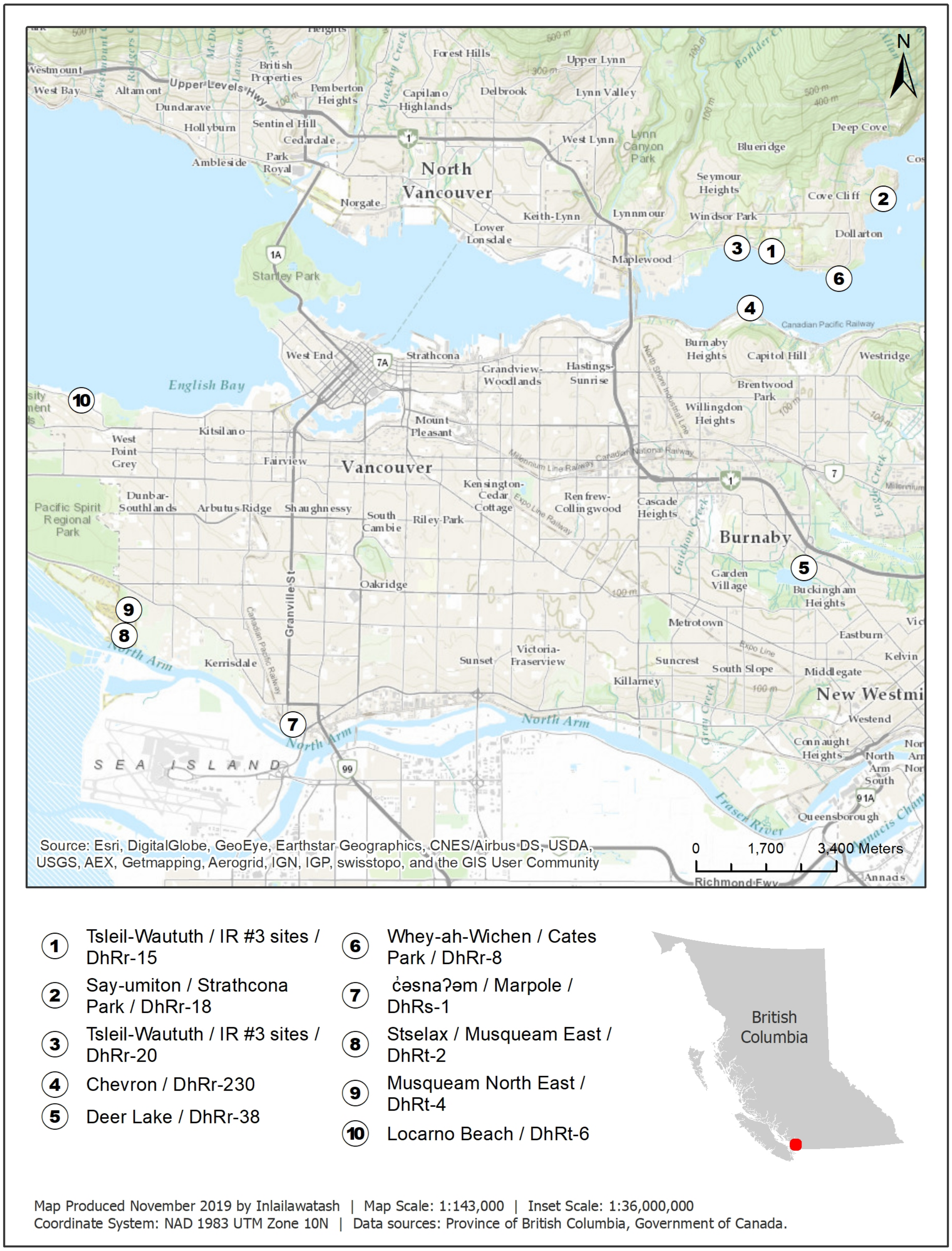


Figure 4.1 Map of Archaeological Sites Associated with Study Objects Investigated in this Thesis Research. Map Credit: Inlailawatash 2019.

The Whey-ah-Wichen site underwent archaeological investigation by Arthur Charlton in 1972. Charlton (1974:7) used auger tests to assess the depth of archaeological deposits that ranged from 10 to 60 cm. He concluded that DhRr-8 was a temporary resource processing camp because of the shallowness of the deposits and lack of obvious house features (Charlton 1974:9). However, DhRr-8 is argued by Morin (2015:205) to better fit the category of a village, based on the fact that there are deeper stratified deposits and an obvious house floor 40 m east of Charlton's excavations. Similar to the IR#3 sites discussed below, DhRr-8 is also subject to tidal erosion in some areas and as a result there are occasionally outwashed archaeological materials. In 2014, the District of North Vancouver undertook shoreline remediation at Whey-ah-Wichen to slow the erosional effect of the winds and tides (Morin 2013; Shepard 2014).

4.1.2 Say-umiton, Strathcona Park (Cove Cliff) DhRr-18

The Say-umiton site is located in a small park nestled in a residential neighborhood of Deep Cove. Tsleil-Waututh knowledge documents the name Say-umiton to mean "the place of good water" (Lepofsky et al. 2007:196). The site was first documented in 1972 by archaeologists Don Abbot and Stephen Carter, although some undocumented excavations are known to have taken place in the 1960s (Lepofsky and Karpiak 2001:18).

In 2001 the Say-umiton site was excavated by a Simon Fraser University (SFU) Archaeological Field School taught by Professor Dana Lepofsky, as part of a community archaeology project undertaken in partnership with the Tsleil-Waututh Nation. In the course of their project, they conducted an intensive intertidal survey and collection of archaeological materials. Morin's study of the Say-umiton materials concluded that the flaked stone assemblage consisted of 47.5% green andesite objects, both formed tools and debitage (2015:116).

4.1.3 Sleil-Waututh, DhRr-15 and DhRr-20, IR #3 Sites

Two documented sites, DhRr-15 and DhRr-20, are adjacent to each other on the Tsleil-Waututh Nation Indian Reserve (IR #3), known in contemporary times as Sleil-Waututh village, named after the people who live there (Morin 2015:199). Throughout this thesis, I will refer to them collectively as the IR #3 sites. While these sites have never undergone systematic archaeological excavation, they have been explored through auger testing (Ritchie 2014) and surface collection. Morin notes that as a result of foreshore erosion, “thousands of artifacts and fire-cracked rock blanket the intertidal areas” (2015:198).

Lithics have been observed on the shore between these sites, and Morin (2015) has argued that they be considered as one large site, however the heaviest concentrations of archaeological materials were found in close proximity to the sites themselves (Lepofsky and Karpiak 2001:72). These are the outwash scatters that are collected and stewarded by community members of the Tsleil-Waututh Nation. Community members’ surface collections are where I first encountered and observed the toolstone referred to as green andesite.

4.1.4 Lorelei Thomas Surface Collections

Lorelei Thomas is my mother. She has been exploring the Inlet and collecting ancestral objects from the shores for as long as I can remember. She was featured in my undergraduate research (Thomas 2016), where I explored community collecting behaviours through interviews and conversations and concluded that surface collection was an act of stewardship. In recent discussion, she mentioned that it had been many years since she had found anything off reserve, but it does not stop her from looking. She curates her collections in many different ways, including some portable storage containers that allow her to travel and share the objects and their connections to our Ancestors with other community members and anyone interested.

While most community collectors focus on whole, complete objects, Lorelei collects all the materials she finds. She has an extensive collection of debitage—the waste products of stone tool manufacture. Because her searching and collecting activities are generally limited to the IR #3 sites, all of her small or large pieces of debitage are curated together with broken tools and placed into various buckets at her home, on her deck or in her yard. In her collection, I identified more than 200 objects made of the green material including debitage, broken pieces and complete tools. She allowed me to use this collection to explore the variation in this toolstone.

4.1.5 Tsleil-Waututh Nation, Steve Carter Surface Collections

The Treaty, Lands and Resources department at Tsleil-Waututh Nation has a small collection of archaeological objects donated by avocational archaeologist, surface collector and friend of the late Chief Leonard George, Stephen Carter. This collection is composed of many stone tools, meticulously documented, from sites in the Burrard Inlet and Indian Arm locality. From the Carter collection, I included 9 projectile points, 2 of which were heavily patinated. These objects all originated from the Say-umiton site. I did not observe any objects made of the green toolstone material from other sites within the Carter Collection.

4.1.6 Deer Lake, DhRr-38, Louis Claude Hill Surface Collections

In conversation with a colleague, I learned that the Burnaby Village Museum has one or more objects made of a similar material. Burnaby Village Museum's archaeological collection consists of surface collected artifacts donated by the descendants of Louis Claude Hill. One of

Burnaby’s earliest settlers, Hill, participated in the British land grab of the 1890s (Braches 2016:61). Hill’s parcel of unceded territory was located at Douglas Road and Sperling Avenue, and included what is now the present day home of the Burnaby Village Museum. In 1894, Hill discovered archaeological deposits on his strawberry farm and recovered many artifacts. In 2002, his descendants donated his collection to the Burnaby Village Museum (www.HeritageBurnaby.ca). I identified one piece which was visually similar to the green toolstone (BV002.57.13) to include in this research.

4.1.7 Chevron DhRr-230

This site is located on the South Shore of Burrard Inlet, in front of the Chevron Refinery, almost exactly across from the previous Tsleil-Waututh village and present day Tsleil-Waututh reserve at IR #3. It is a small lithic scatter, which indicates that it was likely a short term camp for resource harvesting for the ancient inhabitants of the area (Morin 2015:240). Not much else about this site is known. Based on visual similarities, one object from the University of British Columbia’s Laboratory of Archaeology (LOA) collection was included in the study (DhRr-230:4).

4.1.8 Collections Outside the Burrard Inlet Locality

Online assemblages found in the Reciprocal Research Network (www.rrncommunity.org) revealed several objects that looked similar to the toolstone called green andesite. One problem encountered when exploring online assemblages was the inconsistency in material identification labels. For example, within the LOA catalogue, objects of interest were labeled as green chert, green andesite, Anvil Island andesite and even unknown.

It was surprising to discover objects looking similar to the green andesite within assemblages from outside the Burrard Inlet locality. I had planned to focus on the eastern Burrard Inlet area. However, the idea that the material had a larger distribution on the landscape of the region was too interesting to ignore. Because of the small number of objects from these other sites (n=7), they are only briefly listed here: Locarno Beach DhRt-6, c̓əsnaʔəm / Marpole DhRs-1, Stselax / Musqueam East DhRt-2 and Musqueam North East DhRt-4. More details on all study objects can be found in Appendix A.

4.2 Data Collection and Analysis Methods

In total, fifty-one objects were analyzed for elemental concentrations using X-Ray fluorescence spectroscopy. They were selected based primarily on visual criteria as both the colour and texture of the material are very distinctive. Of the analyzed objects, forty-one were surface collected and ten were systematically excavated. X-ray fluorescence spectroscopy is a non-destructive method of analysis commonly used for rocks, minerals and sediments. It works under the premise of scattering and absorption, whereby when struck by the primary x-rays, some are absorbed and some secondary x-rays are scattered in a characteristic way, which can be interpreted to determine the types of atoms present (Pollard and Heron 2008). The XRF analysis methods used in this analysis are described in more detail below, and the findings are discussed in the next chapter.

4.2.1 Elemental Concentrations by Portable X-Ray Fluorescence (Non-Destructive)

Elemental concentrations were collected with an Olympus Vanta C-Series Portable X-ray fluorescence (pXRF). The instrument was rented from REFLEX Instrument North America

Limited. Analyses were carried out using the 'GeoChem-extra' mode with factory settings and "Fundamental Parameters" calibration. No user factors were applied to the results. 'GeoChem-extra' mode varies the current and voltage of the 4-W X-ray tube (with a Rh anode) in combination with two built-in beam filters to improve the fluorescence of both lighter and heavier elements within a single analytical run. Spectra were collected from each object for 60 seconds per analysis (30 seconds on each beam). Objects were each analyzed three times to ensure reproducibility and to evaluate intra-sample heterogeneity. Instrument drift was monitored for potential correction by bracketing samples with the NIST 2711a Montana Road Dust reference material (Mackey et al. 2010). No drift was observed during any analytical sessions and the major, minor, and trace element compositions of NIST 2711a were consistently within 15% of expected concentrations.

