LARGE FELSIC FLOWS IN THE KEWEENAWAN NORTH SHORE VOLCANIC GROUP IN COOK COUNTY, MINNESOTA

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Abstract

The Devil Track and Kimball Creek felsite sequences are thick and extensive volcanic units in the Keweenawan North Shore Volcanic Group in Cook County, Minnesota. The two units are separated by about 210 m of basalt flows and have a combined total thickness of 625 m, or about 11% of the thickness in the northeast limb of the North Shore Volcanic Group. The major goal of the study was to determine the origin of the units: whether they were lava flows, ash flows or rheoignimbrites.

The Kimball Creek felsite sequence has been divided into 4 units on the basis of lithology, chemistry and field evidence. The lowest unit in the Kimball Creek is a porphyritic quartz latite 40 m thick with an extent of at least 7.5 km indicating a very mobile flow. The rock has sparse lineated vesicles, some flow bands and very few visible flattened pumice fragments. The basal quartz latite is tentatively interpreted to be a rheoignimbrite.

The next two subunits up-section are icelandites, the lower one 40 m thick, the upper one 200 m thick. The iclandite units contain plagioclase phenocrysts in holocrystalline groundmasses, vesicles increasing in abundance upward and

highly vesicular tops. Both units lack primary devitrification features and pyroclastic textures. They are interpreted as lava flows.

The highest subunit in the Kimball Creek felsite sequence is a 350-m thick, porphyritic rhyolite that extends inland at least 32 km; it has dimensions more typical of ash flows than of felsic lava flows. Most of the unit is massive and homogeneous with the fine-grained groundmass made up primarily of tabular quartz crystals and subhedral alkali feldspar. Rock near the top and bottom of the unit has flow structures such as lineations and folded bands. The highest known exposure, about 40 m below the present top, contains some fiamme. This unit is interpreted as a rheoignimbrite.

The Devil Track felsite sequence has been divided into a lower porphyritic unit and an upper aphyric unit. The lower unit, the Maple Hill rhyolite, is 110 m thick and extends at least 7 km inland from Lake Superior. It has abundant flow structures and highly vesicular rock near the top. This unit is interpreted to have been an extensive rhyolite lava flow.

The upper Devil Track unit is a remarkably homogeneous, 200-m thick aphyric rhyolite that extends inland from Lake

Superior at least 42 km. It is made up predominantly of fine-grained tabular quartz (tridymite paramorphs) and subhedral alkali feldspar similar to the Kimball Creek rhyolite. It has lineations and bands indicating flowage. The Devil Track is interpreted to be a rheoignimbrite on the basis of its very large extent, low aspect ratio and flow structures, although no pyroclastic textures have been found.

Both the Kimball Creek and Devil Track rhyolites are coarser-grained in the middle compared to the upper and lower parts as a result of the slower cooling in the centers of the units. They are each interpreted to have been deposited as single cooling units at unusually high temperatures. The high temperatures and resulting low viscosity of the glass allowed essentially complete collapse of the pyroclastic flows, homogenization of the glass, flowage, and destruction of pyroclasts. High temperatures also facilitated crystallization which further obliterated pyroclastic textures.

The Devil Track and Kimball Creek felsite sequences may be part of a magmatic suite that formed by fractional crystallization of a parent magma represented by the icelandite lava flows. Maple Hill magma may have been heated by basaltic magma causing superheating and melting of crystals to produce the aphric Devil Track.

Acknowledgements

The author owes thanks to the many people who have helped during the work on this project. J.C. Green suggested the problem, served as the principal advisor and was very helpful in all aspects of this study. The help of Drs. Ronald Morton and Donald Christian as committee members also is greatly appreciated. Funding was provided by the Minerals Division of the Minnesota Department of Natural Resources through its Lithogeochemistry project. Appreciation is also expressed to the Department of Geology at UMD for funding a trip to a professional meeting for the presentation of this research, and for help from all the professors who have contributed to my education. Thanks are also given to my fellow graduate students for their useful discussions and support. I owe special thanks to my mother, Beth Fitz, for her continual moral support. This thesis is dedicated to the memory of my father, Robert L. Fitz.

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CHAPTER I: INTRODUCTION

Location

The Devil Track and Kimball Creek felsites are thick and extensive volcanic sequences that underlie portions of eight townships in south-central Cook County, in northeasternmost Minnesota (Figure 1). The two units crop out near the shore of Lake Superior east-northeast of Grand Marais in T.61 N., Rs.1 and 2 E. They trend westward to the area of Devil Track Lake and further west to the Cascade River in T.62 N., R.2 W., a distance of about 26 km. Outcrops of the Kimball Creek felsite have not been found west of the Cascade River where glacial cover is extensive. The Devil Track rhyolite however, has been found cropping out as far west as SE. 1/4, sec. 34, T.61 N., R.3 W., 42 km along strike from the shore of Lake Superior and probably extends even further west. The units underlie areas represented on the following U.S.G.S. 7.5 minute quadrangle maps from east to west: Marr Island, Kadunce Creek, Grand Marais, Devil Track Lake, Mark Lake, Tait Lake and Lutsen.

Purpose

The purpose of this study was to investigate these two units in greater detail because no in-depth field, stratigraphic, petrographic or chemical reports have

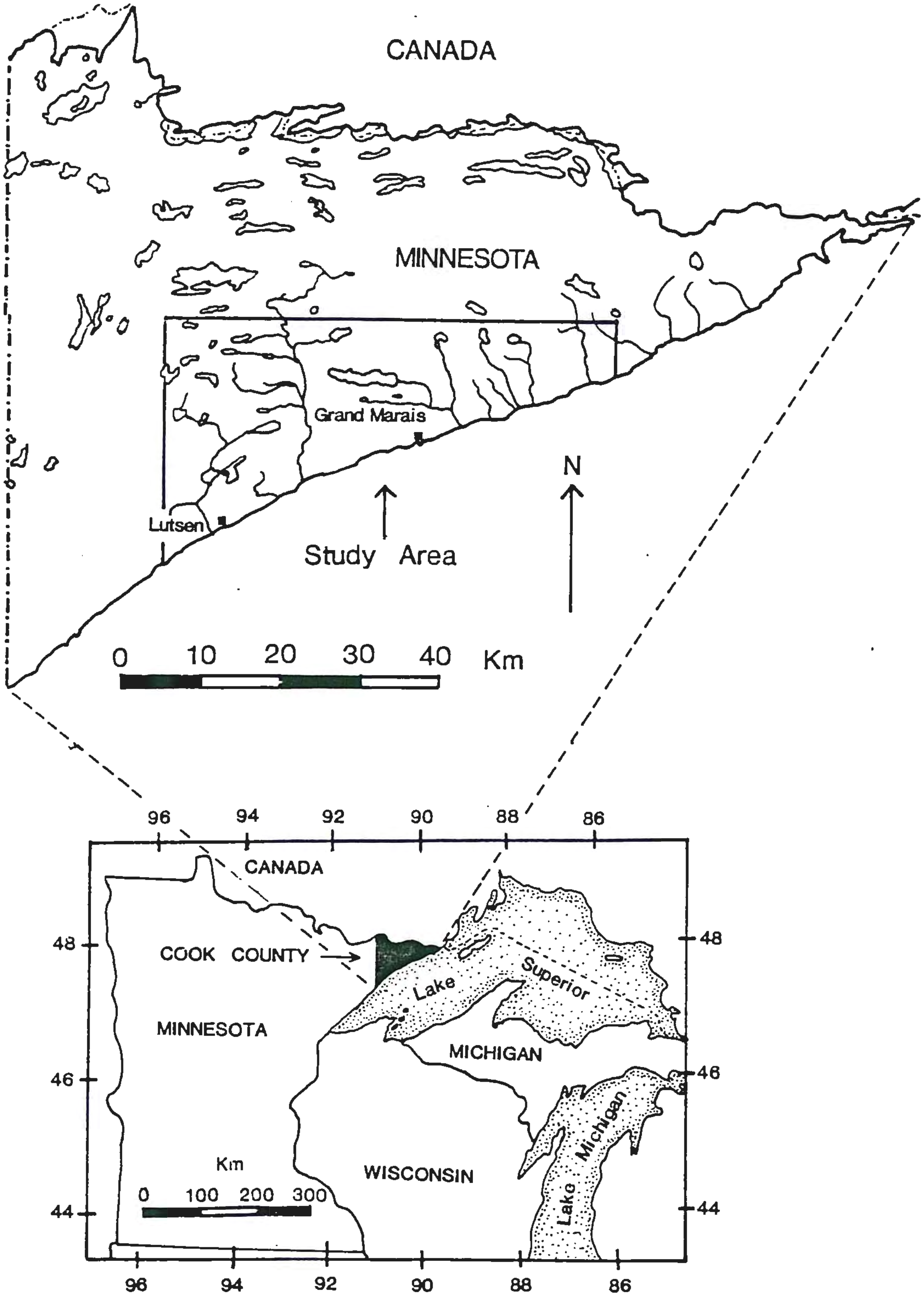


Figure 1. Location of felsites studied.

previously been made of these remarkably large volcanic units. This work was aimed at determining their origin, which is problematic due to the poor exposure in the area and scarcity of original textures. Their great extent and lack of vesicles and flow breccias suggest a pyroclastic origin, yet structures suggestive of flow are present that could indicate an origin by lava extrusion.

Method of study

During several weeks of field work in 1984 and 1985, 160 rock samples were collected and 112 thin sections were studied, some provided by J.C. Green from his previous work. The units were mapped at a scale of 1:24,000 using U.S.G.S. 7.5-minute quadrangle topographic maps as a base. The geologic map was then reduced to 1 inch to 1 mile (1:63,000) for the final map which accompanies this volume (Plate 1). Rocks have been classified according to the nomenclature outlined by Williams, Turner and Gilbert (1982). New chemical analyses were made on 5 samples as part of J.C. Green's 1985 Lithogeochemistry project. Seven pre-existing analyses were provided by J.C. Green (Green, 1972b; L. Haskin and J.C. Green, pers. comm.). Computer programs written by M. Carr (IGPET) and Hardrock Software (EZ-norm) were used to analyze the geochemical data. Petrographic studies included estimation of the percent of phenocrysts and measurements of grain sizes to document variations within units.

Previous Work

The Keweenawan rocks of the North Shore of Lake Superior have been of interest since the late 19th century, mostly as potential hosts for copper, and there have been contributions to the understanding of the Keweenawan by many workers. The findings of the earliest workers are summarized by Elfman (1898).

The first detailed report on the geology of the shore of Lake Superior in Minnesota was by N.H. Winchell (1900). His report, "Minnesota Geological and Natural History Survey" was the result of more than 15 years of work on the first systematic geological survey of the state. Although little investigation was made inland from the shore, most of the Keweenawan flows and intrusive rocks were studied in the field and many in the laboratory as well. Winchell made petrographic studies of the Kimball Creek and Devil Track units and the first chemical analysis of the rhyolite of the Devil Track River.

Inland Cook County was first mapped between 1913 and 1948 by F.F.Grout of the Minnesota Geological Survey and his many assistants, working arduously to map large remote wilderness areas. Published in 1959 by Grout, Sharp and Schwartz, "The Geology of Cook County, Minnesota" named the Devil Track felsite and briefly described both the Devil Track and Kimball Creek units.

The next work done on the felsites was by R. Foster (1962), who mapped the rocks along the Cascade River. Foster mapped and described the felsic units but made no correlations with rocks away from the Cascade River. He also noted the pyroclastic textures of the rocks stratigraphically above the Kimball Creek felsite and named the unit the Cascade River ash-flow tuff.

J.C. Green has been studying the Keweenawan rocks along the shore and in inland Cook County since the early 1960's. His comprehensive chapter on the North Shore Volcanic Group in "The Geology of Minnesota; A Centennial Volume" includes the most detailed report on the Devil Track and Kimball Creek felsites prior to this study (Green, 1972b), and in a more recent paper (Green, 1982) he suggested they were probably pyroclastic flows. Green's mapping, laboratory studies and guidance laid the foundation for this study. Prelimimary accounts of this current study are found in Fitz and Green (1985, 1986).

