**Volcano-Stratigraphy and Major Element Geochemistry of the Southern
Natkusiak Formation Flood Basalts of Victoria Island: Insights Into the Initiation of
the Neoproterozoic Franklin Magmatic Event**

by

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Abstract

Neoproterozoic volcanic rocks of the Franklin Magmatic Event are exposed within the Minto Inlier on Victoria Island, Northwest Territories. This study addresses the physical volcanology, stratigraphy and major element chemostratigraphy of the southern lobe Natkusiak Formation flood basalts. The southern Natkusiak Formation is herein divided into four units. The basal unit consists of rare pillowed flows and common, laterally discontinuous, thin, and lobate high-magnesium tholeiite flows. These are overlain by a massive volcanoclastic conglomerate and quartz-rich volcanoclastic sandstone. The upper volcanic unit comprises thick high-iron tholeiite flows that are utilized as a stratigraphic datum. The four units are correlative to the previously established lower Natkusiak Formation stratigraphy of the northern lobe. Basal units of the volcanic pile show marked lateral thickness variations implying existence of significant topography prior to onset of the main phase of Franklin flood volcanism associated with the breakup of Rodinia.

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Table of Contents

Abstract.....	ii
Acknowledgements.....	iii
Table of Contents.....	v
List of Tables.....	ix
List of Figures.....	x
List of Appendices.....	xiii
Chapter 1: Introduction.....	1
1.1 Study Purpose and Objectives.....	2
1.2 Continental Flood Basalt Provinces: causes, products and architecture.....	3
1.3 The Franklin Magmatic Event on Victoria Island, Arctic Canada: Products, Regional Geology, and Previous Studies.	8
1.3.1 The Franklin Magmatic Event.....	8
1.3.2 The Minto Inlier and Natkusiak Formation.....	8
Chapter 2: Physical Volcanology and Stratigraphy of the Southern Lobe of the Natkusiak Formation.....	17
2.1 Introduction.....	17

2.2 Field Methods and Sampling.....	17
2.3 Southern lobe type section lithostratigraphy.....	19
2.3.1 Basal unit (V_0)	22
2.3.2 Volcaniclastic units C_1 & C_2	25
2.3.3 Flow unit V_1	27
2.4 Volcano-stratigraphic sections and correlations of the southern lobe.....	31
2.5 Volcanic vent complexes.....	32
2.6 Type section mineral chemistry.....	36
Chapter 3: Major and Select Trace Element Geochemistry and Chemostratigraphy of the Southern Lobe, Natkusiak Formation.....	61
3.1 Introduction.....	61
3.2 Sampling and analytical methods.....	61
3.2.1 Field sampling.....	61
3.2.2 Analytical methods.....	63
3.3 Lithogeochemistry: Major and select trace elements.....	65
3.3.1 Major and traces: general behaviour.....	65
3.3.2 Geochemistry of volcaniclastic unit C_1	68

3.3.3 Geochemical alteration in the southern lobe.....	69
3.4 Chemostratigraphy of southern lobe type sections.....	72
Chapter 4: Discussion and Implications.....	83
4.1 Southern lobe lithostratigraphy, regional variations, and implications for the initiation and evolution of the Franklin Magmatic Event.....	83
4.1.1 Significance of the Natkusiak Formation lithostratigraphy.....	83
4.1.2 Significance of southern lobe unit distribution and correlations....	90
4.2 Vent complex or no vent complex?	93
4.3 Geochemistry of the southern lobe, variations within the stratigraphy, and implications.....	96
4.3.1 Implications of southern lobe geochemistry and chemostratigraphy.....	96
4.3.2 Alteration of Natkusiak Formation southern lobe samples.....	100
4.4 Comparisons between the southern and northern lobes of the Natkusiak Formation.....	102
4.4.1 Volcano-stratigraphy.....	102
4.4.2 Chemostratigraphy.....	104

4.5 Summary, conclusions, and additional work.....	107
References.....	116

List of Tables

Table 1.1: Summary of northern lobe Natkusiak Formation volcanic units described by Jefferson et al. (1985).

Table 2.1: Summary of southern volcanic lithostratigraphy

Table 4.1: Summary of most altered samples

Table 4.2: Summary of equivalent northern and southern lobe lithological units

List of Figures

Figure 1.1: Global distribution of LIPs and summary diagram of pyroclasts.....	13
Figure 1.2: Example of a scoria and a spatter cone from Iceland.....	14
Figure 1.3: Distribution of products from the Franklin Magmatic Event in the Canadian Arctic, and regional geology of the Minto Inlier.....	15
Figure 1.4: Stratigraphy of the Shaler Supergroup.....	16
Figure 2.1: Example of typical exposure of the Natkusiak Formation.....	38
Figure 2.2: Natkusiak Formation type section outcrop photo and location map.....	39
Figure 2.3: Stratigraphic column of Natkusiak Formation type section.....	40
Figure 2.4: Field characteristics of basal flows.....	41
Figure 2.5: Field photos and petrographic photomicrographs of the basal flows.....	42
Figure 2.6: Petrographic photomicrographs of the basal flows.....	43
Figure 2.7: Field photos of the volcanoclastic units.....	44
Figure 2.8: Field photos and petrographic photomicrographs of the volcanoclastic units.....	45
Figure 2.9: Field photos of the thick flow unit.....	46
Figure 2.10: Field photos of the thick flow unit.....	47

Figure 2.11: Field photos of the thick flow unit.....	48
Figure 2.12: Petrographic photomicrographs of the thick flow unit.....	49
Figure 2.13: Map of the southern lobe to show locations of stratigraphic sections and cross-sections.....	50
Figure 2.14: Example of a traceable contact in unit V_0	51
Figure 2.15: Legend for stratigraphic sections.....	52
Figure 2.16: Cross-sections A-B and B-C.....	53
Figure 2.17: Cross-sections D-E and F-G.....	54
Figure 2.18: Western and eastern volcanic vent complexes.....	55
Figure 2.19: Field photos of the eastern vent complex.....	56
Figure 2.20: Map of the eastern vent complex.....	57
Figure 2.21: Field photos of the western vent complex.....	58
Figure 2.22: Clinopyroxene core and rim compositions.....	59
Figure 2.23: Plagioclase core and rim compositions.....	60
Figure 3.1: Sample map and locations.....	75
Figure 3.2: Lebas et al. (1986) total alkalis plot, Irvine and Baragar (1971) AFM diagram, and Jensen (1946) ternary plot.....	76

Figure 3.3: Pearce (1996) Zr/Ti, Nb/Y, Pearce and Cann (1973) Zr-Ti-Y Ti/Zr, and Pearce and Cann (1973) Ti-Zr discrimination diagrams.....	77
Figure 3.4: Major oxide plots.....	78
Figure 3.4 con't: Major oxides plots.....	79
Figure 3.5: Alteration diagrams after Large et al. (2001) and Hughes (1972)	80
Figure 3.6: Hydrothermal and diagenetic alteration trends from Large et al. (2001).....	81
Figure 3.7: Chemostratigraphy plots.....	82
Figure 4.1: Examples of type section lithological units throughout the southern lobe...	110
Figure 4.2: Examples of cinder cones from Iceland.....	111
Figure 4.3: Major oxide plots of southern lobe samples showing most alteration.....	112
Figure 4.4: Geochemical comparison between southern and northern lobe samples.....	113
Figure 4.5: Geochemical comparison between southern and northern lobe samples.....	114
Figure 4.6: Schematic block diagrams illustrating the evolution of volcanic stratigraphy in the western southern lobe.....	115

List of Appendices

Appendix 2.1: Table of samples used for petrographic analysis.....	120
Appendix 2.2: Table of stratigraphic sections measured in the southern lobe.....	126
Appendix 2.3: Mineral chemistry for samples analyzed by SEM.....	129
Appendix 3.1: Whole-rock geochemistry of samples from Natkusiak Formation.....	139
Appendix 3.2: University of Ottawa X-Ray Laboratories XRF precisions values.....	150

Chapter 1: Introduction

Large Igneous Provinces (LIPs) are present throughout the geologic record and occupy a significant portion of the Earth's surface (figure 1.1A). There is a strong interest in the study of LIPs because of their relatively high rate of occurrence of about once every ~10Ma since the Archean (Bryan et al., 2010); the complexity of LIP-producing mantle dynamics; the increased atmospheric concentrations of CO₂ and SO₂ produced by mafic flood volcanism, consequent impact on climate, and possible link to mass extinctions; the role of LIPs in continental paleo-reconstructions; and the mineral resource potential.

LIP-forming volcanic events are considered anomalous because of the high volume of intrusive and extrusive mafic material they are capable of producing in such a relatively short period of time; more than 1 000 000 km³ of material in 1 to 5 Ma (Bryan et al., 2010). The extrusive products of LIP-forming magmatic events are predominantly mafic in composition, but can also include felsic material. Extrusive products include thick lava flows, as well as explosive pyroclastic deposits, re-worked volcanoclastic deposits, interflow sedimentary deposits, and volcanic edifices such as scoria cones, and shield volcanoes (Jerram and Widdowson, 2005). LIP intrusive complexes represent part of the magmatic plumbing system and consist of dyke swarms, and a network of feeder sills and dykes (e.g. Bédard et al. (2012)). LIPs are categorized as continental or oceanic. Continental LIPs include Continental Flood Basalt Provinces, Volcanic Rifted Margins, and Silicic LIPs, while oceanic LIPs include Oceanic Plateaus and Ocean Basin Flood Basalts (Bryan and Ernst, 2008).

The nature of the volcanic facies present at the base of a flood basalt sequence provides valuable information about the onset of volcanism, including the environment and mechanism(s) of eruption; this is the focus of the present study. Chapter 1 provides a review of Continental Flood Basalt Provinces (CFBPs), the purpose and objectives of the present study, followed by a description of the Franklin Magmatic Event and its eruptive products in northern Canada. Chapter 2 presents the petrography, volcano-stratigraphy, field relationships, and correlations of the Natkusiak Formation in the southern lobe, as well as the methodology used for field work. Chapter 3 presents major and select trace element data, chemostratigraphy, and alteration chemistry of the southern lobe, as well as geochemical methods. Finally, chapter 4 explores interpretations and implications for the initiation, evolution, and emplacement of the volcanic products in the Natkusiak Formation of the southern lobe.

1.1 Study Purpose and Objectives

The current study is part of the Geological Survey of Canada's Geo-mapping for Energy and Minerals (GEM) initiative. The purpose of this initiative is to produce more complete geological maps of Canada's north as well as identify potential mineral resources. The Victoria Island GEM project is accomplishing this via a series of mapping studies, as well as focused studies on the sedimentary and igneous stratigraphy of the Minto Inlier. The igneous component of the Victoria Island GEM project includes detailed studies on the intrusive and volcanic suites produced by the Franklin Magmatic Event in order to better resolve the temporal and spatial relationships between the magma

plumbing system and the extrusive components, and so clarify the physical and chemical evolution of the magmatic centre. The high quality of preservation of both the intrusive and extrusive units provides a unique opportunity to study both the magma plumbing system and extrusive system in great detail.

This contribution presents the results and implications of detailed and regional-scale mapping and major element geochemistry of the southern lobe of the Natkusiak Formation flood basalts, and provides a comparison between the stratigraphy of the northern and southern lobes. Identification of volcanic facies, stratigraphic correlations, as well as geochemical analyses throughout the southern lobe will help identify vertical and lateral changes in volcanic facies and chemistry. This will help to better understand the emplacement mechanisms and eruption styles of the Natkusiak Formation volcanics, as well as further constrain the paleo-environment, as well as magma composition and evolution.

1.2 Continental Flood Basalt Provinces: causes, products, and architecture

In the literature, LIP and CFBP formation is most often associated with thermochemical mantle plumes, lithospheric extension, and continental breakup. The mantle plume theory provides the heat mechanism necessary to create the large mantle melts that drive flood volcanism, as well as contribute to continental rifting and breakup (Hawkesworth et al., 2000). In the plume-dominated end-member model, an asthenospheric heat anomaly impinges on the lithospheric mantle, inducing domal uplift,

extension, and rifting (Bryan and Ernst, 2008). The subsequent faulting and fracturing aids magma ascent and forms giant radiating dyke swarms, volcanic fissures, and flood basalt provinces (Bryan and Ernst, 2008). In addition, decompression-melting during upwelling, and heat transfer by these magmas to cooler lithospheric mantle may contribute to further lithospheric thinning, as can delamination (Keary et al., 2009). The latter allows for asthenospheric material to upwell (Keary et al., 2009).

Continental Flood Basalt Provinces often have complex magmatic plumbing systems consisting of sills and dykes that are emplaced in low-density country rocks, flat-lying bedded sequences, or both (Cox, 1980). The surficial expressions of the magmatic plumbing system of many mafic LIPS are linear sources, such as volcanic rifts or fissures (e.g. Deccan Traps), point sources such as shield volcanos (i.e. Par-Etendeka Province), or both (i.e. The North Atlantic Igneous Province) (Jerram and Widdowson, 2005). High-volume lava flows of varying thicknesses and aerial extent are probably the most common volcanic product of a CFBP. Lava flows were classified in the 1970s as simple or compound, with lava eruption (effusion) rate the determining factor for flow type (Walker, 1972). Eruption rate is influenced by a number of factors, including lava viscosity, temperature, the volume of available melt, the amount of entrained material, as well as the efficiency of the plumbing system. A compound flow is composed of multiple thinner flows or cooling units emplaced at lower eruption rate, while a simple flow is composed of a single flow unit emplaced at a higher eruption rate (Walker, 1972). The above classification has been used to describe flows in CFBPs (e.g. Passey and Bell (2007)). Mechanisms for flow emplacement include rapid emplacement *via* large lava feeder tubes, or networks of smaller lava tubes, that follow preferred mechanical

pathways in the flow interior (Anderson et al., 1999), and slower emplacement by the injection of fresh molten material under an upper crust, causing it to inflate and propagate (Self et al., 1997). Flows are commonly divided into a flow base, flow core, and flow top. Flow bases and cores can be massive and structureless, display degassing structures such as vesicles and pipe vesicles (Self et al., 1997), as well as cooling structures such as joints (Long and Wood, 1986). Vesicles, having travelled up through the flow interior and accumulate at the top of the flow, often result in a highly vesicular flow top (Self et al., 1997). Cooling (columnar) joints are created by thermal contraction as a flow cools. The cooling, or solidification fronts, move from the base and top of the flow inwards (Budkewitsch and Robin, 1994). Where these fronts meet within the flow is where the contact occurs between the lower colonnade, entablature, and upper colonnade (Long and Wood, 1986). Slower cooling produces large, well-shaped columns oriented perpendicular to the flow base, while faster cooling produces smaller columns arranged in more erratic patterns that may or may not be perpendicular to the flow base. When cooling fronts are radial, a radial pattern of columns will form (Budkewitsch and Robin, 1994).

Volcanic vents and edifices are reported in some flood basalt provinces, most commonly at the onset phase of volcanism. These are usually formed by felsic volcanism or explosive basaltic eruptions (Jerram and Widdowson, 2005). Examples include: a complex of diatremes discovered in Antarctica that are associated with the Ferrar LIP (White and McClintock, 2001), a field of small shield volcanoes, scoria and spatter cones that occur in the Al Haruj flood basalt field in Libya (Németh et al., 2003), and the voluminous Laki basalts of Iceland that were accompanied by fissure-fed scoria and

spatter cones (Thordarson and Self, 1993). Here, emphasis is placed on areally-restricted, explosive, vent-forming basaltic pyroclastic fall eruptions, and their reworked, mafic volcanoclastic products. During a pyroclastic fall, pyroclasts are projected vertically, and fall back to the surface resulting in well bedded pyroclastic deposits of scoria and spatter (Bardintzeff, 2000). Most basaltic pyroclastic eruptions are classified as Hawaiian to Strombolian according to the volcanic explosivity index of Newhall and Self (1982). This means that these eruptions typically have column heights of less than 5 km, ejecta volumes of less than 10^7 cubic metres, and have durations of less than 6 hours. The length of duration of this type of explosive basaltic eruption depends mainly on the amount of dissolved gases present in the rising magma of the shallow plumbing system; with more dissolved gases yielding a more explosive eruption of longer duration, and *vice versa* (Head III and Wilson, 1989). The products of explosive basaltic eruptions will form volcanic edifices and can be comprised of scoria, welded or unwelded spatter, and might include lava flows and ponds (Head III and Wilson, 1989). The type of pyroclast depends on the explosiveness of eruption. Among other factors, the degree of explosiveness is influenced by dissolved gas content. Dissolved gas content also affects the temperature of the pyroclasts, as well as their accumulation rate: the relationship between pyroclast temperature and accumulation rate, and the resulting pyroclast type, is summarized in a diagram by Head III and Wilson (1989) (figure 1.1B). Ash and scoria form from highly explosive eruptions by rapidly expanding volatiles and accumulate around the volcanic vent at the appropriate angle of repose ($\sim 30^\circ$) (Wood, 1980), such as the Eldfell scoria cone formed in 1973 on the island of Heimaey, Iceland (figure 1.2A). Spatter forms from a less explosive eruption and can either remain unwelded and be deposited as pancake-

like blobs, or, if the pyroclast temperature remains high, the spatter will weld and may even agglutinate into flows (Head III and Wilson, 1989), such as the Eldborg spatter cone in western Iceland (figure 1.2B). Commonly, basaltic pyroclastic eruptions begin explosively and become effusive as the system is degassed, with explosiveness and effusiveness varying throughout the eruption. Thus, the resulting pyroclastic deposits are often interbedded, or a transition from one to the other occurs (Head III and Wilson, 1989).

The paleo-environment at the time of flood basalt volcanism, as well as other pre-existing factors such as paleo-topography and the nature of the underlying sediments, can further influence the basal volcanic stratigraphy underlying sediments (Jerram and Widdowson, 2005). For example, the onset of volcanism in the Kangerlussuaq Basin of the East Greenland flood basalt province was marked by explosive hydromagmatic volcanism as magma interacted with an aquifer in underlying early Paleocene sedimentary rocks. In this case, volcanic edifices were built during three cycles of hydromagmatic and magmatic activity, resulting in the creation of topographic highs over which subaerial lava flows were eventually emplaced (Peate, 2003). In contrast, early effusive flows of the Paran-Etendeka CFBP were erupted subaerially into an active aeolian environment of dune-forming crests and troughs. In this case, the lavas followed the pre-existing topography created by the dunes, which is reflected in the architecture of the basal part of the volcanic stratigraphy (Jerram and Widdowson, 2005).

1.3 The Franklin Magmatic Event on Victoria Island, Arctic Canada: Products, Regional Geology, and Previous Studies

1.3.1 Franklin Magmatic Event

The Franklin Magmatic Event occurred at approximate *ca.* 720 Ma and is one of two Neoproterozoic flood basalt provinces in Arctic Canada, the other being the *ca.* 780 Gunbarrel Magmatic Event (Heaman et al., 1992). The Franklin event produced a Continental Flood Basalt Province consisting of an intrusive complex of gabbroic sills and dykes (Franklin sills, Coronation sills), as well as an extrusive flood basalt pile (Natkusiak Formation). The sills and dykes extend from the western Canadian Arctic (Victoria Island and mainland NWT) to the eastern Canadian Arctic (Baffin Island), while the extrusive flood basalt sequence is constrained to two erosional remnants on north-west Victoria Island (Heaman et al., 1992) (figure 1.3A). The Franklin Magmatic Event is believed to have resulted from the separation of Laurentia (Heaman et al., 1992), from supercontinent Rodinia, along Laurentia's western margin around *ca.* 750 Ma (Li et al., 2008). Lithospheric extension leading to uplift, magmatism, and continental breakup is thought to have been initiated by a mantle plume: evidence for the former is preserved as doming and block faulting in the sedimentary record preceding volcanism (Rainbird, 1993).

1.3.2 The Minto Inlier and Natkusiak Formation

The Minto Inlier on northwestern Victoria Island preserves a package of Neoproterozoic sedimentary and igneous rocks gently folded along a northeast-trending

axis (figure 1.3B). The Shaler Supergroup sedimentary rocks comprise a 4 km thick succession of shallow marine carbonate, stromatolitic dolostone, shale, fluvial and deltaic sandstone, and evaporitic units that were deposited within the intracratonic Amundsen basin during the Tonian-Cryogenian Neoproterozoic (Rainbird, 1993; Rainbird et al., 1996). Preliminary Re-Os ages from a unit of black shale in the Wynniatt Formation, and from the Boot Inlet Formation dolostone, indicate depositional ages of 762 ± 46 Ma and 892 ± 13 Ma, respectively (van Acken et al., 2012). Igneous rocks of the Minto Inlier consist of diabasic sills and dykes, as well as the extrusive Natkusiak Formation flood basalts of the Franklin Magmatic Event. The sills and dykes intrude the sedimentary rocks of the Shaler Supergroup and represent the magmatic feeder system to the extrusive basaltic lavas that cap it, with NNW-trending faults guiding melt ascent in many cases (Bédard et al., 2012) (figure 1.4A). Regional deformation is limited to the NW-trending Proterozoic faults, the shallow syncline and $\sim 2^\circ$ dip of the rock units, and a number of post-Proterozoic, E- to NE-trending faults.

The Kilian and Kuujjua formations of the Shaler Supergroup directly underlie the Natkusiak Formation basalts. In the southern lobe the basalts conformably overlie the sandstones of the Kuujjua Formation. Towards the northeast, however, the Kuujjua Formation pinches out so that the basalts unconformably overly carbonate rocks and evaporites of the Kilian Formation (Rainbird, 1993). This, along with other evidence such as faulting and the discovery of rift-related conglomerates, is what led to the suggestion that these depositional relationships may be the result of domal uplift and extension caused by the impingement of a mantle plume on the base of the lithosphere (Rainbird, 1993). The Kuujjua Formation is an alluvial-fluvial, quartz-arenite with well-defined

beds and large compound cross-beds. The paleo-environment for the Kuujjua Formation is thought to have been a large river system with paleocurrents toward the northwest (Rainbird, 1992). About 50 m below the Natkusiak Formation basalt the Kuujjua sandstone locally contains basaltic clasts and interbedded volcanic material suggesting that at least some volcanism was coeval with deposition of the sandstone (Rainbird, 1993). This is further supported by the presence of individual basaltic clasts that are indented by sand grains, suggesting deposition while the clasts were still malleable. The contact between the Kuujjua Formation and the Natkusiak basalts appears to be structurally conformable in many places but is unconformable on a basin-wide scale (Jefferson, 1985) and locally preserves discordances in the order of 20° (Rainbird, 1993).

The extrusive volcanic pile of the Natkusiak Formation is preserved as two lobes trending east-west and southwest-northeast, herein referred to as the southern and northern lobes respectively. Previous studies of the Natkusiak Formation have focused mainly on the northern lobe (Dostal et al., 1985; Jefferson et al., 1985), where approximately 1100 m of volcanic stratigraphy was documented. Dostal et al. (1985) describe the lava flows as subaerial with thicknesses ranging from a few metres to more than 70 m (Dostal et al., 1985). Individual flows have massive bases, amygdaloidal flow tops, as well as plagioclase and pyroxene-phyric sections. In addition, one occurrence of red volcanic sediment at the base of the sequence was noted, as well as a fragmental layer attributed to eruption into shallow water (Dostal et al., 1985). Jefferson et al. (1985) describe seven volcanic members in the northern lobe: the basal member, pyroclastic member, lower massive member, lower recessive member, middle massive member,

upper recessive member, and the upper massive member. Member lithologies are summarized in table 1.1.

Member (Thickness)	Lithology
Upper Massive (>150m)	4-8 flows: blue-green, orange-brown weathering, massive blocky to columnar jointed. Forms top plateau in Trident Creek area.
Upper Recessive (<500m)	20-29 flows: dark green, mainly green-brown weathering, rubbly flaggy breaking.
Middle Massive (80-90m)	4-6 flows: blue-green, orange-brown weathering, massive blocky to columnar jointed, forms top plateau throughout much of region.
Lower Recessive (20-200m)	4-9 flows: dark brown to green, drab green-brown weathering. Locally includes pyroclastic rocks and pillowed lava.
Lower Massive (~75m)	2-5 flows: blue-green to green-grey, orange-brown to brown weathering, massive, cliff-forming, blocky to columnar jointed, forms second lowest plateau.
Pyroclastic (0-100m)	Lower ~10m: locally sedimentary, green to maroon. Upper <90m: lithic lapilli tuff, local tuff-breccia, green (bottom) to maroon (top).
Basal (0- >70m)	0-4 flows: blue-green to green-brown, orange-brown to green-brown weathering, massive, cliff-forming to rubbly. Locally spheroidally weathered or includes hyaloclastic breccia with lithic and volcanic inclusions; isolated to layered pillowed flows in amygdaloidal hyaloclastic matrix. Forms plateau in central and southwestern areas.

Table 1.1: Summary of the northern lobe volcanic facies after Jefferson et al. (1985).

According to Dostal et al. (1985), the northern lobe Natkusiak Formation basalts are typical continental tholeiites without significant crustal contamination based on Sr-Nd-isotopic and INAA trace-element analysis (Dostal et al., 1986). In addition, trace element ratios such as La/Yb, Zr/Y, Ti/V, Y/Nb, and Ti/Zr suggest interaction with a depleted upper mantle similar to N-MORBs (Dostal et al., 1985). Dostal et al. (1985) also identified two fractionation cycles based on systematic changes in MgO and FeO contents with the volcanic stratigraphy with both the upper and lower cycles marked by a decline in MgO and FeO from the base to the top. Other major element trends described by Dostal et al. (1985) include increasing Ti, V, and Zr concentrations with stratigraphic

height. With regards to the trace elements, Dostal et al. (1985) suggested an ocean-floor tholeiitic nature based on T-Zr-Y discrimination diagrams by Pearce and Cann (1973), as well as possible mixing between MORB and Canadian Shield compositions based on Th/La and Ba/La ratios as well as the general compositional variations within the Natkusiak basalts. Finally, the authors suggest low-grade metamorphic alteration for at least one sample based on an enrichment of alkali and alkali-earth elements, as well as high Ba/La (Dostal et al., 1985). A trace-element and isotope study done by Dupuy (1995) identified two end-member samples with differing trace element ratios that cannot be linked only by fractionation or partial melting, as so these authors also proposed source mixing as an important process for the generation of the Natkusiak basalts. U-Pb baddeleyite ages for seven sills from Victoria Island, Coronation Gulf, and Bathurst Inlet, as well as for a diabase dyke from southwestern Baffin Island imply that magmatism occurred at *ca.* 718-723 Ma (Heaman et al., 1992).