4.2.2 Elemental Concentrations by Benchtop X-Ray Fluorescence (Destructive)

With her explicit permission, three pieces of unmodified debitage from the surface collection belonging to Lorelei Thomas were selected from the first 20 samples of IR #3 surface collected debitage for destructive analysis. Based on their silicon concentrations (as determined with pXRF), one from each of the lowest, middle and highest range of silicon concentrations were chosen. These three objects were identified for destructive WD-XRF, and one of these three was selected for the creation of a thin-section (described in section 3.2, above). They were subsampled at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) and only fresh rock chips without weathered surfaces or surface contamination/discolouration were selected for analysis.

After this initial preparation, these three samples were submitted to ALS Global Geochemical Laboratory on June 19th 2019 for ME-XRF26 routine, a destructive method of whole rock analysis. Samples were crushed and pulverized using the CRU-32 and PUL-31 sample preparation packages. Following fusion of each sample into a disk, WD-XRF is used to determine the major rock-forming elements, including Al_2O_3, Fe_20_3, Na_2O, SrO, BaO, K_20, P_2O_5, TiO_2, CaO, MgO SO_3, LOI, Cr_2O_3, MnO and SiO_2. The concentration data from this analysis can be found in Appendix B.

This additional method of analysis offered an opportunity to cross-check major element results from the Olympus pXRF. Based on these results, no post-hoc calibration or adjustment of parameters from default settings for pXRF was deemed necessary (as observed in Frahm 2017). The WD-XRF analysis also provided quantified concentrations of light elements that were not measured by pXRF (specifically NaO), allowing for the plotting of the material on total alkali silica (TAS) diagrams, which are commonly used by geochemists and geologists to identify rock type. In contrast to the pXRF analysis which provides elemental concentrations from a specific location on the sample, the WD-XRF analysis method provides an aggregated suite of elemental concentration values.

Chapter 5: Results and Discussion

In this section I summarize the data from pXRF and WD-XRF analyses in conjunction with the data from Reddy's (1989) published work in the Indian River watershed. Reddy's major, minor and trace element data was obtained with benchtop WD-XRF analyses undertaken at what was then UBC's Department of Geological Sciences (now called PCIGR). I begin by presenting the data, providing an analysis of the data within the theoretical framework of the provenance hypothesis (Wilson and Pollard, 2001), and conclude with a discussion of the implications of the results.

5.1 Major, Minor and Trace Element Concentrations

Table 5.1 presents the data obtained from the three samples that underwent WD-XRF analysis. Most important to my analysis, because of the role they play in determination of igneous rock type (Le Bas et al. 1992), are the SiO_2 and the NaO_2 and K_2O (alkali elements) concentrations of the objects. For these three objects, the SiO_2 ranges from 67.56 to 76.45 wt%, the Na_2O ranges from 2.76 to 5.27 wt%, while the K_2O ranges from 0.8 to 5.25 wt%.

Table 5.1. Major element oxide concentrations in weight percent of samples from IR#3 sites that underwent WD-XRF analysis. The number of reported digits represents the uncertainty for each measurement.

Sample ID	K_2O (wt%)	Na_2O (wt%)	SiO_2 (wt%)
Krt-2	5.06	2.76	75.24
Krt-3	0.8	5.27	67.56
Krt-9	5.25	2.85	76.45

Table 5.2. Major, minor and trace elemental concentration data from study objects collected with pXRF. Concentrations are averages among triplicate analyses and reported uncertainties are external. Concentrations with a ‘<’ prefix are below the limit of detection and thus do not have associated uncertainties. Uncertainties calculated among multiple identical concentrations are also denoted with a ‘<’ prefix.

Sample ID	SiO_2 (wt%)	SiO_2 Error 1 SD (wt%)	Si (wt%)	Si Error 1 SD (wt%)	K (wt%)	K Error 1 SD (wt%)	Ca (wt%)	Ca Error 1 SD (wt%)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
krt-1	80	5	37	5	4.3	0.1	<0.01	-	55	1	13	1	67	1	9	3
krt-2	71	4	33	4	2.9	0.4	<0.01	-	61	2	29	4	61	3	8	1
krt-3	67.2	0.6	31.4	0.6	0.50	0.01	1.32	0.01	11	1	16	1	124	2	7	1
krt-4	68.0	0.5	31.8	0.5	1.24	0.02	2.10	0.02	40	1	18	1	121	1	7	1
krt-5	75	1	35	1	1	0	0.93	0.01	22	<1	36	1	128	1	6	1
krt-6	66.6	0.2	31.1	0.2	4.00	0.05	<0.02	-	48	1	16	2	74	2	11	1
krt-7	77.1	0.6	36.1	0.6	4.01	0.04	<0.01	0.01	86	2	18	1	107	2	7	1
krt-8	77.0	0.3	36.0	0.3	2.61	0.02	1	0	51	1	9	2	98	2	6	1
krt-9	80.6	0.6	37.7	0.6	4.12	0.03	0.01	0.01	48	1	12	1	63	1	8	1
krt-10	78.5	0.4	36.7	0.4	5.35	0.02	<0.01	-	57	1	16	1	91	2	7	1
krt-11	74.5	0.6	34.8	0.6	5.05	0.05	<0.01	-	58	1	28	1	62	2	11	1
krt-12	67.2	0.7	31.4	0.7	3.26	0.04	0.57	0.01	75	1	11	<1	76	1	8	1
krt-13	81	2	38	2	4.63	0.08	<0.01	-	52	<1	15	1	67	1	8	2
krt-14	58	1	27.3	0.7	4.27	0.08	0.1	<0.01	53	2	10	1	68	3	7	1
krt-15	85.0	0.3	39.7	0.3	2.52	0.01	<0.01	-	33	1	13	2	65	2	11	1
krt-16	76	1	35	1	2.47	0.03	0.82	0.01	59	2	42	2	150	2	<1	-
krt-17	77.6	0.4	36.3	0.4	<0.01	-	0.48	0.01	2	2	34	1	263	3	11	1
krt-18	68.8	0.8	32.2	0.8	2	0	<0.01	-	29	1	17	1	143	2	9	1
krt-19	76.0	0.9	35.5	0.9	5.02	0.07	<0.01	-	54	1	28	1	66	1	14	<1
krt-20	77.1	1.0	36	1	4.25	0.03	<0.01	-	52	1	15	1	62	1	8	1
krt-21	76.0	0.1	35.5	0.1	4.47	0.04	<0.01	-	51	1	25	1	85	2	10	1
krt-22	82.1	0.4	38.4	0.4	4.51	0.05	<0.01	-	49	1	12	1	70	2	7	1
krt-23	80.2	0.9	37.5	0.9	4.25	0.08	<0.01	-	51	1	35	2	72	1	17	1
krt-24	84.0	0.6	39.3	0.6	4.36	0.01	<0.01	-	55	1	16	1	67	2	7	1
krt-25	72.0	0.6	33.7	0.6	5.61	0.02	<0.01	-	61	2	11	1	84	1	12	2
krt-26	75.7	0.4	35.4	0.4	4.35	0.06	0.2	<0.01	53	1	12	1	70	1	9	1
krt-27	72.2	0.8	33.8	0.8	4.95	0.05	0.1	<0.01	61	1	23	1	74	1	11	1
krt-28	99	1	46	1	2.08	0.05	0.94	0.01	51	2	35	1	153	2	<2	-
krt-29	77.5	0.5	36.3	0.5	2.45	0.04	<0.01	-	48	1	13	<1	115	1	7	2
krt-30	80.9	0.8	37.8	0.8	<0.01	-	<0.01	-	<1	-	16	1	131	2	6	1
krt-31	72.6	0.5	33.9	0.5	3.53	0.02	0.04	<0.01	42	1	15	1	68	1	12	2
krt-32	79.2	0.7	37.0	0.7	4.55	0.04	0.12	<0.01	55	1	17	<1	75	1	10	1
krt-33	67.8	0.3	31.7	0.3	4.69	0.01	0.41	0.01	56	2	16	<1	71	0	11	1
krt-34	80.0	0.4	37.4	0.4	4.28	0.01	<0.01	-	55	2	12	1	69	0	6	1
krt-35	69.9	0.8	32.7	0.8	3.3	0.06	4.01	0.03	53	1	11	<1	67	1	6	3
krt-36	65.7	0.9	30.7	0.9	5.78	0.07	0.3	<0.01	67	3	34	1	69	2	12	1
krt-37	82.9	0.5	38.7	0.5	3.17	0.01	0.01	0.01	44	1	11	1	69	1	7	2
krt-38	73.6	0.1	34.4	0.1	4.16	0.03	0.26	0.01	53	2	22	1	72	1	12	1
krt-39	81.2	0.4	38.0	0.4	1.87	0.03	0.14	0.01	27	1	19	1	132	1	12	2
krt-44	74.9	0.8	35.0	0.8	3.23	0.06	0.47	0.01	65	1	31	2	75	2	10	2
krt-45	73.3	1.0	34	1	3.71	0.04	0.43	<0.01	48	1	14	1	69	2	16	2
krt-46	71	6	33	6	4.7	0.3	<0.01	-	57	3	11	1	65	3	6	2
krt-47	85.5	0.3	40.0	0.3	4.17	0.01	<0.01	-	51	1	10	1	72	1	9	2
krt-48	81	2	38	2	2.2	0.1	0.74	0.09	43	2	27	1	149	7	9	1
krt-49	79.4	0.5	37.1	0.5	3.54	0.06	0.75	0.01	75	1	14	1	84	1	5	1
krt-50	76.5	0.3	35.8	0.3	2.72	0.04	0.55	0.04	57	1	18	1	84	1	8	1
krt-51	77	6	36	6	5.9	0.3	0.16	0.08	111	1	12	1	94	6	5	<1
krt-52	78	5	36	5	3.7	0.4	0.06	0.01	57	1	14	2	67	1	13	2
krt-53	67.8	0.4	31.7	0.4	1.65	0.01	1.38	0.03	35	<1	28	1	130	2	10	1
krt-55	86.6	0.5	40.5	0.5	2.61	0.02	0.08	<0.01	25	<1	9	1	102	2	2	3

Table 5.2 shows the major, minor and trace elemental concentration data from all study objects that is utilized for these analyses. The SiO_2 concentrations range from 58 to 99 wt%. The Si concentrations range from 27.3 to 46 wt%. The K concentrations range from <0.01 to 5.9 wt%. The Ca concentrations range from <0.01 to 4.01 wt%. For trace elements, the Rb concentrations range from <1 to 111 ppm, the Y concentrations range from 9 to 42 ppm, the Zr concentrations range from 61 to 153 ppm, and the Nb concentrations range from <2 to 17 ppm.

Table 5.3 presents the publicly available major element oxides for the samples from Reddy (1989). K_20 concentrations range from 0.55 to 7.57 wt%, Na_2O concentrations range from 0.44 to 5.84 wt% and SiO_2 concentrations range from 49.52 to 78.75 wt%.

Table 5.4 presents the major, minor and trace element data from Reddy (1989). Si, K and Ca concentrations were calculated from oxides using appropriate conversion factors. Si concentrations range from 23.15 to 36.82 wt%. K concentrations range from 0.46 to 6.28 wt%. Ca concentrations range from 0.29 to 8.46 wt%. Rb concentrations range from 1 to 150 ppm, Y concentrations range from 14 to 32ppm, Zr concentrations range from 68 to 339 ppm and Nb concentrations range from 6 to 30 ppm.

Table 5.3 Major element oxides from Reddy (1989) samples used in this comparison. The number of reported digits represents the uncertainty for each measurement.