Geography

Cook County occupies the extreme northeast portion of Minnesota, commonly referred to as "The Arrowhead" because of its triangular shape and Native American heritage. The area is fairly remote, with the majority of the land held by the Federal Government as part of the Superior National Forest. Preglacial erosion left rugged topography consisting of parallel ridges and valleys. Many of the valleys are now occupied by long narrow lakes. The scenic lakes and dense forests dominated by aspens and conifers gives the region its major industries, tourism and forestry. The cool climate makes outdoor activities comfortable in the summer and challenging at other times of the year. However, the wealth of water and dense forests makes a superb breeding ground for mosquitoes and blackflies which can detract significantly from one's comfort in the summer months. Grand Marais, located 177 km northeast of Duluth, is the closest town to the study area and frequently served as a resupply point for field excursions. Access to the area is by U.S. Highway 61, by the Gunflint Trail (Cook Co. Rt. 12) and by the numerous gravel roads in the region maintained by the U.S. Forest Service.

Regional Geology

The Devil Track and Kimball Creek felsites are part of the Keweenawan North Shore Volcanic Group (Goldich and others, 1961; Green, 1982) (figure 2). Erupted 1100 m.y. ago (Van Schmus and others, 1982), this sequence of approximately 6400 m of lava flows, interflow sedimentary rocks and some tuffs along with the great volume of Keweenawan intrusive rocks represents part of an extensive failed rift system that developed during the Middle Proterozoic (Van Schmus and Hinze, 1985). The North Shore Volcanic Group resembles plateau lavas both physically and chemically, especially those of Iceland (Green, 1972b, 1977, 1982, 1983, in press). The general structure of the North Shore Volcanic Group resembles a large shallow basin tilted slightly southeast with the youngest flows in the middle near Tofte, Minnesota. The sequence northeast of Tofte, of which the Devil Track and Kimball Creek make up about 11% of the thickness, is the northeast limb (Figure 3). The dominant lithology of the sequence is olivine tholeiite basalt which comprises 57 % of the stratigraphic column in the northeast limb. Felsic volcanic rocks make up 25%, intermediate rocks 18% and interflow sediments a minor portion of the thickness in the northeast limb (Green, 1972b).

Felsic volcanic rocks, many believed to be lavas, are scattered throughout the sequence. Thick felsic flows occur at Palisade Head near Silver Bay and Illgen City, and in the Brule River area near Hovland. The Brule River rhyolite may

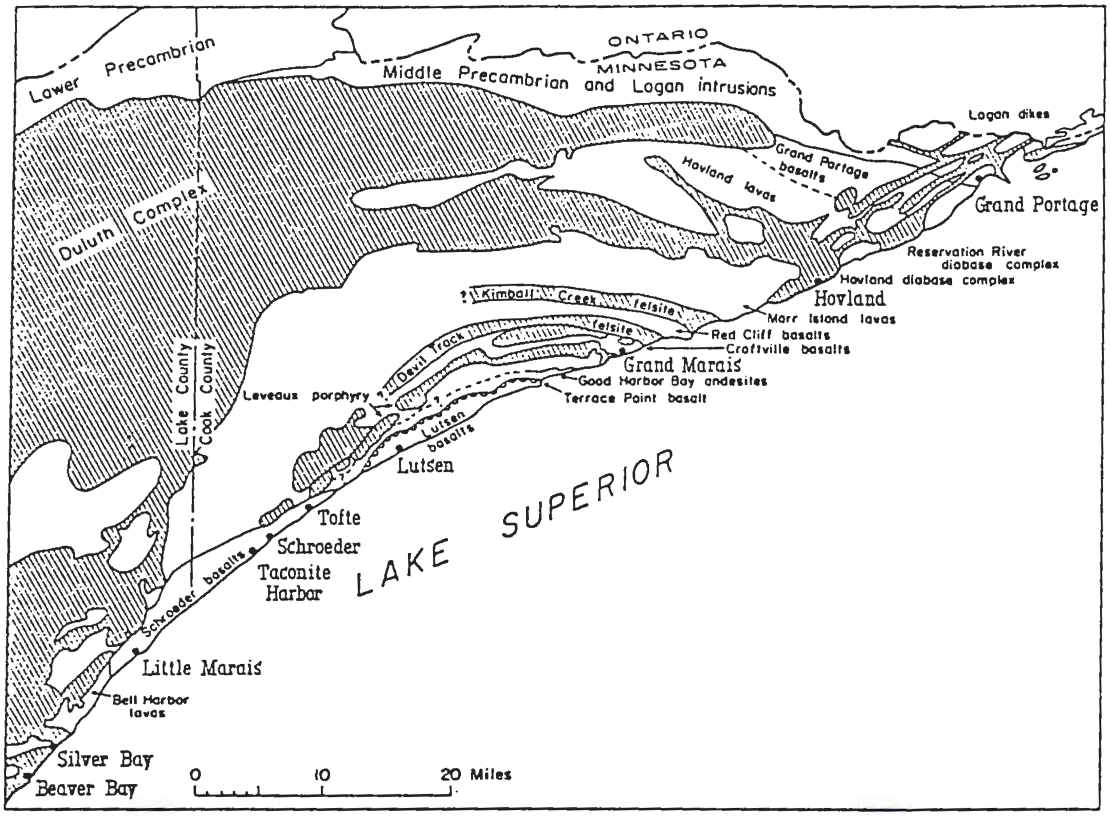


Figure 2. Generalized geologic map of the Northeastern limb of the North Shore Volcanic Group showing the Devil Track and Kimball Creek felsites. From Green, 1972b, Figure V-6.

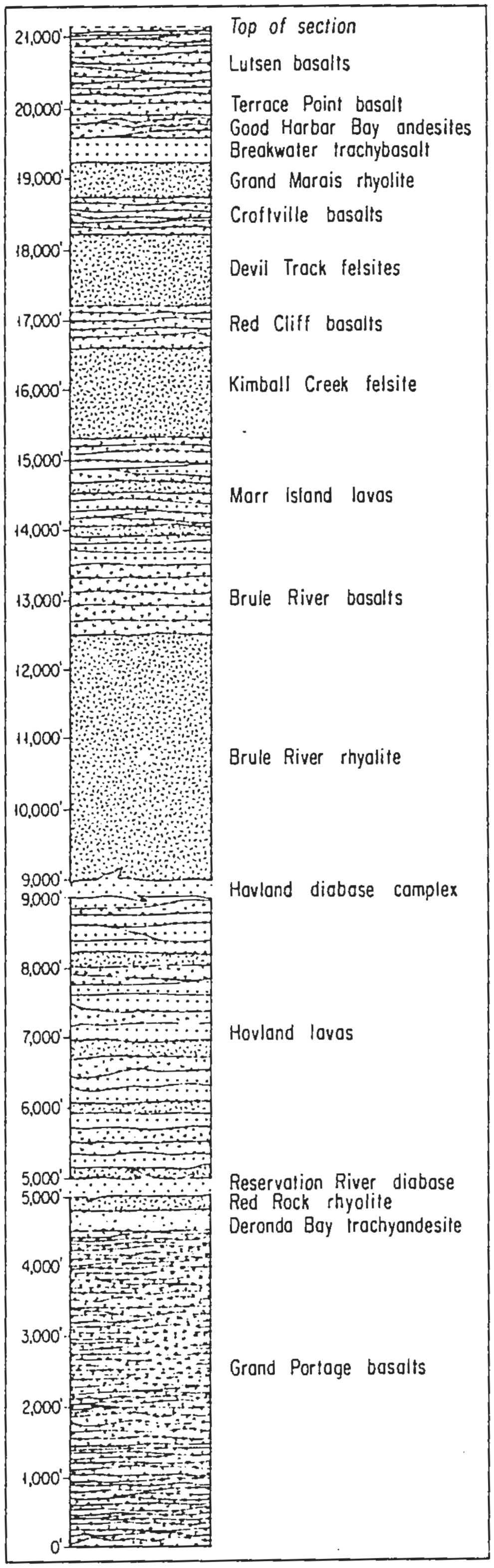


Figure 3. Stratigraphic column of the Norhteast limb of the North Shore Volcanic Group. From Green, 1972b, Figure v-16.

owe its great apparent thickness, nearly 1000 m, to lava ponding, or it could be a dome (Green, 1972b). The great thickness and extent of the Devil Track and Kimball Creek felsites make them the two most voluminous felsic units in the sequence. The only tuffs previously known in the North Shore Volcanic Group are the Cascade River ash flow tuff and an ignimbrite in Duluth (Foster, 1962; Motamedi, 1984).

The North Shore Volcanic Group has been divided into two portions on the basis of magnetic polarity (Green and Books, 1972; Halls and Pesonen, 1982; Morey and Green, 1982). The reversed polarity lower Keweenawan is represented in the North Shore Volcanic Group by the lowest flows in the sequence which are exposed northeast of Hovland and southwest of Duluth. The remainder of the volcanic rocks, including the Devil Track and Kimball Creek felsite sequences, were erupted during the middle Keweenawan, a time of normal magnetic polarity.

Although definite volcanic centers have not been located, it has been shown that deposition during the middle Keweenawan took place in 2 major basins northeast and southwest of an area near what is now Beaver Bay (Jirsa, 1984). Some volcanic units in the northeastern basin, including the Devil Track rhyolite, can be traced across half the basin. During and after eruption of the North Shore Volcanic Group, the bulk of the Duluth Complex, the Beaver Bay Complex and other small intrusions were emplaced within and along the base of the volcanics (Green, 1972a).

Quaternary Geology

Cook County must have been glaciated several times during the Pleistocene, but evidence remains only for the last few advances and retreats during the Wisconsinan. Portions of the field area within 8-15 km of Lake Superior are covered by 2-10 m of till deposited by at least 3 advances of the Superior ice lobe (Hobbs and Goebel, 1982). The older tills are stony with rocks derived from the Superior basin and have a brown, sandy matrix. The younger tills are sandy to clayey as a result of the reworking of proglacial lake sediments. Further inland, the field area is covered by a thin veneer of till deposited by the Rainy ice lobe. For a more complete account of the glacial history see Sharp, 1953; Wright, 1972; and Wright and others, 1969.

Some significant glacial landforms within the study area are the 30-km-long Devil Track esker trending east-west in the area north of Devil Track Lake and the prominent abandoned beach cliff and terrace developed in the felsites northeast of Grand Marais along the north side of U.S. Highway 61. The cliff and terrace mark the shore of Glacial Lake Nipissing which existed in the Superior basin 3500 years ago with a lake level just above the present level (Wright and others, 1969; Farrand and Drexler, 1985).

Canyons 10 to 100 m deep with vertical walls cut in the felsites by several rivers northeast of Grand Marais have geometries indicating they have not undergone glacial erosion. The Poplar river, southwest of the study area in T.60 N., R.3 W., flows through a deep rock gorge which has red clay exposed on the east wall up to 80 m above the river (Sharp, 1953). Sharp suggested that a preglacial rock gorge was filled with clay till to a depth of 70 or more meters. This also could have been true for the canyons cut in the felsites northeast of Grand Marais and the clay helped protect the canyons from glacial erosion, thus maintaining their deep narrow shape. Another possible explanation is that the canyons have been carved since retreat of the glaciers.

CHAPTER II: GENERAL GEOLOGY

Structure

The Devil Track and Kimball Creek felsites strike N.25° W. near the shore of Lake Superior changing to east-west in the middle of the field area near Devil Track Lake and the Cascade River, and about N.50° E. farther to the west, to form an arcuate outcrop pattern (Figure 4). The dip of lava flows in the region is generally about 10° south but few contacts are exposed to provide measurements. Strike is known only from the outcrop pattern and dip must be extrapolated from exposures up and down section where it can be measured. The only exposed contact in the area, located at the base of the Kimball Creek felsite in the eastern part of the area, dips 12° south and Foster (1962) reports dips in the area of the Cascade River to be 15° south. A dip of 12° was used to calculate the thickness of the units in the eastern part of the map area.

The Devil Track and Kimball Creek felsites are extensively jointed by both horizontal and vertical joints (Figure 5). The horizontal joints are generally parallel, spaced 2-5 cm apart, and have variable strikes and dips rarely exceeding 15°. Although locally variable by 10-20° over distances of 10 m or less, the attitude of the subhorizontal joints generally parallels that of local flows and has been used as an indication of the attitude of the felsite units. The vertical joints are spaced 0.25-2 m apart in variable orientations.