Figure 1.1: (A) global distribution and age of Earth LIPs after Bryan and Ernst (2008). (B) summary diagram from Head III and Wilson (1989) of the relationship the temperature of a pyroclast and its accumulation rate.

Figure 1.2: The Eldfell scoria cone on Heimaey Island, Iceland (**A**), and the Eldborg spatter cone in southeast Iceland (**B**). Both photos by the author.

Figure 1.3: (A) distribution across Arctic Canada of volcanic products from the Franklin Magmatic Event, figure after Jefferson et al. (1994). (B) regional geology of the the Minto Inlier, Victoria Island, from Rainbird (1994).

Figure 1.4: Stratigraphy of the Shaler Supergroup (Heaman et al., 1992; Macdonald et al., 2010; Rainbird, 1993; van Acken et al., 2012)

Chapter 2: Physical Volcanology and Stratigraphy of the Southern Lobe of the Natkusiak Formation

2.1 Introduction

The purpose of this chapter is to describe the 200m of volcanic stratigraphy of the southern lobe of the Natkusiak Formation in the context of its lithostratigraphic units and their lateral distribution, flow architecture and structures, and microtextures. These observations provide insight into the environment and mechanisms of deposition, as well as a basis for comparisons with the volcano-stratigraphy of the northern lobe. Here, a volcano-stratigraphic type section is established and 27 additional stratigraphic sections within the southern lobe are presented and correlated. In addition, two newly discovered volcanic vent complexes are presented, as well as mineral chemistry data for phenocryst, alteration, and metal oxide phases from seven samples.

2.2 Field Methods and Sampling

In the field, data collection and observation was limited by the quality of exposure of the Natkusiak Formation. Much of the volcanic stratigraphy is either exposed along cliff faces, as steep sections exposed by river erosion and consisting of both talus slopes and outcrop (figure 2.1A), or as plateaus consisting mostly of felsenmeer (figure 2.1B). The goal for the 2010 field season was to measure in detail two sections through the volcanic stratigraphy in order to create a volcanic type section: these locations were chosen for quality of exposure and relative ease of access. Figure 2.1C shows the location

for detailed section A, and figure 2.2 shows the location for detailed section B: the locations of these sections are indicated as SA and SB on the map of figure 2.13. The cliff faces chosen for detailed sections A and B expose a significant amount of stratigraphy while still being relatively accessible for sampling and detailed volcano-stratigraphy. With the basic lithostratigraphy better understood, the goal for the 2011 field season was to cover as much of the southern lobe as possible in order to map the lateral and vertical extents of the volcanic units. River cuts were favoured because the flanks of the gullies provided the best exposures, and samples were taken from areas that exposed a good amount of stratigraphy or exhibited unusual or informative relationships (i.e. volcanic vent area).

Mapping and note-taking was accomplished using a regular map and notebook, as well as a hand-held mapping device (ArcPad on a Getac©). With the hand-held device, the user enters a station at need, for example at a change in lithology, a contact between units, a change in distance when measuring vertical sections, etc. The information entered for a station includes coordinates, altitude, lithology (rock type, colour, remarkable mineralogy), structures, contacts, rock formation, a photo number, and sample number. The data is then imported into ArcGIS as station points that can be viewed in ArcMap. Many sections though the southern lobe volcano-stratigraphy were traversed by students or research scientists other than the author, such that digital mapping data from other geologists available in ArcMap supplemented the data collected by the author. The supplemental field data were used to construct additional stratigraphic sections to complete the regional cross-sections. However, most unit thicknesses and heights are estimated using elevations (metres above sea level) provided by the Getac© and/or

topographic maps, which does not always yield truly representative thicknesses. Where possible the stratigraphic sections were measured by the author using a Jacob staff or tape measure.

The table of appendix 2.1 is a summary of samples used for petrographic analysis and includes their location, unit, and a summary description of mineralogy and textures. In 2010, samples were cut in Ottawa, ON, at the Geological Survey of Canada, and then sent to Vancouver Petrographics, in Langley, BC, for thin section preparation. In 2011, samples were cut at the University of British Columbia, BC, and then thin section slabs sent to Ottawa to be processed into thin sections at Carleton University, Ottawa, ON. The analytical methods used for geochemical analysis are described in chapter 3. In addition, in 2012, 7 samples were selected for imaging and mineral chemistry analysis using a Camebax MBX Electron Microprobe at the Electron Microprobe Facility, Carleton University. The samples were chosen based on representative locations within the detailed stratigraphic sections A and B, as well as the presence of target plagioclase and clinopyroxene phenocryst phases.

2.3 Southern lobe type section lithostratigraphy

The volcanic type section for the southern lobe is a composite section of detailed sections A and B. The cliff face of section B is used in figure 2.2 to show the individual volcanic units of the stratigraphy, and the schematic stratigraphic type section is presented in figure 2.3. Also in figure 2.2 is a map of the southern lobe indicating the location of the detailed sections.

Four main volcanic lithostratigraphic units have been recognized above the Kuujua Formation and are summarized in table 2.1: the basal V_0 volcanic unit, volcanoclastic unit C_1 and volcanoclastic unit C_2 , and the V_1 flow unit. Stratigraphically higher sheet flows are known to occur in the northern lobe, but these are not preserved in the south. The V_0 and V_1 units extend throughout the entire southern lobe, whereas the C_1 and C_2 volcanoclastic units pinch out to the northwest and are absent in the western part of the area. In the southern lobe, the thick orange-brown weathering flow at the base of unit V_1 appears to be horizontal everywhere exposures are adequate, and thus we use the basal contact of V_{1A} as a stratigraphic datum when measuring sections.

Unit	Approximate thickness (m)	Lithology
Sheet flow unit, third flow – V _{1C}	20	Extrusive volcanic. Thick sheet flow consisting of smaller flows. Weathering pattern is distinct and either occurs as blocks or slabs with partings angular to the flow layers. Native copper is visible in outcrop.
Sheet flow unit, second flow – V _{1B}	15	Extrusive volcanic. Thick sheet flow with a massive base, vesicular top, and a crude, thick, columnar jointing pattern. Weathering colour is a distinct blue-grey, and native copper is visible in outcrop.
Sheet flow unit, first flow – V _{1A}	40	Extrusive volcanic. Thick sheet flow with a colonnade and entablature architecture. Colonnade is made up of large columnar joints, while entablature consists of smaller, more erratic joints. Weathering colour is a distinct orange-brown.
Bedded volcanoclastic member – C ₂	5 to 10	Volcanoclastic, epiclastic, thin bedded with normal grading, some cross-beds present. Usually caps member C ₁ , clasts include volcanics, but quartz grains are dominant.
Massive volcanoclastic member – C ₁	40 to >100	Volcanoclastic, epiclastic, massive and structureless. Thickness varies greatly throughout the SL, clasts are both volcanic and sedimentary, mostly sandstone.
Basal member – V ₀	50	Extrusive volcanic. Contact with K _j Formation is sharp, although pillowed and showing hyaloclastic breccia in some places. Flow type is either thin (1 to 10 m) sheet flows or discontinuous lobate flows. Microtextures vary from fine massive basalt to coarse sub-ophitic basalt. Degree of vesicularity varies throughout V ₀ .

Table 2.1: Summary of southern lobe Natkusiak Formation type section stratigraphy.

2.3.1 Basal unit (V_0)

In the southern lobe the basal unit of the Natkusiak Formation overlies the Kuujjua Formation, an alluvial-fluvial quartz-arenite with well-defined beds and large compound cross-beds. Where it is exposed, the contact between the Kuujjua and the Natkusiak Formations appears sharp and conformable (figure 2.4A). In some locations, within the basal 5 m of V_0 , the basalts are pillowed and hyaloclastic. The pillowed textures are preserved within the basal unit only in a few places, and are usually difficult to identify due to the weathered and crumbly nature of the section. However, their glassy, hyaloclastite-textured rinds are usually visible if not weathered out (figure 2.4B).

The basal V_0 unit ranges in thickness from 30 m to over 100 m. It primarily consists of weathered and crumbly basaltic lava flows traceable horizontally on a scale of about 500 to 1000m, however rarely traceable between stratigraphic sections. Individual flow units range in thickness from 1 to 5 m at the base of V_0 and gradually thicken towards the top of V_0 where they become as thick as 10 m (figure 2.4C). In the field, an individual flow unit was defined as a basalt layer that is continuous in the immediate vicinity of the outcrop with a massive base displaying varying levels of vesicularity, a massive core, and a crumbly top or crust (as per Passey and Bell (2007)). The recessively weathering flow tops usually tend to highlight individual flow units on cliff exposures; a feature that is visible in figure 2.4C. Where weathering was less intense (for example, in protected canyon sections), the architecture of the 1 to 2 m flows is well exposed (figure 2.4D). It appears that architecturally simple, thin flows displaying massive cores of varying degrees of vesicularity, and crumbly vesicular flow tops, is the dominant flow morphology in most of unit V_0 . In addition, what appear to be small (1 to 2m) lobate-

shaped flows with chilled selvages (although the selvages are rarely well-preserved) are present in outcrops at the base of V_0 in some locations (figure 2.4E). In addition, two examples of ropy flow-top texture were found within talus proximal to outcrops of the basal unit (figure 2.5A). A'a-type flow top textures were not recognized in the field.

The contacts between individual flows of unit V_0 are often weathered. However, in some locations they can be well-preserved. When this is the case the top of the underlying flow tends to be rubbly, with flattened to irregularly-shaped vesicles, but in fairly sharp contact with the base of the next flow. The contact itself is commonly marked by a thin, rusty-coloured, hematized or otherwise altered layer, and the first 20 to 50 cm of the overlying flow includes abundant pipe vesicles and amygdules where escaping gases rose from the flow base (figure 2.5B). Both of the latter degassing features are common in the V_0 flows and are shown in greater detail in figure 2.5C and D. Amygdules, originally vesicles, vary in shape, size, and content. The majority are round, no larger than 1 cm in diameter, and contain mostly calcite (i.e. the amygdule in figure 2.5C). However, in some locations they can be larger or smaller, as well as angular and flattened, and may contain additional quartz, prehnite, pumpellyite, and chlorite (i.e. the pipe vesicles in figure 2.5D).

Microscopically, basal unit V_0 lavas are texturally diverse. Most samples are massive, fine grained basalt with a groundmass of small plagioclase laths ($<0.5\text{mm}$), interstitial material (usually altered glass or secondary minerals), with small intergranular crystals of pyroxene, and rare olivine or clinopyroxene phenocrysts (figure 2.5E). Massive samples commonly contain highly sericitized, large ($>1\text{mm}$) plagioclase

lath glomerocrysts showing very slight normal zoning (figure 2.5F). The plagioclase of the glomerocrysts are much more altered than the plagioclase laths of the groundmass.

In other places, the basalt is coarse-grained with a sub-ophitic texture of ~1mm sized, anhedral clinopyroxene phenocrysts intergrown with plagioclase laths (~0.5mm) (figure 2.6A). Most often the texture shows only partial incorporation of the plagioclase laths into the clinopyroxene phenocrysts. However, some examples of this texture tend towards fully ophitic, with plagioclase laths almost completely enclosed within the pyroxenes (figure 2.6B). The sub-ophitic texture does not appear to occur in any specific location within unit V_0 ; the samples showing this texture are distributed throughout the flow units of V_0 .

Vesicles within V_0 can be rounded to irregularly shaped, vary on average from 0.5 to a few cm, and typically contain secondary calcite, quartz, chlorite, prehnite, pumpellyite, with the addition of actinolite and hydrogrossular, either individually or occurring together (figure 2.6C). Hydrogrossular occurs in one sample from the very base of V_0 (figure 2.6D). The most vesicular samples contain 10 to 20% amygdules. Opaque minerals are present in varying quantities within the V_0 flows and are usually either euhedral, dendritic or skeletal, have grown interstitially between crystals of pyroxene and plagioclase (figure 2.6E), or lining amygdules. The opaques of V_0 appear mostly to be Fe-Ti oxides (i.e. magnetite, ilmenite, or hematite), based on colour and crystal habit under reflected light.

2.3.2 *Volcaniclastic units C₁ & C₂*

Two distinct volcaniclastic units (named C₁ and C₂) were identified within the two measured detailed sections. Unit C₁ occurs throughout the southern lobe, with the exception of the western portion, while unit C₂ is only sporadically distributed. The thickness of the C₁ volcaniclastic unit varies from one location to another, ranging from 0 to 50 m, but averages around 10m (figure 2.7 A and B). The contact between the unit V₀ basal flows and the C₁ volcaniclastic unit is weathered, and was not observed. In outcrop, unit C₁ is dark maroon to brown in colour, massive, with no large-scale primary structures such as bedding or jointing. In addition, C₁ commonly displays a crumbly flaky habit evocative of mudstone, but can also be cohesive and dense. Macroscopically, components of unit C₁ include rounded pebble-sized clasts of mud-like material (figure 2.7C), angular basaltic clasts showing varying degrees of vesicularity (figure 2.7D), as well as sandstone clasts varying in size from 0.5 to 5 cm in diameter (figure 2.7E). These components are supported in a finer matrix of mud and smaller clasts. In most localities, it was noted that unit C₁ becomes much redder in colour and more friable towards its top, a feature mildly evident in figure 2.7A. Within this redder section, some clasts appear to have a pale alteration halo surrounding them. The upper contact of unit C₁ is with volcaniclastic unit C₂ where the latter unit occurs. Where unit C₂ does not occur, unit C₁ has a covered contact with unit V₁, with one exception where a crumbly C₁-V₁ contact is visible (figure 2.7F).

Microscopically, unit C₁ is compositionally heterogeneous, and contains angular to sub-rounded scoriaceous basalt clasts; rounded, slightly strained quartz grains; rectangular, elongate, fine-grained mudstone clasts; and dark, small (0.25 to 2mm),

angular to sub-rounded clasts of unidentifiable composition. Clasts range in size from granule to fine cobble (~7cm). In addition, the flat elongate clasts appear to be slightly aligned along their long axes in some locations. The deposits are very poorly sorted, and appear to contain abundant mafic material, mainly as groundmass (figure 2.8A). The macroscopic sandstone clasts observed in unit C₁ are also present microscopically, as can be seen in figure 2.8B. Based on composition (dark colour, high abundance of basalt fragments, and mafic groundmass), C₁ is classified as a mafic volcanoclastic deposit, as described by Ross et al. (2005). Based on clast size and fabric (Wentworth, 1922) C₁ is classified as a volcanic pebble conglomerate.

The C₂ volcanoclastic unit ranges in thickness from 0 to 30 m and has a much more restricted distribution than unit C₁. Where present, it appears to conformably overlie C₁ even though the contact zone is recessive and has not been directly observed. In outcrop, unit C₂ is a pale green to cream colour and is composed of angular to sub-rounded volcanic clasts varying from 0.1 to 5cm in size, as well as coarse to very coarse quartz sand grains. Unit C₁ is planar bedded, with individual beds no thicker than a few centimeters. Beds generally display normal grading, or alternate between being composed either of predominantly coarse or fine material (figure 2.8D). Two instances of cross-bedding were observed within unit C₂. In one location tabular cross-beds are preserved where unit C₂ forms a lens within C₁. At this location, the outcrop consists of planar beds with the exception of a 50 cm section where cross-beds occur (figure 2.8C). At the other location a single set of tabular cross-beds 15 cm thick were observed in a 10 to 15 m thick section of unit C₂. The locations are separated by approximately 10.3 km.

Microscopically, unit C₂ contains well-rounded coarse quartz grains (~30% to >50%), angular scoriaceous basalt clasts (0.5 mm to > 2mm, ~15% to 20%), and rectangular mudstone clasts up to 1 mm in size (~5%). Although C₂ has similar clast types to C₁, C₂ has a higher concentration of quartz sand grains, the quartz sand grains are coarser, and both the clasts and grains often have point contacts and thus the fabric appears more clast-supported than matrix supported. Additionally, C₂ is better sorted, with a calcite cement matrix (figure 2.8E), and a few carbonate clasts. The proportion of quartz grains and calcite cement increases, while the amount of scoriaceous basalt clasts decreases, from the middle to the top of the unit. Based on composition, as well as clast size, sorting, and fabric, C₂ is classified as a quartz-rich volcanoclastic sandstone.

2.3.3 Flow unit V₁

Three basalt sheet flows constitute the upper part of the southern lobe type section. These flows are grouped into unit V₁ and are called V_{1A}, V_{1B}, and V_{1C}. The contact between the C₂ volcanoclastic unit and the overlying first flow of unit V₁ (unit V_{1A}) is generally weathered out for about 1 m. Where preserved, the contact is sharp: figure 2.9A and B show a sharp, planar, C₂-V_{1A} contact that follows the general attitude of the C₂ beds, with the base of the V_{1A} flow highly vesicular but largely unbrecciated. Vesicularity decreases up into the centre of the flow. Figure 2.9C shows a different situation: the C₂-V_{1A} contact is sharp for the most part (i.e. to the left and to the right of the photograph), however in the center of the image, as delimited by the yellow line, is a structure of radial columnar joints occurring at the contact between units. This structure is interpreted to be a lava tube. Immediately to the left of this structure is about 2.5 m of

highly vesicular, brecciated basalt that has a hyaloclastite-like appearance. In locations where units C_1 and C_2 are not present, i.e. the western southern lobe, unit V_1 is thought to conformably overlie unit V_0 , even though the break between units has not been observed in the field, because the flow orientation is similar above and below the supposed contact. Commonly the volcanic succession is only preserved to flow V_{1A} , which tops the plateaus of the southern lobe. In the type section, however, flow V_{1A} and V_{1B} are completely preserved, while V_{1C} is believed to be only partially preserved due to the lack of an obvious flow top (figure 2.10A). Distribution of the unit V_1 flows across the southern lobe is further discussed in the context of stratigraphic sections in section 2.5.

Unit V_1 flows display three different flow architectures. Flow V_{1A} is close to 35 m thick, has a distinct orange to brownish-red weathering colour, and displays a highly vesicular and mildly brecciated flow base as noted in section 2.3.3. The distinct weathering colour of flow V_{1A} becomes a deeper red towards the flow top. V_{1A} has a lower colonnade of thick, well-developed and organized columnar joints up to 0.5 m in diameter, followed by an entablature zone of smaller, poorly developed, erratic columnar joints only about 15 cm in diameter (figure 2.10B). The thickness of the lower colonnade zone appears to vary within the southern lobe; it is thinner in some locations such as those in figures 2.10 A and B, and thicker in other locations such as in figure 2.10 C. An upper colonnade zone is not present within V_{1A} . These features of V_{1A} , as well as its lateral continuity and presence throughout the southern lobe, make it a useful marker unit.

Flow V_{1B} is no more than 10 m thick in the type section and has a distinct blue-green weathering colour that clearly distinguishes it from flows V_{1A} and V_{1C} . The flow

contact between V_{1A} and V_{1B} is typically recessive (figure 2.10 D). Flow V_{1B} is a relatively structureless flow with a massive flow base and highly vesicular flow top (figure 2.11 A). On a large scale V_{1B} appears to weather in thick columns as can be seen in figure 2.10 A, however it is uncertain whether this is the result of pseudo-columnar jointing or is simply a weathering pattern.

Visible occurrences of native copper are noted in flow V_{1B} . The copper is present either as disseminated flecks within the basalt groundmass or as thin linings in calcite-, chlorite-, prehnite-, and quartz-filled amygdules (figure 2.11 B). In addition, the native copper is often accompanied by secondary copper-bearing carbonate minerals such as malachite. The top of flow V_{1B} is a section approximately 60 cm thick of brick-red material resembling a replacement zone. This surface was observed in other locations within the southern lobe and is thus another useful marker horizon (figure 2.11 C).

The contact between flow V_{1B} and V_{1C} above the red replacement unit is crumbly and brecciated, a feature visible in figure 2.11 C. Flow V_{1C} caps the volcanic stratigraphy in the type section with only 15 to 20 m of material preserved. An obvious flow top was not identified and so it is estimated that V_{1C} was once thicker and has since been eroded. This flow weathers a rusty brown colour, has a fine, massive texture in outcrop and contains few amygdules. The base of flow V_{1C} displays a blocky weathering pattern for about 2m and then grades into what appears to be a number of thinner individual flows about 1 to 2 m thick, remaining this way to the top of the outcrop (figure 2.11 D). Visible native copper was also noted within this flow, mostly lining the rare amygdules.

Microscopically, the textures of flows V_{1A} and V_{1C} are almost identical, while that of V_{1B} differs significantly. Samples of flow V_{1A} are fine-grained aphyric basalt, with a

groundmass of plagioclase laths, and small, anhedral, clinopyroxene crystals (figure 2.12A). The abundance of vesicles is low (~2%), and secondary minerals mostly consist of chlorite and calcite present within these vesicles, as well as interstitial chlorite. The primary minerals themselves are not significantly altered, and there is little to no variability in microtexture from the bottom to the top of flow V_{1A} . In contrast to V_{1A} , samples from flow V_{1B} are coarser and display a sub-ophitic texture. The clinopyroxene phenocrysts are sub- to anhedral, 0.5 to 1 mm in size, and either fully or partially enclose plagioclase laths 0.25mm in length. Flow V_{1B} is heavily chloritized in thin section, and this might account for its blue-grey colour in outcrop. Similar to V_{1A} , chlorite is interstitial, as well as present in vesicles; the latter have a higher abundance than in flow V_{1A} , approximately 5% (figure 2.12B). The degree of chloritization in V_{1B} decreases from the bottom to top of the flow. In addition, clinopyroxene crystal size increases from bottom to top. Finally, although native copper was observed in outcrop, none has been observed in the two samples taken from the bottom and top of flow V_{1B} .

Flow V_{1C} displays a microtexture very similar to V_{1A} , with the only significant difference being a slightly finer groundmass and fewer vesicles. Apart from these minor differences, V_{1C} shows the same mineralogy and degree of alteration as V_{1A} (figure 2.12C). In thin section, native copper is present as interstitial flecks, and as crusts within amygdules (figure 2.12C).

2.4 Volcano-stratigraphic sections and correlations of the southern lobe

In total, 34 sections were measured in the southern lobe in order to constrain the lateral distribution of the units identified in the two type sections. Out of the 34 sections, 27 sections preserved enough diagnostic facies and or units to allow accurate correlations. Of these 27 sections, 15 were measured by the author and 12 by others. Figure 2.13 is a map of the southern lobe to show the locations of the measured volcanic sections, their distribution throughout the area, as well as the correlated cross-sections. A summary table of sections measured, including location and a short description, is presented as appendix 2.2.

The best exposures and most complete volcanic sections are located in the central southern lobe. The western southern lobe has good exposure, mostly in river cuts, however it was challenging to assign units in this region due to the absence of the volcanoclastic units which provide a clear boundary between the V_0 and V_1 flows. In the southwestern southern lobe, much of the upper flows (i.e. unit V_{1A} and above) are preserved, however assigning individual flow units based on field relationships alone is challenging because of erosion and discontinuous nature of the flow contacts. Thus, individual flow units in this area are assigned based on comparison of their physical characteristics with those of the flow units of the type section. This method was also sometimes applied to the volcanic stratigraphy in the eastern part of the southern lobe, where the challenge was poor exposure and preservation of the volcanic units.

The correlations made between stratigraphic sections are based on the identification of distinctive contacts and marker units within the volcanic stratigraphy. These contacts and marker units include units C_1 , C_2 , V_{1A} , V_{1B} , as well as the brick-red

weathering surface at the top of flow V_{1B} . The base of flow V_{1A} is used as a stratigraphic datum to correlate the southern lobe volcano-stratigraphic sections. The distinct orange weathering colour and thickness of flow V_{1A} , as well as the nature of its structures (thick columnar joints in the lower colonnade followed by smaller, more erratic joints in the entablature) make it an easily recognizable unit across the southern lobe. In addition, the excellent exposures along long river valleys allow us to suggest that the base of unit V_{1A} was flat during its eruption. Below unit V_{1A} , the volcaniclastic units (C_1 and C_2) are easily recognizable, and although their contacts are commonly covered, they are easily correlated. Individual flows within the basal unit V_0 are difficult to correlate from one location to another due to their thin, highly weathered nature, and the variability in their lateral distribution. For these reasons, individual flows within the V_0 unit are not correlated from one section to the next unless a distinct contact is noted and is traceable, for example the contact in figure 2.14. The volcaniclastic units are easily recognizable, and although their contacts are commonly covered, they are easy to correlate.

The correlations of sections in cross-sections A-B, B-C, D-E, and F-G are presented in figures 2.16 and 2.17, with figure 2.15 showing the legend for the sections. Cross-sections A-B, D-E, and F-G are oriented roughly parallel to the E-W axis of the southern lobe, whereas cross-section B-C is approximately orthogonal to it.

2.5 Volcanic vent complexes

During the 2011 field season, two areas were discovered that are thought to represent the erosional remnants of volcanic vent complexes. The nature of the vents, i.e.

whether they are the erosional remnants of linear or point-source scoria cones, spatter cones, or rootless cones, will be further discussed in chapter 4. Here, the vent complexes are described, with emphasis placed on their physical and facies characteristics. In this study, the vent complexes are referred to as the eastern vent complex (EVC) and the western vent complex (WVC). The two sites are thought to be located at approximately the same stratigraphic level, above the volcanoclastic C_1 and C_2 units and within unit V_1 . Although at a similar stratigraphic level to unit V_1 , the stratigraphy at the WVC and EVC is dissimilar to that of the type section. The volcanic vent sites are preserved in stratigraphic sections 29 and Y. These sites are separated by about 115 km (see section 2.4.1, figure 2.13 for their locations on a map as well as more details).

The EVC has been studied more intensively as it was mapped and sampled over several days. The WVC was visited for one day and a sample profile was collected for isotope geochemistry study at UBC. The stratigraphy is similar at both locations. The base of the succession leading up to the EVC vent necks exposed unit C_2 , however this was not observed at the WVC. Unit V_1 at both sites consists of several dark brown to black weathering thin flows with massive bases and recessive tops for about 30 to 50m. These flows may be single, thick flows, weathered into benches that represent individual cooling units, colonnades, or entablatures (figure 2.18A and B). These are overlain by an orange-red weathering, thick flow. In both locations, the vent necks are preserved within the thicker, orange-weathering flow. This includes vent necks or plugs that have been preferentially preserved among the adjoining eroded basalt flows, rings of scoriaceous material in the areas surrounding these necks, and outcrops of flattened material resembling spatter. It is believed that differential weathering of the sheet flows and other

material above and around the vents occurred, to the point where the vent plugs became erosional outliers.