SAMPLE	K_2O (wt%)	Na_2O (wt%)	SiO_2 (wt%)
86IRD-50	4.8	2.5	75.97
87IRD-166	7.57	1.15	75.76
87IRD-169	2.68	4.64	69.33
87IRD-145	0.99	2.8	54.39
87IRD-145d	1.01	2.82	54.91
87IRD-161	2.16	3.46	64.41
87IRD-75	1.3	3.22	53.4
87IRD-63	1.68	5.56	67.53
86IRD-53a	2.29	2.32	51.63
86IRD-53b	2.3	2.4	51.33
86IRD-161	7.23	0.44	75.02
86IRD-122	5.22	0.92	78.91
86IRD-189	2.86	4.36	71.93
86IRD-193a	1.05	3.07	59.8
86IRD-193b	1.06	3.09	59.69
86IRD-187	0.73	4.1	52.97
86IRD-121	3.69	3.5	74.25
86IRD-121d	3.79	3.61	75.5
87IRD-151a	3	5.41	53.21
87IRD-151b	3.08	5.63	55.04
87IRD-179	0.81	2.83	51.38
87IRD-185	1.75	3.81	52.75
87IRD-97	0.55	5.84	76.73
87IRD-60	0.82	3.16	52.03
87IRD-88	1.11	2.51	50.77
87IRD-64a	1.08	3.19	56.14
87IRD-64b	1.09	3.22	56.17
87IRD-133	0.94	4.05	52.59
87IRD-192	0.93	3.38	56.9
87IRD-192d	0.92	3.51	56.95
87IRD-72	0.67	3.05	52.55
87IRD-72d	0.66	3.18	52.67
87IRD-76	2.87	3.58	51.76
87IRD-79	1.03	1.39	49.52

Table 5.4 Major, minor and trace elemental concentration data from Reddy (1989) for samples used in this analysis. [1]Si = (SiO_2/2.139), [2]K = (K_20/1.205), [3]Ca = (CaO/1.399)

Sample ID	Si (wt%) [1]	K (wt%) [2]	Ca (wt%) [3]	Rb (ppm)	Y (ppm)	Zr (ppm)	Nb (ppm)
86IRD-50	35.52	3.98	0.48	68	17	68	8
87IRD-166	35.42	6.28	0.30	86	14	77	9
87IRD-169	32.41	2.22	0.66	36	18	120	8
87IRD-145	25.43	0.82	5.90	10	20	88	8
87IRD-145d	25.67	0.84	5.95	10	19	87	7
87IRD-161	30.11	1.79	3.62	32	21	188	22
87IRD-75	24.96	1.08	6.16	18	24	130	14
87IRD-63	31.57	1.39	1.13	24	31	349	30
86IRD-53a	24.14	1.90	6.08	40	28	101	7
86IRD-53b	24.00	1.91	6.12	39	28	100	7
86IRD-161	35.41	6.00	0.34	150	24	89	10
86IRD-122	36.82	4.33	0.29	112	19	79	10
86IRD-189	34.05	2.37	0.94	11	28	95	7
86IRD-193a	27.92	0.87	5.21	13	24	152	11
86IRD-193b	27.91	0.88	5.22	14	26	157	12
86IRD-187	24.76	0.61	4.35	11	28	95	7
86IRD-121	35.34	3.06	0.64	66	18	77	10
86IRD-121d	35.30	3.15	0.66	66	18	76	10
87IRD-151a	25.82	2.49	2.39	61	20	88	7
87IRD-151b	25.73	2.56	2.46	62	21	88	6
87IRD-179	24.02	0.67	6.65	13	32	116	8
87IRD-185	24.66	1.45	5.65	24	31	145	12
87IRD-97	35.87	0.46	0.69	7	28	195	11
87IRD-60	24.32	0.68	6.84	10	26	95	7
87IRD-88	23.74	0.92	7.11	19	28	96	7
87IRD-133	24.59	0.78	5.05	14	32	120	8
87IRD-64a	26.25	0.90	6.13	19	25	107	6
87IRD-64b	26.26	0.90	6.06	1	25	106	6
87IRD-192	26.60	0.77	5.70	11	30	135	7
87IRD-192d	26.62	0.76	5.61	11	30	133	8
87IRD-72	24.57	0.56	6.66	13	26	109	8
87IRD-72d	24.62	0.55	6.69	13	26	107	8
87IRD-76	24.20	2.38	4.55	40	27	108	7
87IRD-79	23.15	0.85	8.46	14	27	114	8

5.1.1 Rock Type Classification

First, I created a total alkali silica (TAS) diagram, commonly used by geologists to aid in the classification of rock type. TAS diagrams rely on using the weight percentage (wt%) of SiO_2 as a parameter to determine the ultra-basic (ultra-mafic), basic (mafic), intermediate and acidic (felsic) types of igneous rocks and have been used by geologists for over a hundred years (Le Bas et al. 1992). The International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Igneous Rocks established the accepted SiO_2 bounding values at 45, 52, 57 and 63 wt% SiO_2 (see Le Bas et al. 1992). While Reddy didn't use a TAS diagram for his rock type classifications, he did use a FeO_{total}/MgO versus SiO_2 diagram (1989:92), which still relies heavily on the SiO_2 wt% boundaries between types of igneous rocks.

Generally, the TAS diagram is unsuitable for archaeological contexts because the Na concentrations of a geological material are best obtained through destructive methods of testing, such as the WD-XRF analysis, which is typically impossible to undertake on archaeological objects. However, with permission, I was able to select three unmodified flakes for destructive testing that appeared to be 'green andesite' and for which Si concentrations were measured non-destructively with pXRF. The flakes originated from the personal surface collection of Lorelei Thomas. I intended to capture the range of Si concentrations as measured by pXRF, so I selected flakes from the low, middle and high ranges of Si. The TAS diagram showcasing these objects is Figure 5.1.

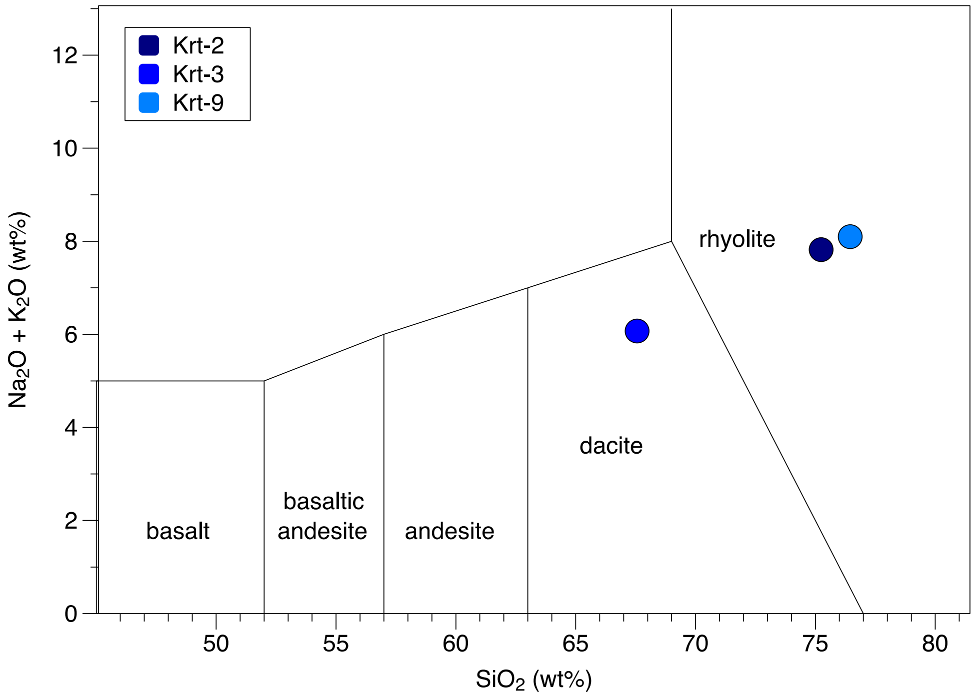


Figure 5.1 Total Alkali Silica Diagram for study objects that underwent WD-XRF analysis.

As previously mentioned, a destructive method of testing such as WD-XRF analysis is required to obtain the Na concentrations necessary to calculate the total alkaline elemental concentrations (the sum of oxides of Na and K). I then assessed if it would be possible to use the acidic TAS diagram categories (e.g., basaltic to rhyolitic) to loosely categorize the original magma compositions (mafic to felsic) of all the samples analyzed non-destructively with pXRF by plotting the silica weight percentages. This can be seen in Figure 5.2.

Table 5.5 Summary of Volcanic Units Identified by Reddy and Samples Included in this Study.

Volcanic and Intrusive Units Identified By Reddy (1989)	Number of Samples Included in this Study
Quartz Feldspar Rhyolite Intrusives	3
Dykes Late Intrusives	7
Lower Goat Mountain Formation Indian River Valley	2
Middle Goat Mountain Formation Indian River Valley	10
Middle Goat Mountain Formation Stawamus River Valley	12

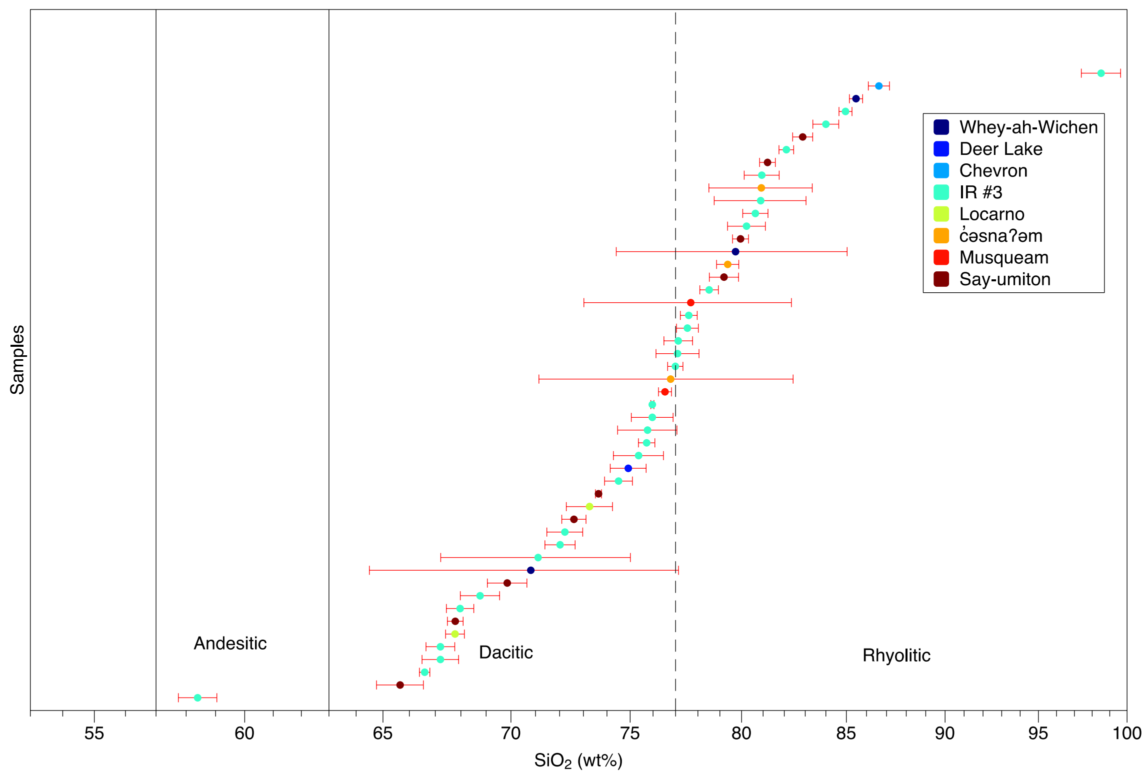


Figure 5.2 SiO_2 (wt%) for all study objects, by associated Site, with external (i.e., among multiple analyses) uncertainty (2SD).