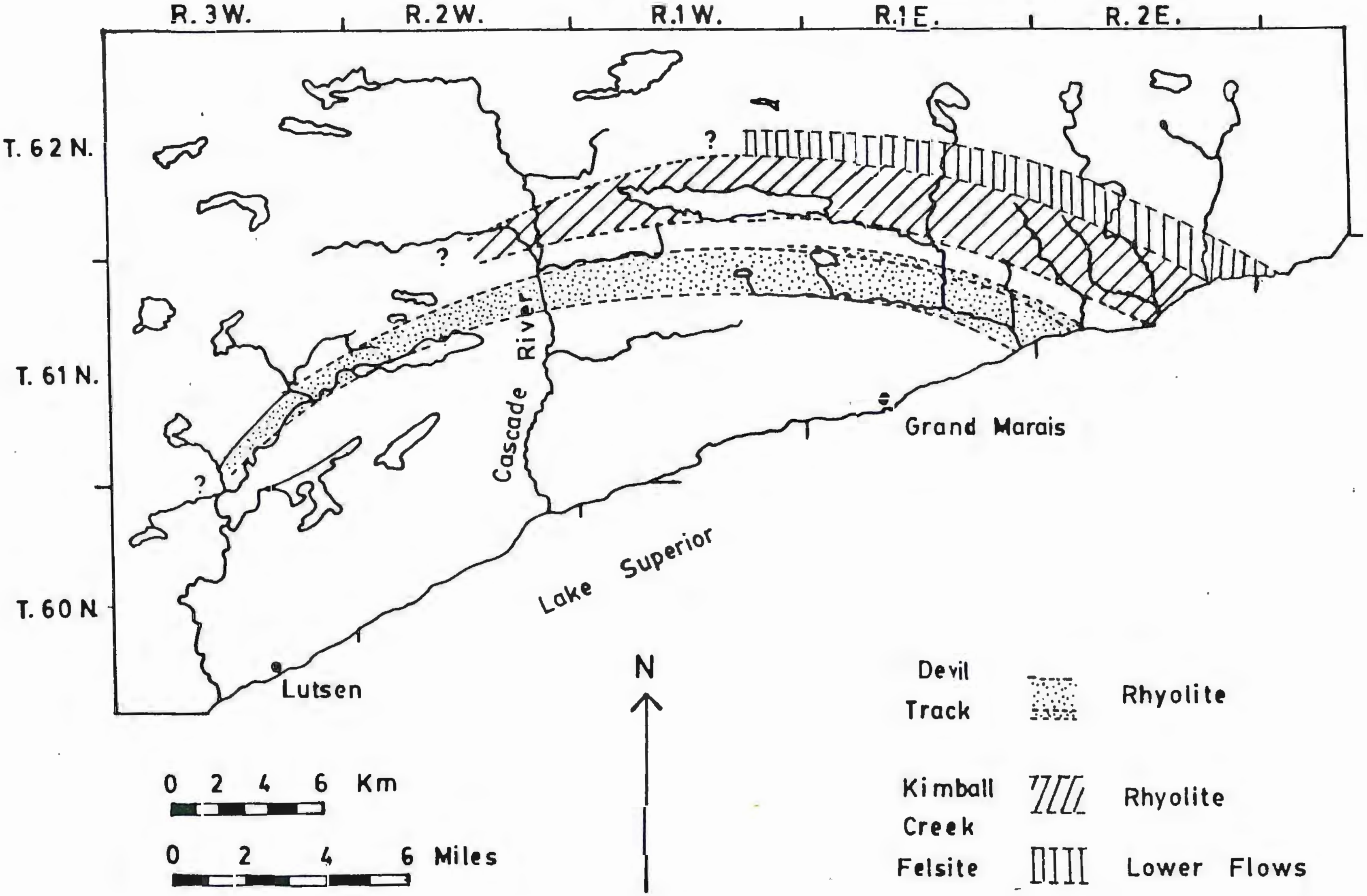


Figure 4. Generalized geologic map of the felsites.

Figure 5. Typical sheeting joints in the Kimball Creek rhyolite.

No columnar jointing has been found, although "pseudo-columns" formed by intersecting joint sets are present locally.

Exposure

As a result of the abundant close joints the rock breaks into platy fragments and is easily eroded. The rivers northeast of Grand Marais in T.61 N., Rs.1 and 2 E. and T.62 N., R.2 E. have eroded spectacular deep and narrow canyons into the felsites. The Devil Track River and Kimball Creek, for which the units are named, flow through such gorges. Kadunce Creek has also cut a narrow canyon through the Kimball Creek felsite. The wave action of Lake Superior has exploited the nonresistant felsite resulting in the recessed shorelines east and west of Red Cliff. The erosion of the felsite characteristically leaves large talus slopes and beaches of flat red shingle.

The nonresistant nature of the felsite units combined with a moderately thick cover of glacial drift causes the units to be poorly exposed away from streams and the lake shore. Most of the data were collected in the eastern part of the field area, east of Grand Marias where the units are exposed along the shore of Lake Superior and in river valleys. However, exposures that have not undergone recent erosion are generally deeply weathered and lichen-covered rendering them less useful than the river and shoreline exposures. Nevertheless, every outcrop, no matter how strongly weathered, is important to tracing the extent of the units. This is especially the case west of the Cascade River where dissection by rivers has been less thorough and exposure is poor. The Cascade River provides the only good exposures in the western part of the map area and is particularly valuable since it flows perpendicular to strike and exposes many units.

Correlations

Correlation of outcrops separated by several kilometers of concealed rock was done by extrapolating outcrop pattern, by tracing trends in topographic features, and by lithology and chemistry. Characteristics such as the abundance and type of phenocrysts, grain size, textures, banding and vesicularity were useful. After consideration of all available data, assigning an isolated outcrop to a unit can be done with some certainty, but the stratigraphic position of an isolated outcrop within a unit often cannot be determined.

Nearly all contacts are concealed. Topographic features were often an aid to inferring concealed contact locations. Ridges and valleys trend parallel to the outcrop pattern of the volcanic units in the area and must reflect resistant and nonresistant horizons in the stratigraphy. This is especially useful for the Devil Track rhyolite which forms a ridge extending fairly continuously from southeast of Devil Track Lake westward to Caribou Lake. The ridge generally has lakes or streams in the parallel valleys on either side which are inferred to lie near the less resistant contacts. Exposure along the ridge is limited, but there is enough to assure the ridge is held up by rhyolite. The trend of the Kimball Creek felsite is not as well defined by geographic features but there are some small ridges trending parallel to the inferred strike in T.62 N., R.1 E. Mississippi Creek and the small ridges parallel to it in the area west of the Cascade River may reflect trends in the Kimball Creek felsite, but no outcrop was found in the area.

In many areas where bedrock outcrops are rare, angular chips of red felsite can be found in soils. The great quantity and angularity of the fragments in places imply that felsite bedrock is not far below.

Aeromagnetic Signature

Aeromagnetic maps produced by the Minnesota Geological Survey were studied to help trace the units across areas of poor exposure (Chandler, 1980). The usefulness of these maps is minimal as some linear magnetic trends coincide with the structure of the units whereas in other areas there seems to be little connection. For example, a linear magnetic high trends parallel to the ridge held up by the Devil Track rhyolite for most of the length of the ridge. However, at sec. 34, T.62 N., R.1 E., the linear magnetic high cuts across an area underlain by basalt of the Red Cliff basalts, and to the east trends parallel to the inferred trend of the Kimball

Creek felsite. In secs. 3,4,5, T.61 N., R.2 E., a magnetic high follows near the base of a rhyolite subunit of the Kimball Creek felsite for approximately 5 km. It is curious that felsic rocks at the surface produce magnetic highs in some areas whereas one would expect the basaltic rocks on either side to have relatively higher magnetic intensities. It seems likely that areas underlain by tilted volcanic strata would show linear magnetic trends but many such areas have circular magnetic highs and lows. These discrepancies may represent local areas oxidized by hydrothermal systems.

The aeromagnetic maps were useful in exploring the area southwest of Pike Lake in secs. 9,16,17, T.60 N., R.2 E., as a guide to possibly finding the western-most outcrops of the Devil Track rhyolite. Neither the ridge held up by the Devil Track nor the linear magnetic high extend southwest of Pike Lake. However, there are a series of circular magnetic lows that form a crude line extending southwest from the westernmost known outcrop of the Devil Track at S.E. 1/4, sec. 34, T.61 N., R.3 W. It is possible these lows result from the magnetic contrast of the Devil Track rhyolite with local mafic flows and intrusions since characteristic flat rhyolite chips of Devil Track lithology are plentiful in soils of the area.

Mapping Problems

There are several significant problems created by the poor exposure of the felsites. The poor exposure in the western part of the field area precludes determining with confidence the extent of the felsites on land. How far the units extend under Lake Superior also is unknown, so the extent and volume of neither the original or the preserved deposits can be determined accurately. The thickness of the units is accurately known only close to where the units intersect the shore of Lake Superior, and in areas where exposure is poor, the proximity of enclosing stratigraphic units may be the only indication of thickness. Because few contacts are exposed, the nature and attitude of the contacts and the nature of the rocks near the contacts are unknown. The location and type of eruptive centers is a problem not unique to this investigation as no vents have been located for any Keweenawan extrusive rocks in Minnesota (Green, 1972b).

General Stratigraphy

The general stratigraphy in the eastern part of the field area near Lake Superior will be outlined here (Figures 3, 6) and described in greater detail in the following chapter. The Kimball Creek felsite sequence overlies the amygdaloidal flow top of the youngest basalt of the Marr Island lavas. The Marr Island lavas are composed of tholeiitic basalt, intermediate and felsic flows (Green, 1972b). The 625-m-thick Kimball

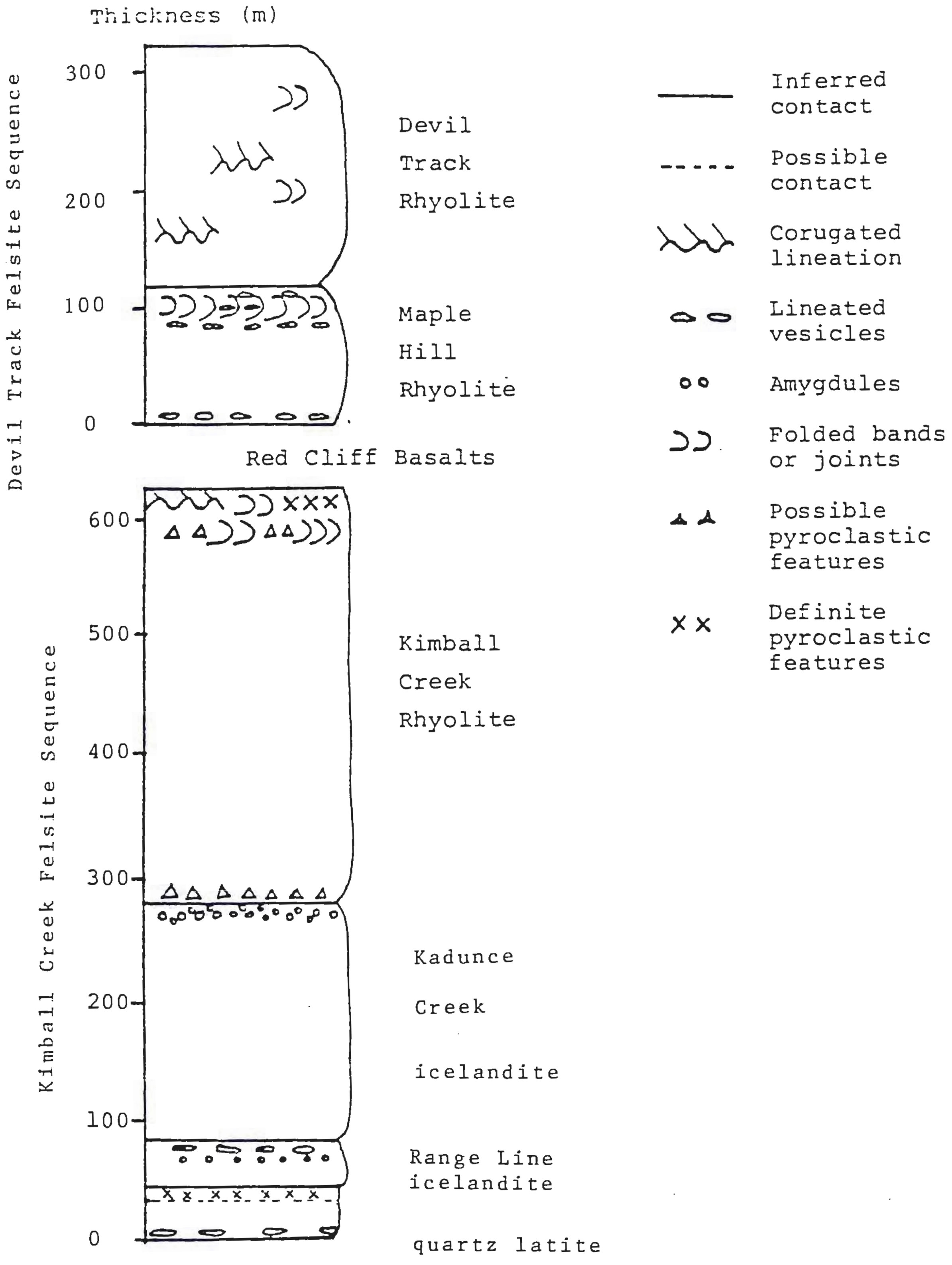


Figure 6. Stratigraphic column of the Devil Track and Kimball Creek felsite sequences.