At the eastern vent complex, 5 to 10 volcanic vent necks are preserved along a NW-SE trending plateau face. Along this plateau, a cluster of five necks in a 25 m x 25 m area was chosen for a brief detailed study (figure 2.18C). The necks consist of massive, fine-grained, non-vesicular basalt that weathers to a rusty orange-brown colour. No obvious volcanic structures were noted in them. The necks at the EVC vary from 4 to 12 metres in diameter, and 5 to 10 metres in height (figures 2.18D and E, and figure 2.19A), and although these structures are erosional outliers, in the detailed study area they are contained within a semi-circular bowl whose 'walls' rise to about the same height as the plugs. The circular space between the necks and the 'walls' of the bowl is occupied by deposits of loose scoria that are unlithified, unstratified, and do not display bedding or other obvious depositional structures (figure 2.19B). The scoriaceous pieces are abundant but not uniformly distributed (i.e. the thicknesses of the deposits vary). The individual clasts are 2 to 15 cm in size, fine and crystal-poor, with centimetre-sized vesicles occasionally filled with calcite (figure 2.19C). In addition to the scoriaceous material, several small (2 to 5 m) outcrops of flaggy appearance with distinct bedding-parallel partings, and tops composed of pancake-sized circular structures were noted (figure 2.19D). These occur throughout the EVC, on the outside of the "bowl" containing the plugs and scoria. In the field these were interpreted as flattened spatter, and since individual spatter fragments are visible, the ejecta did not fully coalesce into lava flows (agglutinate) (figure 2.19E). The spatter deposits, as well as the other basalt material on the outside of the "bowl", display a fabric dipping away from the centre of the "bowl". At

the SE side of the study area the fabric dips at approximately 45° , trending 80° (figure 2.19F). At the NW side of the study area the fabric trends at 300° and dips at 10° , and at the NE end the fabric trends at 125° and dips at 82° . Figure 2.20 shows aerial and panoramic views of the EVC overlain with colours representing the three main lithologies present; vent plugs, scoria, and the 'bowl' containing these, including the bowl walls. Spatter was not included as their outcrops are few and spread out in the area.

The western vent complex (WVC) was not studied in detail by this author, and the following observations are compiled from a digital notes database. Vent plugs at the WVC are generally smaller than those of the EVC, with the exception of the one in figure 2.21 A and B. The plugs of the WVC are described as averaging at 2m in diameter, and being surrounded by outcrops of orange-brown weathering basalt. Similar to the EVC, the WVC contains loose, unlithified, scoriaceous pieces (figure 2.21 C). In addition, several outcrops were noted to display pancake-sized circular structures similar to the variably welded spatter interpreted at the EVC (figure 2.21 D). Native copper is noted at the WVC within the vesicles of a highly vesicular sample of basalt (figure 2.21 E).

Several samples of the WVC were examined in thin section; one was fine-grained basalt, similar to unit V_{1A} , another was coarse and sub-ophitic, similar to unit V_{1B} . The third, sample 10RAT-TD129B01, shows a porphyritic-like texture where amalgamations of coarse plagioclase and clinopyroxene crystals occur throughout a fine-grained basalt groundmass (figure 2.21 F). The crystals of the large plagioclase and clinopyroxene are not intergrown, appear broken at their edges, and some of the plagioclase appear to show a slight sieve texture. This, coupled with the fact that the amalgamations of coarse

plagioclase and clinopyroxene exhibit separate clinopyroxene-rich and plagioclase-rich domains, leads us to suggest that these are small diabase xenoliths. Implications of this are discussed in chapter 4.1.2.

2.6 Type section mineral chemistry

Mineral chemistry data were collected for pyroxenes, feldspars, alteration minerals and native elements from 7 samples located throughout the stratigraphy of the volcanic type section. Data are presented in Appendix 2.3.

Figure 2.22 shows total and average core and rim compositions for the probed pyroxenes plotted on pyroxene quadrilaterals, as well as wollastonite endmembers as a function of stratigraphic level. There is a clear spread of pyroxene core and rim compositions across the augite fields and into the pigeonite field of the quadrilateral in figure 2.22A. V_0 cores all plot as augite. V_0 rims are also augite, with the exception of two rims that plot as more Fe-rich augite. V_1 cores plot as augite, with the exception of one core that is Fe-rich, and two cores that plot as intermediate pigeonite. V_1 rims plot as augite, with two showing more Fe-rich rims, and one plotting completely in the ferroaugite field. One V_1 rim also plots in the intermediate pigeonite field. The cores of V_0 pyroxenes are more calcic than the rims, and this is also true, but to a lesser extent, in V_1 samples. The diagram of figure 2.22C also shows that the pyroxenes have more calcic cores and ferro-magnesian rims. In particular, two cores and one rim very low Ca ($\sim Wo_{10}$); these are the same as the same analyses that plot in the pigeonite field of 2.22A. In V_0 , cores stay consistent at about Wo_{40} , whereas rims increase from $\sim Wo_{30}$ to Wo_{42} . In

V₁, cores and rims show a very slight decrease in Wo content, but of a small range (~5%). Figure 2.22B shows the averages of combined cores and rims for each volcanic unit: the results reflect what was previously described, with V₀ pyroxenes plotting as augite, and V₁ plotting as augite.

When calculated from the data sheets the composition average indicates diopside (Mg_{0.9}Ca_{0.75}Si_{1.92}O₆) with Fe_{0.25} for unit V₀, and diopside (Mg_{0.84}Ca_{0.70}Si_{1.95}O₆) with Fe_{0.36} for unit V₁.

Figure 2.23A shows the plagioclase cores and rims on an albite, anorthite, orthoclase ternary diagram. Most plot between An₄₀ and An₈₀, and in a very general sense the cores are more anorthitic, whereas the rims are more albitic. A cluster occurs at the Albite apex and likely represents samples that have undergone low-temperature replacement: alteration is elaborated upon in chapter 3. No orthoclase component was detected. Averages for plagioclase from units V₀ and V₁ are also plotted; V₀ averages An₄₀ while V₁ averages An₆₀.

The interstitial alteration mineral common in the samples is chlorite (clinochlore), with Mg₃Fe_{1.5}Al_{1.5}Si_{3.4}O₁₀(OH)₈. The opaque mineral probed in V₀ has an average Fe/Ti cation ratio of 2.7/1, whereas the opaque mineral probed in V_{1A} has an average Fe/Ti ratio of 3.8/1. The oxides in the V₀ sample show a semi-skeletal crystal shape with good crystal edges, whereas the oxide probed in the V_{1A} sample is a complete crystal, sub- to euhedral, and intergrowing with the clinopyroxenes. The cation ratios yield a mineral formula of Fe_{2.7}TiO₄ for V₀ and Fe_{3.8}TiO₆ for V_{1A}, suggesting ulvospinel and magnetite respectively.

Figure 2.1: Examples of typical Natkusiak Formation exposure in the southern lobe. (A) shows a typical steep river cut with covered sides consisting mostly of talus, and (B) shows the Natkusiak Formation exposed as a plateau, again mostly consisting of talus and felsenmeer. (C) shows the cliff face measured for detailed section A (location indicated on map of figure 2.2).

Figure 2.2: Type section of the southern lobe, represented by detailed section B. Locations of detailed sections A and B are circled in yellow on the inset map. Type section unit divisions are indicated - (Kj) Kuujua Formation, (V0) basal unit, (C1) volcaniclastic unit 1, (C2) volcaniclastic unit 2, (V1) sheet flow unit which is further divided into flows A, B, and C.

Figure 2.3: Generalized stratigraphic section for the southern lobe.

Figure 2.4: Structures characteristic of unit V0 basal flows. **(A)** sharp, conformable contact between underlying sandstone and flow, hammer at the bottom of the image, for scale. **(B)** pillow with most of the chilled selvage at its bottom weathered out, a common occurrence in the case of the highly weathered basal flows. **(C)** cliff face where individual V0 flow units are recognizable due to their recessive flow tops. Note the apparent change in flow thickness from the bottom of the image to the top. Scale is field assistant circled in yellow. **(D)** shows the common thin sheet lobe flow morphology of V0, with flow base, core, and top indicated. Hammer for scale in the centre of the image. **(E)** shows an example of pahoehoe toes at the base of V0, hammer for scale.

Figure 2.5: Structures and microstructures characteristic of unit V0 basal flows, continued. (A) example of ropy flow-top texture found in talus proximal to outcrops of V0, photo by Trent Dell'Oro, (B) example of a typical flow contact. Inset photo is a close-up of contact showing abundant amygdules and pipe vesicles rising from the base of the overlying flow. (C) shows a round, ~1cm wide vesicle filled with calcite, and (D) pipe vesicles filled with chlorite; hammer pick for scale. (E) (sample 10RAT-NW065A01, 2.5x, plane polarized light) common texture of fine grained basalt with a ground-mass of plagioclase laths and few phenocrysts, as indicated. (F) (sample 10 RAT-NW064B01, 5x, plane polarized light) sericitized plagioclase glomerocryst with the same image under crossed polarized light inset to show sericite alteration. Pl = plagioclase, cpx = clinopyroxene.

Figure 2.6: Microstructures characteristic of unit V0 basaltic flows, continued. **(A)** (sample 10RAT-NW015A02, 2.5x, crossed polarized light) example of sub-ophitic texture, with clinopyroxene (cpx) and plagioclase (pl) indicated. **(B)** (sample NW067A01, 5x, crossed polarized light) example of a clinopyroxene phenocryst intergrown with plagioclase laths. **(C)** (sample 10RAT- NW064B01, 20x, plane polarized light) vesicle lined with acicular actinolite crystals and infilled with calcium carbonate. **(D)** (sample 10RAT-NW064B01, 10x, crossed polarized light) example of hydrogrossular garnet in a sample from the very base of V0. **(E)** (sample 10RAT-NW015A02, 5x, plane polarized reflected light) interstitial Fe-oxides developed between plagioclase laths. Cpx = clinopyroxene, Pl = plagioclase.

Figure 2.7: Characteristics of volcanoclastic unit C1. Photos **A** and **B** show typical exposures of unit C1 and thickness variations. Outcrop in **(A)** has a minimum thickness of about 8 m, with field assistant circled for scale. Outcrop in **(B)** has a minimum thickness of about 20 m, its extent represented by the yellow bar and units marked. **(C)** shows the crumbly nature of C1; circled are rounded clasts. **(D)** and **(E)** show more cohesive examples of C1, with a vesicular basalt clast shown in **(D)** and a quartz-rich sandstone clast shown in **(E)**. **(F)** shows the one locality where unit C1 directly underlies and is in contact with unit V1. The unclear, brecciated contact is located between the yellow lines.

Figure 2.8: Textural characteristics of units C1 and C2. (A) (sample 10RAT-NW017A02, 2.5x, plane polarized light) microtextures and components of unit C1. (B) (sample 10RAT-NW068A03, 2.5x, crossed polarized light) sandstone clast in C1. (C) and (D) macroscopic characteristics of unit C2 in two separate locations: (C) unit C2 interbedded plane-bedded and planar-tabular beds, hammer, for scale, is 40cm. (D) granules and sand grains of C2, as well as normally graded beds, direction indicated by arrow, and alternating beds of coarse and fine material. (E) (sample 10RAT-NW017B01, 2.5x, plane polarized light) C2 microfabric from a non-graded sample.

Figure 2.9: Characteristics of the contact between bedded volcanoclastic unit C2 and sheet flow unit V1A. (A) shows units C1, C2, and V1A. The C1-C2 contact is usually recessive, but in this location, the C2-V1A contact is well preserved and sharp. The white box shows a close-up, image (B). Note the vesicular base of flow V1A. (C) another example of the C2-V1A contact with columnar joints organised in a radiating pattern as indicated by the yellow line. Details in text. Note that scale bars in (A) and (C) were inferred from other field photographs where scales were present.

Figure 2.10: Flow architecture and styles of unit V1. **(A)** flows V1A, V1B, and V1C in the southern lobe type section. V1C is thought to be only partially preserved due to the lack of an obvious flow top. The outcrop from the top of C2 to the top of V1C is 70m. **(B)** lower colonnade and entablature zones of flow V1A. From the base of the lower colonnade to the top of the outcrop is 10 to 15 m. **(C)** example of a thick lower colonnade zone within V1A, as well as the well-developed and organized nature of the columnar joints within that zone. Field assistant circled in yellow for scale. **(D)** weathered and recessive contact between flows V1A and V1B, field assistants for scale. Note the blue-green weathering colour of 1B.

Figure 2.11: Characteristics of V1 unit flows, continued. (A) flow V1B's massive base and vesicular top, Jacob staff for scale. (B) sample of flow V1B with native copper completely infilling an amygdale (arrow). Photo credit Luke Ootes. (C) red weathered top of V1B followed by the base of flow V1C, with a close-up view in the inset photo. The red top is indicated by the white arrows and the white line indicates the contact between the two flows. For scale, the red unit is 60 cm thick. (D) shows the thin flows of V1C, contact drawn again in white and field assistant circled for scale.

Figure 2.12: Unit V1 microtextures. **(A)** (sample 10RAT-NW69A05, 2.5x, XPL) typical fine basalt microtexture of flow V1A. **(B)** (sample 10RAT-NW69A06, 2.5x, PPL) coarser and sub-ophitic texture of flow V1B, as well as the abundant chlorite, as indicated. **(C)** (sample 10RAT-NW069A08, 2.5x, XPL) shows the fine texture of flow V1C, and **(D)** shows the same sample in reflective light with an example of native copper occurring as a crust lining an amygdale. Cpx = clinopyroxene, Chl = chlorite, Pl = plagioclase.

Figure 2.13: Composite Landsat image of the southern lobe Natkusiak Formation. Location indicated by boxed area in inset map. Stratigraphic section numbers and locations are shown, as well as cross-sections A-B, B-C, D-E, and F-G.

Figure 2.14: An example of a traceable contact in the basal V0 flows, from section 4 (left) and section 8 (right). Contact is indicated in both photos by the yellow line. On the left, a hammer is circled for scale.

Figure 2.15: Lithology and symbols legend for the stratigraphic sections presented in figures 2.16 and 2.17.

Figure 2.16: Cross-sections A-B and B-C. Each section(s) is identified by the number above it, and vertical scale is located to the left of the cross-section. For legend see figure 2.15. Note that solid lines represent correlations made with confidence, while dotted lines represent inferred correlations. Vertical scale is exaggerated by approximately 40 times to emphasize relief, and horizontal distance is not to scale

Figure 2.17: Cross-sections D-E and F-G. Each section(s) is identified by the number above it, and vertical scale is located to the left of the cross-section. For legend see figure 2.15. Note that solid lines represent correlations made with confidence, while dotted lines represent inferred correlations. Vertical scale is exaggerated by approximately 40 times to emphasize relief, and horizontal distance is not to scale

Figure 2.18: Photos from the EVC and WVC. (A) and (B) show the stratigraphy at both locations for comparison. Photos: Trent Dell’Oro. (C) the plateau face along which the volcanic plugs are preserved. The yellow box indicates the area studied in detail. Photo: Trent Dell’Oro. (D) example of a smaller volcanic plug, author for scale. (E) example of a larger volcanic plug, author for scale. Photos by Dominique Weiss.

Figure 2.19: Photos from the EVC (A) detail of a vent plug, hammer for scale. (B) volcanic neck, the walls of the ‘bowl’, and the scoriaceous deposits, circled humans for scale. Photo: Luke Ootes. (C) close-up of the loose, un lithified scoriaceous material. Photo: Dominique Weiss. (D) and (E) are examples of the spatter-like structures found, hammers for scale. (D) is an example of what would be ‘unwelded’ spatter, and (E) is a more welded, almost completely agglutinated, example. Photo E: Trent Dell’Oro. (F) dipping fabric of the ‘walls’ surrounding the bowl containing the plugs and scoria; in this example dip is at 45 degrees.

Figure 2.20: Aerial view (A) and panoramic view facing SW (B) of the focus area at the EVC, enhanced with colours representative of the lithologies present. The dark brown represents the vent plugs, the pale purple represents the area occupied by loose scoriaceous clasts, and the pale brown represents the material surrounding the “bowl”, including its walls. The letters A, B, C, D, and E, identify the individual plugs in each photo.

Figure 2.21: Photos from the WVC (A) and (B) show the same outcrop interpreted to represent a volcanic neck from two opposing directions. The red lines define the edge of the plug. In B, circled is a backpack for scale. (C) a piece of scoriaceous material from at the site and (D) pancake-like layering interpreted as spatter. (E) sample of highly vesicular basalt with oxidized copper and malachite filling vesicles. (F) (sample 10RAT-TD129B01, 2.5x, XPL) diabase xenocrysts proximal to the plugs of the WVC. All phtos but (F) by Trent Dell'Oro.

Figure 2.22: Mineral chemistry data for pyroxene phenocrysts from selected samples. (A) shows pyroxene core and rim compositions on a clinopyroxene quadrilateral, and (B) shows the average pyroxene composition for units V0 and V1. Pyroxene quadrilaterals are after Poldervaart and Hess 1951. (C) shows Wollastonite endmember core and rim compositions throughout the stratigraphy. The green and brown fields correspond to units V0 and V1, respectively.

Figure 2.23: Mineral chemistry data for plagioclase phenocrysts plotted on a Albite - Anorthite - Orthoclase ternary diagram.

Chapter 3: Major and Select Trace Element Geochemistry and Chemostratigraphy of the Southern Lobe, Natkusiak Basalts

3.1 Introduction

Major element geochemistry is a fundamental tool for evaluating the chemical behavior and nature of igneous rocks. This study principally seeks to evaluate the behavior of the major, minor, and selected trace elements of the southern lobe Natkusiak Formation. A concurrent study completed at the University of British Columbia focuses on the trace and isotope geochemistry (Dell'Oro, 2012). The main purpose of the geochemical part of this study is to document how the geochemistry varies through the volcanic stratigraphy, and compare the geochemical characteristics of the southern lobe to those of the northern lobe. The following section investigates rock classification and discrimination diagrams, major- and trace-element behavior, alteration, and chemostratigraphy. Comparisons with northern lobe geochemistry are presented in chapter 4.

3.2 Sampling and analytical methods

3.2.1 Field sampling

Samples for geochemical analysis were collected during both the 2010 and 2011 field seasons. In 2010 the two type sections (A and B) that were measured for detailed volcano-stratigraphy were sampled with the goal of producing vertical geochemical profiles to better understand the changes in rock chemistry with stratigraphic height. The

detailed sections were sampled as systematically as possible, flow by flow where possible, from the base of the Natkusiak Formation to the topmost exposed sheet flow. Eleven samples were collected and analyzed for section A, and twenty-one samples were collected and analyzed for section B.

In 2011, four main areas across the southern lobe were sampled for geochemistry based on exposure and accessibility. These sample areas were chosen in order to increase the southern lobe coverage from West to East, rather than with the intention of creating full chemostratigraphic profiles. One sample location is a small erosional outlier of Natkusiak Formation that is the southern tip of the northern lobe, however geochemical and isotopic data (Dell'Oro, 2012) indicate that these lavas are part of the southern lobe suite. From West to East the sample areas are named Group I, Group II, Group III, and Group IV. Group I samples ($n=7$) are a supplementary sample set of unit V_1 . Group II samples ($n=9$) represent a geochemical profile through 3 flows of unit V_1 that have field characteristics similar to unit V_0 . Group III sample was collected from unit V_1 across a valley from type section B. Group IV samples ($n=9$) represent a geochemical profile of 9 samples through the stratigraphy of a small erosional outlier of Natkusiak Formation. The geochemistry is presented within the context of the lithostratigraphy (i.e. variations between units V_0 and V_1) without specifying individual trends within sample groups. Figure 3.1 is a cropped map of the southern lobe modified from Hubert et al. (2005) with sample locations indicated by stars. In the same figure are the two detailed stratigraphic type sections showing the locations of the samples used for the chemostratigraphy.

3.2.2 Analytical methods

Sample preparation and whole rock geochemical analyses were performed at the Geological Survey of Canada (GSC), Québec and Ottawa divisions, the University of British Columbia, and the University of Ottawa. Whole rock geochemical data are presented in Appendix 3.1. In 2010, the least altered and least vesicular portion of each sample was cut out using a diamond saw at GSC Ottawa. The samples were powdered using a planetary agate mortar, were fused on a Claisse fluxer using lithium metaborate and lithium bromide, and then digested in nitric and hydrochloric acids prior to analysis by inductively coupled plasma-atomic emission spectrometry (ICP-AES) at the INRS-ETE laboratories, GSC Québec, with an analytical detection limit of $<0.05\%$ and a precision of $\pm 3\%$. Full lab procedures are as described in Leclerc et al. (2011). Standard reference materials used for the 2010 samples analysed at the INRS-ETE laboratories are USGS materials BCR-2 and BHVO-2 (basalt standards) and are included within the data table of appendix 3.1. In addition, one duplicate analysis is also included and indicated within the data table.

In 2011, samples were processed at the Pacific Centre for Isotopic and Geochemical Research (PCIGR), University of British Columbia, using a hydraulic crusher with Tungsten-Carbide plates and an agate planetary mill. Prior to analysis by X-Ray Fluorescence Spectrometer (XRF) at the X-Ray Laboratory, University of Ottawa, the samples were fused into glass beads using 1g of sample and 4g of flux (flux composition is 78.52% lithium tetraborate and 21.47% lithium metaborate). The samples were fused using a Claisse Fluxer in crucibles made of 95% platinum and 5% gold over a flame for approximately 18 minutes, and then poured into moulds of the same material as

the crucibles. The XRF analyses were done at 3kW, with a rhodium tube as the x-ray source. Precision for each major and trace element is indicated in the data table of appendix 3.1. The standard reference materials used for the 2011 samples analysed at the University of Ottawa X-Ray Laboratory are USGS material BCR-2 (basalt standard) and international standard DR-N (diorite standard) and are included within the data table of appendix 3.1. The samples' year of collection, and thus the analytical technique used, is indicated by the first two numbers for each sample, either 10 (2010) or 11 (2011).

Within this study's dataset, Zr, Nb, and Y were only analyzed for the samples collected in 2011, which does not include samples from unit V_0 . Thus, for the classification diagrams of figure 3.3, unit V_0 trace element data are supplemented with data from Dell'Oro (2012) (included in the data table of appendix 3.1) in order to fully represent the lithostratigraphy in the context of these diagrams. For reproducibility and consistency, the supplemental data have also been plotted in the classification diagrams of figure 3.2, as well as the major element variation diagrams of figure 3.4. Where used, the supplemental data are indicated by a different symbol as shown in the symbol legends.

For plotting, all analytical data used are normalized to 100% dry rock equivalent.

3.3 Lithogeochemistry: Major and select trace elements

3.3.1 Majors and traces: general behaviour

Figure 3.2A shows a total-alkalis *versus* silica plot after LeBas et al. (1986). Most samples plot as basic and sub-alkaline in composition, within the basalt field with SiO_2 concentrations between 48 and 52 wt% and total alkalis of 1.5 to 5 wt%. A cluster of samples from unit V_0 plot in the slightly more alkalic trachy-basalt field with up to 6.5 wt% total alkalis. On an AFM diagram after Irvine and Baragar (1971), V_1 samples plot within the tholeiitic field, with the V_0 samples showing a spread that straddles the dividing curve between the tholeiitic and calc-alkaline fields (figure 3.2B). The samples progress from a more magnesian (unit V_0) to ferrous (unit V_1) composition. For comparison, figure 3.2C shows the ternary diagram for basalt classification after Jensen (1976). This plot, similar to Irvine and Baragar's AFM diagram, is useful because it does not utilize fluid-mobile alkali elements. On this diagram all samples plot within the high-magnesium tholeiitic basalt and the high-iron tholeiitic basalt fields. All V_0 samples plot in the high-magnesium tholeiitic basalt field. V_1 samples plot in both high-magnesium tholeiitic basalt and high-iron tholeiitic basalt fields.

Figure 3.3 shows three basalt classification diagrams that are based on immobile trace elements. Both V_0 and V_1 samples plot in a tight cluster in the sub-alkaline basalt field on the Zr/Ti vs. Nb/Y after Pearce and Cann (1973) (figure 3.3A). A Zr-Ti-Y ternary plot after Pearce and Cann (1973) suggests the tectonic setting of eruption (island-arc, ocean-floor, calc-alkali, or within-plate), while a Ti-Zr discrimination plot, also after Pearce and Cann (1973), indicates a geochemical signature similar to calc-

alkaline basalts, low-potassium tholeiites, mid-ocean ridge basalts (MORBs), or a transitional field between the two latter. Most samples from unit V_0 plot in the field of ocean-floor basalts on the Zr-Ti-Y plot (figure 3.3B). V_1 samples straddle the within-plate and ocean-floor fields of the Zr-Ti-Y plot. Unit V_0 samples plot within the low-potassium tholeiite and MORB fields on the Ti/Zr discrimination plot (Figure 3.3C), whereas samples from unit V_1 only plot within the MORB field. Both lithostratigraphic units show a spread of values and a positive correlation between Ti and Zr. The average Ti/Zr ratio for V_0 is 177 and the average Ti/Zr ratio for V_1 is 164.

Major and minor elements are plotted against MgO to show how their concentrations vary as magnesium content evolves. For many elements, two distinct geochemical groups are defined by lithological units V_0 and V_1 (figure 3.4). On an MgO vs SiO_2 plot (figure 3.4A) samples are scattered with higher MgO concentrations in unit V_0 (11.12 to 7.81 wt%) than in unit V_1 (8.1 to 6.2 wt%). $\text{Fe}_2\text{O}_{3\text{T}}$, P_2O_5 and TiO_2 (figure 3.4B, C, and D) show a similar behaviour of increasing enrichment with decreasing MgO, with samples from unit V_0 being depleted in those elements as compared to the samples from unit V_1 . Unit V_0 shows a scatter in Fe_2O_3 with one outlier that plots in the V_1 cluster (sample 10RAT-NW16B03), and another showing very low Fe (sample 10RAT-TD16A1). Unit V_1 samples are characterized by higher Fe_2O_3 than V_0 samples and show increasing Fe_2O_3 with decreasing MgO. In unit V_0 , P_2O_5 concentrations are scattered, but form two distinct groups in unit V_1 . Similar to Fe_2O_3 , V_0 and V_1 samples define two distinct clusters on the MgO vs. TiO_2 plot. Unit V_0 is characterized by low TiO_2 (0.96 and 1.14 wt%), whereas unit V_1 is characterized by high TiO_2 values (1.24 and 1.81 wt%). V_1 samples form a weak negative correlation with MgO.