Next, I incorporated the major elemental information from geological outcrop samples analyzed by Reddy (1989) from the Indian River and the Stawamus River Valleys. In total, Reddy (1989) analyzed 31 samples and 10 duplicates for major, minor and trace elements. His methods of analysis included the crushing, pulverizing and fusion of geological samples into pellets, which were then analyzed with WD-XRF analysis, which makes this data useable for comparison. Of those 41 samples, I used the 26 fine-grained samples and 8 duplicates to compare with the study objects (see Table 5.5 and Appendix D for more information). To begin, I plotted a second TAS diagram (Figure 5.3) to investigate if there were any rock types similar to the study objects that I have identified to be the toolstone known as ‘green andesite.

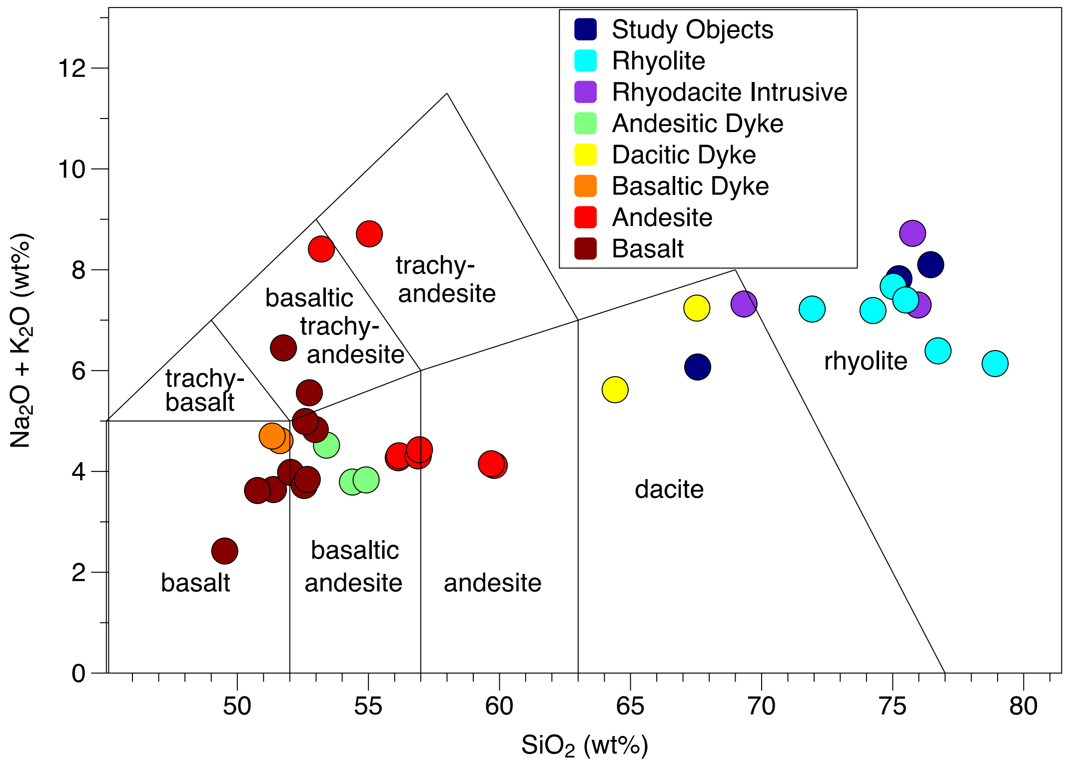


Figure 5.3 Total Alkali Silica Diagram for study objects that underwent WD-XRF analysis, plotted with Reddy's (1989) IRW samples. Dark blue markers indicate study objects analyzed for this thesis research and other colours indicate data from Reddy (1989).

As Figure 5.1 shows, none of the three samples that underwent WD-XRF analysis can be classified as andesitic. Further, as Figure 5.2 shows, even without the alkali elemental concentrations, all but one of the study objects fall outside of the andesitic category. This apparent outlier (Krt-14) is discussed more extensively below. Figure 5.3 shows that there is some overlap between those three study objects that underwent WD-XRF analysis with the rhyolitic samples Reddy identified in his work (1989:89).

The study objects cluster closely with rhyolites from the Lower and Middle Goat Mountain Formations and from the rhyodacitic intrusive units which Reddy describes as "quartz feldspar porphyritic rhyodacite intrusives" (1989:70). Note here that the andesite dykes that had previously been attributed as the source of the toolstone called green andesite (Toffolo et Al. 2019; Lepofsky, Trost and Morin 2007; Morin 2015) belong to Unit D “Late Stage Intrusive Dykes” (Reddy 1989:71), and all of these andesite dyke samples fall within the basaltic andesite category of the TAS diagram and outside of the study object cluster.

5.2 Implications for Object Provenance

Again, since it is possible that the origin of this material known as green andesite is within the Indian River watershed, and since it seems that Reddy’s (1989) thesis is the inspiration for the green andesite label, it is only appropriate that I use the element concentration data available in his thesis to exclude possible geological source affiliations for my study objects. Both Figures 5.4 and 5.5 show that the study objects overlap with the rhyolites, the quartz feldspar porphyritic rhyodacite intrusives and the dacite dyke samples (Reddy 1989). Based on major and minor element compositions, the basalt, andesite, basalt dyke and andesite dyke samples can be excluded as similar material types. This, in conjunction with the WD-XRF results plotted in the TAS diagrams (Figures 5.1 and 5.3), allow me to confidently conclude that the study objects exhibit a range of silica concentrations and are not andesitic with the possible exception of sample Krt-14. They are typically rhyolitic and dacitic. Andesite, dacite, and rhyolite refer to specific extrusive igneous rock types identifiable by the presence of interlocking crystals and other textural characteristics. Without petrographic analysis to determine if the analyzed materials are igneous in origin (i.e., they show interlocking crystals), we cannot use these terms in any capacity except as modifiers (e.g., andesitic, dacitic, and rhyolitic).

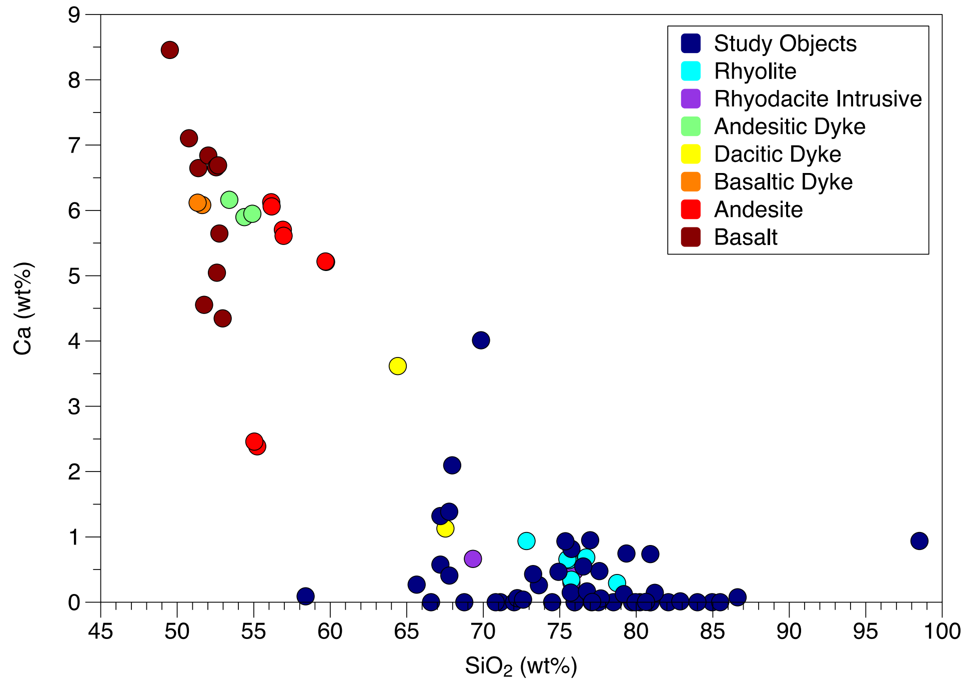


Figure 5.4 SiO_2 (wt%) versus Ca (wt%) concentrations of study objects and geological samples from IRW.

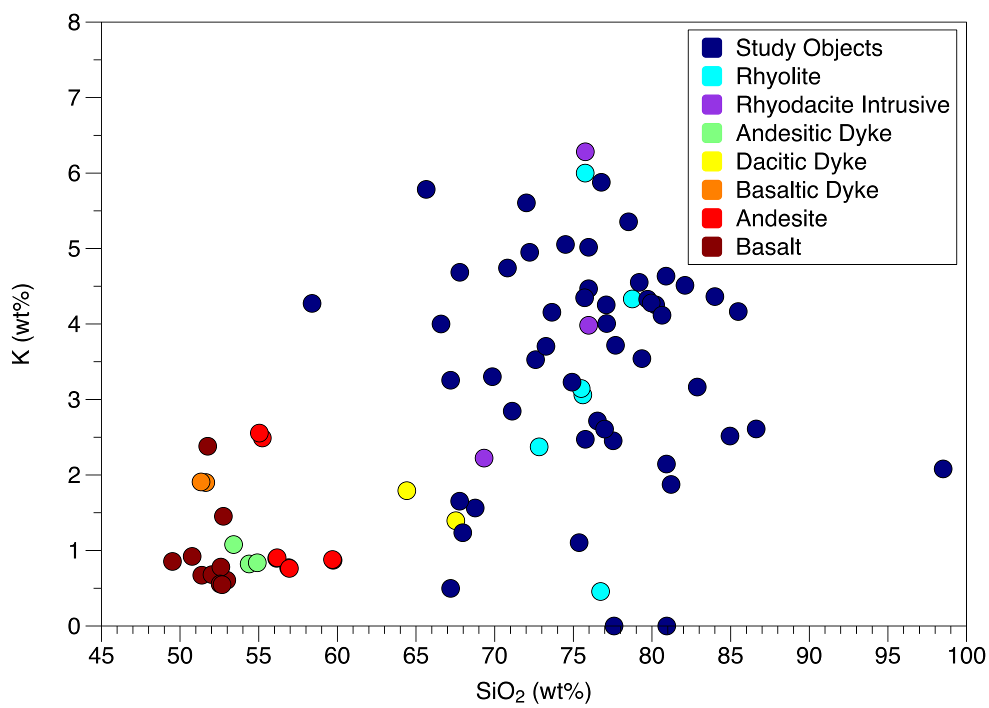
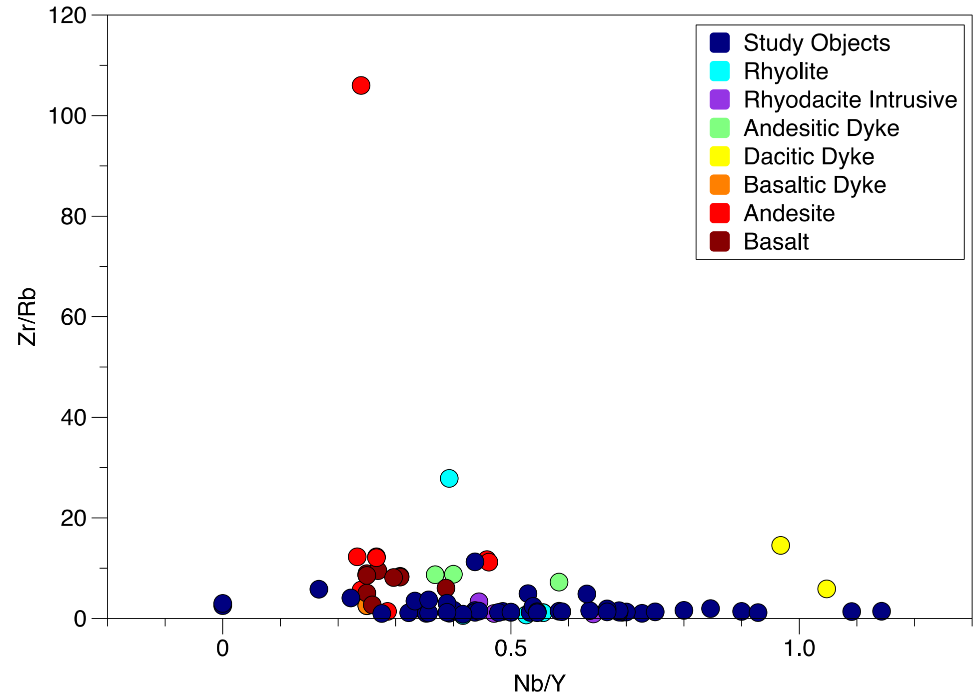