Creek felsite sequence has been divided into four units on the basis of field evidence, chemistry and lithology; these vary in composition from rhyolite to icelandite. The Kimball Creek felsite sequence is overlain by about 210 m of basalt flows, typically ophitic, of the Red Cliff basalts. The Red Cliff basalts are overlain by the Devil Track felsite sequence, which has been divided into two units. The lower 110-m-thick unit is porphyritic rhyolite named the Maple Hill rhyolite; the upper is a 200-m-thick, homogeneous, aphyric rhyolite, the Devil Track rhyolite proper. The Devil Track is overlain by the Croftville basalts and locally by sandstone. The bedrock is overlain unconformably by Pleistocene glacial drift.

Alteration

The Keweenawan extrusive rocks in this area have undergone burial metamorphism in the zeolite facies (Green, 1972b). None of the rocks examined has been completely changed to secondary minerals but the alteration is locally intense enough to make mineral identification difficult even in thin section. Mafic silicate minerals have been the most-strongly affected, only rarely escaping total destruction. Relict clinopyroxene is occasionally seen associated with the products of alteration. Opaque rims on grains and opaque outlines of pseudomorphs of mafic silicates are common. For example, subhedral, six-sided opaque outlines are believed to have been fayalitic olivine grains but no fresh olivine has been found in the volcanic rocks. Iron-rich olivine is common in associated intermediate and felsic intrusive rocks (J.C. Green, pers. communication).

Small, anhedral opaque scraps are very common in the groundmass of all felsic rocks examined. The scraps could be the remnants of primary opaque minerals, mostly magnetite, or the alteration product of mafic silcate minerals in the groundmass. All opaque scraps and subhedral blocky grains interpreted as primary magnetite crystals have undergone some oxidation resulting in hematite coatings on opaque grains and rusty-brown staining of the feldspar in the surrounding groundmass. The brown staining of both plagioclase and alkali feldspar is very common in groundmass grains and in some cases in the phenocrysts as well. The hematite imparts the characteristic rusty-red to pink color to the rocks. Only local areas within two subunits of the Kimball Creek felsite have escaped penetrative brown staining of feldspars and in those areas the rock is light gray. In the transition zones between red and gray felsite, the rock is commonly gray with red mottling. A good example occurs in Cliff Creek in secs. 9,10, T.61 N., R.2 E., near the middle of the top unit of Kimball Creek felsite where there are several zones of both red and gray rock with mottled transitional zones between. The red staining does not show any relation to stratigraphy or to other signs of alteration such as dusty kaolinization, alteration of mafic silicate minerals or alteration of feldspar phenocrysts.

The most common evidence of alteration besides the red staining, is dusty kaolinization which obscures grain boundaries, particularly between grains of the same mineral such as the anhedral alkali feldspar grains abundant in the groundmass of the felsites. This is also true for plagioclase laths in the groundmass of intermediate rocks. The alkali feldspar phenocrysts have abundant rounded, bleb-like holes probably resulting from magmatic resorption (Cox and others, 1979; Noble, 1970). The resorbed texture, combined with later alteration of local areas has yielded uneven grain boundaries and common blebs of total alteration, giving the crystal a spongy appearance in thin section.

Quartz shows little alteration, but slightly dusty primary grains commonly can be distinguished from the clear secondary quartz overgrowths in amgdules.quartz overgrowths in amgdules.

CHAPTER III: UNIT DESCRIPTIONS

Kimball Creek Felsite Sequence

The 625 m thick Kimball Creek felsite is one of the thickest felsic sequences in the North Shore Volcanic Group. It has been divided into four units (Figure 6) which range in composition from rhyolite to icelandite and in thickness from 40 m to 350 m. The division into subunits has been done on the basis of lithology, chemistry and field evidence suggestive of contacts between flow units. All four units are exposed in the eastern part of the map area near Lake Superior but only two have been found west of R.1 W. Each of the four subunits is described in order going up-section. Chemical analyses are presented and discussed in Chapter V. A discussion and interpretation are given for each unit in Chapter VI.

Basal quartz latite

The lowest unit is a porphyritic quartz latite 40 m thick. The unit is exposed in road cuts on Highway 61 at NW 1/4, sec.6, T.61 N., R.3 E. and in Kadunce Creek in NW 1/4, sec. 35, T.61 N., R.2 E. where its basal contact with the underlying basalt flow of the Marr Island Lavas is exposed. There is another exposure of the unit 20 km to the west at SW 1/4, sec. 14, T.62 N., R.1 W. No chemical analysis is available for this unit. It has been called a quartz latite on the basis of the approximately equal amount of plagioclase and alkali feldspar phenocrysts and quartz making up greater than 10% of the rock.

Quartz phenocrysts and altered feldspar phenocrysts, together make up 2-5% of the rock. The quartz phenocrysts are equant, 1-2 mm across and subhedral with rounded and embayed margins. Plagioclase phenocrysts are equant to rectangular in cross section, about 1-2 mm across and stained rust-colored. The alkali feldspar phenocrysts are 1-2 mm across, have uneven, rounded margins and numerous resorption blebs, a dusty appearance in thin section and rusty-red staining.

Other less abundant phenocrysts are magnetite and possible pseudomorphs after mafic silicate minerals. Magnetite grains are abundant, ranging from anhedral scraps to subhedral equant grains and in size from microlites to phenocrysts 2.5 mm across. Much of the anhedral magnetite could be an alteration product but the subhedral, equant grains are probably primary. The possible mafic silicate phenocrysts are now opaque skeletal outlines of subhedral to anhedral prismatic crystals. They probably were fayalite and/or ferroaugite/hedenbergite.

The groundmass is dark brown, altered and very fine-grained. Dusty feldspar laths and opaque granules and scraps are dominant. The opaque scraps are so abundant the groundmass is densely speckled and dark in plane-polarized light. Variations in the abundance of the scraps results in lighter and darker patches and bands in the groundmass. Fluorite is found in trace amounts.

The westernmost outcrop of this subunit is at SW 1/4, sec.14, T.62 N., R.1 W. (samples DT-11, 27), 20 km west along strike from the best exposures in Kadunce Creek. The rock there is a banded, maroon, porphyritic quartz latite with abundant rock fragments. It has phenocrysts of quartz and kaolinitized feldspar in an altered dark brown groundmass with contorted and discontinuous banding. The banding locally bends around pumice blocks. The groundmass is dark brown with much hematite and is rich in opaque scraps similar to the opaques in the groundmass at Kadunce Creek. The only differences between the rock at Kadunce and that further west are that the western outcrop has a distinctly banded groundmass and some pumice.

In the lowest few meters of the unit, the rock is cut by numerous red, fine-grained, granular veins 2-25 mm across (samples MI-53, KC-87) and contains abundant xenoliths making up approximately 10% of the rock. The granophyre veins are randomly oriented, curving, and have sharp to unclear contacts. Some fragments of the felsite form inclusions in the veins. The origin of these veins is unknown.

Xenoliths near the base of the quartz latite vary in size (0.5-5 cm) and shape but most have rounded edges and sharp contacts. They are aphanitic, dark brown to black and made up of plagioclase microlites and abundant opaque scraps and some plates (0.1-0.5 mm), some of which show a crude radial arrangement. One xenolith observed in thin secton is a fragment 2 mm across of quartz and alkali feldspar in micrographic intergrowth.

At the exposed contact between the lowest unit of the Kimball Creek and the underlying amygdaloidal flow top of the youngest basalt flow of the Marr Island lavas, the base of the Kimball Creek is amygdaloidal, but not brecciated. The amygdules are present only in the lowest 1 m with massive rock above (samples KC-14, 87). Amygdules within 10 cm of the contact are lineated (Figure 7). Phenocrysts are more abundant near the base than higher in the unit, making up about 5% of the rock in the lowest few meters. Above the amygdaloidal and massive zones exposed in Kadunce Creek, the subunit has common subhorizontal sheet jointing. Banding, most of which is vertical, some contorted, is seen only on the most-weathered surfaces. Phenocrysts show a crude orientation parallel to the banding at the few locations where banding was observed. Amygdules are present near the top of the unit. The upper contact is not exposed. The contact at the base of the unit is the only exposed contact in the field area.

Figure 7. Lineated amygdules from the bottom 10 cm of the basal quartz latite subunit of the Kimball Creek felsite. Sample KC-87.

A thin section of vertically banded rock from near the bottom of the unit shows the dark discontinuous banding is made up of individual linear fragments (Figure 8). The fragments are foliated parallel to their length and bend around phenocrysts. They vary in size and curvature, make up approximately 30% of the rock, and give the rock an overall streaked appearance. Parallel to dark fragments are light-colored streaks in the groundmass, commonly grading into narrow, wavy quartz veins. These fragments are collapsed pumice lapilli.

In Kadunce Creek, approximately 100 m downstream from the stratigraphically highest definite outcrop of the quartz latite unit, is an isolated exposure of rock that is different texturally from all other rocks in the area (KC-60). It is light gray to pink, fine-grained and made mostly of irregularly-shaped brown and pink fragments containing small planar vesicles. Thin sectioning of this rock reveals brown, opaque, unwelded, devitrified glass shards (Figure 9). Areas between the shards are filled with fine-grained quartz. The rock is sparsely porphyritic with quartz and altered feldspar phenocrysts. Because only one outcrop was found the extent of this rock type is unknown. It is possible its extent is fairly large, but the rock is easily eroded so the unit may not be exposed elsewhere.

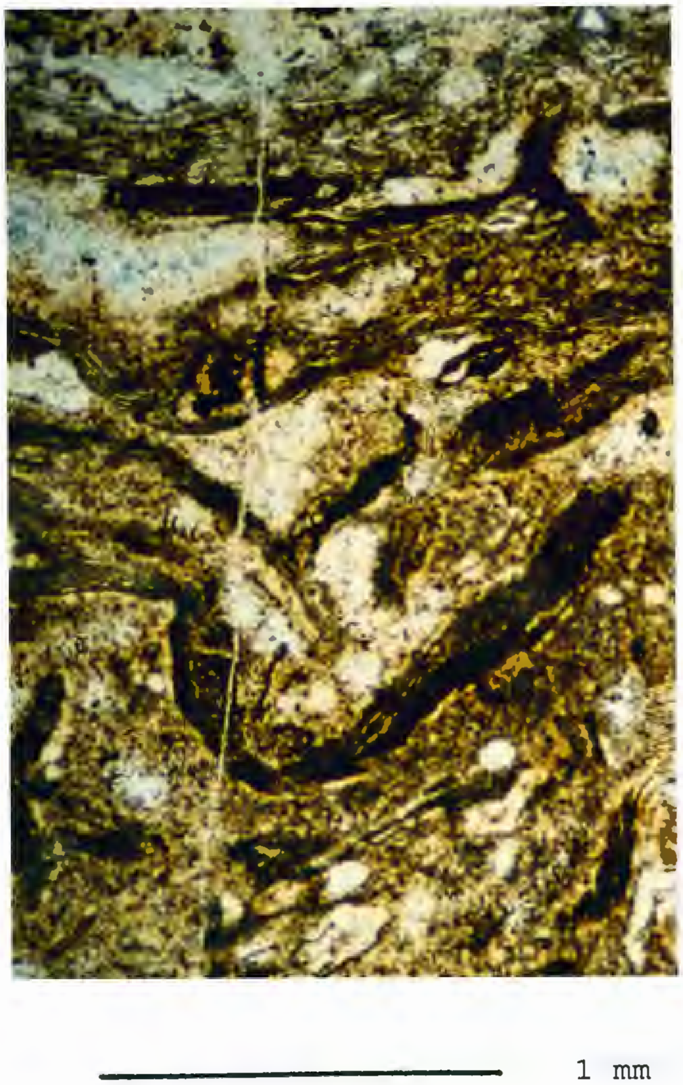


Figure 8. Photomicrograph of collapsed pumice in the basal quartz latite unit, of the Kimball Creek felsite. Plane polarized light, sample KC-58.