Al_2O_3 concentrations (figure 3.4E) decrease as MgO decreases, however the correlation is weak. K_2O concentrations (figure 3.4F) shows significant scatter, likely due to alteration. Unit V_0 shows higher values of both oxides (14.45 to 16.13 wt% Al_2O_3 and 0.31 to 3.82 wt% K_2O) as compared to unit V_1 (13.68 to 15.78 wt% Al_2O_3 and 0.06 to 0.95 wt% K_2O). In addition, within the scatter of V_0 K_2O concentrations, there are two clusters of samples showing decreasing K_2O with decreasing MgO: one cluster follows into the V_1 cluster and shows relatively low K_2O , while the other displays very high potassium values. For CaO and Na_2O concentrations (figure 3.4G and H), geochemical behaviour differs depending on lithological unit. Unit V_0 shows two distinct clusters in CaO vs MgO space; one as a positive correlation with lower values of CaO between 6.61 and 8.55 wt%, and one with as a negative correlation with CaO values between 10.85 and 12.07 wt%. Although values are scattered, V_1 shows a general enrichment in CaO as MgO concentrations decrease. For Na_2O , unit V_0 shows a spread with concentrations between 1.34 and 4.57 wt%, and V_1 shows a spread of Na_2O concentrations between 1.71 and 4.06 wt%; no distinct pattern is obvious.

Natkusiak Formation samples show variable scatter on MgO vs trace element plots; however, they are generally clustered based on lithostratigraphic unit similar to the major elements. Similar to TiO_2 , vanadium (figure 3.4I) is enriched as MgO decreases, with unit V_0 showing the lowest values (291 to 342 ppm), and V_1 showing the highest values (314 to 436 ppm). In contrast, chromium and nickel (figure 3.4J and K) both decrease as MgO decreases. Unit V_0 shows a cluster of Cr concentrations distinct from V_1 , with higher Cr concentrations of 370 to 518 ppm than unit V_1 (117 to 293 ppm). The exception is sample 10RAT-NW15A03 (231 ppm Cr), which is also more evolved and

plots with unit V₁ samples. Ni concentration decreases linearly for both lithostratigraphic units, with the exception of sample 10RAT-NW69A05 from unit V₁ (365 ppm, circled). Cu concentrations (figure 3.4L) are scattered in unit V₀ with values ranging from 52 to 172 ppm, but show a slight negative correlation with MgO for unit V₁ with values from 48 to 324 ppm. On a CaO/Al₂O₃ vs. MgO plot for olivine, plagioclase, and pyroxene fractionation (figure 3.4M), the lithological units each define their own trend of increasing CaO/Al₂O₃ ratio as the rocks evolve and MgO is depleted. This trend is similar to that of CaO vs. MgO and so is likely influenced by variations in calcium. Scandium (figure 3.4N) shows a slight decrease with decreasing MgO.

3.3.2 Geochemistry of volcanoclastic unit C₁

Ideally, a study of grain and clast provenance would help constrain the sources of volcanic and sedimentary components within unit C₁. However, it is beyond the scope of the current study, and so as a small reconnaissance study, whole-rock geochemical data for the three volcanoclastic samples from unit C₁ are plotted with the lava data of units V₀ and V₁ (figure 3.4 and 3.4 con't). The volcanoclastic samples are plotted with the intention to determine whether a significant volcanic detritus component is present, which would be reflected as enrichments in elements such as Mg, Fe, Ti, Ni, Cr, and Cu. The data may also speak to the source of these volcanic components.

In figure 3.4 A the volcanoclastic samples show higher SiO₂ concentrations than the volcanics (~53 to 55 wt%) consistent with presence of detrital quartz and quartzite (figure 2.8A, B), but similar MgO (~7 wt%) consistent with abundant mafic clasts. Unit

C₁ shows low Fe₂O₃ similar to the lowest concentrations of unit V₀ (10.2 – 10.6 wt%) (figure 3.4 B). TiO₂ concentrations for C₁ resemble the higher V₀ values (1.06 wt%), while Cu is quite low relative to both volcanic units (31.5 to 38.9 ppm) (figure 3.4 H and L). Unit C₁ Cr and Ni concentrations are clustered amongst the lowest values of both volcanic units at about 118 ppm Cr and 80 ppm Ni (figure 3.4 J and K).

3.3.3 Geochemical alteration in the southern lobe

Element mobilization within the volcanic pile affects major element concentrations and can cause alteration such as sericitization, albitization, chloritization, as well as the precipitation of calcite in amygdules. This is especially true for elements such as Ca, Na, K, Mg, and Fe because these are the elements that are commonly gained or lost during the alteration processes mentioned above. Petrographically, the Natkusiak Formation samples show signs of alteration and so the purpose of this section is to test the extent to which the geochemistry has been affected. The diagrams in figure 3.5 are chosen based on the fact that they account for the gain/loss of Na, Ca, and K, that appear to be the elements most affected by mobilization. To a lesser extent these alteration plots also take into account mobility of Fe and Mg, which is important because these elements are used to define the rock type.

The first diagram is an alteration box plot that shows the Carbonate-Chlorite-Pyrite Index (CCPI) against the Ishikawa Index (AI) to determine the type and severity of alteration in volcanic rocks (3.5 A). Even though the alteration box plot is meant to clarify the relationship between the lithogeochemistry, alteration mineralogy, and

alteration zoning of an economically viable volcanic package, specifically of a volcanogenic-hosted massive sulphide deposit (Large et al., 2001) , this plot can also be useful for the general quantification of alteration in mafic volcanic rocks and is used in that context. Both the AI and CCP indices are a measure of the ratio of elements gained to elements gained and lost. In the case of the AI the ratio is $(K_2O + MgO) / (K_2O + MgO + Na_2O + CaO)$ and represents the breakdown of Na-plagioclase and volcanic glass into sericite and chlorite (Large et al., 2001). Samples with an AI of 20 to 60 are considered of primary composition (unaltered), samples with an AI less than 20 have been albitized, and samples with an AI more than 65 have been sericitized. The AI approaches 100 in rocks that have had complete replacement of feldspars and glass by sericite and chlorite. The Natkusiak samples show a spread of AIs between 30 and 60.

The CCPI is calculated based on the ratio of $MgO + FeO / MgO + FeO + Na_2O + K_2O$ and represents the replacement of albite, potassium feldspar, or sericite, with Mg-Fe chlorite, as well as carbonate alteration and the addition of pyrite, magnetite, and hematite (Large et al., 2001). It is important to note that the CCP Index is affected by magmatic fractionation (i.e. felsic vs. mafic nature) so that unaltered basalts typically show a range in values between 70 and 90 (Large et al., 2001) and will plot at the top and centre of the alteration box plot (Large et al., 2001).

The alteration box plot for the Natkusiak Formation samples is presented in figure 3.5A with fields for least altered volcanics and mineral end-members after Large et al. (2001) indicated, as well as samples showing most intense alteration circled in red. Although there is a spread of values, almost all samples plot within the range of unaltered

basalt. The V_0 unit shows a slightly wider range in both indices than the V_1 unit. CCPI for unit V_0 varies from 76 to 92, while AI varies from 38 to 57. CCPI for unit V_1 varies from 80 to 91.5, while AI varies from 32 to 44. Large et al. (2001) describe a number of possible hydrothermal (figure 3.6A) and diagenetic (figure 3.6B) alteration trends within the alteration box plot. The limited spread of values in the alteration box plot for the southern lobe samples most resembles the hydrothermal chlorite-carbonate and sericite-carbonate trends, and does not correspond to any diagenetic trends (i.e. seawater alteration).

The second alteration plot used is the Igneous Spectrum/spillite plot after Hughes (1972) (figure 3.5B). This diagram compares the total alkalis ($K_2O + Na_2O$) with the ratio of potassium to total alkalis, giving an indication of the amount of potassium and sodium gained or lost in the system. Unaltered mafic rocks plot roughly between the two curves on the diagram; altered rocks plot to the left of the lines if potassium was lost and to the right of the lines if potassium was gained. Spilites (albitized mafic rocks) and keratophyres plot where indicated, to the left of the lines.

Most of the samples from unit V_1 of the Natkusiak plot within the curves of unaltered mafics, however some plot in the spilite range representing potassium loss. The samples from unit V_0 show a much larger spread. Three V_0 samples plot with V_1 samples with 4 to 5 wt% K_2O+Na_2O and at values of 10 to 30 for K variability ($100 \cdot K_2O / (K_2O + Na_2O)$). Three other V_0 samples also plot with V_1 samples and show a similar trend for K variability, however have much lower K_2O+Na_2O concentrations at about 1 to 2 wt%. In addition, there are two clusters of four samples each that plot at

similar K_2O+Na_2O values as the other V_0 and V_1 samples, but with higher K variabilities of 45 to 65 and 40 to 50. These samples are circled in red and are the same samples as the V_0 samples circled in the alteration box plot (figure 3.5A).

3.4 Chemostratigraphy of southern lobe type sections

As the geochemical data have already been described in the context of the lithogeochemistry (chapter 3.3), the purpose of this section is to identify variations in chemistry with stratigraphic height. Whole-rock geochemical data are plotted against stratigraphic height in figure 3.7. The stratigraphic datum used in this section is the base of the Natkusiak Formation at its contact with the underlying Kuujua sandstone. Only data from the two type sections measured in 2010 are used as these were meant to be complete volcano- and chemo-stratigraphic profiles. The symbols used show whether the sample belongs to the basal (V_0) or the sheet flow unit (V_1), or type section A or B.

Despite some similarities, there is an overall marked difference in chemistry between the basal V_0 unit and the stratigraphically higher V_1 unit, as was previously determined. SiO_2 (figure 3.7A) concentrations for unit V_0 form a cluster with no obvious stratigraphic trend. In unit V_1 SiO_2 remains relatively stable with the exception of the top three samples that show slightly higher SiO_2 concentrations. MgO (figure 3.7B) decreases up section in unit V_0 but stabilizes in unit V_1 at around 7 to 8 wt% Mg, with the exception of one outlier (6.7 wt %, sample 10RAT-NW-19A04). There is a gradual increase in total Fe_2O_3 through V_0 , followed by two trends in V_1 (figure 3.7C). V_1 samples from section A form a cluster with total Fe_2O_3 ranging from 13.2 to almost 14.3 wt%,

while V_1 samples from section B are fairly constant with the exception of one outlier (sample 10RAT-NW69A08 at 13.6 wt% Fe_2O_3). TiO_2 content shows a marked difference in concentration between the V_0 and V_1 units with unit V_0 displaying much lower concentrations than unit V_1 . Both units show a slight decrease in TiO_2 up section, and there is one outlier sample with very high relative titanium (1.8 wt%).

The alkalis show variable concentrations within the stratigraphy. CaO concentrations (figure 3.7E) are grouped into two clusters for unit V_0 , with an overall increase up section. The clusters represent higher and lower CaO values (10.5 to 12 and 7.5 to 8.5 wt%, respectively), however do not appear to completely depend on the sample's position within the V_0 stratigraphy, even though the plot makes it appear as though the samples from lower in the stratigraphy are higher in CaO. Unit V_1 shows fairly consistent calcium. However, in section B there are two outliers with lower CaO concentrations (samples 10RAT-NW69A05 and NW69A06). The nature of the sodium concentrations in unit V_0 and V_1 appear to mirror those of the calcium concentrations (figure 3.7F). Sodium data are clustered into three groups: low, medium, and high Na_2O . In this case, the clusters appear to depend on stratigraphic position within V_0 ; low Na_2O (~1.5 wt%) are located at the base of V_0 while high Na_2O are at the top (~4 wt%). Within unit V_1 , Na-content is consistent between approximately 1.5 and 2.5 wt% with the exception of two outliers with higher Na_2O at 3.5 and 4 wt% (samples 10RAT-NW69A05 and NW69A06). In terms of potassium content, the concentrations remain consistent within the entire stratigraphy with a range between 0.1 and 1 wt% K_2O . The only exception is a group of samples within the first 30 metres from the base of unit V_0 that have higher K_2O values, between 2.4 and 4 wt%. Finally, aluminum content shows a

simpler story with a decrease in Al_2O_3 up section in unit V_0 , and fairly consistent concentrations, despite a very slight decrease, in unit V_1 . The exception in V_1 is a sample of lower Al_2O_3 at 13.7 wt%.

Four trace elements are shown in figure 3.7: Cu, Cr, Ni, and V. Copper concentrations show a lot of scatter and no trends within the stratigraphy. Cu concentrations do not exceed ~200 ppm, with the exception of two samples from unit V_1 , section A, that show Cu concentrations around 300 ppm. As CaO and Na_2O did, chromium and vanadium show mirroring trends. Cr content in unit V_0 is much higher than in unit V_1 , with the exception of one sample that has a Cr-content similar to those of V_1 . V_1 samples show consistent Cr concentrations up section, with one outlier visible near the top of the stratigraphy (sample 10RAT-NW69A05). On the other hand, V concentrations are much lower in unit V_0 than in V_1 , similar to the distribution of TiO_2 . Vanadium concentrations remain consistent throughout V_1 , with the exception of one sample with a much higher V concentration (10RAT-NW19A04). Nickel concentrations stay fairly consistent throughout the entire volcanic stratigraphy with just a slight decrease from the base of unit V_0 to the top of unit V_1 . The sample showing a very high Ni concentration is the same sample that shows the high Cr value.

Figure 3.1: Sampling locations for whole-rock geochemistry. Map is cropped and modified from Hulbert et al. 2005, and shows locations of samples from the 2010 and 2011 field seasons; section A is designated by the blue star, section B is designated by the red star, all other locations are designated by black stars. Stratigraphic type sections A and B are also shown with sample locations indicated within the stratigraphy.

Figure 3.2: Classification diagrams for southern lobe Natkusiak Formation basalts. **(A)** Plot of total-alkalis vs. SiO_2 after LeBas et al., 1986, to show rock classification based on alkalis and silica content. **(B)** AFM diagram after Irvine and Baragar, 1971, to show the tholeiitic and calc-alkaline trend. **(C)** Ternary diagram using aluminium, iron and titanium, and magnesium, after Jensen 1976, for comparison with Irvine and Baragar's ternary plot. High-iron tholeiite (HFT) and high-magnesium tholeiite (HMT) fields have been added. Note that the supplementary data, as discussed in the text, is here represented by the upside-down triangles.

Figure 3.3: Classification diagrams for the southern lobe Natkusiak Formation basalts. **(A)** Zr/Ti vs. Nb/Y basalt discrimination diagram after Pearce 1996 (after Winchester and Floyd 1977), to show the classification of samples based on immobile elements. **(B)** Basalt classification diagram of Zr vs. Ti/100 vs. Y*3 after Pearce and Cann, 1973, to discriminate between island-arc basalts (field A), ocean-floor basalts (field B), calc-alkaline basalts (field C), and within-plate basalts (field D). **(C)** Basalt discrimination diagram of Ti vs. Zr after Pearce and Cann, 1973. Low-K tholeiites plot in fields LKT and B, calc-alkali basalts plot both in field B and the calc-alkali field, and ocean-floor basalts plot in fields B and MORB. Note that the supplementary data, as discussed in the text, is here represented by the upside-down triangles. Symbol legend is in figure 3.2.

Figure 3.4: Select major oxide and trace elements plotted against MgO concentrations to show variations as samples evolve from high to low MgO concentrations. Oxide amounts are in weight percent, trace amounts are in parts per million.

Figure 3.4, con't: Select major oxide and trace elements plotted against MgO concentrations to show variations as samples evolve from high to low MgO concentrations. Oxide amounts are in weight percent, trace amounts are in parts per million.

Figure 3.5: Alteration diagrams to assess alteration of the Natkusiak Formation samples. **(A)** Alteration box plot after Large et al., 2001. Alteration mineral end-members are shown (large dots), as well as fields (boxes) for least altered rocks depending on igneous rock type. **(B)** Igneous spectrum plot after Hughes, 1972. Samples showing most intense alteration are circled in red.

Figure 3.6: (A) Hydrothermal and (B) diagenetic alteration trends modified from Large et al. (2001).

Figure 3.7 : Geochemical profiles through the stratigraphy of sections A and B. Symbols are based on lithostratigraphic units and the stratigraphic datum (0 m) used is the base of the Natkusiak Formation at the contact with the underlying Kuujjua Formation sandstone.

Chapter 4: Discussion and Implications

4.1 Southern lobe lithostratigraphy, regional variations, and implications for the initiation and evolution of the Franklin Magmatic Event

4.1.1 Significance of the Natkusiak Formation lithostratigraphy

The first 200 m of volcanic stratigraphy within the Natkusiak Formation of the southern lobe displays four well-defined units: 7 to 10 basal basalt flows (V_0), two volcanoclastic units with distinct structures and thus differing mechanisms of deposition (C_1 and C_2), and a unit (V_1) of thick flows characteristic of other flood basalt provinces (Bryan et al., 2010). It is suggested that this volcano-stratigraphy records the initiation of volcanic activity (V_0), a hiatus (C_1 - C_2), and the transition to the main phase extrusive volcanism (V_1) of the Franklin Magmatic Event. Lava-sediment interaction below the contact between the Kuujjua and Natkusiak Formations is thought to represent a brief volcanic ‘precursor’ event and indicates that some of the early magmatism was coeval with deposition of the fluvial sands (R. Rainbird, pers. comm., 2012).

It is hypothesized that the V_0 member flows represent the onset-phase of flood volcanism, as described by Jerram and Widdowson (2005). The basal V_0 lava flows have smaller volumes than the thick V_1 sheet-like flows, they are not laterally extensive, and the individual flows themselves are discontinuous in nature and untraceable on a horizontal scale larger than 1000m. The discontinuous nature of the V_0 flows may be due to their emplacement into local paleo-topographic lows, a process made evident from the stratigraphic cross-sections and further discussed in section 4.1.2. V_0 flows are thin, simple flows as described by Walker (1972), with vesicular flow bases, massive cores,

and highly vesicular flow tops. The abundant vesicles of V_0 flows are degassing features that indicate that the basal lavas were likely volatile-rich. No lava feeder tubes, or collapse and draining features common to inflated lava flows, were observed within the V_0 stratigraphy; however it is entirely possible that these features are not preserved. Moreover, Self et al. (1998) explain that the end product of an inflated sheet flow can display a flow base, core and vesicular flow top architecture without significant collapse features in the top crust, and so this might be the case for the V_0 flows. In either case, as no proximal magmatic source or feeder mechanism was directly observed for the V_0 flows, they would likely have required a relatively high eruption rate despite their relatively low-volume to have been distributed within the area occupied by the southern lobe.

The locally pillowed and hyaloclastic nature of the V_0 unit indicates eruption onto wet, unlithified, sandy sediment of the Kuujjua Formation alluvial-fluvial system and into associated bodies of water. The interaction between basal volcanic facies and underlying sediments is a common phenomenon in other flood basalt provinces, such as the Etendeka Continental Flood Basalts, where basal flows intermingle with aeolian sediments of the Huab basin, or the Deccan Traps in India where onset-phase, fissure-fed tholeiitic flows interact and in some places are intercalated with sedimentary formations (Jerram and Widdowson, 2005). The fine microtexture of intergrown plagioclase laths and small clinopyroxene crystals of most V_0 and V_1 flows is typical of continental tholeiites, as was previously stated by Dostal et al. (1985) and Dupuy (1995) for the Natkusiak basalts. However, the increased coarseness of some V_0 intergrowth

microtextures, as well as the coarse sub-ophitic texture of flow V_{1B} , is intriguing. Possibilities that might explain this phenomenon include the following:

- 1) The coarse samples from unit V_0 and V_{1B} might originate from the centre of a/the flow, were insulated, and thus allowed to cool at a slower rate to form coarser crystals. Cooling rates may have been variable throughout section V_0 .
- 2) The flows of V_0 showing the coarse microtextures are in fact sills emplaced within the extrusive pile, as documented by Dostal et al. (1985) in the northern lobe where dykes cutting through the volcanic stratigraphy feed irregular lenses of diabase intercalated with the lava flows.

Secondary minerals such as chlorite, prehnite, and actinolite within the volcanic pile suggests low-grade sub-greenschist facies metamorphism, and may be the result of burial (Schiffman, 1995). Based on a similar mineral assemblage, burial metamorphism was also suggested for the northern lobe Natkusiak Formation (Dostal et al., 1985). Within the southern lobe, the presence of hydrogrossular in unit V_0 is suggestive of calcium carbonate metasomatism. Calcium carbonate metasomatism may be the result of circulating calcium-rich brines originating from the underlying carbonate rock sequences of the Shaler Supergroup (unpublished). In addition, the high abundance of hydrothermal alteration minerals within the southern lobe volcano-stratigraphy such as sericite and albite; the precipitation of many of the secondary minerals within vesicles and veinlets; as well as the presence of redistributed secondary native copper as flecks, sheets, and linings within amygdules (Jefferson et al., 1985), suggests hydrous alteration and metasomatism. Hydrothermal fluid circulation through the volcanic pile would have been

encouraged by the heat of the volcanic pile. Additionally, albitization is suggested by some feldspar core and rim analyses, as well as the alteration geochemistry of V_0 samples. Alteration is further discussed in section 4.3.2.

It is hypothesized that the presence of two volcanoclastic units in the central and eastern parts of the southern lobe represents a hiatus in volcanism, but of unknown timespan. Due to the rarity of pyroclastic components such as accretionary lapilli, scoria, blocks and bombs, the absence of pyroclastic depositional structures, and the abundance of clastic components including rounded quartz grains, it is proposed that unit C_1 is a re-worked (epiclastic) mafic volcanoclastic rock. Further to this, unit C_1 has a scaly habit, probably reflecting the presence of abundant phyllosilicate minerals (i.e. mud). These deposits either filled existing topographic lows, excavated channels in the underlying V_0 unit, or both. Mafic volcanoclastic deposits intercalated with lavas are well-documented in many flood basalt provinces such as the Yemen province, the Deccan Plateau, parts of the North Atlantic Igneous Province, and the Siberian Platform (Ross et al., 2005). The volcanoclastic deposits vary in nature from structureless to layered to brecciated, and can include a variety of materials including altered glass, basaltic clasts, country rock fragments, and quartz grains (Ross et al., 2005). Ross et al. (2005) also suggest that the presence of quartz grains within mafic volcanoclastic deposits indicates a possible interaction between the magma and the underlying consolidated or unconsolidated sediments, a feature predominant in unit C_1 .

The actual mechanism of deposition for unit C_1 is still uncertain. Given the thick, massive nature of C_1 , as well as the pebble-sized or smaller and compositionally

heterogeneous clasts, the fine muddy groundmass, the very slight alignment of the elongate clasts, and the lack of obvious sedimentary structures such as planar or cross-bedding, a mass flow mechanism of deposition such as a mudflow or lahar is inferred. A mass flow might have occurred as a gravity flow caused by slope instability and collapse on the flanks of paleo-valleys initiated, for example, by seismicity. A mass flow would have re-worked some of the V_0 flows as well as any pre-existing fallout or sedimentary deposits. The debris flows that carried unit C_1 material would have exploited any pre-existing topographic lows, and may also have further excavated channels. It is also possible that unit C_1 might represent a debris avalanche such as in the Mawson Formation of the Ferrar Large Igneous Province, central Allan Hills, Antarctica, where a 180m-thick debris avalanche deposit was identified despite a complete lack of a steep volcanic edifice (Reubi et al., 2005). In addition, Reubi et al. (2005) argue that in large igneous province settings enough topography can exist from pre-eruptive uplift, faulting, and fluvial valley incision to cause the formation of debris avalanches. Therefore, although unit C_1 lacks the large boulders, blocks, and megablocks typical of large debris avalanche deposits (Leyrit, 2000), its components could very well represent a mass or debris flow caused by seismic activity-induced liquefaction or slope instability.

The capping C_2 deposit is a more mature, quartz-rich volcanoclastic sandstone that contains a high proportion of clastic to mafic components, as well as planar and local cross-beds. Easily weathered volcanic components such as scoriaceous basalt clasts are less well preserved in unit C_2 than C_1 . This, along with the higher proportion of clastic components and sedimentary structures of C_2 , leads to the interpretation that the transportation distance might have been greater for C_2 material than C_1 material, and that

the former was deposited by moving water and might represent the temporary re-activation of small rivers associated with the Kuujjua regional river deposystem. The nature of the contact between units C_2 and V_{1A} further supports the idea that unit C_2 was deposited by water because the basalts above the contact show varying degrees of water-lava flow interaction. Where preserved, the base of V_{1A} is a sharp contact with undisturbed underlying sedimentary beds suggesting a passive, slow emplacement of the sheet flow (Passey and Bell, 2007) over less water-saturated sediment. However, in these cases there are always abundant pipe vesicles present at the base of the flow, suggesting at least a small degree of underlying sediment fluid saturation and degassing into the flow base. In at least one other location the basal V_{1A} contact indicates a more extreme interaction between the flow and underlying wet sediments (from figure 2.9C): an area of highly brecciated hyaloclastite is located directly adjacent to an undisturbed flow base. This also implies that the variations in sediment water content of unit C_2 varied on a local scale. Finally, the observed interbedded plane-bedded and planar-tabular cross-bedded instance in unit C_2 indicates fluctuating flow conditions (Boggs, 2006).

One scenario that could generate both units C_1 and C_2 is that the rivers that deposited the Kuujjua Formation were temporarily obstructed by the basal flows of unit V_0 and subsequently re-activated following a dam burst (Kataoka et al., 2008; Macias et al., 2004; Park and Schmincke, 1997). The dam burst could have generated a mass flow (unit C_1), as well as allowed for the re-activation of small rivers (unit C_2). The re-activated rivers would have re-worked volcanic material and incorporated quartz grains and carbonate clasts from the previously dammed river system. An alternative scenario is that fault tectonics generated an entirely new hydraulic network regionally orthogonal to

the defunct Kuujjua Formation river system, accompanied by sufficient rainfall and earthquakes to accomplish the same result. In summary, C_1 and C_2 represent two units of re-worked volcanic material likely deposited by mass flows and small, re-activated or newly developed rivers. As such, both volcanoclastic units appear to record a pause and change in style of volcanism prior to the initiation of the main phase of flood volcanism.