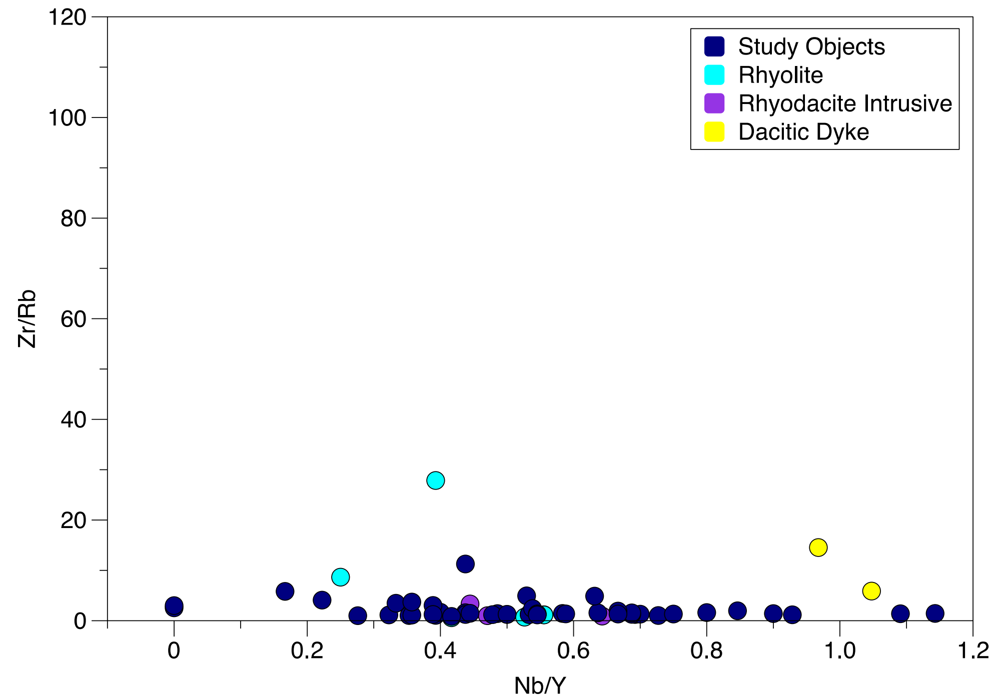
Figure 5.5 SiO_2 (wt%) versus K (wt%) concentrations of study objects and geological samples from IRW.

As Figure 5.6a shows, the trace element ratios for nearly all study objects overlap with all of Reddy's (1989) samples from the Indian River watershed. Based on these trace element ratios, the basalt, andesite, basalt dyke and andesite dyke samples from Reddy (1989) are clustered tightly with the study objects, although they are not the same rock type as the study objects. Similarly, Figure 5.7a shows that based on these trace elements, the basalt, andesite, basalt dyke and andesite dyke samples are again clustered tightly with the study objects, when they were excluded in previous figures based on their being completely dissimilar rock types. Both Figures 5.6b and 5.7b show less overlap between the study objects and the dacitic dyke geological samples, even though they are composed of a similar rock type. Thus, without the identification of rock type using major and minor elements and/or petrography prior to the comparison of the trace element composition of artifacts and possible source materials, the study objects would have been incorrectly sourced to geologic units that are compositionally dissimilar. With the use of only one, solitary proxy (trace elements), this erroneous association would unfortunately have been undetectable ('the sourcing myth'; Luedtke, 1992).

Finally, in Figure 5.8a there again appears to be a lot of overlap in the compositions of the study objects and all geological samples from Reddy (1989). However, I have established that the basalts, andesites, and the basalt and andesite dykes must be excluded as potential sources for this material.

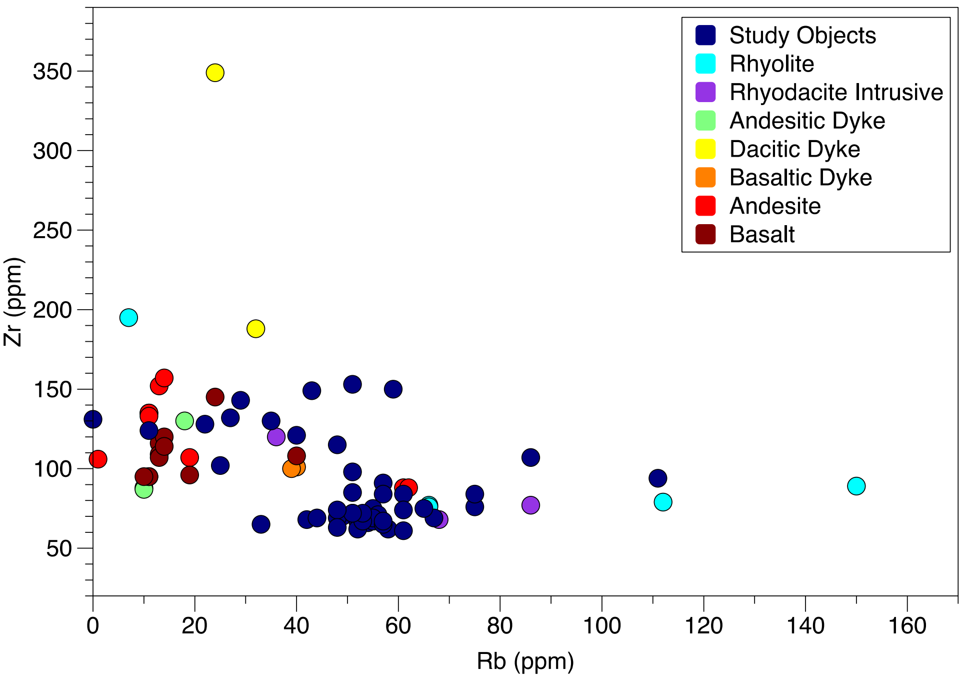


a.

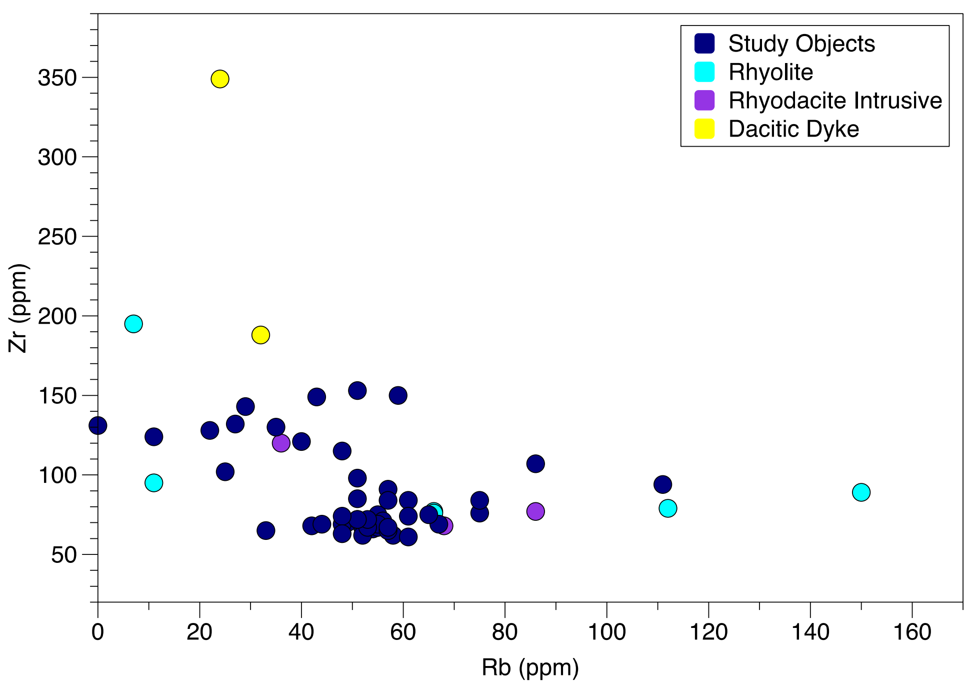


b.

Figure 5.6 a. Trace element ratios of Zr/Rb versus Nb/Y of study objects and geological samples from the IRW. b. Trace element ratios of study objects and those geological samples which have not been excluded on the basis of major and minor elements.

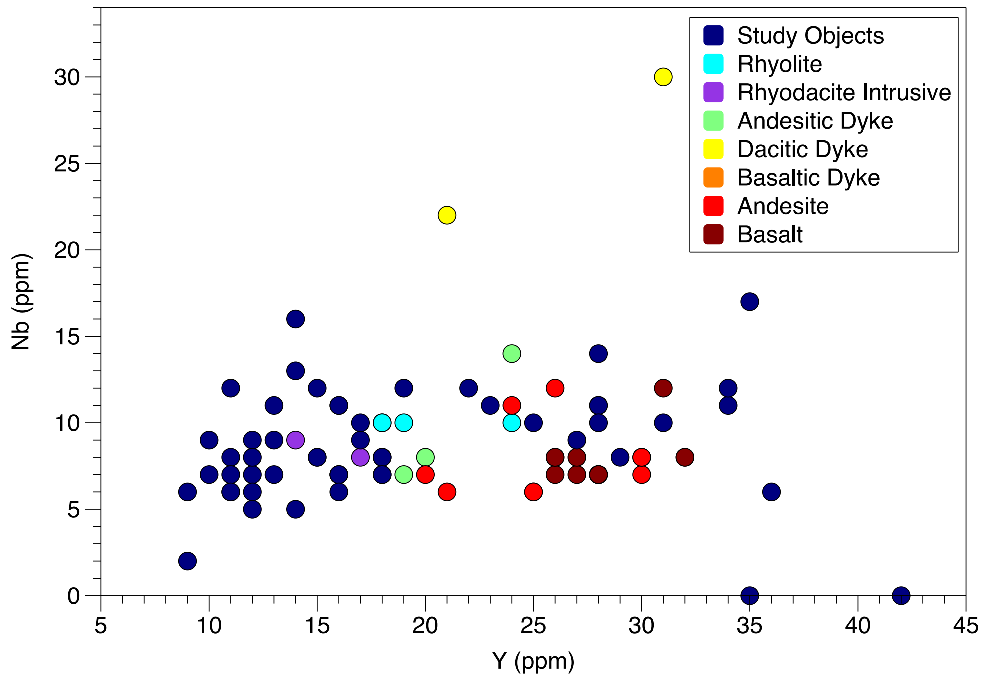


a.

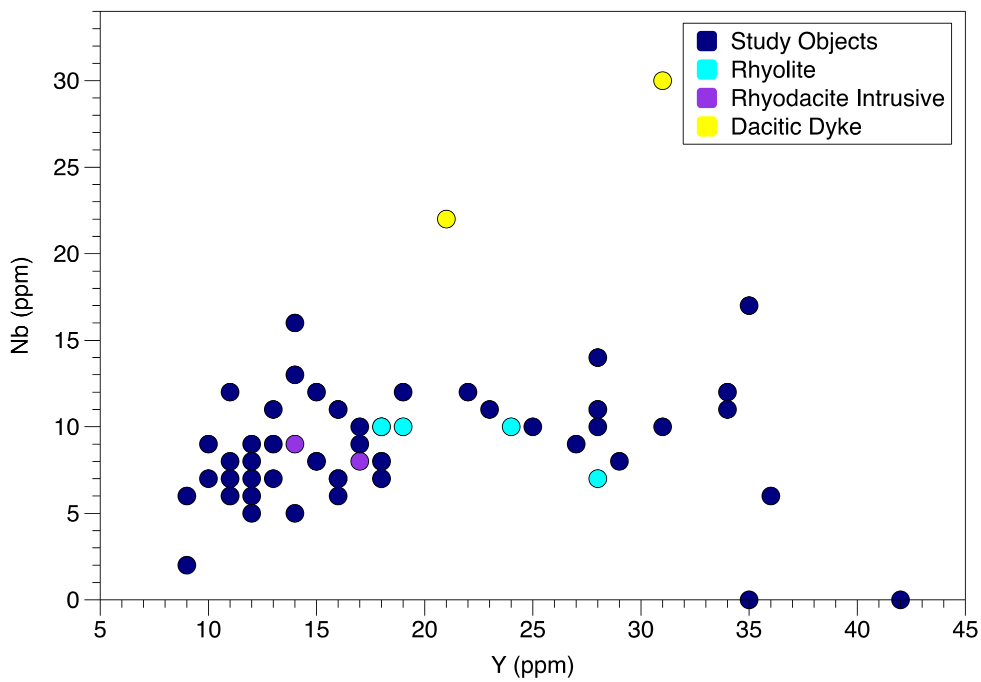


b.