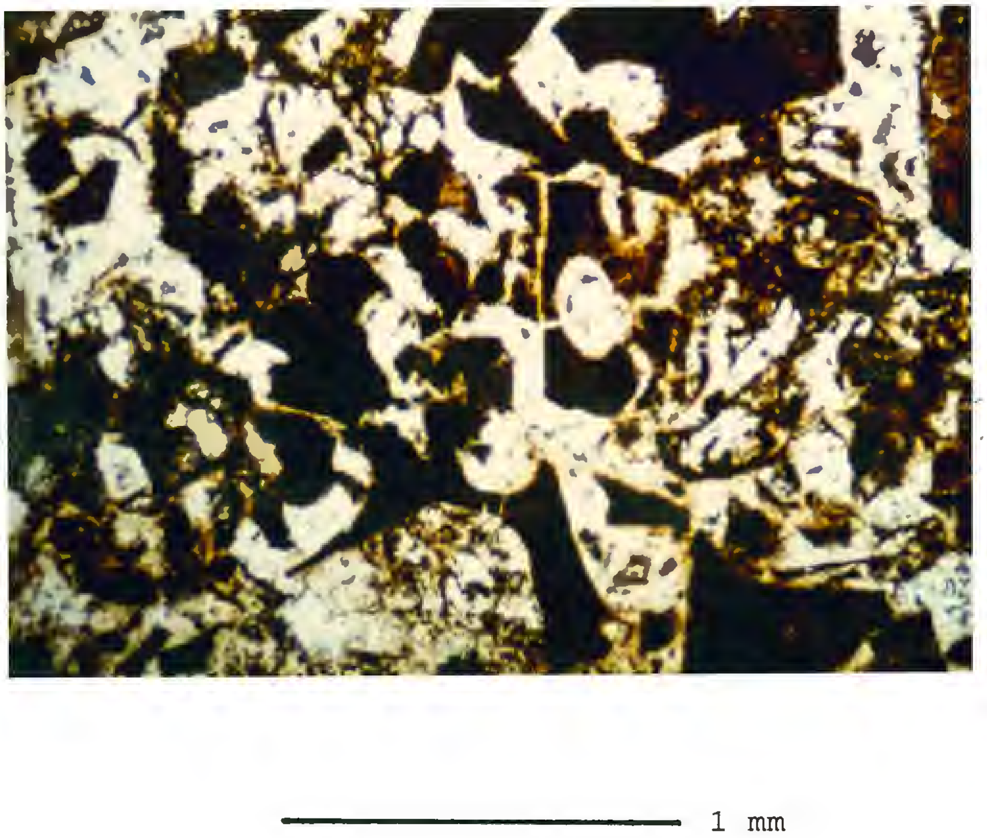


Figure 9. Photomicrograph of unwelded shards in an isolated outcrop stratigraphically above the basal quartz latite, Kimball Creek felsite. Plane polarized light, sample KC-60.

Range Line icelandite

The second oldest unit in the Kimball Creek felsite is a 40-m-thick porphyritic icelandite. There are good exposures of the unit on Highway 61 at Range Line 2 E., and the unit is hereby named the Range Line icelandite. It is also exposed in Kadunce Creek and further west in a road cut on Forest Service road 27 in SW 1/4, sec.14, T.62 N., R.1 W. It was not found in the nearly complete section exposed in the Cascade River, thus limiting its known extent to 23 km. Near the base the rock is massive, hard and relatively free of joints so it forms a resistant ledge in Kadunce Creek. Its actual base is not exposed. Higher in the subunit there are sheet joints and amygdules. Amygdules range from lineated, with long axes 1-3 cm, to round and baseball-sized (Figure 10). The stratigraphically highest exposure is very amygdaloidal with amygdules making up about 40% of the rock (sample KC-63). Amygdules in this unit commonly are filled with calcite or laumontite, much of which has been weathered out.

Mafic phenocrysts and a brown, fine-grained groundmass in contrast with the light-colored plagioclase phenocrysts in a locally glomeroporphyritic texture give the rock a distinctive appearance. Phenocrysts of plagioclase, magnetite, augite and pseudomorphs after mafic silicate minerals in a groundmass dominated by plagioclase laths give this rock a modal composition similar to icelandites described by

Figure 10. Elongate vesicles near the top of the Range Line icelandite unit of the Kimball Creek felsite. SE 1/4, sec. 35, T.62 N., R.2 E.

Carmichael (1964). Plagioclase phenocrysts, making up approximately 5% of the rock, are equant to lath-shaped subhedral crystals 1-2 mm across, which commonly occur in clusters. All that remains of the mafic silicate phenocrysts are hollow opaque rims, some of which have 8 sided subhedral shapes (pyroxene?). Opaque phenocrysts also occur as slender plates, probably ilmenite or perhaps they are replaced quenched-textured minerals. Some apatite phenocrysts 2-3 mm long are also present. The phenocrysts are set in an altered groundmass dominated by plagioclase laths in random orientation (Figure 11). Dusty alkali feldspar and minor amounts of anhedral quartz occur intersitially. Some quartz forms poikilitic areas. Magnetite is present as scraps of various sizes and as equant, subhedral crystals. The groundmass is brown due to abundant magnetite scraps and hematite staining.

Kadunce icelandite

Stratigraphically above the lower icelandite is another porphyritic icelandite unit 200 m thick. This subunit is exposed in secs. 1, and 2, T.61 N., R.2 E., along Highway 61 and in the spectacular gorge cut by Kadunce Creek, for which it is hereby named. The unit has abundant small platy joints throughout, causing the rock to form gorges where cut by rivers and to have few exposures elsewhere. Exposures of the unit have only been found east of Range 1 E. in the Kadunce Creek

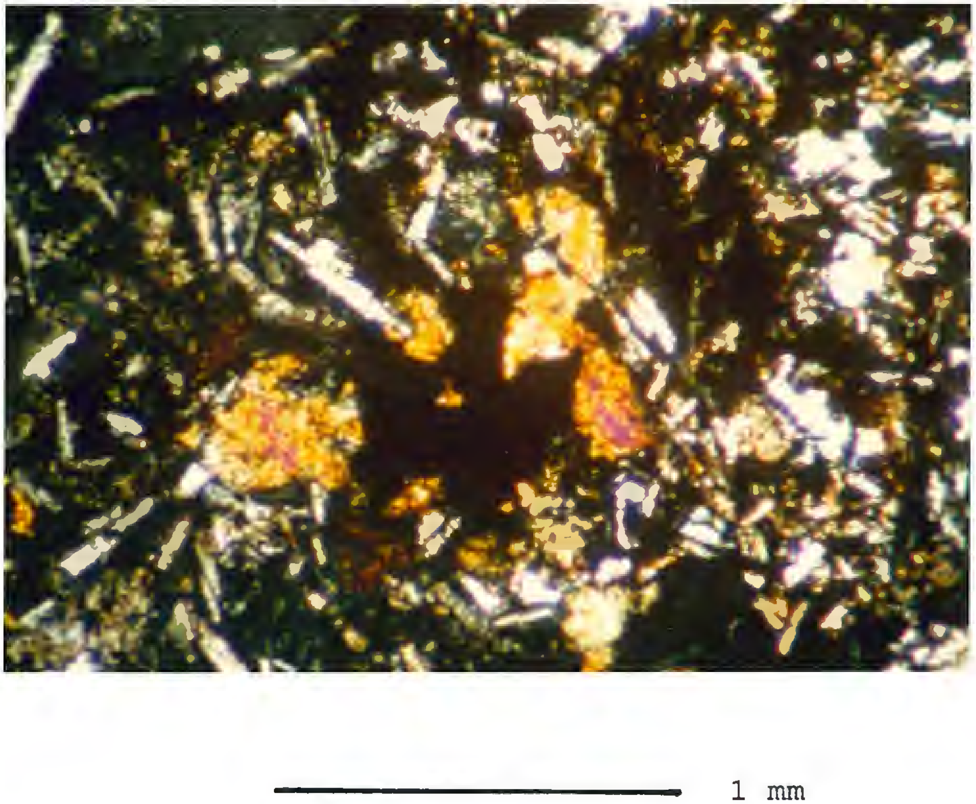


Figure 11. Clusters of mafic microphenocrysts, augite and magnetite, in the Range Line icelandite unit of the Kimball Creek felsite; crossed polars.

quadrangle and it is unknown how far the unit extends to the west under the concealing cover of glacial drift. The unit does not extend as far west as the Cascade River where the bedrock section is well exposed.

Plagioclase phenocrysts and augite and magnetite microphenocrysts are set in a fine-grained red or grey groundmass. Phenocrysts commonly occur in clusters. Nearly all clusters observed in thin section are composed of numerous plagioclase laths in random orientation with at least one pyroxene or pseudomorph after a mafic silicate (fayalite) phenocryst and/or magnetite microphenocryst. Very few clusters contained only plagioclase even though plagioclase phenocrysts are the most abundant in the rock. Small amounts of apatite are also present as microphenocrysts, some quite long and slender (0.2 x 2.6 mm up to 0.4 x 5 mm). Some plagioclase phenocrysts are also remarkably long and slender and yet unbroken. Phenocrysts make up only about 1-2% of the rock in most of the subunit, but near the top the percentage rises to 5-7%. Because of the limited exposure, it is unknown whether this change is abrupt or occurs gradually near the top of the unit.

The groundmass is red or gray with rusty red mottling. It is composed of plagioclase laths with interstitial alkali feldspar, clinopyroxene, and some quartz. Magnetite occurs as scraps and subhedral crystals ranging from 0.1-0.5 mm. Some of the opaque material is in the form of 8-sided subhedral crystal shapes, perhaps representing oxidized pyroxene or olivine microphenocrysts.

Vesicles and amygdules are scarce in most of the unit but there is a zone of highly vesicular rock near the top. The thickness of the zone is unknown as it is only exposed in two places in Kimball Creek. In the top zone vesicles make up 15-30% of the rock, with thin strands separating vesicles, giving a frothy appearance. The stratigraphically highest exposure, which is vesicluar, is within 5 m stratigraphically of the base of the overlying rhyolite unit.

Kimball_Creek_rhyolite

The top subunit of the Kimball Creek felsite sequence is 350 m thick near the shore of Lake Superior and is the most laterally extensive subunit, extending as far west as the Cascade River. It is unknown how far west of the Cascade River it extends because of a large swampy area of no outcrop along strike to the west. With the exception of a slight variation in phenocryst percentage with stratigraphic position, most of the unit is quite homogeneous. The typical rock type will be described first followed by descriptions of the distictive top and bottom zones.