Following the volcanoclastic depositional events and peneplanation, the main phase of flood volcanism began. This event produced a succession of thick, laterally continuous sheet-like flows typical of flood basalt provinces (Bryan et al., 2010). The internal architecture and structures of these flows (thickness, colonnade and entablature columnar jointing, sheet-like nature) are typical of the high-volume and high eruption rate of main phase volcanism in most other flood basalt provinces (Jerram and Widdowson, 2005). In addition, based on the presence of preserved agglutinated spatter and volcanic vent complexes, the known extensional regime, and the presence of fault-guided V_0 -type magma in the underlying Shaler rocks (Bédard et al., 2012), we suggest that the V_1 flows, and likely the V_0 flows as well, were produced from volcanic fissures capable of forming both explosive (fire fountain) and effusive (lava flow) deposits.

Flow V_{1A} shows a well-developed lower colonnade and central entablature, corresponding to a Type III flow according to Long and Wood (1986). The thickness of the lower colonnade varies throughout the southern lobe; in some locations it is thinner such as those in figures 2.10 A and B, and thicker in other locations such as in figure 2.10 C. This means that the contact between the colonnade and entablature of V_{1A} occurs at different vertical positions depending on location. As this contact represents the meeting

location of lower and upper solidification fronts, we can say that the cooling time and rate of flow V_{1A} was locally variable. In addition, where the lower colonnade is thinner, cooling occurred faster, as opposed to areas where the colonnade is thicker (Long and Wood, 1986). As water availability is an important factor influencing the rate of cooling and column-formation (Long and Wood, 1986), this might imply that the C_2 sediments were more water-saturated where thinner colonnades occur in V_{1A} . For example, the radial joints in the contact from figure 2.9C were the result of a curved cooling front similar to examples found elsewhere (figure 4.1 A). Irregular cooling features are heavily influenced by water availability, and so elements such as rain-fall and flooding are important environmental factors (Long and Wood, 1986).

Flow V_{1B} and V_{1C} do not display well-formed tiers of colonnades and entablatures. V_{1B} displays a crude columnar pattern similar to a colonnade but is not divided into tiers. The top of V_{1B} is a red, probably subaerial 'lateritic' weathering surface and suggests that some time passed before V_{1C} was emplaced. The base of V_{1C} may represent a lower colonnade of small joints, however the body of the flow consists of individual thin flows indicating that V_{1C} is a compound flow and was emplaced as a succession of thin sheet flows (Passey and Bell, 2007).

4.1.2. Significance of southern lobe unit distribution and correlations

The cross-sections of figures 2.16 and 2.17 show the thickness and distribution of volcanic units throughout the southern lobe. In general, the volcanic pile appears to be thickest in the western southern lobe. With the base of unit V_{1A} as a datum, the basal unit

V_0 appears to thin towards the east and south, and follow topographic depressions. Although not correlated in the sections, the most traceable flows of unit V_0 are the thicker ones that occur near the top of the unit; whereas the thin ones at the base are usually too recessive in section to be individually identifiable and traced. Volcaniclastic unit C_1 appears to follow the same topography as unit V_0 . The bedded volcaniclastic unit C_2 either caps C_1 , or appears alone within a channel-shaped topographic low.

The volcano-stratigraphy in the west (cross-sections A-B and F-G), consist of only units V_0 and V_1 ; as no volcaniclastic units are present. In some sections (ex: S20, SB) a clear succession of flows V_{1A} , V_{1B} , and V_{1C} is distinguishable. However, in poorly exposed sections where one or more of the sheet flows are missing (ex: S18 and S4), it is difficult to positively identify which flow is present. For example, in these situations it is often difficult to distinguish flow V_{1A} from V_{1C} because the entablature of V_{1A} is similar to the base of V_{1C} . However, throughout most of the southern lobe, V_{1C} 's individual thin flows appear similar to "bedding", and contain angled to parallel partings likely caused by physical weathering from unloading (figure 4.1B), whereas V_{1A} 's colonnade and entablature weathers clearly into blocks (figure 4.1C). V_{1B} is almost always distinguishable because of its distinct grey-blue weathering colour (figure 4.1 D).

In the central southern lobe (cross-section B-C) unit V_0 thins slightly from NW to SE. The volcaniclastic units are present further south, and pinch out towards the NW in a pattern of pinch and swell on a regional scale, suggesting a deposition into paleovalleys oriented approximately NNE to NE with a maximum relief of 50 to 100 m. In addition, the dark red weathering layer noted at the top of flow V_{1B} of the type section is also present in situ in section 13 and within talus of V_{1A} in section 11 and is used as a marker

unit. Finally, flows V_{1B} and V_{1C} are present only in a few sections of the central southern lobe (S9, S20, and S13), but elsewhere have been eroded away.

The eastern southern lobe (cross-section D-E) is unremarkable, mostly because the exposure was poor. Unit V_0 shows a consistent thickness for about 30km and then becomes recessive. Where the volcanoclastic units crop out, they are thin. Small outcrops or subcrops of the volcanoclastic unit were noted along the entire D-E cross-section and so we know that they extend at least 80 km from the central southern lobe. Exposures of V_1 sheet flows are sparse to non-existent in this area.

The thickness variations of units V_0 , C_1 , and C_2 suggest that varying amounts of paleo-topography existed when these units were deposited. Together, the basal unit V_0 and the massive volcanoclastic unit C_1 occur within the paleo-topographic lows, with the C_2 unit occurring above and capping C_1 . The paleo-topographic lows might be products of the pre-existing physiography at the time, prior to emplacement of V_0 , and would represent valleys or channels carved by the major river system responsible for the deposition of the Kuujjua Formation sandstones. However, paleovalleys appear to trend to the NE, almost normal to the estimated paleoflow of the river system according to Rainbird (1992). Alternatively, the topographic lows could be graben-like troughs resulting from extensional faulting related to the uplift that immediately preceded the Franklin Magmatic Event. A third option might be that the mass flows depositing the C_1 unit excavated channels in the underlying V_0 unit. Although we cannot exclude this third hypothesis, we do not favour it due to the lack of supporting field evidence and because in well-documented situations of volcanoclastic sediment redistribution, material tends to follow pre-existing river valleys rather than carve them outright (Kataoka et al., 2008;

Macias et al., 2004; Park and Schmincke, 1997; Reubi et al., 2005; Ross et al., 2005). Consequently, we suggest that the topographic lows were mostly pre-existing, formed either by fluvial erosion or extensional faulting.

Four schematic block diagrams that summarize the pre-phase, onset-phase, and main-phase of volcanism are presented in figure 4.6. The representative stratigraphy is based on cross-sections A-B and B-C presented in figure 2.16. Note: For the purpose of a complete emplacement model, units C_1 and C_2 are deposited as the result of a mass flow (C_1) and river reactivation (C_2) in the scenario presented by the diagrams of figure 4.6.

4.2 Vent complex or no vent complex?

The two intriguing sites discovered in 2011 that appear to preserve a number of volcanic vent plugs, unlithified scoria, and even spatter, are thought to represent the remnants of small volcanic vent complexes within the stratigraphy of the Natkusiak Formation. Volcanic vent complexes are becoming better documented in continental flood basalt provinces (for example, Jerram and Widdowson (2005); White and McClintock (2001); Németh et al. (2003); and Thordarson and Self (1993)), and although there is limited evidence preserved in the case of the western and eastern vent complexes (WVC and EVC) of the southern lobe, it is comparable to what is seen elsewhere.

No volcanic root or plumbing system is exposed beyond the necks (plugs) themselves, and so it is difficult to conclude whether these vents were the result of point-source or linear volcanism, or whether they are phreatomagmatic or magmatic in origin.

The preserved vent necks of the EVC are aligned approximately NW-SE, which is the trend of the regional faulting within the Minto Inlier thought to be associated with the rift-related extensional regime of the time, as well as the trend of the regional dykes. If magma ascending one of these faults became a volcanic fissure, this would be a plausible scenario for a cone row to form, similar to the Laki cone row of Iceland (figure 4.2A) (Thordarson and Self (1993); Thordarson and Larsen (2007)). The necks might represent small point sources developed above a fissure that began erupting explosively to form the pyroclastic cone deposits, and ended effusively to form sheet flows. The opposite could also be possible, with the sheet flows being emplaced before the scoria deposits: this is more plausible given the succession of thin flows beneath the vent necks in the stratigraphy at the sites, and would explain the discrepancy between the stratigraphy of the vent complexes and that of the type section. In either case the vents would have subsequently been filled with the following pulse of magmatism. The scoria pyroclasts represent a cooler, more explosive eruption, while the spatter accumulations represent hotter, more molten material, ejected much less explosively and as the result of expanding gas bubbles reaching the surface of the vent (Head III and Wilson, 1989). Given the presence of both scoria and spatter, it is inferred that the vents experienced variable degrees of explosiveness. The pyroclastic deposits are not visibly interbedded, although they may have been at one time. Spatially, the scoria is located closer to the vent necks than the spatter, which occurs on the outside of the “bowl”, so one could postulate that the eruption began explosively and waned with time. However, there is not enough evidence preserved at this site to determine a clear relationship between the two pyroclast types and thus state this with confidence.

There is no evidence at either vent complex to support the vents' origin as diatremes except the presence of basalt pyroclasts: this idea is suggested based on the fact that breccia pipes (with a possible phreatomagmatic origin) were observed in the northern lobe (Jean Bédard 2013, pers. Comm.). If the underlying volcaniclastics had been water saturated, the interaction between the wet volcanic sediments and rising magma could have caused phreatomagmatic eruptions. Similarly, the vents of the EVC and WVC could also be pseudocraters formed when a lava flow passes over underlying wet sediments (typically wetlands) causing a steam explosion with no magmatic root, such as those that are part of one of the Eldgjá lava flow field in Iceland (figure 4.2B). The question in this case is whether the vent plugs represent a deep magmatic root, or are just a neck of solidified basalt.

It is mostly the western vent complex that lacks convincing evidence: the rings of scoriaceous material are less pronounced, and the vent necks are smaller, more abundant, and display a blocky weathering pattern. Thus, a possibility for this location is that the “necks” are the erosional remnants of structures such as the one in figure 4.2C, interpreted to be a tumulus. Structures such as these could weather as mounds similar to those of the WVC. On the other hand, it is possible that the WVC has experienced more erosion than the EVC, wiping away almost all of the vent deposits. In either case, according to Wood (1980), larger cones are fed from deeper sources and smaller cones are fed from shallower sources, indicating that the WVC and EVC both had shallow sources (i.e. < 100 m). There is also a temporal implication, since cinder cone eruptions last only hours to months, and then would have been buried by the following sheet flows (Wood, 1980). This may have been a contributing factor to their remarkable preservation.

Lastly, there are implications for the diabasic xenoliths observed in a sample from the WVC. These could have originated in one of the plumbing system's shallow reservoirs and been disaggregated from the rest of the crystallizing diabase mush by an injection of a fresh magma or crystal slurry. The system then becomes over-pressured, effectively causing the disaggregated material to be carried up and extruded onto the surface as xenocrysts. The vents simply offer a direct mechanism for eruption, and may be a proximity indicator if the xenocrysts cannot travel far. The idea of a disaggregated mush is explored by Passmore et al. (2011), and is being tested in the context of the Natkusiak Formation and underlying sills by Ph.D. candidate Ben Hayes at the University of Cardiff, in Wales.

4.3 Geochemistry of the southern lobe, variations within the stratigraphy, and implications

4.3.1 Implications of southern lobe geochemistry and chemostratigraphy

The standard rock classification diagrams used for extrusive volcanics indicate that the southern lobe basalts of the Natkusiak Formation are tholeiitic, despite a weak calc-alkaline signature (diagrams A and B of figure 3.2). It is thought that the higher concentration of total alkalis is likely the result of their remobilization due to alteration, and it is for this reason that the plot after Jensen (1976) is especially useful (figure 3.2 C). Jensen's version of the AFM diagram uses aluminium instead of total alkalis and gives us a better idea of rock type because aluminium is immobile whereas sodium and calcium are commonly mobile during alteration. There is a much more limited compositional

range when the southern lobe Natkusiak samples are plotted on Jensen's ternary diagram; it points to high-Fe and high-Mg tholeiitic natures. The strong Fe-enrichment trend (up to 15 wt% as Fe_2O_3) of the basalts, especially in the V_1 unit, is characteristic of tholeiitic basalts. The scatter in Fe for V_0 may be alteration-related and will be further discussed in section 4.3.2. The classification of tholeiitic basalt agrees with the mineral assemblage of plagioclase, clinopyroxene (augite), Fe-oxides and little to no olivine.

The major and select trace elements suggest that unit V_0 and V_1 are two distinct geochemical groups. Magnesium concentrations are higher at the base of the volcanic pile in unit V_0 than they are in unit V_1 , indicating that unit V_1 is more geochemically evolved than unit V_0 . This is further supported by the evolution in SiO_2 , Fe_2O_3 , and TiO_2 from the base to the top of the stratigraphy. The more evolved nature of the stratigraphically higher sheet flows could be explained by fractionation and removal of mineral phases such as olivine, clinopyroxene, and plagioclase, occurring as the volcanic pile grows. For example, the progressive depletion of Al_2O_3 from unit V_0 to V_1 might be the result of plagioclase fractionation. The overall low Ni concentrations of the entire volcanic pile suggest that these are not primary magmas and that some fractionation and removal of mafic mineral phases occurred at depth. With regards to titanium, considering its immobile nature, the strong difference in TiO_2 concentrations between units V_0 and V_1 suggests that besides fractionation, another magmatic process such as mixing, assimilation, or separate magma sources is responsible for the generation of basalts from either unit. Other elements show a similar shift in concentration between units V_0 and V_1 , such as Fe, Al, Cr, and V. Low and high-Ti basalts are common in many CFB provinces, such as the Parana basalts (Piccirillo et al., 1989) and those of the Gunbarrel Magmatic

Event (Dudas and Lustwerk, 1997). Finally, as an incompatible element, copper should increase in concentration as samples evolve from low to high MgO. However, in the case of unit V₁, Cu is progressively depleted from the base of the unit to the top. This also occurs to a lesser extent in unit V₀, however the scatter hides any significant trend. Thus, Cu has likely been remobilized.

The immobile trace elements Ti, Zr, and Y provide further insight on rock type, tectonic setting, and magma source. Although the total alkalis suggest a range of rock-types spanning from basalt to trachy-basalt for units V₀ and V₁, the ratio of Zr to Ti plotted against the ratio of Nb to Y suggests otherwise: these immobile trace elements indicate a sub-alkaline basalt nature for both units V₀ and V₁ (figure 3.3A). The Zr, Ti, Y ternary diagram of figure 3.3B indicates an ocean-floor setting for unit V₀, and an ocean-floor/within plate setting for unit V₁. The Ti/Zr ratio diagram of figure 3.3C indicates a transitional signature between low-potassium tholeiites and mid-ocean ridge basalts (MORB) for unit V₀, and a MORB signature for unit V₁. Thus, similar to the major and other trace elements, the immobile trace element plots of figure 3.3B and C suggest that the units defined based on their lithostratigraphy might also be distinct geochemical units. We herein refer to units V₀ and V₁ as both distinct lithostratigraphic and lithogeochemical units.

In summary, barring alteration, the variability of major and trace element compositions in unit V₀, as well as the higher Mg, Fe, and Al concentrations, might be controlled by fractionation at depth and indicate that V₀ represents a less evolved magma than V₁. In addition, the lower Ti and Zr concentrations of V₀ relative to V₁ suggests that

other magmatic processes may have occurred, such as varying degrees of mixing and assimilation, as well as intermittent magma pulses: these processes may be the result of a newly established magmatic plumbing system. Conversely, the relative stability of major and trace element compositions in unit V_1 , as well as lower Mg and higher Ti and Zr concentrations relative to V_0 , may reflect a more homogeneous magma as the result of a more established magmatic plumbing system. Further, a MORB signature in an intraplate setting is consistent with previous studies of the Natkusiak Formation basalts which proposed a depleted upper mantle source for magmatism (Dostal et al., 1985). Finally, although not implicitly discussed in the context of this study, previous studies also determined minimal crustal contamination of the Natkusiak basalts by Precambrian basement during magma ascent as indicated by small variations in K, Li, Rb, Ba, and Th (Dostal et al. (1985) and Dupuy (1995)).

For the volcanoclastic rocks, it would be useful to test whether the provenance for most of the C_1 material is volcanic in nature, and whether sources of this volcanic material are the basalt lava flows (unit V_0). Although some general observations can be made when comparing the whole-rock geochemistry between these units, no real conclusions can be made without a more thorough study of the unit C_1 volcanic clasts specifically. The reason for this is the heterogeneous nature the volcanoclastic components - the whole-rock geochemistry of a re-worked epiclastic rock is an average of multiple components. The concentration of any component thought to reflect the volcanic contribution might be lower than expected because of dilution by all the other components. Taking these potential biases into consideration, the MgO content of the volcanoclastic rocks is similar to the lowest unit V_0 Mg values, as are Fe and Ti. Ni and

Cr are low, but still within the range for unit V_1 at least. The high silica content of the volcanoclastic samples relative to the V_0 basalts likely reflects the clastic sedimentary component, i.e. the quartz grains and quartz arenite clasts from the Kuujjua Formation. Zr data are not available for units C_1 and C_2 . Thus, although geologically the source for the volcanic components of units C_1 and C_2 are probably the basal basalts flows (V_0), nothing conclusive can be said utilizing the whole-rock geochemistry.

4.3.2 Alteration of Natkusiak Formation southern lobe samples

Two alteration diagrams were presented in figure 3.5. The most altered samples, according to these diagrams, are summarized in table 4.1. These samples all belong to the base of the V_0 unit, within the lowermost 30m of volcanic stratigraphy. Figure 4.3 shows select major element plots with the altered samples indicated by black stars to determine whether these are samples displaying unusual major element concentrations – when this is the case they are circled in red. Generally, the altered samples are all randomly distributed within the spread of V_0 major element concentrations. However, the V_0 samples showing MgO and FeO enrichment, for example, as well as FeO depletion, are part of the suite of altered samples. The same can be said about the samples with unusually high calcium and potassium. For sodium, the altered samples define two trends, one showing consistent low Na, and one showing higher Na that becomes depleted along with MgO. The two trends correspond to the two clusters of low and high $Na_2O + K_2O$ on the Igneous Spectrum alteration diagram (figure 3.5 B). The altered samples from table 4.1 are fairly evenly distributed amongst the spread of Cu

concentrations in V_0 , include all the high MgO samples, as well as the V_0 samples with very high Ba (10RAT-NW15A03 at 1127 ppm) and Sr (10RAT-NW67A01 at 2119ppm).

Sample	Stratigraphic level (m)	Lithostratigraphic unit
NW64B01	1.8	V_0
NW64B02	3	V_0
NW65A01	3.5	V_0
NW66A01	6.7	V_0
NW15A03	9	V_0
NW16B02	17	V_0
NW16B04	19	V_0
NW16B03	23	V_0
NW67A01	29	V_0

Table 4.1: Samples showing most alteration.

In basalts Ca and Na are almost always mobilized during alteration, while elements such as Mg, Fe, K, Sr, and Ba, can show varying degrees of mobilization. It is clear that in the case of the basal (V_0) Natkusiak basalt samples sodium and calcium have been mobilized to a certain degree - Na depletion might be caused by the breakdown of Na-plagioclase, while Ca enrichment might be the result of calcite precipitation within vesicles caused by the circulation of Ca-rich fluids or brines. The thick succession of carbonate sedimentary rocks underlying the Natkusiak Formation might be the source of the calcium in these fluids. Mg-enrichment is usually caused by hydrothermal alteration (alteration to Mg-chlorite), as is Fe-depletion. In addition, sub-greenschist facies metamorphism has been suggested for the Natkusiak Formation (Dupuy, 1995), a process during which Fe, Mg, Na and K are all mobile (Pearce, 1976) and alteration includes

albitization, potassium feldspar formation, calcite, and epidote alteration (Large et al., 2001).

The alteration of the Natkuaish samples is reflected in the major element distributions, including the high calcium, low sodium V_0 samples, as well as the intense sericitization and chloritization present in thin section. Alteration is also reflected in the mineral chemistry for feldspar: the core and rim compositions that plot in the albite apex of figure 2.23 belong to samples of table 4.1 and thus do not reflect primary compositions. Secondary minerals in the samples from table 4.1 include calcite, prehnite, pumpellyite, quartz, sericite, hydrogrossular, actinolite, and minor sulphides (S, Fe, Cu). Thus, it is inferred that the V_0 samples, and to a lesser extent the V_1 samples, have experienced varying degrees of both sub-greenschist facies metamorphism and hydrothermal alteration.

4.4 Comparisons between the southern and northern lobes of the Natkusiak Formation

4.4.1 Volcano-stratigraphy

In the northern lobe, a similar stratigraphic succession to that described in the southern lobe has been documented for the bottom ~300m of the Natkusiak Formation. The correlations between lithological units are based on studies done by Dostal et al. (1985) and Jefferson et al. (1985), and are summarized in table 4.2.

Jefferson et al. (1985) describe a 'basal member' up to 70 m thick that pinches out locally. Jefferson et al. (1985) also note the existence of pillowed lava and hyaloclastite within that unit and suggest that it is the result of its eruption into shallow water. Dostal et al. (1985) report basal flows of various thicknesses with massive bases and vesicular flow tops. However, within the northern basal member Jefferson et al. (1985) observed massive columnar-jointed cliff forming flows, which are not present in the south. In the northern lobe, near the mouth of Trident Creek, a thin (1 m) basal hyaloclastite breccia, succeeded by massive 2 m thick V_0 flows that are overlain by a deposit similar to C_1 , were observed (J. Bédard pers. comm., 2013). We believe that the V_0 unit in the Southern lobe correlates with the 'basal member' described by Jefferson et al. (Jefferson et al., 1985) in the northern lobe, although there are subtle differences.

With regards to the volcanoclastic units, in the northern lobe, Dostal et al. (1985) report the presence of a unit of red volcanic sediments they call the 'red-bed member'. A sample from this unit examined in thin section contains an abundance of reworked volcanic material as well as rounded quartz grains, and so this unit likely correlates with the unit C_1 unit of the southern lobe. Jefferson et al. (1985) report a 'lithic pyroclastic member' composed of unsorted, unwelded material, with a large range in thickness (70 to 100 m), and a base composed of shallow-water turbidite sequences. The turbidite sequences are overlain by maroon and green re-worked volcanic units (Jefferson et al., 1985). Jefferson et al. (1985) suggested the presence of pyroclastic fallout deposits because of the presence of accretionary lapilli. However, Jefferson et al. (1985) interpreted the bulk of the massive, structureless volcanoclastic material (facies that dominates C_1 in the southern lobe) as mass flow deposits.

We propose that unit V_1 in the south is equivalent to the ‘Lower Massive Member’ described by Jefferson et al. (1985). The flows of the ‘Lower Massive Member’ are 10 to 50 m thick, blue-grey-green weathering to orange-brown, massive, cliff-forming, and columnar jointed (Jefferson et al., 1985). Dostal et al. (1985), noted a distinctive flow (‘Rosetta Flow’), above the red volcanic sedimentary unit, and traceable over 25 km. This may be the same flow as our V_{1A} unit, which we use as our stratigraphic base datum. Units above the first four sheet flows in the north do not have preserved equivalents in the south.

Northern Lobe (Jefferson et al., 1985)	Northern lobe (Dostal et al., 1985)	Southern lobe (this study)
Lower Massive Member	- - Rosetta Flow	V_{1C} : Sheet flow unit, third flow V_{1B} : Sheet flow unit, second flow V_{1A} : Sheet flow unit, first flow
Lithic Pyroclastic Member	- Red Bed Member	C_2 : Volcaniclastic unit, bedded C_1 : Volcaniclastic unit, massive
Basal Member	-	V_0 : Basal unit

Table 4.2: Summary of equivalent northern and southern lobe lithostratigraphic units.

4.4.2 Chemostratigraphy

Geochemical data from samples taken of the northern lobe in the 80’s by Bob Baragar (Dostal et al., 1985) are compared to data from this study, mostly in a stratigraphic context. Note that the stratigraphy sampled in the northern lobe has a thickness of over 800m, while that of the southern lobe is preserved only to about 150m.

Figure 4.4A shows the same incompatible trace element classification diagram used in chapter 3, with the northern lobe data added. The northern lobe data forms a tight cluster close to the southern lobe data suggesting that trace element concentrations are

effectively the same; the small difference may be analytical in nature. Figure 4.5 shows select major and trace elements from the southern and northern lobes plotted against stratigraphic height with the contact with the underlying sedimentary unit as a stratigraphic datum: the northern lobe samples in red are those identified in the northern lobe stratigraphy of figure 4.4B. Plots A and B show MgO and TiO₂ against all 800m of northern lobe stratigraphy; these oxide trends are almost identical between the northern and southern lobes. In addition, Dostal et al. (1985)'s two MgO cycles are visible and separated at about 325m.

The other diagrams of figure 4.5 plot the geochemistry against the first 200 m of stratigraphy for the sake of comparing similar stratigraphic thicknesses. Notable is that the first 200m of northern lobe stratigraphy appears to show the same abrupt change in Ti, Fe, Cr, and V concentration that is observed in the southern lobe. In addition, there are notable similarities between the trends of unit V₁ and the northern lobe above 50m for MgO, TiO₂, Al₂O₃, K₂O, and to a lesser extent Fe₂O₃, CaO, Cr, Ni, and V. In the northern lobe, Fe₂O₃ content is a bit lower, while Ni content is a bit higher. CaO, Cr, and V show a larger spread of values. Unit V₀ samples from the southern lobe are not geochemically similar to those from the basal 50 metres of the northern lobe, with the exception of TiO₂, V, K₂O and to a lesser extent MgO. It is possible that this reflects the smaller sample number (4 samples) of the northern lobe basal flows. For Fe₂O₃, Al₂O₃, and Ni, the first 50m of northern and southern lobe geochemistry is very dissimilar. Northern lobe Fe₂O₃ concentrations are higher and show a different trend, northern lobe Al₂O₃ concentrations shows a similar trend but much lower concentrations, and Ni content is higher. Al₂O₃ is actually very low for the first 50m of the northern lobe, which is unusual because Al₂O₃

is usually stable and relatively immobile. There are a few possibilities for the difference in chemistry between the first 50m of the southern and northern lobes:

- 1) The sample set for the southern lobe basal flows is larger than that of the northern lobe and this is likely to be reflected in the data trends.
- 2) There was a different fractionation, assimilation/contamination, or mixing process involved with the northern lobe basal flows.

- 3) The northern lobe basal data points might represent sills rather than flows. Reasons for this include poor exposure of the mafic rocks at the base of the stratigraphy leading to confusion, as originally described by Baragar (1976); geochemical data for the basal 50m of the northern lobe resembles the sill data from Dostal et al. (1985); and while the southern lobe basal flow (V_0) data is fairly uniformly distributed, the northern lobe basal data has a much more erratic spread, which could be explained by one or more differentiated sills.