Figure 5.7 a. Zr versus Rb of study objects and geological samples from the IRW. B. Zr versus Rb of study objects and those geological samples which have not been excluded on the basis of major and minor elements..



a.



b.

Figure 5.8 a. Nb versus Y of study objects and geological samples from the IRW b. Nb versus Y of study objects and those geological samples which have not been excluded on the basis of major and minor elements.

Based on the major and minor elemental concentrations, I can exclude the basalt, andesite, as well as the basalt and andesite dyke geological samples because they are different rock types. In addition, I can confidently exclude the dacitic dykes as a potential source because they are compositionally different from the study objects based on trace elements. Without excluding these sources based on composition, we would not be able to confidently exclude them based on trace elements alone. Therefore, all Indian River watershed sources except the Lower and Middle Goat Mountain Formation rhyolites and the quartz feldspar porphyritic rhyodacite intrusives can be consistently excluded as potential source affinities for all analyzed study objects.

5.3 Challenges

None of the analyzed samples can be classified as andesitic with the exception of one outlier. Study object Krt-14 is a projectile blank or preform which, like all others analyzed in this study, visually appears to be made of the material known as 'green andesite'. The initial pXRF analysis reading of the SiO_2 concentration for this object was 58.39 wt%. It was not selected to undergo destructive WD-XRF analysis, because, as a projectile blank or preform, it doesn't meet the criteria of an unmodified flake. Visual inspection reveals that it is compositionally heterogeneous, as there appears to be a contact of two material types in the middle. It is possible that this internal structure was an imperfection in the material that caused the projectile blank to be discarded and remain unfinished. This internal plane is likely representative of different lithologies with different SiO_2 concentrations.

I had the opportunity to resample this object on both faces. These additional analyses showed that the two faces of the preform indeed have different chemical compositions. The initial face tested (side A) had 54.23 SiO_2 wt% while the opposite face (side B) had 73.0 SiO_2 wt% (see Appendix E for photos of both sides, and resampling data). Ultimately, even though side A of this object plots in the andesitic range, it still cannot be considered andesite without petrographic analysis of textural relationships. Additionally, due to the surface morphology of the artifact and the challenges with measuring accurate Si concentrations with pXRF in atmosphere (most of which have been overcome with the Olympus Vanta series analyzers), the Si concentrations of the three samples analyzed with WD-XRF are consistently within 5% of the concentrations measured with pXRF in the same specimens (Appendix C), this lower silica concentration may be an instrumental artifact. If so, the concentration measured by pXRF is most likely an underestimation of Si, as interference with light elements would most likely decrease, not increase, Si concentrations. This suggests that if the Si concentrations are inaccurate for any of the analyses we conducted, they are likely lower than the actual 'true' value. This further supports that the objects referred to as 'green andesite' are at minimum dacitic in composition on average, with the potential of being even more felsic.

It is important to understand the rationale for the inclusion of multiple graphs representing the trace element concentrations and ratios. Without having identified the rock type of the study objects using major and minor elemental chemistry, it would appear as though there was overlap amongst all categories of rock type and the study objects (see Figures 5.7a, 5.8a and 5.9a for examples). Without the major and minor elemental data, it would appear as though the study objects could in fact be from the andesite dykes which Reddy (1989) documented in the Indian River Watershed. Utilizing major and minor elemental data to define rock types ensures that we are not comparing apples to oranges, figuratively speaking.

Chapter 6: Conclusion

I set out to explore a toolstone known as green andesite in the archaeological literature that features heavily in assemblages from Burrard Inlet. I had one main question: is it actually andesite? I determined that no, it is not andesite. Observed sedimentary petrographic textures suggest that it is not an extrusive igneous rock, and although it may be andesitic in some rare cases, it is more likely to be dacitic or rhyolitic. I can confidently conclude that the toolstone formerly known as green andesite is likely a volcanic sedimentary rock (perhaps a cherty tuff), with a typically dacitic to rhyolitic composition. Until a geological source for the material is found, I cannot definitively call it anything else. The next question I hoped to answer was: can known sources from within the Indian River watershed be excluded for this material? I determined that no, not all of them can be excluded as potential sources for the green toolstone.

Archaeologists assess rock type in the field and lab based on generalized characteristics. This sometimes results in the reproduction of an incorrect label throughout scholarly literature and archaeological discourse. In the past, this toolstone was called green andesite, and the designation has been reproduced in the literature and a handful of circular citations. Tofflo et al. (2019), Morin (2016), Reimer (2011), Lepofsky et al. (2007), Lepofsky and Karpiak (2001) all discuss this green andesite material, and several even speculate that it looks visually similar to the Anvil Island andesite documented by Reimer (2011). Reddy (1989) is likely the origin of this green andesite label, as in his thesis, he describes andesite and dacite dykes that crisscross the Indian River valley. While Reddy (1989) is likely the inspiration for the label, archaeologists are the source of the error in naming this toolstone.

Based on coverage in the archaeological literature, I assumed that this material was localized to Burrard Inlet, but my research indicates that it has a much more extensive spatial distribution. Fifty-one objects were included in the study, and from these, three pieces of unmodified debitage from IR #3 were submitted for destructive analysis. The major, minor, trace element and ratio data for these study objects spans a range of concentrations. None of the objects submitted for WD-XRF are andesitic. Based on silica content alone, all but one study object fall outside the andesitic range. The study objects are thus not from the andesite dykes that are the origin of the label green andesite. The basalts, andesites, and the basalt and andesite dykes from Reddy (1989) must be excluded as potential sources for this material due to their compositional dissimilarity.

All Indian River watershed sources except the Lower and Middle Goat Mountain Formation rhyolites and the quartz feldspar porphyritic rhyodacite intrusives can be consistently excluded as potential sources for all analyzed study objects, based on trace element concentrations. The outlier Krt-14 that falls into the andesitic range is compositionally heterogeneous. It is possible that based on the method of analysis the silica concentration is underestimated, and it may actually be dacitic. Had rock type not been established before trace element analysis, it would appear as though the study objects were geochemically similar to all rock types from the Indian River watershed, including the andesite dykes. Establishing rock type first, and then exploring multivariate and multiproxy approaches to toolstone sourcing studies and to the provenance hypothesis (McMillan et al. 2019) is the best defence against falling prey to the ‘sourcing myth’ (Ludtke 1992). Based on the major, minor and trace element concentrations, in conjunction with the Raman spectroscopy results and the petrographic findings, I have shown that the toolstone formerly known as green andesite is likely a volcanic sedimentary rock with a typically dacitic to rhyolitic composition.

6.1 Larger Implications for Archaeology and Future research directions

One problem I encountered while searching for objects to include in my study was an inconsistent material type classification between sites, regions, repositories, archaeologists and even the laboratory technicians entering data into repository catalogues. I hope that this research can be an important first step towards starting discussions and revisiting classifications throughout the region. At the very least, I hope that it inspires us as archaeologists to pause before reproducing unverified conclusions.

There are several directions future research could take. At the time of writing, I have made a connection with a geologist currently doing work in the Indian River watershed. When he learned that I was studying a green toolstone that could be called a “cherty tuff”, he gave me a bag of samples and a location to find the source. I intend to submit some of these geological samples to ALS for the ME-XRF26 analysis so I can compare the major, minor and trace element chemistry. If and when a geological source can be found, I would like to explore the material’s tool making qualities with experimental archaeology. Next, while time is a dimension I excluded from this study, it might be an interesting factor to include in later work. After exploring repositories and catalogues to correct the miscategorization issues, it would be useful to use temporal data associated with systematically excavated artifact assemblages to explore spatial and temporal trends.

Finally, and perhaps most excitingly, a preliminary exploration of the artifact catalogues from around the lower mainland suggest that this material, or objects that appear to be made of the same material, are not isolated to the Burrard Inlet locality. As my research shows with the inclusion of sites outside the Burrard Inlet area, the distribution of this toolstone goes much further than previously thought. It is also possible that multiple geological contexts for materials like this toolstone could be found across the landscape. A collaborative investigation with neighbouring Nations in the Coast Salish continuum would be a valuable next step. Together we could geochemically explore previously excavated assemblages and geological contexts within our territories and across the landscape to unravel the petrogenesis of this toolstone formerly known as green andesite.

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Appendices

Appendix A Study Objects

Table A.1 Elemental concentration data collected by pXRF for study objects analyzed in this thesis research used to create the averaged values reported in tables in text. All reported uncertainties are internal (instrumental).

Study Identifier	Repository Identifier	Repository / Collector	Site Name	Borden Number	Si (ppm)	Si Error 1 SD (ppm)	K (ppm)	K Error 1 SD (ppm)	Ca (ppm)	Ca Error 1 SD (ppm)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
Krt-1	n/a	LMT	Whey-ah-Wichen / Cates Park	DhRr-8	387062	701	43951	106	0	90	55	1	13	1	68	1	5	1
Krt-1	n/a	LMT	Whey-ah-Wichen / Cates Park	DhRr-8	365731	732	43162	112	0	103	56	1	12	1	66	1	11	1
Krt-1	n/a	LMT	Whey-ah-Wichen / Cates Park	DhRr-8	365356	727	42736	111	0	102	54	1	13	1	66	1	11	1
Krt-2	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	342960	772	26437	87	0	120	64	1	33	1	57	1	7	1
Krt-2	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	326969	789	29482	98	0	129	60	1	26	1	63	1	9	1
Krt-2	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	327382	788	29434	97	0	128	60	1	27	1	62	1	8	1
Krt-3	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	312927	994	5050	50	13275	63	12	1	17	1	123	2	6	1
Krt-3	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	313993	993	4916	49	13200	63	12	1	16	1	126	2	8	1
Krt-3	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	315514	995	4949	50	13076	63	10	1	15	1	123	2	6	1
Krt-4	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	316316	1092	12360	75	20813	90	41	1	17	1	121	2	8	1
Krt-4	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	318693	1098	12467	76	21117	91	39	1	19	1	122	2	8	1
Krt-4	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	318224	1093	12262	75	20932	90	41	1	19	1	120	2	6	1
Krt-5	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	349967	1136	11029	70	9242	57	22	1	36	1	128	2	7	1
Krt-5	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	352100	1142	11042	70	9336	57	22	1	36	1	128	2	6	1