Outcrops of this unit are generally sheet-jointed, red, or in places gray or gray with red mottling, and have common light streaks and subhorizontal quartz veinlets 2-50 cm long, and white feldspar phenocrysts. The similarity of the attitudes of most sheeting joints to those of the few exposed flow contacts in the area indicates the joints are generally parallel to the stratigraphic surfaces. There is a gradation from the common subhorizontal bleached streaks to quartz veinlets to open fractures with quartz crystals protruding into the void. The most-common veinlets are 1-2 mm wide containing anhedral quartz crystals; these are bordered by 1-2 mm-wide zones of light-colored groundmass (Figure 12). The light-colored borders are zones where hematite stains are

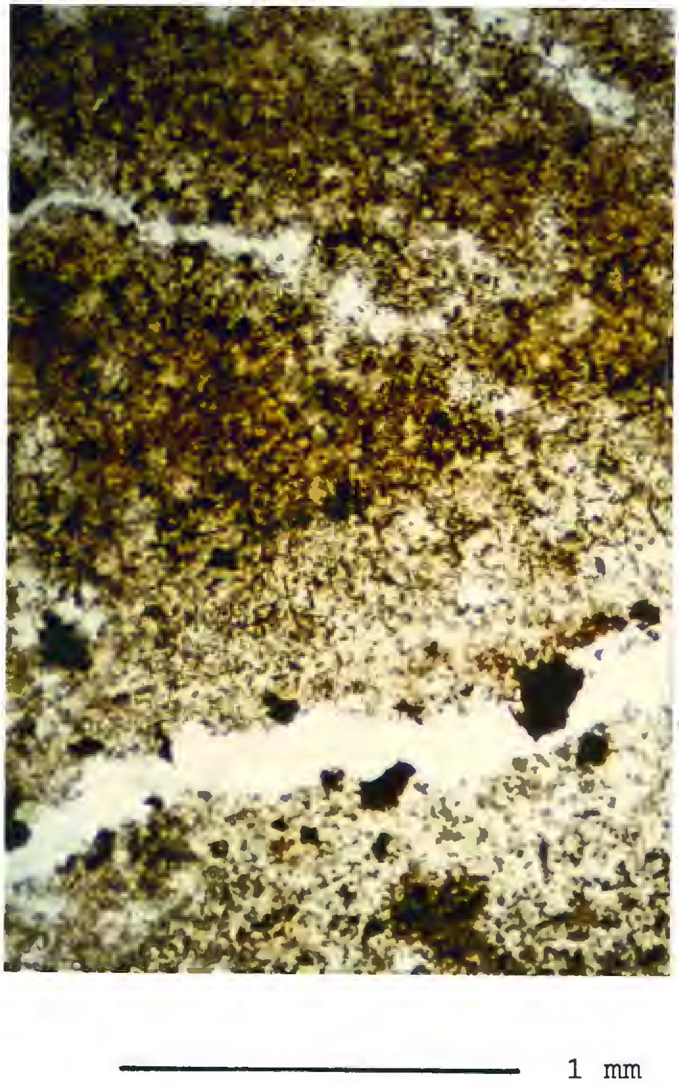


Figure 12. Photomicrograph of quartz veinlets bordered by lighter groundmass near the top of the Kimball Creek rhyolite. Sample KC-6, plane polarized light.

absent and opaque grains are much less abundant but larger in comparison to those in the surrounding groundmass.

The phenocrysts are typically white, moderately to strongly altered, subhedral crystals of plagioclase and alkali feldspar in approximately equal amounts. Tiny apatite inclusions are present in some plagioclase phenocrysts. Rounded, irregular and jagged borders on phenocrysts are common and were probably produced by magmatic resorption and later alteration. However, some crystals with jagged edges may be broken (Figure 14). Very few quartz phenocrysts have been found and all had deeply embayed margins. Other phenocrysts are magnetite, sparse augite and some apatite and zircon microphenocrysts.

Phenocrysts make up approximately 1-3% of the rock in most of the subunit, but they constitute about 3-5% of the rock near the top and 5-7% at the lowest outcrop.

The groundmass of this unit is dominated by platy quartz crystals and anhedral alkali feldspar, mostly in random orientation. The platy quartz occurs as single plates and as groups of slender, parallel or slightly radiating plates. The quartz crystals making up radial clusters are in general exceptionally long slender plates (Figure 15). Quartz also occurs as anhedral interstitial masses which may have filled voids such as diktytaxitic cavities. The anhedral areas may have platy quartz crystals extending from the margins or platy crystals may be visible as more dusty strips within the

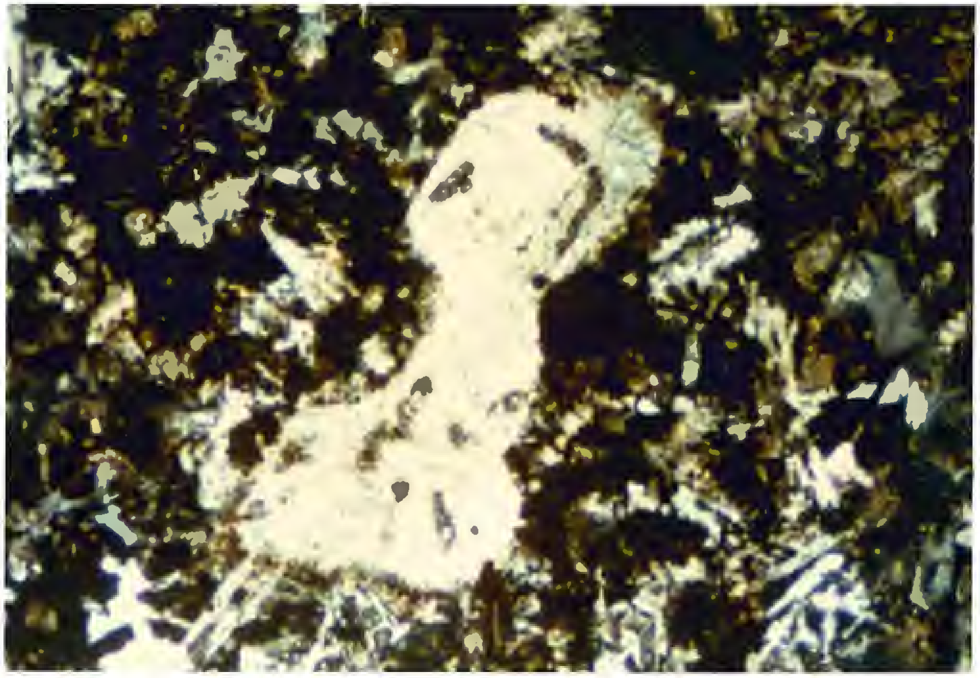


Figure 13. Plagioclase phenocryst with embayed margins and resorption blebs in typical groundmass of platy quartz (white), alkali feldspar (tan), and opaque grains and scraps. Kimball Creek rhyolite, sample KC-20, crossed nicols.

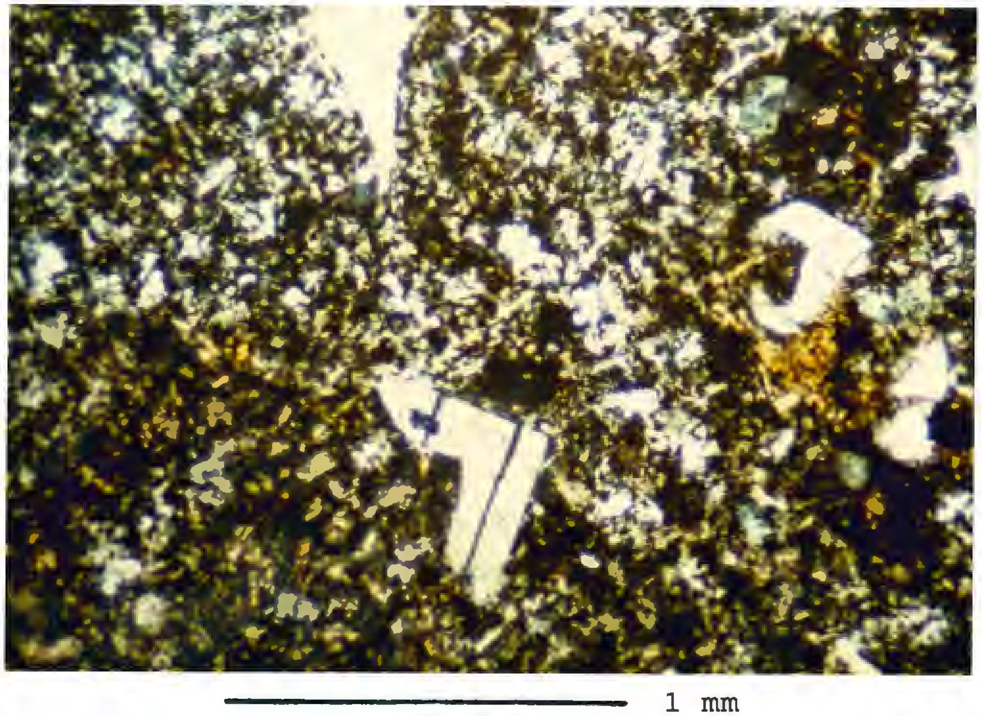


Figure 14. Broken phenocrysts in the Kimball Creek rhyolite. Sample KC-33, crossed nicols.

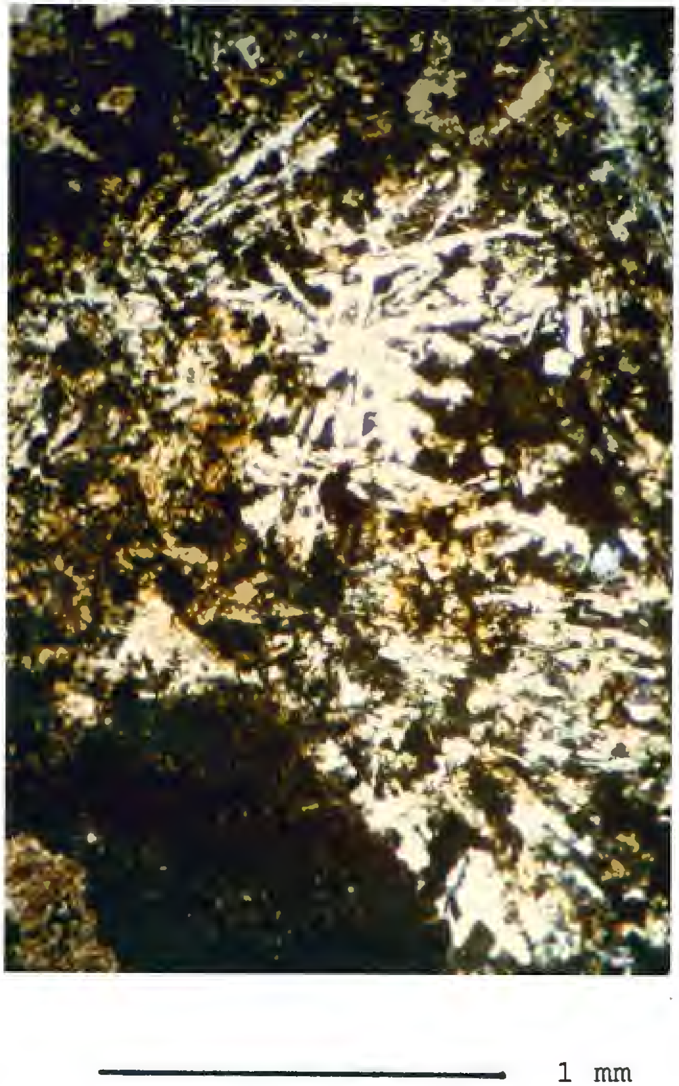


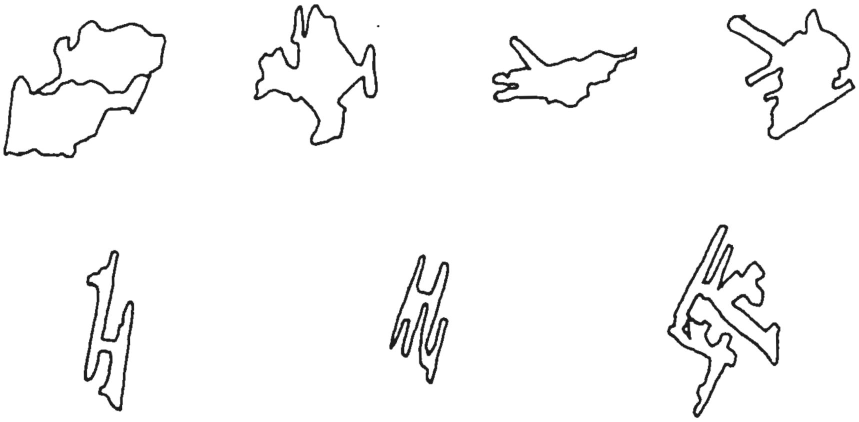
Figure 15. Tabular quartz forming a radial cluster. At lower left is an altered alkali feldspar phenocrysts near extinction. Kimball Creek rhyolite. Sample KC-20. Crossed nicols.

anhedral quartz. Overgrowths on plates create a whole range of crystal morphologies from single plates to poikilitic areas to anhedral masses (Figure 16). The tabular shape implies that these quartz crystals are tridymite paramorphs.