In summary, major and select trace elements of the southern lobe stratigraphy are comparable to that of the northern lobe, primarily above 50m. The basal flows of the southern lobe, unit V_0 , do not geochemically resemble the basal flows of the northern lobe, with the exception of Ti, V, and to a certain degree Ni. As there is a similar geochemical break in Ti, Fe, and Cr in the first 200m of northern lobe basalts, perhaps the northern lobe records a similar shift in volcanism as the southern lobe.

4.5 Summary, conclusions, and additional work

The southern lobe of the Natkusiak Formation preserves up to 200 m of volcano-stratigraphy representing the early stages of volcanism related to the Franklin Magmatic Event. The volcano-stratigraphy of the southern lobe resembles the pre-, onset-, and main phases of flood basalt volcanism of other volcanic provinces in the style of lava-sediment interaction, laterally impersistent basal flows, laterally continuous sheet flows, as well as intercalated volcanoclastic units.

The onset of volcanism is represented by the laterally discontinuous V_0 unit basal flows erupted into topographic lows in relatively modest volumes, probably from volcanic fissures, and to a lesser extent from volcanic vents. The topographic lows were locally occupied by water, evidence for which is provided by features such as pillows and hyaloclastite. Paleo-topography might have been generated by pre-eruptive faulting, carved out by the rivers responsible for the deposition of the Kuujjua Formation sandstones, or both. The two volcanoclastic units follow the same paleo-topographic lows and record a regional change and possible hiatus in volcanic activity. The mechanism for the deposition of unit C_1 is interpreted to be a mass flow produced from slope instability or a dam burst, whereas the quartz-rich, volcanic, fine-pebble conglomerate (unit C_2) that caps unit C_1 contains structures indicative of moving water and was probably deposited by rivers as small-scale channels. If this is the case, the C_2 unit could indicate the temporary re-activation of the local river system dammed by V_0 flows prior to the onset of the main phase of volcanism as represented by the sheet flows of unit V_1 above. The thick and laterally continuous nature of the V_1 flows is good evidence that they represent

a well-established volcanic plumbing system and the beginning of the main phase of high-volume flood volcanism. The volcanic vent complexes identified in the southern lobe are interpreted as such based on the preservation of vent necks and proximal pyroclastic accumulations. The presence of both scoria and spatter indicate that the degree of explosiveness of volcanism varied, perhaps beginning explosively and subsequently waning as degassing took place. Volcanism is estimated to have been fissure fed based on the linear arrangement of the preserved vent necks.

Based on their physical characteristics, I have found that the four units identified within the volcanic pile of the southern lobe correlate with units described in the northern lobe by Dostal et al. (1985) and named by Jefferson et al. (1985). The V_0 unit correlates well with Jefferson et al. (1985) 'Basal Member', C_1 and C_2 with the 'Pyroclastic Member', and V_1 with the 'Lower Massive Member'. Geochemically, the Natkusiak southern lobe basalts are high-magnesium (unit V_0) and high-iron (unit V_1) tholeiites with ocean-floor (MORB) and within-plate signatures as indicated by the immobile trace elements, which is more or less consistent with what previous studies indicate with regards to the northern lobe volcanic pile. Geochemical breaks are present in the first 200 m of both the southern and northern volcanic stratigraphy, especially with regards to titanium, iron, and chromium, suggesting that this portion of northern and southern lobe stratigraphy records similar changes in magma source, mixing, or assimilation characteristics.

The basal V_0 southern lobe Natkusiak samples show the most alteration, with calcium and sodium showing the most remobilization. Alteration is interpreted as being

principally hydrothermal in nature as indicated by the secondary minerals present in outcrop and thin section, as well as the alteration diagrams. Fluids may have been calcium-rich brines sourced from the thick succession of underlying carbonate rocks of the Shaler Supergroup, with hydrothermal circulation encouraged by the heat of the volcanic pile and subvolcanic plumbing system.lol

Suggestions for additional work include the following:

- 1) Basalt and sedimentary clast studies for units C₁ and C₂ to test for provenance.
- 2) A study to better estimate the volume of mafic material emplaced by the Franklin Magmatic Event in order to better understand the CO₂ and SO₂ contributions to the atmosphere.
- 3) With a more complete volcano-stratigraphy established across the southern lobe, additional mineral chemistry analyses coupled with a thorough study of diabase xenoliths within the lavas will help further establish and understand the spatial temporal relationships between the Franklin sills and Natkusiak Formation.
- 4) The significance of copper occurrences in the southern lobe is being investigated by a study at McGill University, Montreal.

Figure 4.1: (A) radial jointing caused by a curved cooling front, such as that observed in a lava tube. Photo taken in southwest Iceland by the author. (B) characteristic angled unloading fractures/partings of flow V1C from S9 in the central southern lobe (recall figure 2.11D from the type section), (C) characteristic blocky weathering pattern caused by V1A's entablature at SY in the western southern lobe (recall figure 2.10B), and (D) shows flow V1B at S17 in the southwestern southern lobe, weathering its characteristic blue-grey colour (recall figure 2.10D).

Figure 4.2: (A) well-known row of scoria cones along a volcanic fissure produced by the Laki eruption in the 18th century, Iceland. Photo from Thordarson and Larsen (2007). (B) field of rootless cones (pseudocraters) formed over a lava flow field from the Eldgja eruption, Iceland. Photo by author. (C) structure resembling a tumuli in unit V1. Combined flows are approximately 15 to 20m thick.

Figure 4.3: Major element diagrams to show where the most altered samples of table 4.1 plot.

Figure 4.4 : Comparison of select major and trace elements between southern and northern lobes. **(A)** Zr/Ti vs. Nb/Y after Pearce (1996). See legend in figure 4.5 for symbols. **(B)** relevant figure for the plots of figure 4.5; the northern lobe samples represented by red circles in the geochemical plots of figure 4.5 are identified in the northern lobe stratigraphy by the red squares. Figure is modified from Dostal et al (1985).

Figure 4.5 : Comparison of select major and trace element chemostratigraphy between the southern and northern lobes. Symbol legend is at the top, with the red circles representing the northern lobe samples indicated in the stratigraphy of figure 4.4.

1) Pre - Braided river system, Kuujjua Formation

2) Onset - Basal flows and river damming - V0

3) Onset - Mass/debris flow and river reactivation - C1 and C2

4) Main phase - Laterally extensive sheet flows - V1

Figure 4.6: Schematic block diagrams showing one possible scenario for the deposition of volcanic units observed in the southern lobe. **1)** shows the pre-volcanism paleo-environment - a large braided river system responsible for the deposition of the Kuujua Formation sandstone (after Rainbird, 1992). **2)** shows the onset phase of volcanism and the emplacement of the V0 basal flows into pre-existing topographic lows. Rivers may have been dammed. **3)** shows the emplacement of volcaniclastic units C1 and C2 - C1 as a mass/debris flow caused by gravity or from a dam burst, and C2 from a re-activated river. **4)** shows the beginning of main phase volcanism with the emplacement of the laterally extensive, thick, sheet flows of unit V1. **Notes:** Red arrow in (1) indicates North and the letters in 3 and 4 provide spacial orientation and refer to cross-sections A-B and B-C.

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Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
10RAT-NW15A02	Section A	V0	7.5	Texture: sub-ophitic with 25% 0.5-1mm cpx, 30-40% ~0.5mm pl. Pl has albite twinning, >50% An according to the Michel-Levy method without crosshairs. Interstitial is brown alteration. A few glomerocrysts: ~1mm pl, intensely sericitized Sub-ophitic pl is relatively unaltered as compared to pl glomerocrysts. Fe-Ti oxide present between groundmass pl. 5-10% vesicles filled with unidentifiable alteration.
10RAT-NW15A03	Section A	V0	9	Texture: sub-ophitic with 10% 0.5-1mm cpx, 40% ~0.5mm pl Fe-Ti oxide present between groundmass pl. 5-10% vesicles filled with unidentifiable alteration.
10RAT-NW16B02	Section A	V0	17	5-10% vesicles filled with chl & calcite. Highly altered sample - many unidentifiable components. Texture: Groundmass of ≤0.5mm pl, few relict cpx intergrowing with pl. Alteration: interstitial chl, cal in vesicles.
10RAT-NW16B03	Section A	V0	23	Very similar to 016B02, however less overall alteration. Interstitial chl & cal. Texture: Groundmass of ≤0.3mm pl, few relict cpx intergrowing with pl.
10RAT-NW16B04	Section A	V0	19	Texture: ~70% ≤0.2mm pl and ~1mm cpx? groundmass. 2% relict cpx, ~0.5mm. ~10% vesicles, cal-filled. ~5% skeletal Fe-Ti oxide growing between groundmass pl. Few instances of py.
10RAT-NW17A01	Section A	C1	36	Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 5%. Basalt fragments: ~40% with varying vesicle abundances and sizes. Mud clasts, 5%: elongate and imbricate in some places. Interstitial material, 'matrix', is mostly calcite. Some clasts have alteration haloes of calcite.
10RAT-NW17A02	Section A	C1	42	Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 8-10%. Basalt fragments: ~15% with varying vesicle abundances and sizes. Calcite fills vesicles. Mud clasts (~1mm, 10%), these definitely seem to be aligned along their long axes. Matrix' appears to be a mixture of fine mud, lithic components and calcite cement. No fiamme, etc., to indicate welding or hot deposition.
10RAT-NW17B01	Section A	C2	47	Heterolithic. Qtz grains: angular to rounded, ~0.2 to 1mm, 20-40%. Basalt fragments: ~20%, up to 2mm, with varying vesicle abundances and sizes. Calcite fills vesicles. Mud clasts (0.5-1mm, 10%). No alignment of No matrix, calcite cement.

Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
10RAT-NW19A01	Section A	V1A	50	Texture: Uniform, pl laths (~40-50% $\leq 0.2\text{mm}$) and small cpx (30- 40%, ~0.1mm). Fine basalt.
10RAT-NW19A02	Section A	V1A	64	Disseminated Fe-Ti oxides, 2-5%. Texture: Uniform, pl laths (~40-50% $\leq 0.1\text{mm}$) and small cpx (20-30%, ~0.1mm). Fine basalt.
10RAT-NW19A03	Section A	V1A	64	Sericite alteration in pl, no significant Fe-Ti oxides. Interstitial chl, chl also present lining the few vesicles present. Texture: Uniform, pl laths (~40-50% $\leq 0.2\text{mm}$) and small cpx (30- 40%, ~0.1mm). Fine basalt.
10RAT-NW19A04	Section A	V1A	56	Disseminated Fe-Ti oxides, 2-5%. Texture: Uniform, pl laths (~40-50% $\leq 0.2\text{mm}$) and small cpx (30- 40%, ~0.2mm). Fine basalt.
10RAT-NW64B01	Section B	V0	1.8	Disseminated Fe-Ti oxides, 2-5%. Brown alteration material. Texture: Groundmass of pl laths (~40-50% $\leq 0.5\text{mm}$) and small cpx (5- 15%, 0.1mm). A few cpx phenocrysts, ~0.5mm. Vesicles of recrystallized quartz? that are lined with calcite. Pl glomerocrysts, ~1-2mm, are completely sericitized. Interstitial chl, vesicles filled with pum, chl, cal. Interstitial brown alteration. One vesicle lined with chl contains isotropic crystals, some are less isotropic and show high relief...AZ advises hydrogrossular.
10RAT-NW64B02	Section B	V0	3	Very altered sample, pretty useless. Texture: Groundmass of pl laths (~20-40% $\leq 0.5\text{mm}$). A few cpx phenocrysts preserved, ~0.5mm. Relict sub-ophitic texture of cpx crystals intergrowing with the pl laths.
10RAT-NW65A01	Section B	V0	3.5	Pl laths are sericitized, brown alteration, vesicles (~5%) filled with chl, cal, qtz. Texture: Uniform, pl laths (~40-50% $\leq 0.5\text{mm}$) and small cpx (5-10%, ~0.2mm). More cpx phenocrysts (~1mm) than previous samples, intergrowing with pl groundmass, & a few sericitized pl glomerocrysts.
10RAT-NW66A01	Section B	V0	6.7	Interstitial chl, brown alteration. Intensely altered sample - pl and cpx groundmass similar to previous.
10RAT-NW66A02	Section B	V0	8	Texture: Groundmass pl laths (~30% $\leq 0.1\text{mm}$) and small cpx (40- 60%, $\leq 0.1\text{mm}$). Fine basalt. Some pl are larger (up to ~0.5mm), vesicles about 10% and irregularly shaped. Same alteration as previous.

Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
10RAT-NW66A03	Section B	V0	10	Py and chp? Associated with Fe-Ti oxides. Texture: Sub-ophitic to ophitic, pl laths (~0.5-1mm) and cpx (~0.5-1mm). Pl sericitized. Fe-Ti oxides and py/chp.
10RAT-NW66A04	Section B	V0	13	Texture: Sub-ophitic to ophitic, pl laths (~0.5-1mm) and cpx (~0.5-1mm). Pl sericitized.
10RAT-NW66A05	Section B	V0	20	Texture: Sub-ophitic to ophitic, pl laths (~0.5-1mm) and cpx (~0.5-1mm). Pl sericitized. Interstitial chl.
10RAT-NW67A01	Section B	V0	29	Texture: Groundmass pl laths (~30%, 0.1-0.5mm) and small cpx (40- 60%, ~0.1-0.2mm). Few cpx phenocrysts (~1-2mm) growing with pl laths - sub to fully ophitic. Interstitial chl, chl lines vesicles ($\leq 5\%$).
10RAT-NW67A02	Section B	V0	34	Texture: Groundmass pl laths (~30%, 0.1-0.5mm) and small cpx (40- 60%, ~0.1-0.2mm). Few cpx phenocrysts (~1-2mm) . Brown interstitial alteration.
10RAT-NW67A03	Section B	V0	36	Texture: Groundmass pl laths (~30%, 0.1-0.5mm) and small cpx (40- 60%, ~0.1-0.2mm). Few cpx phenocrysts (~1-2mm) . Brown interstitial alteration.
10RAT-NW68A01	Section B	C1	60	Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 5%. Basalt fragments: ~40% with varying vesicle abundances and sizes. Mud clasts, 5%: elongate and imbricate in some places. Interstitial material, 'matrix', is mostly calcite. Some clasts have alteration haloes of calcite.
10RAT-NW68A02	Section B	C1	63	Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 5-10%. Basalt fragments: small and difficult to recognize in this sample. Mud clasts, 5%: elongate. Pl laths (~0.2mm) present, ~2%.
10RAT-NW68A03	Section B	C1	63	Interstitial material, 'matrix', is dark, isotropic material. Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 5%. Basalt fragments: ~40% with varying vesicle abundances and sizes (up to 2mm). Mud clasts, 5%: elongate. Interstitial material, 'matrix', is mostly calcite. Some clasts have alteration haloes of calcite. 3mm sandstone clast present in section, as well as a few instances of sericitized pl laths, 0.1~1mm.
10RAT-NW101A01	Section B	C2	85	Looks like a sandstone...components are laminated, and graded.

Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
				Heterolithic. Qtz grains: angular to rounded, ~0.2 to 0.5mm, 25-30%. Basalt fragments: ~10% with varying vesicle abundances and sizes (up tp 2mm). Mud clasts, 5%: elongate, imbricate along long axis.
10RAT-NW101A02	Section B	C2	87	Space between components, 'matrix', are small calcite crystals. Ungraded, proportion of qtz grains much higher.
10RAT-NW101B01	Section B	V1A	90	Heterolithic. Qtz grains: sub-rounded to rounded, ~0.2 to 0.5mm, 50-60%. Basalt fragments: ~5-10% with varying vesicle abundances and sizes (up tp 2mm). Mud clasts, 5%. Very fine basalt. Texture: Uniform, pl laths (~60-70% ≤ 0.1 mm) and small cpx (20- 30%, ≤ 0.1 mm).
10RAT-NW69A02	Section B	V1A	95	Vesicles are ~0.5mm, 2%, and perfectly round. Filled with cal. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤ 0.2 mm) and small cpx (20- 30%, ≤ 0.3 mm).
10RAT-NW69A03	Section B	V1A	98.8	Fine basalt. Texture: Uniform, pl laths (~60-70% ≤ 0.2 mm) and small cpx (20- 30%, ≤ 0.3 mm).
10RAT-NW69A04	Section B	V1A	116	Brown alteration. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤ 0.2 mm) and small cpx (20- 30%, ≤ 0.3 mm).
10RAT-NW69A05	Section B	V1A	127	Few vesicles, irregular shape, empty. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤ 0.2 mm) and small cpx (20- 30%, ≤ 0.3 mm).
10RAT-NW69A06	Section B	V1B	130	Irregular shaped, elongate vesicles. Empty or contain chl. Larger vesicle (1 noted) contains cal also.
10RAT-NW69A07a	Section B	V1B	138	Coarse, sub-ophitic basalt. Texture: Pl laths (~50% 0.5mm) and cpx (20- 30%, 0.5-1mm). 10-15% chl filling voids/replacing a mineral.
10RAT-NW63A01	Section B	V1B	140	Very coarse, sub-ophitic basalt. Texture: Pl laths (~50%, 0.5-1mm) and cpx (20- 30%, 1-2mm).
10RAT-NW69A08	Section B	V1C	148	Brown alteration interstitial. Almost entire ts is isotropic, with the exception of veinlets filled with chl, cal, qtz Fine basalt. Texture: Uniform, pl laths (~50-60% ≤ 0.2 mm) and small cpx (30- 40%, ≤ 0.3 mm).
				Few vesicles, irregular shape, cal. Disseminated Fe-Ti oxides, native Cu - one lining a vesicle and a fleck, ≤ 0.1 mm.

Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
11RAT-TD129C01	I	V1	-	Coarse, sub-ophitic basalt. Texture: Pl laths (~25-30% 0.5-1mm) and cpx (20- 20-25%, 1-2mm).
11RAT-TD129E01	I	V1	-	Pl altered to sericite, intersertal chlorite and altered glass (brown material) Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.3mm).
11RAT-TD129A01	I	V1	-	Brown intersertal material - altered glass? Coarse, sub-ophitic basalt. Texture: Pl laths (~25-30% 0.5-1mm) and cpx (20- 20-25%, 1-2mm).
11RAT-TD129B01	I	V1	-	Some sericite alteration on the plagioclase laths but not as pervasive as other samples, large skeletal Fe-Ti oxides. Very fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.1mm) and small cpx (20- 30%, ≤0.1mm).
11RAT-TD129F01	I	V1	-	Glomerocrysts up to 3mm present, consist of albite, anorthite, cpx and ol? Crystals are coarse (1-2mm), with broken edges - look like diabase. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.3mm).
11RAT-TD129D01	I	V1	-	Interstitial chl. Coarse, sub-ophitic basalt. Texture: Pl laths (~50% 0.5mm) and cpx (20- 30%, 0.5-1mm). 10-15% chl filling voids/replacing a mineral.
11RAT-TD129G01	I	V1	-	Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.4mm).
11RAT-TD43B01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.3mm).
11RAT-TD043C01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.3mm).
11RAT-TD73A01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.5mm) and small cpx (20- 30%, ≤0.3mm).
11RAT-TD72B01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% ≤0.2mm) and small cpx (20- 30%, ≤0.3mm). Interstitial chl.

Appendix 2.1: Petrographic summary of thin sections.

Sample	Group	Unit	Stratigraphic level (m above basal Natkusiak fm contact)	Petrographic summary
11RAT-TD72C01	IV	V1	-	Fine basalt. Texture: Uniform, pl laths (~60-70% $\leq 0.2\text{mm}$) and small cpx (20- 30%, $\leq 0.4\text{mm}$).
11RAT-TD72D01	IV	V1	-	Interstitial chl, and chl in few irregularly shaped vesicles. Fine basalt. Texture: Uniform, pl laths (~60-70% $\leq 0.2\text{mm}$) and small cpx (20- 30%, $\leq 0.3\text{mm}$).
11RAT-TD72E01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% $\leq 0.2\text{mm}$) and small cpx (20- 30%, $\leq 0.3\text{mm}$). Interstitial chl.
11RAT-TD72F01	IV	V1	-	Fine basalt. Texture: Uniform, pl laths (~60-70% $\leq 0.2\text{mm}$) and small cpx (20- 30%, $\leq 0.3\text{mm}$). Larger cpx fragments (~1mm) present.
11RAT-TD72G01	IV	V1	-	Interstitial chl. Fine basalt. Texture: Uniform, pl laths (~60-70% $\leq 0.1\text{mm}$) and small cpx (20- 30%, $\leq 0.1\text{mm}$).
11RAT-NW135A01	II	V1	-	Glomerocrysts up to 3-4mm present, consist of albite, anorthite, cpx and ol? Crystals are coarse (1-2mm), and completely round. Looks like diabase. Coarse, sub-ophitic basalt. Texture: Pl laths (~50% 0.5mm) and ol altering to iddingsite? (20- 30%, 0.5-1mm).
11RAT-NW135B02	II	V1	-	Heavily altered, full of brown material, components unidentifiable.
11RAT-NW135C01	II	V1	-	Coarse basalt, ophitic. Texture: Pl laths (~50% 0.5mm) and cpx (20- 30%, 0.5-1mm).
11RAT-NW137A01	II	V1	-	Very coarse, ophitic basalt. Texture: Pl laths (~50%, 0.5-1mm) and cpx (20- 30%, 1-2mm). Vesicles filled with acicular apple green - pump.

Appendix 2.2: Southern lobe stratigraphic sections

Section	Location	Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ W)	Approximate thickness (m)	Notes/Summary
SA	Central SL	71.137281	115.161138	70	Detailed section A: Kj/Nk contact, V0 flows mostly exposed with covered sections here and there. Outcrop of C1 and C2 preserved, ~20m of V1 with entablature visible.
SB	Central SL	71.071094	115.211864	160	Detailed section B: Kj/V0 contact not preserved, however ~7 to 9 flows preserved in V0 with flow contacts just slightly recessive. Cover between V0 and C1, and C1/C2 contact recessive. C2 has a poorly preserved, but visible, contact with V1A. V1A shows a thin colonnade and thick entablature, followed by V1B, contact recessive. V1B shows massive base and vesicular top, with a ~60cm layer of brick-red material at the very top - weathering horizon. V1B/V1C contact preserved and sharp. ~20m of V1C preserved - this flow is composed of individual thinner (~1m) units.
S1	Western SL	71.04416	116.29675	80	Composite section through V0 and into V1; no unit contacts preserved. Only small outcrops of V0 noted, V1 outcrop shows columnar jointing.
S2	Western SL	71.03831	115.896317	140	Thick succession of V0 outcrops, however only one flow contact preserved. Pillows and pahoehoe toes noted at base of section, one occurrence of ropy flow top texture found in talus proximal to an outcrop of V0 flow. Contact with V1 not preserved.
S4	Western SL	71.010688	115.836155	140	Thick succession of ~9 V0 flows preserved, with well-defined flow contacts. V0 flows show massive bases with vesicular flow tops - basal V0 flows of this section show pipe vesicles (degassing), as well as large jasper veins. Contact with V1A not preserved - top most outcrop of the section shows V1A entablature.
S7	Western SL	71.067223	115.779842	110	Canyon section through V0 and into V1, similar to S25. Contact between units recessive, however basal V0 shows pillows, pahoehoe toes and hyaloclastite.
S8	Western SL	71.072305	115.729057	120	Canyon section through V0 and into V1, similar to S7. Contact between units recessive, however contacts between flows in V0 are visible. ~6 flows thought to be preserved. Basal V0 shows pillows, pahoehoe toes and hyaloclastite. Native Cu noted mid-section. V1A shows jointing.
S9	Central SL	71.100381	115.46465	110	Contact with Kj preserved and sharp, with pipe vesicles rising into V0. V0 here is not thick, only ~35m, and contact with V1 not preserved. V1 shows columnar jointing.
S10	Central SL	71.060841	115.289579	140	Composite section of a plateau - Kj/V0 contact preserved and sharp, and within V0 are interbedded sandstones with pillows in the basalts at their contacts. C2 directly overlies V0, contact is sharp. V1A shows a sharp contact with C2, as well as a colonnade.

Appendix 2.2: Southern lobe stratigraphic sections

Section	Location	Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ W)	Approximate thickness (m)	Notes/Summary
S11	Central SL	71.043208	115.25027	120	Composite section from a plateau. V0 preserved, but not V0/C1 contact. C2 pinches out along the plateau, however exact location is unknown. Contacts between C1, C2, and V1A all preserved and sharp - C1/V1A contact very poor however. V1A shows colonnade and entablature, brick-red weathering horizon of V1B noted in talus of V1A in this section - V1B may be preserved further up but poor exposure makes it difficult to tell.
S12	Central SL	71.047676	115.201485	150	Composite section with main features as dykes/sills preserved at the base, and a laterally thickening unit C1. Kj/V0 contact recessive, however what look like sills/dykes are preserved between the Kj first outcrops of V0 - they appear to be moving up section and feeding into V0. Small outcrop of C1 occurs, and then thickens laterally to the East. C1/V1A contact not preserved.
S13	Central SL	71.011803	115.030122	120	Steep river cut with base of unit C1. Thin, cross-bedded C2 outcrop occurs within C1, contacts are recessive. C2 caps C1 at this location, with a sharp, undisturbed, contact with V1A. Base of V1A shows degassing (pipe vesicles), followed by colonnade and entablature. V1A/V1B contact not accessible and so not observed. V1B shows red weathering horizon at top, followed by V1C. Contact is sharp.
S14	Central SL	71.000054	115.141482	30	Small section of C1 followed by V1 - dyke thought to penetrate into V1. Poor exposure in this area.
S15	Eastern SL	71.199143	114.381607	40	Poor exposure. Two small outcrops of V0, followed by 5-10m outcrop of C1. No contacts preserved.
S16	Eastern SL	71.203338	114.315159	40	Poor exposure. Two small outcrops of V0, no contacts preserved.
S17	Western SL	70.985141	115.793714	100	Composite section of 3 sections from (S17, S28, and S19) from 3 river cuts in the area. Confusing stratigraphy because of lack of basal reference: about 30m of V1A is thought to be preserved here, however the lower contact with V0 is not preserved. Moving up section (south down the river), V1A colonnade and entablature is exposed, followed by V1B and a small outcrop identified as V1C. Basal part of this section is anomalous with regards to the southern lobe type section.
S18	Western SL	70.965078	116.006118	40	Poor exposure with two flows resembling V1A and V1B preserved - no contacts preserved.
S20	Central SL	71.048686	115.274525	130	Section similar to S10 - only two outcrops totaling ~20m of V0 preserved, contact with C2 weathered. C2/V1A contact nicely preserved and sharp, with abundant vesicles/pipe vesicles present in the base of V1A. V1B and V1C also preserved, however contacts are recessive.