Study Identifier	Repository Identifier	Repository / Collector	Site Name	Borden Number	Si (ppm)	Si Error 1 SD (ppm)	K (ppm)	K Error 1 SD (ppm)	Ca (ppm)	Ca Error 1 SD (ppm)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
Krt-5	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	355020	1146	11057	70	9403	57	22	1	37	1	129	2	5	1
Krt-6	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	311047	1176	40161	173	0	202	49	1	18	1	75	2	10	1
Krt-6	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	311862	1175	40127	173	0	201	48	1	16	1	75	2	12	1
Krt-6	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	311068	1169	39751	171	0	201	47	1	14	1	72	2	11	1
Krt-7	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	359129	1112	39989	151	145	45	85	1	18	1	107	2	6	1
Krt-7	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	360337	1111	39924	150	0	161	86	1	17	1	105	2	7	1
Krt-7	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	362098	1115	40268	151	0	160	88	1	18	1	108	2	7	1
Krt-8	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	359913	1036	26176	105	9512	59	50	1	10	1	100	2	7	1
Krt-8	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	359133	1031	26013	104	9455	58	52	1	9	1	99	1	6	1
Krt-8	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	360708	1032	26042	104	9466	58	51	1	7	1	96	1	5	1
Krt-9	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	375919	1027	41133	139	152	43	47	1	13	1	63	1	7	1
Krt-9	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	376531	1026	41074	139	0	142	49	1	12	1	63	1	9	1
Krt-9	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	378542	1027	41314	139	0	141	49	1	11	1	62	1	9	1
Krt-10	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	366123	981	53460	165	0	142	56	1	17	1	93	1	7	1
Krt-10	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	368066	983	53598	165	0	142	57	1	15	1	90	1	7	1
Krt-10	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	366978	979	53584	165	0	141	58	1	16	1	91	1	6	1
Krt-11	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	347867	1055	50805	175	0	156	59	1	27	1	64	1	12	1
Krt-11	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	347125	1052	50458	174	0	155	58	1	29	1	63	1	12	1
Krt-11	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	349820	1054	50363	173	0	155	57	1	27	1	60	1	10	1
Krt-12	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	312507	1040	32560	131	5704	51	75	1	11	1	76	1	7	1
Krt-12	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	314162	1041	32367	130	5733	52	75	1	11	1	77	1	9	1

Study Identifier	Repository Identifier	Repository / Collector	Site Name	Borden Number	Si (ppm)	Si Error 1 SD (ppm)	K (ppm)	K Error 1 SD (ppm)	Ca (ppm)	Ca Error 1 SD (ppm)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
Krt-12	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	315846	1046	32752	132	5805	52	76	1	11	1	75	1	9	1
Krt-13	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	375096	1025	46018	152	0	135	52	1	14	1	67	1	6	1
Krt-13	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	375470	1029	46237	153	0	136	52	1	14	1	68	1	10	1
Krt-13	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	383998	1021	46792	151	0	130	52	1	16	1	67	1	9	1
Krt-14	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	271411	1020	42579	172	860	44	55	1	10	1	68	1	7	1
Krt-14	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	273024	1021	42396	171	887	44	51	1	10	1	65	1	7	1
Krt-14	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	274456	1026	43203	174	933	46	54	1	11	1	71	1	8	1
Krt-15	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	397894	1007	25231	95	0	119	33	1	12	1	67	1	11	1
Krt-15	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	396415	1003	25123	95	0	119	33	1	15	1	64	1	11	1
Krt-15	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	397259	1003	25124	95	0	119	34	1	13	1	65	1	12	1
Krt-16	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	350727	992	24538	97	7991	52	58	1	40	1	148	2	0	2
Krt-16	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	355434	1002	24844	98	8191	53	61	1	42	1	151	2	0	2
Krt-16	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	356419	1002	24829	98	8271	54	59	1	43	1	150	2	0	2
Krt-17	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	362013	1083	0	124	4888	42	3	1	35	1	264	2	10	1
Krt-17	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	362422	1079	0	124	4682	41	0	1	33	1	260	2	12	1
Krt-17	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	363732	1081	0	123	4711	42	3	1	33	1	265	2	11	1
Krt-18	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	319452	1005	15612	80	0	160	29	1	16	1	142	2	8	1
Krt-18	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	322985	1011	15651	80	0	159	29	1	17	1	145	2	8	1
Krt-18	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	321966	1008	15610	80	0	159	30	1	17	1	143	2	10	1
Krt-19	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	352671	1057	49816	171	0	150	55	1	28	1	67	1	14	1
Krt-19	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	356335	1064	50500	173	0	150	54	1	27	1	66	1	14	1

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Krt-19	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	356434	1061	50174	172	0	149	53	1	28	1	66	1	14	1
Krt-20	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	357860	1039	42381	148	0	146	53	1	14	1	61	1	7	1
Krt-20	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	361350	1045	42676	149	0	146	52	1	15	1	63	1	9	1
Krt-20	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	362042	1043	42527	148	0	145	51	1	16	1	63	1	8	1
Krt-21	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	355219	1023	44855	151	0	133	52	1	24	1	86	1	11	1
Krt-21	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	355319	1019	44705	150	0	132	50	1	24	1	86	1	9	1
Krt-21	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	354994	1018	44476	150	0	132	50	1	26	1	83	1	11	1
Krt-22	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	383214	1038	45373	149	0	125	49	1	12	1	69	1	6	1
Krt-22	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	383477	1034	44855	147	0	124	48	1	12	1	69	1	8	1
Krt-22	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	384732	1036	45160	148	0	123	49	1	13	1	72	1	7	1
Krt-23	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	374411	1053	42555	146	0	133	51	1	35	1	72	1	16	1
Krt-23	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	373444	1051	42127	144	0	133	52	1	33	1	73	1	16	1
Krt-23	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	377393	1059	42932	147	0	133	51	1	37	1	72	1	18	1
Krt-24	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	391020	992	43606	136	0	111	56	1	17	1	67	1	6	1
Krt-24	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	393432	991	43616	136	0	110	55	1	15	1	65	1	8	1
Krt-24	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	393722	992	43711	136	0	110	54	1	16	1	68	1	7	1
Krt-25	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	334986	1091	55915	198	0	150	62	1	11	1	84	2	13	1
Krt-25	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	337387	1093	56079	198	0	149	59	1	10	1	84	2	10	1
Krt-25	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	337660	1094	56156	199	0	149	61	1	11	1	85	2	12	1
Krt-26	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	353616	1034	43782	150	1465	42	53	1	12	1	71	1	9	1
Krt-26	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	354943	1033	43422	149	1492	42	54	1	11	1	69	1	10	1

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Krt-26	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	353392	1028	43230	148	1474	42	52	1	13	1	69	1	8	1
Krt-27	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	335845	1053	49228	173	641	43	61	1	23	1	73	1	10	1
Krt-27	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	337656	1055	49538	173	589	42	62	1	22	1	74	1	11	1
Krt-27	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	339368	1057	49754	174	589	43	60	1	24	1	75	1	11	1
Krt-28	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	457519	1104	20548	89	9278	55	51	1	36	1	151	2	0	2
Krt-28	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	461940	1108	20926	90	9436	56	49	1	34	1	155	2	0	2
Krt-28	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	462138	1108	20953	90	9384	56	52	1	36	1	154	2	0	2
Krt-29	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	361358	1026	24363	98	0	124	48	1	13	1	115	1	6	1
Krt-29	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	362391	1028	24735	100	0	124	48	1	13	1	114	1	9	1
Krt-29	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	363665	1026	24499	99	0	124	47	1	13	1	115	1	7	1
Krt-30	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	376829	1044	0	115	0	124	0	1	16	1	130	1	7	1
Krt-30	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	377825	1043	0	115	0	123	0	1	16	1	130	1	5	1
Krt-30	n/a	LMT	Sleil-Waututh / IR 3	DhRr-15/20	380542	1048	0	114	0	123	0	1	17	1	133	1	6	1
Krt-31	DhRr18-1	TWN	Say-umiton / Strathcona	DhRr-18	338281	1045	35151	132	420	38	43	1	15	1	69	1	13	1
Krt-31	DhRr18-1	TWN	Say-umiton / Strathcona	DhRr-18	339286	1045	35295	132	386	37	42	1	14	1	67	1	10	1
Krt-31	DhRr18-1	TWN	Say-umiton / Strathcona	DhRr-18	340654	1049	35388	133	374	38	42	1	16	1	67	1	12	1
Krt-32	DhRr18-3	TWN	Say-umiton / Strathcona	DhRr-18	368915	1029	45393	151	1238	42	55	1	17	1	75	1	9	1
Krt-32	DhRr18-3	TWN	Say-umiton / Strathcona	DhRr-18	369777	1030	45435	151	1230	41	56	1	17	1	76	1	11	1
Krt-32	DhRr18-3	TWN	Say-umiton / Strathcona	DhRr-18	371940	1034	45750	151	1233	42	55	1	17	1	75	1	9	1
Krt-33	DhRr18-4	TWN	Say-umiton / Strathcona	DhRr-18	316060	992	46856	163	4058	45	55	1	16	1	71	1	12	1
Krt-33	DhRr18-4	TWN	Say-umiton / Strathcona	DhRr-18	317449	994	46906	163	4029	45	56	1	16	1	71	1	11	1

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Krt-33	DhRr18-4	TWN	Say-umiton / Strathcona	DhRr-18	317067	991	46801	162	4176	46	58	1	16	1	71	1	10	1
Krt-34	DhRr18-5	TWN	Say-umiton / Strathcona	DhRr-18	372806	1033	42872	143	0	127	55	1	11	1	69	1	6	1
Krt-34	DhRr18-5	TWN	Say-umiton / Strathcona	DhRr-18	374432	1032	42779	143	0	127	56	1	12	1	69	1	7	1
Krt-34	DhRr18-5	TWN	Say-umiton / Strathcona	DhRr-18	374090	1031	42732	143	0	127	53	1	13	1	69	1	6	1
Krt-35	DhRr18-6	TWN	Say-umiton / Strathcona	DhRr-18	324919	1002	32711	123	39777	131	52	1	11	1	66	1	6	1
Krt-35	DhRr18-6	TWN	Say-umiton / Strathcona	DhRr-18	326198	1005	33083	124	40094	132	54	1	11	1	66	1	4	1
Krt-35	DhRr18-6	TWN	Say-umiton / Strathcona	DhRr-18	328594	1008	33259	124	40455	133	54	1	11	1	68	1	9	1
Krt-36	DhRr18-8	TWN	Say-umiton / Strathcona	DhRr-18	304649	1020	57453	202	2703	47	64	1	33	1	71	1	11	1
Krt-36	DhRr18-8	TWN	Say-umiton / Strathcona	DhRr-18	307284	1025	57937	204	2660	47	70	1	34	1	67	1	13	1
Krt-36	DhRr18-8	TWN	Say-umiton / Strathcona	DhRr-18	308758	1025	58135	204	2706	47	67	1	34	1	69	1	13	1
Krt-37	DhRr18-18	TWN	Say-umiton / Strathcona	DhRr-18	386600	1098	31698	121	198	39	44	1	11	1	68	1	9	1
Krt-37	DhRr18-18	TWN	Say-umiton / Strathcona	DhRr-18	387016	1200	31622	144	0	174	44	1	12	1	69	1	6	1
Krt-37	DhRr18-18	TWN	Say-umiton / Strathcona	DhRr-18	388728	1096	31635	120	162	38	45	1	11	1	70	1	6	1
Krt-38	DhRr-8-452	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	344066	1035	41617	147	2613	43	54	1	23	1	73	1	12	1
Krt-38	DhRr-8-452	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	344647	1036	41677	147	2715	43	54	1	21	1	71	1	12	1
Krt-38	DhRr-8-452	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	344173	1034	41405	146	2493	42	51	1	21	1	72	1	11	1
Krt-39	DhRr-8-515	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	379893	1054	18845	84	1415	36	27	1	20	1	132	2	13	1
Krt-39	DhRr-8-515	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	378721	1048	18577	83	1481	36	26	1	19	1	132	2	13	1