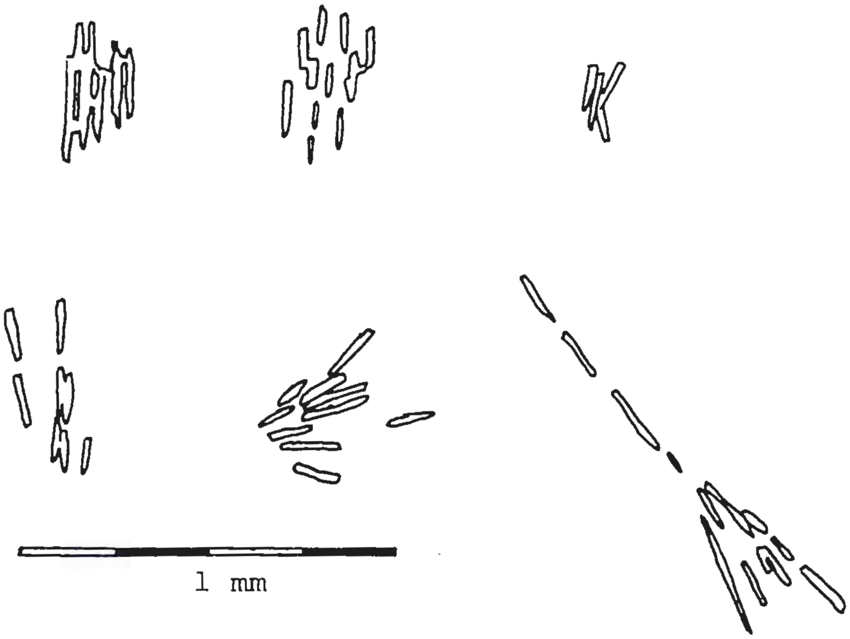
Alkali feldspar in the groundmass is most commonly anhedral but also occurs as subhedral laths and blocks. It is difficult to distinguish individual grains due to the low birefringence and dusty alteration. Some spherulitic clusters appear to be composed entirely of alkali feldspar and have radial extinction.

Opaques in the groundmass range in morphology from anhedral scraps to subhedral or euhedral blocks of magnetite and in size from microlites 0.1 mm across to phenocrysts 2 mm across. Much of the larger anhedral opaques could be the alteration product of mafic silicate minerals because relict outlines of clinopyroxene are locally present. Some clinopyroxene escaped total alteration and small relict pieces remain with the associated products of alteration.

Other minerals found in trace amounts are apatite, zircon, chlorite and fluorite. Some apatite and zircon crystals are large enough to be considered microphenocrysts. Fluorite is only rarely found, typically in cavities.



Anhedral quartz masses gradational to groups of fused plates in optical continuity.



Groups of plates in optical continuity, some with slight radiating pattern.

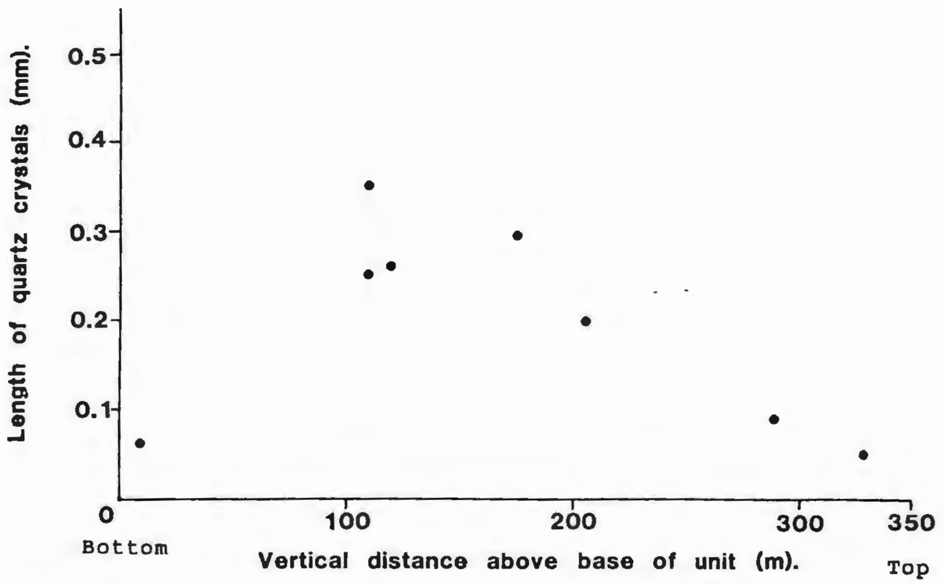
Figure 16. Typical quartz morphologies in the middle of the Kimball Creek rhyolite. All drawn from sample KC-17.

A visual estimate of the modal composition of a typical sample of this rhyolite is: plagioclase phenocrysts, 2% ; anhedral groundmass alkali feldspar, 55% ; quartz, 35% ; opaque, 7% ; apatite, hematite and other minerals, 1%.

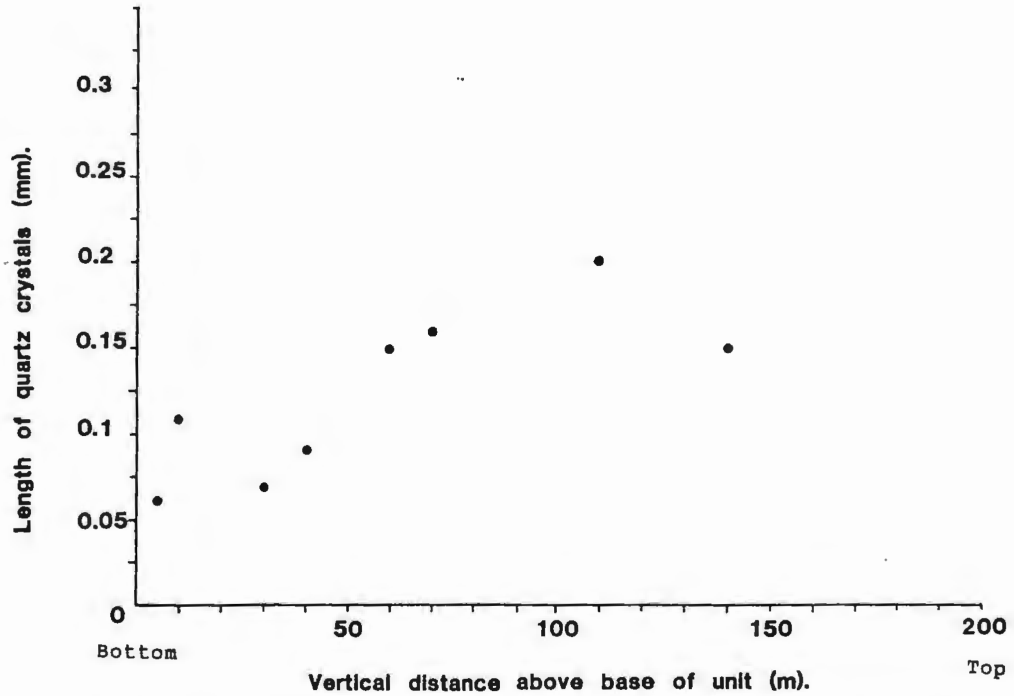
The groundmass is aphanitic throughout but relatively coarser-grained near the middle. The long axes of single quartz plates (tridymite paramorphs) in the groundmass of eight samples from different stratigraphic levels in the unit were measured to document the variation in grain size. Fifty grains from each thin section were measured, then averaged. The average quartz plate varied from less than 0.1 mm near the top and bottom of the unit to 0.2 mm half way to the middle to 0.3 mm near the middle of the unit (Figure 17-A).

Inclusions are rare; they were found only near the base in Kimball Creek and near the middle of the unit. One fragment in the middle is a porphyritic intermediate volcanic rock 25 cm in length with its long axis oriented subhorizontally.

Although neither the upper or lower contacts of this unit is exposed, the rock observed near the contacts is unique and especially informative. The lowest exposed rock is in Kimball Creek in NW 1/4, sec. 3, T.61 N., R.2 E. (sample KC-92). The outcrop is approximately 50 m south of the closest outcrop which is rubbly, highly vesicular rock near the top of the underlying Kadunce icelandite. This distance represents



Length of quartz crystals vs. stratigraphic position in the Kimball Creek rhyolite.



Length of quartz crystals vs. stratigraphic position in the Devil Track rhyolite.

Figure 17. Lengths of tridymite paramorphs in the Devil Track and Kimball Creek rhyolites.

approximately 5 m of covered stratigraphy and the maximum height the rhyolite outcrop could be above the base of the unit. The rock at the lowest outcrop has conspicuous closely-spaced, thin banding that varies in attitude but is vertical or steeply dipping over much of the outcrop. The bands are locally folded (Figure 18). Close examination reveals the banding is made up of thin, discontinous, 2-10 mm wide, light-colored streaks, some quartz veinlets and wider light-orange bands accentuated by weathering. Macroscopically these light streaks resemble collapsed pumice lapilli.

In thin section the banding is expressed by different concentrations of minute opaque scraps. Some of the quartz veinlets are made of short (about 2 mm) segments which have slightly s or z curves and are arranged en echelon (Figure 19). The en echelon orientation is consistent throughout a thin section and phenocrysts near the veinlets are commonly parallel to the en echelon segments. Between the streaks and bands the rock is aphanitic, dense, almost glassy-looking dark marroon material. In thin section few discernable crystals are present in the dark brown groundmass. The thin streaks, which commonly bend around phenocrysts, range from quartz-filled veinlets to slightly lighter areas in the dense groundmass. The closest outcrop up-section is a typical outcrop of this subunit.

Rock near the top of the rhyolitic subunit is exposed near the south and southeast shore of Devil Track Lake and in the

Figure 18. Discontinuous bands forming a tight isoclinal fold within 5 m of the base of the rhyolite. NE 1/4, sec.3, T.61 N., R.2 E.

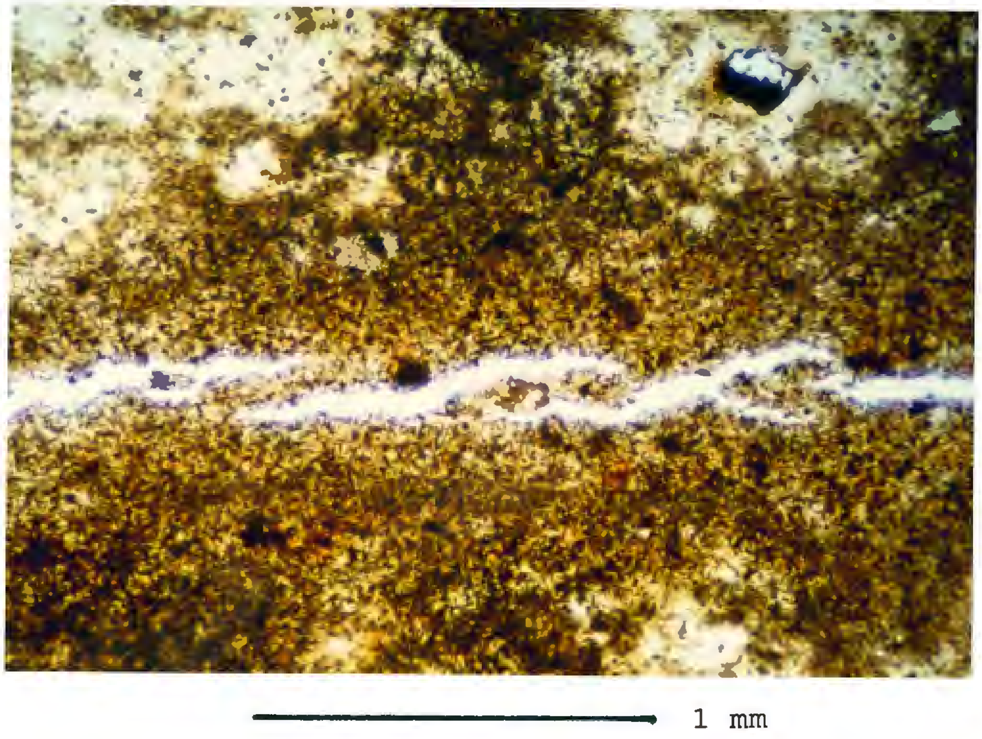


Figure 19. Photomicrograph of en enchelon quartz veins in outcrop shown in figure 18. Plane polarized light, sample KC-92.