Appendix 2.2: Southern lobe stratigraphic sections

Section	Location	Latitude (°N)	Longitude (°W)	Approximate thickness (m)	Notes/Summary
S21	Eastern SL	71.291778	114.074854	65	Composite section of two plateaus ~2.2km apart. Bottom part of section shows a volcanic conglomerate with almost vertical contact to Kj - Kj appears to be folded. Volcanic conglomerate is interlayered with flows - labelled V0. Top part of section does not preserve Kj/V0 contact. However, top of Kj outcrop shows bubble tubes with sandstone rinds. Small sub-crop of C1 is followed by V1A toping the plateau. Cu noted here as flecks and lining amygdulites.
S22	Eastern SL	71.151869	114.733027	40	Short section through V0 - flow tops are recessive, only massive bases preserved.
S23	Eastern SL	71.182976	114.615425	40	Short section through V0 - flow tops are recessive, only massive bases preserved. Contact with Kj preserved & sharp.
SY	Western SL	70.973915	116.058437	70	Stratigraphic section of the Western Vent Complex - below the vent necks the basalt units weather in benches, with recessive tops. The vent necks occur at the top of the plateau. Native Cu was noted at the base of the section.
S24	Western SL	71.002253	115.952748	90	Poor exposure. Within the 90m, only 3 outcrops occur and no contacts preserved. Small outcrops of V0, V1A, and V1C.
S25	Western SL	71.057263	115.89779	120	Canyon section through V0 and V1A - V0 contact with Kj preserved: pillows, pahoehoe toes, and hyaloclastite noted. ~5 flow contacts preserved in V0, contact with V1 not preserved and no structures noted in V1.
S26	Central SL	71.109039	115.264127	50	V0 and V1 exposed, ~4 flows visible in V0, contacts covered.
S27	Central SL	71.128268	115.195892	60	Small outcrops of V0 exposed, about 10m of V1 exposed. Small outcrop of C2. No contacts.
S29	Eastern SL	71.393939	113.24829	160	Stratigraphic section of the Eastern Vent Complex. Base of section is Kuujua river - outcrop of C1, followed by V units. Up a hill and much cover, C1 crops out again before the volcanic stratigraphy begins - we believe there is a fault in the area. Below and above the vent necks the basalt units weather in benches, with recessive tops.

Appendix 2.3: Mineral chemistry data

Pyroxenes

	diopside-pure	NW015-A02-1	NW015-A02-2	NW015-A02-3	NW016-B04-1	NW016-B04-2	NW016-B04-3	NW016-B04-7	NW066-A03-1	NW066-A03-2
Strat level (m)		7.5	7.5	7.5	19	19	19	19	10	10
<i>Oxides (wt%)</i>										
SiO ₂	55.49	53.40	52.83	51.01	51.40	51.12	51.72	51.01	51.22	51.43
Al ₂ O ₃		1.50	1.74	1.76	3.57	3.27	3.40	3.80	3.51	2.83
TiO ₂		0.39	0.30	0.72	0.47	0.44	0.45	0.55	0.45	0.55
Cr ₂ O ₃		0.03	0.41	0.02	1.15	0.90	1.13	1.13	1.20	0.11
FeO		9.03	6.52	15.84	6.58	6.20	5.79	6.18	6.62	8.78
MnO		0.24	0.15	0.37	0.18	0.13	0.12	0.15	0.17	0.21
NiO		0.03	0.03	0.02	0.04	0.03	0.04	0.04	0.01	0.00
MgO	18.61	16.81	16.88	15.31	16.75	16.31	16.00	16.02	16.83	16.84
CaO	25.90	18.45	20.07	14.25	18.86	20.02	20.71	19.97	19.23	18.15
Na ₂ O		0.16	0.17	0.16	0.21	0.20	0.18	0.19	0.20	0.16
Total	100.00	100.04	99.10	99.46	99.20	98.61	99.53	99.03	99.45	99.09
<i>Formula (6 oxygen)</i>										
Si	2.000	1.968	1.955	1.936	1.901	1.905	1.908	1.893	1.89	1.916
Al	0.000	0.065	0.076	0.079	0.155	0.143	0.148	0.166	0.15	0.124
Ti	0.000	0.011	0.008	0.021	0.013	0.012	0.012	0.015	0.01	0.015
Cr	0.000	0.001	0.012	0.000	0.034	0.026	0.033	0.033	0.04	0.003
Fe	0.000	0.278	0.202	0.503	0.203	0.193	0.179	0.192	0.20	0.274
Mn	0.000	0.007	0.005	0.012	0.006	0.004	0.004	0.005	0.01	0.007
Ni	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.00	0.000
Mg	1.000	0.924	0.931	0.867	0.923	0.906	0.880	0.886	0.93	0.935
Ca	1.000	0.728	0.796	0.580	0.747	0.799	0.818	0.794	0.76	0.725
Na	0.000	0.012	0.012	0.012	0.015	0.014	0.013	0.014	0.01	0.012
Σ cations	4.000	3.994	3.998	4.009	3.999	4.005	3.996	3.999	4.01	4.011
mg#	100.000	76.844	82.198	63.288	81.943	82.413	83.115	82.217	81.92	77.363
<i>Ratios</i>										
Ca/(Ca)(Fe)(Mn)(Mg)	0.500	0.377	0.413	0.297	0.399	0.421	0.436	0.424	0.40	0.375
Mg/(Ca)(Fe)(Mn)(Mg)	0.500	0.477	0.482	0.442	0.491	0.476	0.468	0.472	0.49	0.482
Fe/(Ca)(Fe)(Mn)(Mg)	0.000	0.144	0.104	0.256	0.108	0.102	0.095	0.102	0.11	0.141
Total	1	0.998	0.999	0.996	0.998	0.999	0.999	0.999	1.00	0.998

Appendix 2.3: Mineral chemistry data

Pyroxenes

	NW066-A03-3	NW066-A03-4	NW066-A03-5	NW067-A03-1	NW067-A03-2	NW067-A03-3	NW067-A03-4	NW067-A03-7	NW067-A03-8	Average V0
Strat level (m)	10	10	10	36	36	36	36	36	36	
<i>Oxides (wt%)</i>										
SiO ₂	52.68	51.25	49.78	50.71	52.23	51.48	51.82	51.33	52.67	51.62
Al ₂ O ₃	2.09	3.22	2.15	3.35	2.03	3.14	2.61	3.26	1.69	2.72
TiO ₂	0.27	0.61	0.93	0.64	0.30	0.42	0.60	0.45	0.31	0.49
Cr ₂ O ₃	0.65	0.12	0.01	0.53	0.81	1.03	0.07	1.12	0.47	0.60
FeO	6.80	8.78	17.32	7.59	6.36	6.65	8.64	5.97	6.49	8.12
MnO	0.19	0.23	0.44	0.15	0.15	0.17	0.18	0.15	0.20	0.20
NiO	0.05	0.01	0.02	0.01	0.05	0.01	0.04	0.03	0.05	0.03
MgO	18.15	16.00	12.61	15.25	17.70	16.55	15.85	16.06	17.67	16.31
CaO	18.73	19.73	16.33	20.16	18.85	19.24	19.05	20.29	19.25	18.96
Na ₂ O	0.17	0.19	0.20	0.17	0.16	0.18	0.17	0.19	0.15	0.18
Total	99.79	100.13	99.78	98.56	98.66	98.87	99.04	98.85	98.95	99.23
<i>Formula (6 oxygen)</i>										
Si	1.934	1.899	1.913	1.903	1.938	1.912	1.933	1.908	1.950	1.920
Al	0.091	0.140	0.097	0.148	0.089	0.138	0.115	0.143	0.074	0.119
Ti	0.008	0.017	0.027	0.018	0.008	0.012	0.017	0.013	0.009	0.014
Cr	0.019	0.003	0.000	0.016	0.024	0.030	0.002	0.033	0.014	0.018
Fe	0.209	0.272	0.557	0.238	0.197	0.207	0.269	0.185	0.201	0.254
Mn	0.006	0.007	0.014	0.005	0.005	0.005	0.006	0.005	0.006	0.006
Ni	0.002	0.000	0.000	0.000	0.002	0.000	0.001	0.001	0.002	0.001
Mg	0.993	0.884	0.722	0.853	0.979	0.916	0.882	0.890	0.975	0.904
Ca	0.737	0.783	0.672	0.810	0.749	0.766	0.761	0.808	0.763	0.755
Na	0.012	0.014	0.015	0.012	0.012	0.013	0.012	0.014	0.011	0.013
Σ cations	4.009	4.019	4.019	4.003	4.003	3.999	3.998	3.999	4.004	4.004
mg#	82.632	76.462	56.473	78.188	83.229	81.601	76.592	82.753	82.910	78.452
<i>Ratios</i>										
Ca/(Ca)(Fe)(Mn)(Mg)	0.380	0.404	0.345	0.426	0.389	0.405	0.398	0.429	0.394	0.395
Mg/(Ca)(Fe)(Mn)(Mg)	0.511	0.454	0.367	0.448	0.507	0.484	0.460	0.471	0.501	0.471
Fe/(Ca)(Fe)(Mn)(Mg)	0.107	0.140	0.283	0.125	0.102	0.109	0.140	0.098	0.103	0.132
Total	0.998	0.998	0.995	0.999	0.998	0.998	0.998	0.999	0.998	0.998

Appendix 2.3: Mineral chemistry data

Pyroxenes

	NW019-A01-1	NW019-A01-2	NW019-A01-3	NW019-A01-4	NW019-A01-5	NW019-A01-7	NW019-A01-8	NW019-A01-9	NW019-A01-10	NW019-A01-11
Strat level (m)	50	50	50	50	50	50	50	50	50	50
<i>Oxides (wt%)</i>										
SiO ₂	52.31	50.78	51.67	51.90	49.90	50.16	51.94	50.42	50.04	43.51
Al ₂ O ₃	2.12	1.13	0.68	2.12	1.83	0.86	2.19	1.28	0.51	0.00
TiO ₂	0.49	0.74	0.49	0.45	0.92	0.67	0.51	0.85	0.55	0.00
Cr ₂ O ₃	0.27	0.02	0.01	0.29	0.23	0.00	0.29	0.02	0.02	0.00
FeO	8.01	16.41	23.67	7.81	15.81	24.36	8.93	17.17	28.64	1.04
MnO	0.21	0.35	0.51	0.19	0.38	0.53	0.19	0.34	0.54	0.00
NiO	0.03	0.04	0.04	0.03	0.04	0.01	0.02	0.01	0.06	0.00
MgO	15.77	12.53	17.47	16.22	11.91	14.74	15.68	11.81	13.99	0.00
CaO	19.51	16.40	4.55	20.16	17.56	7.69	19.83	17.07	4.89	15.09
Na ₂ O	0.19	0.25	0.06	0.19	0.33	0.00	0.00	0.00	0.00	3.21
Total	98.89	98.64	99.13	99.36	98.91	99.02	99.57	98.97	99.23	62.97
<i>Formula (6 oxygen)</i>										
Si	1.950	1.963	1.981	1.931	1.930	1.956	1.934	1.952	1.970	2.436
Al	0.093	0.051	0.031	0.093	0.083	0.040	0.096	0.058	0.024	0.000
Ti	0.014	0.021	0.014	0.013	0.027	0.020	0.014	0.025	0.016	0.000
Cr	0.008	0.001	0.000	0.008	0.007	0.000	0.009	0.001	0.001	0.000
Fe	0.250	0.530	0.759	0.243	0.511	0.794	0.278	0.556	0.943	0.049
Mn	0.006	0.011	0.016	0.006	0.012	0.017	0.006	0.011	0.018	0.000
Ni	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.002	0.000
Mg	0.876	0.722	0.999	0.900	0.687	0.857	0.871	0.682	0.821	0.000
Ca	0.779	0.679	0.187	0.804	0.728	0.321	0.791	0.708	0.206	0.905
Na	0.014	0.018	0.004	0.014	0.025	0.000	0.000	0.000	0.000	0.348
Σ cations	3.992	3.999	3.992	4.012	4.011	4.005	3.999	3.993	4.001	3.738
mg#	77.819	57.660	56.823	78.727	57.323	51.891	75.788	55.073	46.542	0.000
<i>Ratios</i>										
Ca/(Ca)(Fe)(Mn)(Mg)	0.409	0.352	0.096	0.413	0.378	0.163	0.408	0.364	0.105	0.949
Mg/(Ca)(Fe)(Mn)(Mg)	0.458	0.372	0.509	0.461	0.354	0.431	0.447	0.348	0.413	0.000
Fe/(Ca)(Fe)(Mn)(Mg)	0.131	0.273	0.387	0.125	0.264	0.399	0.143	0.284	0.474	0.051
Total	0.998	0.996	0.992	0.998	0.996	0.993	1.00	1.00	0.99	1.00

Appendix 2.3: Mineral chemistry data

Pyroxenes

	NW019-A03-10	NW019-A03-11	NW019-A03-12	070-A01-1	070-A01-2	070-A01-3	070-A01-10	070-A01-11	Average V1
Strat level (m)	64	64	64	75	75	75	75	75	
<i>Oxides (wt%)</i>									
SiO ₂	52.01	49.09	52.14	52.38	52.84	52.90	53.74	50.66	51.02
Al ₂ O ₃	2.06	1.07	1.91	2.72	2.06	1.88	1.72	4.27	1.69
TiO ₂	0.46	0.97	0.51	0.58	0.44	0.51	0.42	1.03	0.59
Cr ₂ O ₃	0.31	0.00	0.19	0.59	0.42	0.26	0.16	0.33	0.19
FeO	7.62	23.87	8.63	7.41	7.63	8.35	10.07	9.32	13.04
MnO	0.18	0.53	0.21	0.14	0.20	0.21	0.23	0.25	0.29
NiO	0.05	0.03	0.05	0.00	0.00	0.03	0.05	0.03	0.03
MgO	16.28	9.97	16.55	15.66	16.69	16.70	18.32	15.33	14.20
CaO	19.96	13.48	19.01	20.53	19.45	18.77	15.57	19.17	16.04
Na ₂ O	0.25	0.20	0.23	0.24	0.25	0.18	0.15	0.28	0.33
Total	99.19	99.21	99.42	100.27	99.99	99.79	100.42	100.67	97.43
<i>Formula (6 oxygen)</i>									
Si	1.936	1.945	1.939	1.928	1.945	1.952	1.965	1.87	1.971
Al	0.090	0.050	0.084	0.118	0.089	0.082	0.074	0.19	0.075
Ti	0.013	0.029	0.014	0.016	0.012	0.014	0.012	0.03	0.017
Cr	0.009	0.000	0.006	0.017	0.012	0.008	0.005	0.01	0.006
Fe	0.237	0.791	0.268	0.228	0.235	0.258	0.308	0.29	0.418
Mn	0.006	0.018	0.007	0.004	0.006	0.007	0.007	0.01	0.009
Ni	0.002	0.001	0.002	0.000	0.000	0.001	0.001	0.00	0.001
Mg	0.903	0.589	0.917	0.859	0.916	0.919	0.998	0.84	0.798
Ca	0.796	0.572	0.758	0.809	0.767	0.742	0.610	0.76	0.662
Na	0.018	0.015	0.016	0.017	0.018	0.013	0.010	0.02	0.031
Σ cations	4.011	4.009	4.010	3.997	4.001	3.995	3.990	4.01	3.987
mg#	79.199	42.681	77.359	79.020	79.588	78.107	76.419	74.58	63.589
<i>Ratios</i>									
Ca/(Ca)(Fe)(Mn)(Mg)	0.411	0.293	0.390	0.427	0.400	0.387	0.318	0.40	0.370
Mg/(Ca)(Fe)(Mn)(Mg)	0.465	0.299	0.470	0.452	0.476	0.477	0.519	0.44	0.411
Fe/(Ca)(Fe)(Mn)(Mg)	0.122	0.402	0.138	0.120	0.122	0.134	0.160	0.15	0.216
Total	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.997

Appendix 2.3: Mineral chemistry data

Feldspars

	albite-pure	anorthite - pure	albite-pure	NW015-A02-4	NW015-A02-5	NW015-A02-6	NW015-A02-7	NW016-B04-4	NW016-B04-5	NW016-B04-8ref
Strat level (m)										
Oxides (wt%)				7.5	7.5	7.5	7.5	19	19	19
SiO ₂	68.73	43.20	69.31	47.89	54.45	48.77	55.66	70.69	70.07	56.58
MgO										
Al ₂ O ₃	19.44	36.64	19.51	32.05	27.84	31.88	27.50	20.48	19.89	26.83
FeO			0.00	0.85	0.99	0.90	0.90	0.10	0.22	1.22
CaO		20.16	0.02	16.40	11.64	16.01	11.10	0.28	0.21	10.52
Na ₂ O	11.83		11.79	2.15	4.65	2.29	5.20	10.67	11.01	5.31
K ₂ O			0.01	0.09	0.24	0.08	0.27	0.13	0.13	0.39
Total	100.00	100.00	100.68	99.43	99.81	99.93	100.63	102.35	101.54	100.84
Formula (8 oxygen)										
Si	3.000	2.000	3.00	2.22	2.47	2.24	2.50	3.00	3.01	2.54
Al	1.000	2.000	1.00	1.75	1.49	1.73	1.46	1.03	1.01	1.42
Fe	0.000	0.000	0.00	0.03	0.04	0.03	0.03	0.00	0.01	0.05
Ca	0.000	1.000	0.00	0.81	0.57	0.79	0.54	0.01	0.01	0.51
Na	1.001	0.000	0.99	0.19	0.41	0.20	0.45	0.88	0.92	0.46
K	0.000	0.000	0.00	0.01	0.01	0.00	0.02	0.01	0.01	0.02
Σ cations	5.001	5.000	4.99	5.01	4.99	5.00	5.00	4.93	4.95	4.99
End members										
Ab	1.000	0.000	1.00	0.19	0.41	0.20	0.45	0.98	0.98	0.47
An	0.000	1.000	0.00	0.80	0.57	0.79	0.53	0.01	0.01	0.51
Or	0.000	0.000	0.00	0.01	0.01	0.00	0.02	0.01	0.01	0.02

Appendix 2.3: Mineral chemistry data

Feldspars

	NW016-B04-9	NW066-area1-6	NW066-area1-7	NW066-area1-8	NW066-area1-9	NW066-area1-10	NW067-A03-5	NW067-A03-6	NW067-A03-9	NW067-A03-10
Strat level (m)	19	10	10	10	10	10	36	36	36	36
Oxides (wt%)										
SiO ₂	69.24	51.67	48.60	49.45	52.22	56.08	66.88	67.66	67.88	68.25
MgO										
Al ₂ O ₃	19.79	29.75	31.78	30.74	29.00	27.13	21.60	20.24	20.06	20.04
FeO	0.18	0.88	0.77	0.77	1.08	1.00	0.77	0.12	0.12	0.09
CaO	0.29	13.98	16.02	15.14	12.92	10.47	1.75	0.68	0.69	0.76
Na ₂ O	11.68	3.64	2.42	2.97	4.00	5.37	10.11	10.97	10.91	11.02
K ₂ O	0.10	0.11	0.14	0.09	0.17	0.33	0.11	0.36	0.20	0.12
Total	101.28	100.04	99.73	99.17	99.38	100.39	101.23	100.04	99.87	100.29
Formula (8 oxygen)										
Si	2.99	2.36	2.24	2.29	2.39	2.53	2.90	2.96	2.97	2.97
Al	1.01	1.60	1.73	1.67	1.57	1.44	1.10	1.04	1.04	1.03
Fe	0.01	0.03	0.03	0.03	0.04	0.04	0.03	0.00	0.00	0.00
Ca	0.01	0.68	0.79	0.75	0.63	0.51	0.08	0.03	0.03	0.04
Na	0.98	0.32	0.217	0.27	0.36	0.47	0.85	0.93	0.93	0.93
K	0.01	0.01	0.008	0.01	0.01	0.02	0.01	0.02	0.01	0.01
Σ cations	5.00	5.01	5.010	5.01	5.00	5.00	4.97	4.99	4.98	4.98
End members										
Ab	0.98	0.32	0.213	0.26	0.36	0.47	0.91	0.95	0.96	0.96
An	0.01	0.68	0.779	0.73	0.63	0.51	0.09	0.03	0.03	0.04
Or	0.01	0.01	0.008	0.01	0.01	0.02	0.01	0.02	0.01	0.01

Appendix 2.3: Mineral chemistry data

Feldspars

	Average V0	NW019-A01-12	NW019-A01-13	NW019-A01-14	NW019-A03-1	NW019-A03-2	NW019-A03-3	NW019-A03-4	NW019-A03-5
Strat level (m)		50	50	50	64	64	64	64	64
<i>Oxides (wt%)</i>									
SiO ₂	58.94	53.31	52.07	50.05	50.31	50.03	49.96	49.20	50.74
MgO									
Al ₂ O ₃	25.68	28.40	29.10	30.16	31.83	30.86	31.64	31.88	29.97
FeO	0.65	1.04	1.09	1.31	0.55	0.92	0.51	0.59	1.21
CaO	8.17	11.79	12.62	14.01	15.36	14.71	15.23	15.52	13.77
Na ₂ O	6.73	4.73	4.30	3.38	2.90	3.16	2.89	2.69	3.50
K ₂ O	0.18	0.27	0.21	0.12	0.08	0.14	0.05	0.05	0.16
Total	100.35	99.53	99.40	99.03	101.02	99.82	100.27	99.93	99.35
<i>Formula (8 oxygen)</i>									
Si	2.62	2.44	2.39	2.32	2.28	2.30	2.28	2.26	2.34
Al	1.36	1.53	1.57	1.64	1.70	1.67	1.70	1.72	1.63
Fe	0.02	0.04	0.04	0.05	0.02	0.04	0.02	0.02	0.05
Ca	0.40	0.58	0.62	0.69	0.75	0.72	0.74	0.76	0.68
Na	0.57	0.42	0.38	0.30	0.25	0.28	0.26	0.24	0.31
K	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.00	0.01
Σ cations	4.99	5.02	5.02	5.02	5.00	5.01	5.00	5.00	5.01
<i>End members</i>									
Ab	0.59	0.41	0.38	0.30	0.25	0.28	0.25	0.24	0.31
An	0.40	0.57	0.61	0.69	0.74	0.71	0.74	0.76	0.68
Or	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.00	0.01

Appendix 2.3: Mineral chemistry data

Feldspars

	NW019-A03-6	NW019-A03-7	NW019-A03-8	NW019-A03-9	070-A01-4	070-A01-5	070-A01-6	070-A01-7	070-A01-8
Strat level (m)	64	64	64	64	75	75	75	75	75
<i>Oxides (wt%)</i>									
SiO ₂	52.52	58.47	51.31	56.33	69.84	53.14	54.90	55.57	53.86
MgO									
Al ₂ O ₃	29.42	26.73	30.14	26.93	20.42	29.56	28.53	28.45	28.96
FeO	1.01	0.95	1.04	1.05	0.14	0.93	0.90	0.88	0.88
CaO	12.92	9.22	14.01	9.97	0.29	13.72	11.98	11.74	12.86
Na ₂ O	4.20	6.35	3.42	5.53	11.67	3.86	4.74	4.83	4.34
K ₂ O	0.18	0.42	0.14	0.35	0.39	0.07	0.11	0.13	0.08
Total	100.25	102.14	100.07	100.17	102.74	101.27	101.17	101.60	100.97
<i>Formula (8 oxygen)</i>									
Si	2.39	2.58	2.34	2.54	2.98	2.39	2.46	2.48	2.42
Al	1.58	1.39	1.62	1.43	1.03	1.57	1.51	1.49	1.54
Fe	0.04	0.04	0.04	0.04	0.01	0.04	0.03	0.03	0.03
Ca	0.63	0.44	0.69	0.48	0.01	0.66	0.58	0.56	0.62
Na	0.37	0.54	0.30	0.48	0.96	0.34	0.41	0.42	0.38
K	0.01	0.02	0.01	0.02	0.02	0.00	0.01	0.01	0.00
Σ cations	5.01	5.01	5.00	5.00	5.00	5.00	5.00	4.99	5.00
<i>End members</i>									
Ab	0.37	0.54	0.30	0.49	0.97	0.34	0.41	0.42	0.38
An	0.62	0.43	0.69	0.49	0.01	0.66	0.58	0.57	0.62
Or	0.01	0.02	0.01	0.02	0.02	0.00	0.01	0.01	0.00

Appendix 2.3: Mineral chemistry data

Feldspars

	070-A01-9	Average V1
Strat level (m)	75	
<i>Oxides (wt%)</i>		
SiO ₂	59.27	53.94
MgO		
Al ₂ O ₃	26.53	28.86
FeO	0.65	0.87
CaO	9.33	12.17
Na ₂ O	6.24	4.60
K ₂ O	0.19	0.17
Total	102.22	100.61
<i>Formula (8 oxygen)</i>		
Si	2.60	2.43
Al	1.37	1.54
Fe	0.02	0.03
Ca	0.44	0.59
Na	0.53	0.40
K	0.01	0.01
Σ cations	4.98	5.00
<i>End members</i>		
Ab	0.54	0.40
An	0.45	0.59
Or	0.01	0.01

Appendix 2.3: Mineral chemistry data

Chlorite

	NW016-B04-6
<i>Oxide (wt%)</i>	
SiO ₂	33.53
Al ₂ O ₃	14.19
TiO ₂	0.00
Cr ₂ O ₃	0.07
FeO	17.94
MnO	0.21
NiO	0.03
MgO	19.68
CaO	0.66
Na ₂ O	0.04
K ₂ O	0.10
Cl	0.00
F	0.00
TOTAL	86.45
O _≠ F,Cl	0.000
Σ - O _≠ F,Cl	86.45
<i>Formula (28 oxygen)</i>	
Si	6.8237
Al	3.4035
Ti	0.0000
Cr	0.0113
Fe	3.0532
Mn	0.0365
Ni	0.0052
Mg	5.9719
Ca	0.1431
Na	0.0154
K	0.0000
Σ cations	19.4638
F	0.0000
Cl	0.0000
Fe/FeMnMg	0.3369
Al(IV)	1.1763
Al(VI)	2.2272