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Krt-39	DhRr-8-515	TWN	Whey-ah-Wichen / Cates Park	DhRr-8	380414	1052	18804	84	1381	36	27	1	19	1	133	2	10	1
Krt-44	BV002.57.13	BVM	Deer Lake	DhRr-28	351712	1049	32536	123	4695	46	65	1	33	1	77	1	10	1
Krt-44	BV002.57.13	BVM	Deer Lake	DhRr-28	348227	1039	31987	121	4596	45	65	1	29	1	75	1	8	1
Krt-44	BV002.57.13	BVM	Deer Lake	DhRr-28	350875	1046	32384	122	4670	46	66	1	30	1	73	1	12	1
Krt-45	DhRt-6:6065	LOA	Locarno Beach	DhRt-6	340243	1134	36825	148	4304	49	49	1	13	1	66	1	17	1
Krt-45	DhRt-6:6065	LOA	Locarno Beach	DhRt-6	344802	1147	37232	150	4319	50	48	1	15	1	70	2	14	1
Krt-45	DhRt-6:6065	LOA	Locarno Beach	DhRt-6	342393	1138	37093	149	4243	49	47	1	15	1	70	2	16	1
Krt-46	DhRr-8a:25	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	348100	1027	49394	166	0	132	60	1	12	1	69	1	8	1
Krt-46	DhRr-8a:25	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	322285	1054	46495	170	0	149	54	1	10	1	63	1	7	1
Krt-46	DhRr-8a:25	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	322785	1055	46354	170	0	149	56	1	12	1	63	1	4	1
Krt-47	DhRr-8a:27	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	398963	1029	41647	136	0	115	52	1	10	1	71	1	8	1
Krt-47	DhRr-8a:27	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	399478	1031	41607	136	0	115	51	1	10	1	72	1	9	1
Krt-47	DhRr-8a:27	LOA	Whey-ah-Wichen / Cates Park	DhRr-8	400463	1032	41698	136	0	115	50	1	9	1	72	1	11	1
Krt-48	Ma:7406	LOA	c̓əsnaʔəm / Marpole	DhRs-1	372310	1016	21351	88	8070	49	45	1	28	1	153	2	10	1
Krt-48	Ma:7406	LOA	c̓əsnaʔəm / Marpole	DhRs-1	379137	1021	20886	87	7727	49	42	1	27	1	154	2	8	1
Krt-48	Ma:7406	LOA	c̓əsnaʔəm / Marpole	DhRs-1	383538	1049	22124	92	6286	47	41	1	26	1	141	2	10	1
Krt-49	Ma:3561	LOA	c̓əsnaʔəm / Marpole	DhRs-1	369823	1072	35165	129	7596	53	76	1	13	1	84	1	5	1
Krt-49	Ma:3561	LOA	c̓əsnaʔəm / Marpole	DhRs-1	370964	1072	35360	130	7380	52	74	1	14	1	85	1	5	1
Krt-49	Ma:3561	LOA	c̓əsnaʔəm / Marpole	DhRs-1	372197	1074	35712	131	7404	52	75	1	15	1	84	1	4	1

Study Identifier	Repository Identifier	Repository / Collector	Site Name	Borden Number	Si (ppm)	Si Error 1 SD (ppm)	K (ppm)	K Error 1 SD (ppm)	Ca (ppm)	Ca Error 1 SD (ppm)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
Krt-50	MuE:3488	LOA	Stselax / Musqueam East	DhRt-2	358568	1076	27400	111	5926	48	58	1	19	1	84	1	8	1
Krt-50	MuE:3488	LOA	Stselax / Musqueam East	DhRt-2	357256	1056	26979	108	5286	45	56	1	17	1	83	1	8	1
Krt-50	MuE:3488	LOA	Stselax / Musqueam East	DhRt-2	357590	1055	27096	108	5177	45	56	1	18	1	84	1	9	1
Krt-51	Ma:8577	LOA	c̓əsnaʔəm / Marpole	DhRs-1	343735	1059	57065	193	2545	48	110	1	12	1	88	1	5	1
Krt-51	Ma:8577	LOA	c̓əsnaʔəm / Marpole	DhRs-1	365631	1075	59983	197	1218	47	112	1	13	1	99	2	5	1
Krt-51	Ma:8577	LOA	c̓əsnaʔəm / Marpole	DhRs-1	367429	1073	59279	194	1180	47	110	1	11	1	94	2	5	1
Krt-52	MuNe:1007	LOA	Musqueam North East	DhRt-4	374200	1095	37762	138	580	40	58	1	12	1	68	1	11	1
Krt-52	MuNe:1007	LOA	Musqueam North East	DhRt-4	362939	1111	38637	145	408	41	56	1	15	1	67	1	14	1
Krt-52	MuNe:1007	LOA	Musqueam North East	DhRt-4	352399	1118	35156	138	694	40	58	1	16	1	67	1	13	1
Krt-53	DhRt-6:5954	LOA	Locarno Beach	DhRt-6	315863	1001	16577	80	14144	64	35	1	28	1	131	2	10	1
Krt-53	DhRt-6:5954	LOA	Locarno Beach	DhRt-6	317137	1000	16539	80	13818	63	35	1	29	1	131	2	9	1
Krt-53	DhRt-6:5954	LOA	Locarno Beach	DhRt-6	317490	1001	16459	80	13576	63	35	1	27	1	127	2	10	1
Krt-55	DhRr-230:4	LOA	Chevron	DhRr-230	405237	1085	26141	102	802	37	25	1	9	1	103	2	5	1
Krt-55	DhRr-230:4	LOA	Chevron	DhRr-230	406046	1084	26161	102	737	36	25	1	10	1	102	2	0	2
Krt-55	DhRr-230:4	LOA	Chevron	DhRr-230	403619	1077	25993	101	721	36	25	1	9	1	100	2	0	2

Appendix B WD-XRF Results from ME-XRF Analysis (ALS Global Geochemical)

Table B.1 Complete table of all oxides from WD-XRF analysis

Sample	Al_2O_3 (wt%)	BaO (wt%)	CaO (wt%)	Cr_2O_3 (wt%)	Fe_2O_3 (wt%)	K_2O (wt%)	MgO (wt%)	MnO (wt%)	Na_2O (wt%)	P_2O_5 (wt%)	SO_3 (wt%)	SiO_2 (wt%)	SrO (wt%)	TiO_2 (wt%)	Total (wt%)
Krt-2	12.69	0.27	0.49	<0.01	2.79	5.06	0.35	0.04	2.76	0.02	0.01	75.24	0.02	0.07	99.86
Krt-3	16.44	0.06	2.2	<0.01	3.2	0.8	2.09	0.1	5.27	0.21	<0.01	67.56	0.06	0.33	99.34
Krt-9	12.25	0.31	0.31	<0.01	1.54	5.25	0.24	0.03	2.85	0.02	<0.01	76.45	0.02	0.06	99.25

Table B.1 WD-XRF and pXRF SiO_2 concentrations.

Sample	**SiO_2 (wt%)**
Krt-2	75.24
Krt-2 pXRF	71.11
Krt-3	67.56
Krt-3 pXRF	67.20
Krt-9	76.45
Krt-9 pXRF	80.64

Appendix C IRW Samples from Reddy (1989)

Table C.1 Data from Reddy (1989), selected fine-grained samples and duplicates.

Sample #	Type	Ba (ppm)	Cr (ppm)	Nb (ppm)	Ni (ppm)	Rb (ppm)	Sr (ppm)	V (ppm)	Y (ppm)	Zr (ppm)	Si (wt%)	K (wt%)	Ca (wt%)
86IRD-50	Rhyodacite Intrusive	2343	0	8	2	68	110	19	17	68	35.51	3.98	0.48
87IRD-166	Rhyodacite Intrusive	3286	1	9	0	86	117	36	14	77	35.41	6.28	0.30
87IRD-169	Rhyodacite Intrusive	862	3	8	3	36	125	55	18	120	32.41	2.22	0.66
87IRD-145	Andesitic Dyke	418	94	8	5	10	607	205	20	88	25.42	0.82	5.90
87IRD-161	Dacitic Dyke	877	6	22	6	32	607	65	21	188	30.11	1.79	3.62
87IRD-75	Andesitic Dyke	330	34	14	40	18	552	207	24	130	24.96	1.08	6.16
87IRD-145d	Andesitic Dyke	405	140	7	70	10	615	206	19	87	25.67	0.84	5.95
87IRD-63	Dacitic Dyke	489	3	30	9	24	440	12	31	349	31.57	1.39	1.13
86IRD-53a	Basaltic Dyke	942	68	7	56	40	502	268	28	101	24.13	1.90	6.08
86IRD-53b	Basaltic Dyke	969	69	7	56	39	499	262	28	100	23.99	1.91	6.12
86IRD-161	Rhyolite	1797	1	10	5	150	63	20	24	89	35.41	6.00	0.34
86IRD-122	Rhyolite	846	3	10	2	112	47	9	19	79	36.81	4.33	0.29
86IRD-189	Rhyolite	252	146	7	79	11	397	206	28	95	34.04	2.37	0.94
86IRD-193a	Andesite	255	4	11	7	13	366	106	24	152	27.92	0.87	5.21
86IRD-121	Rhyolite	1323	1	10	1	66	143	16	18	77	35.34	3.06	0.64
87IRD-151a	Andesite	1150	6	7	13	61	267	219	20	88	25.82	2.49	2.39
87IRD-97	Rhyolite	140	7	11	7	7	85	13	28	195	35.87	0.46	0.69
87IRD-64a	Andesite	165	111	6	61	19	429	178	25	107	26.24	0.90	6.13
87IRD-192	Andesite	509	76	7	49	11	690	210	30	135	26.60	0.77	5.70
86IRD-187	Basalt	252	146	7	79	11	397	206	28	95	24.76	0.61	4.35
86IRD-193b	Andesite	259	4	12	7	14	379	102	26	157	27.90	0.88	5.22
86IRD-121d	Rhyolite	1328	146	10	0	66	141	13	18	76	35.29	3.15	0.66
87IRD-151b	Andesite	1116	7	6	15	62	270	226	21	88	25.73	2.56	2.46
87IRD-179	Basalt	321	172	8	95	13	511	220	32	116	24.02	0.67	6.65
87IRD-185	Basalt	627	66	12	35	24	541	231	31	145	24.66	1.45	5.65
87IRD-60	Basalt	422	105	7	64	10	550	215	26	95	24.32	0.68	6.84
87IRD-88	Basalt	216	119	7	70	19	557	235	28	96	23.73	0.92	7.11
87IRD-64b	Andesite	153	111	6	58	1	423	183	25	106	26.26	0.90	6.06
87IRD-133	Basalt	309	162	8	81	14	462	228	32	120	24.58	0.78	5.05
87IRD-72	Basalt	216	136	8	67	13	527	224	26	109	24.56	0.56	6.66
87IRD-72d	Basalt	199	181	8	65	13	518	224	26	107	24.62	0.55	6.69
87IRD-76	Basalt	670	137	7	74	40	340	222	27	108	24.19	2.38	4.55
87IRD-79	Basalt	246	211	8	97	14	530	268	27	114	23.15	0.85	8.46
87IRD-192d	Andesite	508	136	8	47	11	687	214	30	133	26.62	0.76	5.61

Appendix D The Outlier, Krt-14

Figure D.1 Study object Krt-14, both faces**.**

Table D.1 Study Object Krt-14 elemental concentration data collected by pXRF for multiple analyses on both faces. All reported uncertainties are internal (instrumental).

Study Identifier	Si (ppm)	Si Error 1 SD (ppm)	K (ppm)	K Error 1 SD (ppm)	Ca (ppm)	Ca Error 1 SD (ppm)	Rb (ppm)	Rb Error 1 SD (ppm)	Y (ppm)	Y Error 1 SD (ppm)	Zr (ppm)	Zr Error 1 SD (ppm)	Nb (ppm)	Nb Error 1 SD (ppm)
Krt-14a	343496	981	28548	106	2167	37	50	1	27	1	64	1	10	1
Krt-14a	339817	990	34995	125	857	37	51	1	32	1	66	1	16	1
Krt-14a	341506	975	28483	106	2198	37	49	1	28	1	66	1	9	1
Krt-14a	338369	986	34663	123	833	36	50	1	32	1	66	1	13	1
Krt-14a	343114	978	28457	106	2168	37	48	1	29	1	67	1	9	1
Krt-14b	246575	1061	35984	166	1453	42	56	1	10	1	70	2	11	1
Krt-14b	255778	993	35624	150	1744	41	51	1	10	1	68	1	7	1
Krt-14b	249713	1075	36066	167	1460	43	54	1	13	1	71	2	12	1
Krt-14b	257893	1005	36163	153	1770	41	51	1	9	1	70	1	6	1
Krt-14b	257766	1004	36344	154	1777	40	51	1	11	1	72	1	6	1