Fe-Ti oxides

	NW015-A02-8	NW015-A02-9	Average V0	NW019-A01-6
<i>Oxide (wt%)</i>				
SiO ₂	0.33587	0.36582	0.350845	0.05348
Al ₂ O ₃	1.61	1.85	1.73166	1.47
TiO ₂	27.33	25.65	26.489775	20.37
Cr ₂ O ₃	0.08	0.10	0.09135	0.15
FeO	63.97	64.16	64.067945	69.89
MnO	1.68	1.51	1.594655	1.11
NiO	0.02	0.06	0.03818	0.09
MgO	0.06	0.09	0.07628	0.10
CaO	0.04	0.07	0.05597	0.07
TOTAL	95.14	93.86	94.49666	93.31
<i>Formula (32 oxygen)</i>				
Si	0.11	0.12	0.113636889	0.02
Al	0.610	0.713	0.661200064	0.595
Ti	6.589	6.306	6.44756229	5.259
Cr	0.021	0.026	0.023407176	0.042
Fe	17.154	17.540	17.34729307	20.065
Mn	0.457	0.417	0.437069396	0.323
Ni	0.005	0.015	0.00999523	0.024
Mg	0.031	0.043	0.036871052	0.052
Ca	0.014	0.025	0.019462033	0.026
Σ cations-T	24.988	25.205	25.0964972	26.404

Appendix 3.1: Whole rock lithogeochemistry

Sample Group	BCR-2 INRS-ETE standard - basalt	BHVO-2 INRS-ETE standard - basalt	BCR-2 UofO XRF standard - basalt	DR-N UofO XRF standard - diorite
Unit	-	-	-	
Strat level (m above Kj/Nk contact)	-	-	-	
<i>Major elements (wt%)</i>				
Al ₂ O ₃	13.52		13.63	13.31
CaO	7.26		10.96	7.06
Fe ₂ O ₃ *	13.72		12.23	13.77
K ₂ O	1.80		0.50	1.76
Mg#				
MgO	3.59		7.30	3.57
MnO	0.19		0.16	0.20
Na ₂ O	3.09		2.15	3.08
P ₂ O ₅	0.36		0.26	0.36
SiO ₂	54.18		49.97	53.66
S	0.04		0.04	
TiO ₂	2.26		2.73	2.24
Total	100.23		100.10	99.21
LOI	0.00		0.00	0.50
<i>Trace elements (ppm)</i>				
As	50		50	
Ba	682		130	388
Cd	40		34	
Co	40		47	46
Cr	15		289	34
Cu	14		122	
Mo	231		9	
Ni	18		120	3
Sc	34		32	
Sr	341		395	
V	423		324	396
Zn	133		103	200
Ga				126
La				12
Pb				12
Rb				33
Sr				48
Th				331
U				23
Y				10
Zr				34
Nb				181
Ce				14
Nd				54

Appendix 3.1: Whole rock lithogeochemistry

Sample	10RAT-NW-15-A02	10RAT-NW-15-A03	10RAT-NW-16B02	10RAT-NW-16-B03	10RAT-NW-16-B04	10RAT-NW-17-A01	10RAT-NW-17-A02
Group	Section A	Section A	Section A	Section A	Section A	Section A	Section A
Unit	V0	V0	V0	V0	V0	C1	C1
Strat level (m above Kj/Nk contact)	7.5	9	17	23	19	36	42
<i>Major elements (wt%)</i>							
Al ₂ O ₃	14.73	15.54	15.69	15.70	16.23	12.43	12.02
CaO	10.85	6.62	7.58	6.70	7.32	9.09	11.23
Fe ₂ O ₃ *	11.03	11.83	12.07	13.57	11.52	10.64	10.61
K ₂ O	0.31	2.46	3.31	3.57	1.20	2.37	1.81
Mg#	4.17	4.17	4.17	40.70	47.24	42.91	42.57
MgO	0.218	0.218	0.218	8.38	9.29	7.20	7.08
MnO	2.75	2.75	2.75	0.15	0.11	0.12	0.13
Na ₂ O	0.231	0.231	0.231	2.11	3.04	2.68	2.66
P ₂ O ₅	0.08	0.07	0.06	0.07	0.08	0.07	0.07
SiO ₂	51.34	50.36	48.33	48.44	49.89	54.17	53.20
S	0.04	0.02	0.02	0.03	0.03	0.03	0.03
TiO ₂	1.11	1.10	1.04	1.11	1.14	1.08	1.05
Total	98.56	101.36	100.39	99.72	99.78	99.00	99.26
LOI	3.34	4.88	7.48	7.48	7.63	9.70	10.91
<i>Trace elements (ppm)</i>							
As	50	50	50	50	50	50	50
Ba	60	1127	220	220	135	274	229
Cd	31	35	32	37	35	30	28
Co	45	42	50	47	42	32	28
Cr	519	231	443	393	415	118	119
Cu	125	99	57	163	172	39	32
Mo	< 9	< 9	< 9	< 9	< 9	< 9	< 9
Ni	134	103	148	121	134	76	75
Sc	46	42	44	46	47	30	28
Sr	135	302	134	149	144	112	96
V	318	330	315	342	337	274	235
Zn	86	79	73	79	77	62	60
Ga							
La							
Pb							
Rb							
Sr							
Th							
U							
Y							
Zr							
Nb							
Ce							
Nd							

Appendix 3.1: Whole rock lithogeochemistry

Sample	10RAT-NW-19-A01	10RAT-NW-19-A02	10RAT-NW-19-A03	10RAT-NW-19-A04	10RAT-NW-63-A01	10RAT-NW-64-B01	10RAT-NW-64-B02
Group	Section A	Section A	Section A	Section A	Section B	Section B	Section B
Unit	V1	V1	V1	V1	V1	V0	V0
Strat level (m above Kj/Nk contact)	50	64	64	56	140	1.8	3
<i>Major elements (wt%)</i>							
Al ₂ O ₃	14.16	14.43	14.21	14.01	10.60	15.53	16.09
CaO	11.35	11.59	11.19	10.52	7.84	12.08	8.37
Fe ₂ O ₃ *	13.65	13.23	13.90	14.30	10.31	10.83	11.18
K ₂ O	0.15	0.09	0.28	0.35	7.51	0.99	1.19
Mg#	37.73	39.22	37.34	34.16	24.12	48.07	49.50
MgO	7.44	7.69	7.45	6.68	2.95	9.02	9.86
MnO	0.21	0.17	0.20	0.20	0.06	0.14	0.15
Na ₂ O	1.96	1.76	1.92	2.40	0.18	1.35	1.69
P ₂ O ₅	0.09	0.09	0.07	0.13	0.05	0.05	0.07
SiO ₂	49.40	49.37	49.20	49.39	59.48	48.78	50.13
S	0.03	0.04	0.03	0.06	0.02	0.14	0.08
TiO ₂	1.42	1.39	1.40	1.81	0.83	0.96	1.03
Total	100.11	99.96	99.34	100.09	99.90	99.73	100.00
LOI	1.06	3.10	2.16	1.60	7.08	6.14	5.83
<i>Trace elements (ppm)</i>							
As	50	50	50	50	50	50	50
Ba	57	26	59	61	623	96	146
Cd	38	38	41	41	28	29	34
Co	48	47	49	47	19	41	34
Cr	183	190	185	144	120	370	420
Cu	191	325	188	269	360	92	116
Mo	< 9	< 9	< 9	< 9	< 9	< 9	< 9
Ni	122	125	127	100	63	145	130
Sc	40	41	41	41	23	44	44
Sr	158	144	144	153	33	140	156
V	375	378	372	436	219	307	312
Zn	100	104	102	163	38	87	86
Ga							
La							
Pb							
Rb							
Sr							
Th							
U							
Y							
Zr							
Nb							
Ce							
Nd							

Appendix 3.1: Whole rock lithogeochemistry

Sample	10RAT-NW-65-A01	10RAT-NW-66-A01	10RAT-NW-66-A03	10RAT-NW-66-A04	10RAT-NW-67-A01	10RAT-NW-67-A02	10RAT-NW-67-A03
Group	Section B	Section B	Section B	Section B	Section B	Section B	Section B
Unit	V0	V0	V0	V0	V0	V0	V0
Strat level (m above Kj/Nk contact)	3.5	6.7	10	13	29	34	36
<i>Major elements (wt%)</i>							
Al ₂ O ₃	16.1	15.8	15.5	15.0	14.8	14.5	14.7
CaO	13.0	8.5	11.7	11.9	7.5	8.5	8.3
Fe ₂ O ₃ *	10.3	11.7	10.7	11.5	11.7	11.8	11.0
K ₂ O	1.2	1.3	0.5	0.2	3.8	0.4	0.8
Mg#	46.1	51.5	48.1	45.9	43.8	42.5	48.4
MgO	7.9	11.1	8.9	8.8	8.2	7.8	9.3
MnO	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Na ₂ O	1.4	1.6	1.4	1.4	2.2	4.6	3.8
P ₂ O ₅	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SiO ₂	48.4	48.6	49.8	49.7	50.0	51.1	50.7
S	0.1	0.0	0.0	0.0	0.0	0.0	0.0
TiO ₂	1.1	1.0	1.1	1.0	1.1	1.0	1.0
Total	99.3	100.1	100.2	99.1	100.7	99.8	100.0
LOI	8.4	7.6	5.0	3.9	4.1	4.6	4.3
<i>Trace elements (ppm)</i>							
As	50	50	50	50	50	50	50
Ba	98	66	48	42	279	59	218
Cd	29	32	33	33	35	33	28
Co	36	38	41	40	42	40	45
Cr	377	394	402	453	376	409	422
Cu	131	165	118	88	52	149	103
Mo	< 9	< 9	< 9	< 9	< 9	< 9	< 9
Ni	142	159	130	114	127	132	144
Sc	45	44	44	43	44	43	42
Sr	157	113	137	133	2119	108	338
V	325	314	316	310	322	308	291
Zn	74	86	98	74	85	83	86
Ga							
La							
Pb							
Rb							
Sr							
Th							
U							
Y							
Zr							
Nb							
Ce							
Nd							

Appendix 3.1: Whole rock lithogeochemistry

Sample	10RAT-NW-68-A01	10RAT-NW-69-A02	10RAT-NW-69-A03	10RAT-NW-69-A04	10RAT-NW-69-A05	10RAT-NW-69-A06	10RAT-NW-69-A08
Group	Section B	Section B	Section B	Section B	Section B	Section B	Section B
Unit	C1	V1	V1	V1	V1	V1	V1
Strat level (m above Kj/Nk contact)	60	95	98.8	116	127	130	148
<i>Major elements (wt%)</i>							
Al ₂ O ₃	12.41	14.57	14.31	14.55	13.73	14.26	14.61
CaO	11.16	10.83	9.95	10.93	7.11	7.74	10.73
Fe ₂ O ₃ *	10.24	13.42	13.40	13.41	13.39	13.51	13.08
K ₂ O	1.25	0.60	0.70	0.32	0.95	0.88	0.18
Mg#	44.23	38.04	39.74	39.60	39.54	39.24	39.62
MgO	7.31	7.42	7.96	7.92	7.88	7.85	7.72
MnO	0.12	0.17	0.19	0.21	0.15	0.20	0.19
Na ₂ O	3.11	2.05	2.38	2.07	3.99	3.54	1.89
P ₂ O ₅	0.08	0.08	0.09	0.09	0.09	0.08	0.09
SiO ₂	53.07	49.27	49.45	48.94	51.12	50.40	50.04
S	0.05	0.03	0.04	0.04	0.02	0.02	0.03
TiO ₂	1.06	1.42	1.39	1.38	1.39	1.36	1.31
Total	98.01	100.42	100.54	99.76	100.09	100.22	99.04
LOI	10.47	1.71	2.48	2.85	3.31	2.71	1.01
<i>Trace elements (ppm)</i>							
As	50	50	50	50	50	50	50
Ba	266	71	49	28	110	161	41
Cd	28	38	38	40	36	38	36
Co	34	48	47	46	46	49	49
Cr	119	182	185	190	293	195	168
Cu	32	96	150	161	68	49	128
Mo	< 9	< 9	< 9	< 9	< 9	< 9	< 9
Ni	86	116	114	111	365	123	111
Sc	29	41	41	41	41	41	41
Sr	297	161	158	154	215	336	152
V	282	373	373	376	369	366	359
Zn	97	90	101	126	110	96	94
Ga							
La							
Pb							
Rb							
Sr							
Th							
U							
Y							
Zr							
Nb							
Ce							
Nd							

Appendix 3.1: Whole rock lithogeochemistry

Sample Group Unit Strat level (m above Kj/Nk contact)	10RAT-NW-101-B01 Section B V1 90	10RAT-NW-101-B01 duplicate Section B V1 90	11RAT-TD129C1 I V1 -	11RAT-TD129E1 I V1 -	11RAT-TD129A1 I V1 -	11RAT-TD129B1 I V1 -
<i>Major elements (wt%)</i>						
Al ₂ O ₃	15.78	15.15	14.22	14.24	15.24	14.63
CaO	10.54	10.10	10.20	11.40	11.23	11.07
Fe ₂ O ₃ *	12.24	11.73	13.58	13.06	13.11	14.20
K ₂ O	0.39	0.36	0.16	0.45	0.44	0.27
Mg#	41.26		37.91	40.06	35.57	32.74
MgO	7.74	7.43	7.46	7.86	6.52	6.22
MnO	0.21	0.20	0.19	0.18	0.19	0.22
Na ₂ O	2.88	2.74	3.36	1.83	2.04	2.04
P ₂ O ₅	0.10	0.10	0.11	0.10	0.12	0.13
SiO ₂	48.37	45.98	49.26	49.47	49.48	49.47
S	0.04	0.03				
TiO ₂	1.54	1.48	1.35	1.30	1.51	1.63
Total	99.96	100.11	96.59	98.14	97.77	98.53
LOI	4.66	4.66	3.20	1.40	1.80	0.80
<i>Trace elements (ppm)</i>						
As	50	50				
Ba	50	47	29	67	52	41
Cd	34	32				
Co	51	44	61	60	54	55
Cr	198	190	182	161	124	117
Cu	204	190				
Mo	< 9	9				
Ni	129	118	128	110	82	82
Sc	45	43				
Sr	147	140				
V	411	392	342	326	333	352
Zn	222	214	98	89	96	98
Ga			12	11	10	13
La			18	9	11	18
Pb			10	17	25	7
Rb			5	13	16	8
Sr			206	139	148	152
Th			11	17	23	13
U			3	7	8	2
Y			18	18	21	23
Zr			80	77	90	101
Nb			5	6	5	7
Ce			-16	2	28	30
Nd			-6	8	12	2

Appendix 3.1: Whole rock lithogeochemistry

Sample	11RAT-TD129F1	11RAT-TD129D1	11RAT-TD129G1	11RAT-TD43B1	11RAT-TD043c1	11RAT-TD73A1	11RAT-TD72B1
Group	I	I	I	IV	IV	IV	IV
Unit	V1	V1	V1	V1	V1	V1	V1
Strat level (m above Kj/Nk contact)	-	-	-	-	-	-	-
<i>Major elements (wt%)</i>							
Al ₂ O ₃	14.08	14.25	14.44	14.42	14.21	13.91	14.31
CaO	11.17	9.27	11.97	8.94	9.40	8.13	9.72
Fe ₂ O ₃ *	13.24	13.97	12.75	13.64	13.02	14.51	13.06
K ₂ O	0.26	0.18	0.31	0.43	0.56	0.86	0.59
Mg#	39.53	38.86	40.06	38.62	40.73	35.00	39.75
MgO	7.79	7.99	7.67	7.72	8.06	7.03	7.75
MnO	0.21	0.19	0.25	0.21	0.21	0.22	0.19
Na ₂ O	1.72	3.39	1.87	3.35	3.26	3.61	3.21
P ₂ O ₅	0.10	0.11	0.11	0.11	0.10	0.13	0.10
SiO ₂	50.08	49.16	49.21	49.72	49.76	49.90	49.64
S							
TiO ₂	1.24	1.37	1.32	1.33	1.29	1.57	1.29
Total	97.17	96.27	97.82	96.88	97.32	97.01	97.53
LOI	4.20	3.80	2.20	3.10	2.60	3.00	2.50
<i>Trace elements (ppm)</i>							
As							
Ba	54	21	51	124	70	115	83
Cd							
Co	52	61	60	58	58	62	56
Cr	166	197	162	164	166	147	176
Cu							
Mo							
Ni	116	115	111	110	117	103	115
Sc							
Sr							
V	323	342	338	330	314	372	335
Zn	95	96	147	90	88	98	86
Ga	11	9	11	9	7	12	4
La							
Pb	15	15	19	10	31	14	25
Rb	8	5	10	10	14	28	16
Sr	133	197	144	316	265	212	321
Th	14	12	19	11	21	13	24
U	4	4	8	4	12	5	10
Y	20	23	18	21	21	23	21
Zr	75	83	78	87	82	95	87
Nb	5	5	5	6	6	6	5
Ce	31	24	19	-20	7	3	21
Nd	8	5	13	-1	2	4	5

Appendix 3.1: Whole rock lithogeochemistry

Sample	11RAT-TD72C1	11RAT-TD72D1	11RAT-TD72E1	11RAT-TD72F1	11RAT-TD72G1	11RAT-NW135A1	11RAT-NW128A1
Group	IV	IV	IV	IV	IV	II	II
Unit	V1	V1	V1	V1	V1	V1	V1
Strat level (m above Kj/Nk contact)	-	-	-	-	-	-	-
<i>Major elements (wt%)</i>							
Al ₂ O ₃	14.44	13.68	13.99	14.27	13.90	14.61	14.60
CaO	8.89	9.52	9.35	10.69	11.57	11.98	12.07
Fe ₂ O ₃ *	13.45	14.10	14.36	12.69	13.72	14.10	14.04
K ₂ O	0.43	0.59	0.06	0.51	0.31	0.31	0.09
Mg#	39.28	34.93	33.15	41.53	35.36	34.82	36.25
MgO	7.83	6.81	6.41	8.11	6.76	6.78	7.19
MnO	0.20	0.22	0.20	0.22	0.23	0.21	0.25
Na ₂ O	3.44	2.76	4.06	2.68	2.14	1.98	1.76
P ₂ O ₅	0.11	0.13	0.13	0.11	0.12	0.11	0.11
SiO ₂	49.74	50.46	49.77	49.26	49.72	48.38	48.37
S							
TiO ₂	1.32	1.59	1.58	1.32	1.43	1.42	1.41
Total	97.20	97.66	95.22	97.75	99.16	97.19	96.28
LOI	2.60	1.90	4.30	2.20	0.50	3.00	3.60
<i>Trace elements (ppm)</i>							
As							
Ba	145	81	5	112	61	30	30
Cd							
Co	62	55	58	56	55	61	56
Cr	170	143	153	230	131	163	181
Cu							
Mo							
Ni	112	101	104	115	104	128	114
Sc							
Sr							
V	334	371	404	332	355	359	347
Zn	90	100	80	94	112	106	96
Ga	9	8	11	6	12	7	10
La	28	3		7	8	1	23
Pb	12	26	8	32	14	29	12
Rb	11	17	4	18	12	15	5
Sr	313	175	46	161	141	151	160
Th	13	22	9	25	17	26	17
U	7	10	5	14	9	15	11
Y	19	27	24	23	23	23	21
Zr	85	100	92	83	86	83	81
Nb	5	7	7	7	5	5	5
Ce	23	38	-11	26	-6	8	7
Nd	3	13	5	10	5	4	16

Appendix 3.1: Whole rock lithogeochemistry

Sample	11RAT-NW135B2	11RAT-NW135C1	11RAT-NW135D1	11RAT-NW135E1	11RAT-NW136A1	11RAT-NW137A1	11RAT-NW138A1
Group	II	II	II	II	II	II	II
Unit	V1	V1	V1	V1	V1	V1	V1
Strat level (m above Kj/Nk contact)	-	-	-	-	-	-	-
<i>Major elements (wt%)</i>							
Al2O3	14.80	14.62	14.01	13.92	14.24	13.95	14.32
CaO	11.94	10.15	8.92	11.52	8.53	10.10	11.84
Fe2O3*	13.70	14.03	13.33	13.32	14.58	13.76	13.26
K2O	0.11	0.23	0.87	0.10	0.70	0.49	0.33
Mg#	38.44	37.17	36.78	36.62	38.99	36.14	38.09
MgO	7.70	7.47	6.98	6.92	8.39	7.01	7.34
MnO	0.20	0.20	0.20	0.19	0.23	0.20	0.19
Na2O	1.80	2.88	3.37	3.14	3.20	3.22	1.82
P2O5	0.11	0.11	0.11	0.12	0.11	0.11	0.10
SiO2	48.15	48.80	50.78	49.37	48.49	49.63	49.40
S							
TiO2	1.38	1.36	1.28	1.29	1.41	1.40	1.27
Total	95.22	95.73	96.84	96.18	95.88	96.00	97.66
LOI	4.80	3.50	3.00	3.40	3.80	3.20	1.50
<i>Trace elements (ppm)</i>							
As							
Ba	45	126	113	5	102	66	82
Cd							
Co	57	65	58	60	62	53	58
Cr	183	228	211	190	178	182	163
Cu							
Mo							
Ni	123	135	134	109	106	114	112
Sc							
Sr							
V	351	341	297	305	348	351	327
Zn	100	93	86	74	103	87	87
Ga	13	9	7	11	4	9	11
La			4			0	16
Pb	7	8	4	20	27	9	13
Rb	5	6	27	9	20	21	11
Sr	152	284	225	60	204	134	143
Th	13	13	12	21	22	14	15
U	5	4	4	8	9	6	7
Y	20	20	21	22	22	22	18
Zr	82	84	85	81	86	81	79
Nb	6	6	5	6	5	5	4
Ce	-15	15	-2	23	37	29	-10
Nd	-11	0	2	3	4	14	-4

Appendix 3.1: Whole rock lithogeochemistry

Sample	11RAT-NW161A1	10RAT TD 15 A2	10RAT TD 16 A1	10RAT TD 16 A3	10RAT TD 18 A1	10RAT TD 18 A2	10RAT TD 55 A1
Group	III	Section A	Section A	Section A	Section A	Section A	Section A
Unit	V1	V0	V0	V0	V0	V0	V0
Strat level (m above Kj/Nk contact)	-	-	-	-	-	-	-
<i>Major elements (wt%)</i>							
Al2O3	14.43	14.73	16.54	15.23	14.90	16.07	15.32
CaO	10.15	13.63	17.04	6.38	9.31	6.55	10.30
Fe2O3*	13.38	11.09	8.58	12.03	12.16	12.40	11.62
K2O	0.17	0.34	3.10	3.65	4.15	1.09	0.94
Mg#	39.08						
MgO	7.72	8.31	6.69	8.25	7.46	9.63	9.73
MnO	0.23	0.17	0.20	0.16	0.20	0.11	0.23
Na2O	2.87	1.49	1.64	2.17	2.10	3.21	1.29
P2O5	0.11	0.07	0.07	0.07	0.06	0.07	0.07
SiO2	49.40	48.94	44.82	50.74	48.42	49.54	49.27
S							
TiO2	1.42	1.05	1.11	1.15	1.07	1.14	1.03
Total	96.48	100.20	99.77	100.20	99.97	100.06	100.26
LOI	3.50	4.83	13.69	6.69	9.13	8.15	5.69
<i>Trace elements (ppm)</i>							
As							
Ba	54						
Cd							
Co	63						
Cr	177	448	442	320	316	403	394
Cu		86	150	48	68	137	110
Mo							
Ni	115	145	129	121	117	137	146
Sc		44	46	44	44	45	43
Sr							
V	357	312	318	332	322	324	300
Zn	127						
Ga	7						
La	16						
Pb	22						
Rb	8						
Sr	152						
Th	24						
U	12						
Y	21	21	24	22	21	19	19
Zr	84	58	62	67	60	63	58
Nb	5	5	6	6	5	6	5
Ce	-17						
Nd	-1						

Appendix 3.1: Whole rock lithogeochemistry

Sample Group	10RAT TD 55 A3	10RAT TD 55 A4	10RAT TD 55 A5	10RAT TD 55 A6	10RAT TD 56 A1	10RAT TD 57 A1
Unit	Section A	Section A	Section A	Section A	Section A	Section A
Strat level (m above Kj/Nk contact)	V0	V0	V0	V0	V0	V0
-	-	-	-	-	-	-
<i>Major elements (wt%)</i>						
Al ₂ O ₃	14.89	14.95	14.68	15.24	15.36	15.17
CaO	12.61	12.11	7.32	7.51	9.32	11.50
Fe ₂ O ₃ *	12.01	11.28	11.53	11.89	11.85	11.52
K ₂ O	0.25	0.58	6.50	2.07	0.78	0.86
Mg#						
MgO	8.51	8.05	8.25	8.30	10.87	9.25
MnO	0.19	0.16	0.23	0.18	0.14	0.15
Na ₂ O	1.42	1.60	0.83	3.34	1.53	1.36
P ₂ O ₅	0.06	0.09	0.06	0.07	0.07	0.07
SiO ₂	48.86	49.84	49.28	50.21	48.68	48.88
S						
TiO ₂	1.03	1.18	1.02	1.01	1.08	1.01
Total	100.77	100.20	100.35	100.40	100.48	101.25
LOI	4.13	4.22	4.27	3.79	6.00	5.01
<i>Trace elements (ppm)</i>						
As						
Ba						
Cd						
Co						
Cr	406	314	433	400	345	394
Cu	82	97	209	38	137	125
Mo						
Ni	127	115	139	146	114	150
Sc	42	43	42	41	44	43
Sr						
V	300	311	297	295	313	309
Zn						
Ga						
La						
Pb						
Rb						
Sr						
Th						
U						
Y	18	24	18	17	20	16
Zr	57	79	58	56	58	53
Nb	5	7	5	5	5	5
Ce						
Nd						

Appendix 3.2: University of Ottawa X-Ray Laboratories XRF precisions values

Major elements (wt%)	Precision*
SiO ₂	0.5
TiO ₂	1.9
Al ₂ O ₃	1.2
Fe ₂ O ₃ *	1.6
MnO	3.4
MgO	1.7
CaO	1.9
Na ₂ O	2.7
K ₂ O	6.5
P ₂ O ₅	5
LOI	5
Trace elements (ppm)	
V	4
Cr	6.4
Co	16
Ni	16.7
Zn	3.1
Rb	3.5
Sr	2.2
Y	6.3
Zr	3.5
Nb	11.5
Ba	7.5

* Precision is the average % difference between each duplicate and the mean of the all duplicate runs.