Cascade River at NW 1/4, sec. 36, T.62 N., R.2 W. These areas have been closely examined and will be described moving up section. The stratigraphically lowest features indicative of the top zone are sparse cavities about 0.5 cm across. The groundmass around cavities and extending in crude linear zones away from cavities contains more platy quartz and is coarser-grained than the surrounding groundmass. The finer-grained areas have less quartz and in some areas visible quartz is almost completely absent.

Closer to the top the platy quartz is much less abundant or completely lacking and anhedral quartz and dark bands composed of wavy segments are common. Some micrographic intergrowths of quartz and alkali feldspar are present. Sheet joints parallel the banding in places and in one location in the Cascade River in the NW 1/4, sec. 36, T.62 N., R.1 W., the banding and joints are folded into a large recumbent fold with small lineations on joint surfaces (sample ML-47).

Just south of Devil Track Lake in the NE 1/4, sec.36, T.62 N., R.1 W. is an informative outcrop and talus slope of rhyolite. Weathered surfaces on the rhyolite have distinct light-colored tabular fragments 1-5 mm long making up approximately 15-20% of the rock. The long axes of fragments are oriented in a plane, forming a foliation. Rocks showing bands concentrated with light-colored fragments separated by typical red rhyolite were found in the talus (Figure 20, samples DT-24, 25, 33-37).

The stratigraphically highest known outcrop of the rhyolitic subunit is at the shore of Lake Superior in the SW 1/4, sec. 1, T.61 N., R.2 W. (samples KC-6, 116, 117). The outcrop is 200 m northeast of the basal basalt outcrops of the Red Cliff basalts at Red Cliff. This distance represents 40 m of stratigraphy and the maximum stratigraphic depth the rhyolite outcrop could be below the contact. The rock at this outcrop is especially informative because it is freshly eroded by the waves of Lake Superior and because of its unique character. It also provides an uncommon horizontal perspective not provided by the numerous vertical outcrops in the river canyons.

The most-conspicuous features of the outcrop are numerous straight or curved bands, joints and linear structures. The continuous, light-colored or red bands are typically 0.5-2 cm wide and vary between straight and tightly folded. The typical subhorizontal sheet joints are sparse at this outcrop and where present, the joints parallel banding even where folded. The common linear structures are straight, parallel ridges with heights of 1-5 cm that resemble a corrugation (Figure 21).

Figure 20. Sample from near the top of the Kimball Creek rhyolite having light-colored fragments concentrated in bands. Sample DT-24, NE 1/4, sec. 36, T.62 N., R.1 W.

Figure 21. Corrugated lineations near the top of the Kimball Creek rhyolite. SW 1/4, sec. 10, T.61 N., R.2 E.

The rock is aphanitic, red, porphyritic felsite with common light spots around weathered feldspar phenocrysts. The groundmass is very fine-grained, making distinction of individual grains difficult even in thin section. Tiny opaque scraps dominate and create a generally dusty appearance with variations in abundance producing dark patches and curvilinear features. Some of the patches are diffuse, others almost entirely opaque scraps and hematite. One small area of the outcrop contains abundant conspicuous dark tabular fragments that resemble fiamme (Figure 22). The dark red fragments are generally 2-10 cm long and subparallel yielding a crude foliation which is folded. In thin section the fragments bend around phenocrysts, have sharp terminations and an internal microfoliation (Figure 23). Some contain phenocrysts, some have bulbous centers and all are 5 to 20 times longer than they are thick.

Another unique feature observed in this outcrop is a small area of coarser rock with abundant diktytaxitic cavities that may be a degassing structure.

Devil Track felsite sequence

Maple_Hill_rhyolite

The lower of the two units of the Devil Track felsite sequence is a porphyritic rhyolite that has been informally

Figure 22. Flattened pumice fragments concentrated in folded bands. This is at the stratigraphically highest outcrop of the Kimball Creek rhyolite. SW 1/4, sec. 10, T.61 N., R.2 E.

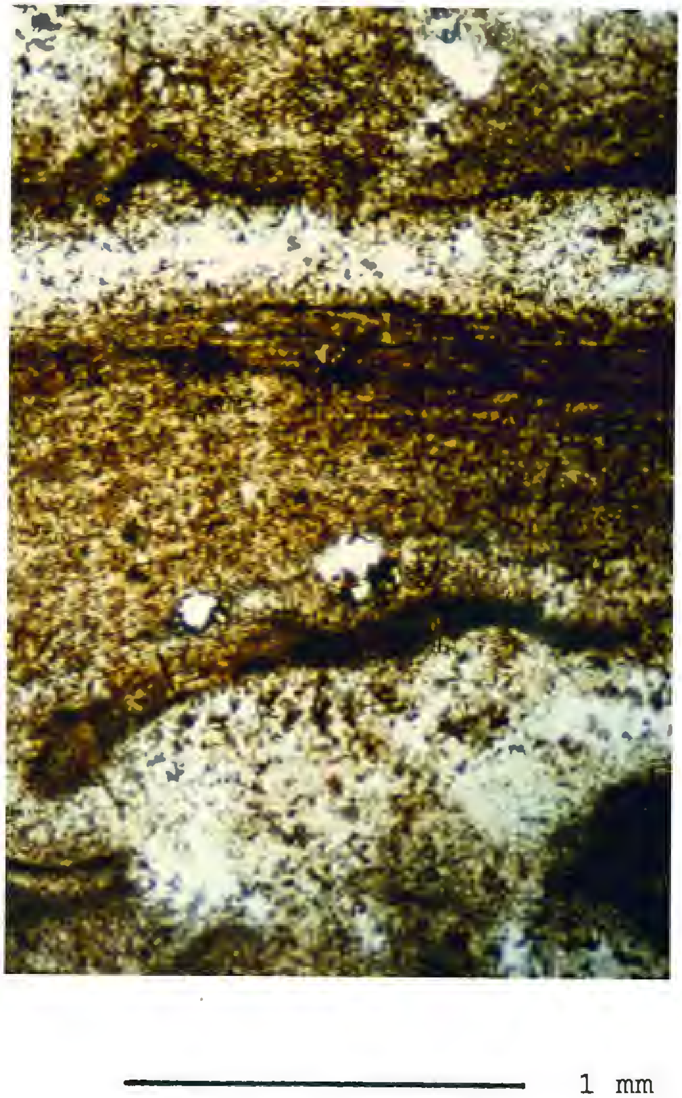


Figure 23. Photomicrograph of the fiamme shown in figure 22. Sample KC-116, plane polarized light.

named the Maple Hill rhyolite by Green (1972b). The 110 m thick Maple Hill unit is exposed in the abandoned Nipissing cliff in SE 1/4, sec.7, T.61 N., R.2 E., in Woods Creek, and to the west in a few areas near Maple Hill including the Devil Track River canyon.

Rock near the base of the unit is aphanitic, flow-banded and contains linear vesicles. One area of observed in Woods Creek has horizontal linear vesicles with a trend of N.50° W., and another area has vertical vesicles (sample GM-77). Light-colored bands 1-2 mm wide are ubiquitous in the unit and vary in attitude from nearly horizontal close to the base to vertical in the middle of the flow to variable and contorted near the top (Figure 24). Vesicles are most abundant near the top where they are commonly arranged in folded bands parallel to the light-colored banding (Green, 1970). Long axes of feldspar phenocrysts generally are aligned parallel to the bands. In the Nipissing cliff N.7° W. of Guano Rock is a remarkable outcrop of banded rhyolite where the bands form a large recumbent fold 3-4 m high (Figure 25). Spherical nodules, probably spherulites, are 0.25 to 1.0 cm in diameter and are commonly arranged in bands. They stand out on weathered surfaces and may be interbanded with 2-cm-thick bands of massive rhyolite. They are most abundant near the top and bottom of the unit.

Figure 24. Horizontal flow bands in the Maple Hill rhyolite. SE 1/4, sec. 7, T.61 N., R.2 E.

Figure 25. Large fold near the top of the Maple Hill rhyolite. SE. 1/4, sec. 7, T.61 N., R.2 E.

The red rhyolite contains approximately 4-6 % alkali feldspar phenocrysts and 2-4% locally embayed quartz phenocrysts. Zircon is present as rare microphenocrysts and fluorite is rarely seen in cavities. Basalt rock fragments 1-5 cm across are common. The groundmass is aphanitic, spherulitic and contains anhedral quartz, poikilitic tridymite paramorphs, alkali feldspar laths and opaque scraps and plates. Some groundmass opaque crystals are long and slender, some are branching in a dendritic form as seen in thin section. These were probably quenched-textured mafic silicate minerals.

Near the base of the unit the groundmass is uniform dark red-brown aphanitic material with no identifiable crystals visible in thin section.

Devil_Track_rhyolite

The upper unit of the Devil Track is 200 m thick and is the most extensive of all units in the study area, extending from the shore of Lake Superior inland at least 42 km. The unit probably extends even further west as evidenced by the abundant, flat red rhyolite chips found at the surface in NE 1/4, sec.10, T.60 N., R.3 W. Due to the poor exposure in the western part of the field area it is uncertain how thick the unit is there, but the absence of the ridge held up by the Devil Track rhyolite and the proximity of bedrock basalt ridges on either side suggests the unit is thinner west of

Pike Lake or R.2 W. However, if the dip is steeper than that further east, the unit would only appear to be thinner. Although it may thin to the west, there is no evidence of thinning eastward toward the shore of Lake Superior so it is possible that the thickest part of the unit is under Lake Superior.

Outcrops of this unit are remarkably homogeneous, fine-grained, aphyric red to pink rhyolite. Vesicles and phenocrysts are very rare. The abundant jointing is consistent throughout the unit and, with local exceptions, the attitude of the subhorizontal joints generally parallels the attitude of the stratigraphic contacts in the area. All fresh surfaces of the rock look similar and without structure, but weathered surfaces are light orange with light banding. The banding varies from thin lamellae to bands 1-2 mm wide and is generally subhorizontal and parallel to the joints. Locally the bands are tightly folded, especially near the top of the unit where folds vary from small contortions to folds covering entire outcrops several meters across (Figure 26). This aspect is very similar to the structures near the top of the Kimball Creek rhyolite. The bands on the outcrops along the

Joints commonly parallel bands around the hinge of folds. The best example of this was found in the Cascade River in SW 1/4, sec.1, T.61 N., R.2 W. (sample ML-26).

Figure 26. Folds in banding in the Devil Track rhyolite. SW 1/4, sec. 7, T.61 N., R.2 E.

lakeshore are generally nearly vertical with consistent strikes. Continuous, linear ridges 0.25-1 cm high on horizontal joint surfaces, similar to those at the top of the Kimball Creek unit are also common on horizontal exposures along the shore and have remarkably consistent trends. Subhorizontal veinlets of anhedral quartz are commonly parallel to and gradational into joints. The thin veinlets 1-2 mm wide are especially abundant in the lowest known outcrop of the subunit in the Nipissing cliff in SE 1/4, sec.7, T.61 N., R.2 E. (sample KC-110). They are bordered by rims of bleached rhyolite. The rhyolite of this unit is dominated by a network of platy quartz crystals (tridymite paramorphs) and anhedral alkali feldspar similar to the top rhyolitic unit of the Kimball Creek felsite. Quartz plates in random orientations are commonly connected by secondary quartz overgrowths to form a poikilitic network that may enclose alkali feldspar grains.

Cavities are not abundant, but where present they commonly contain small tabular quartz crystals. In thin section the tabular crystals are seen in cavities which are otherwise empty, or else filled with calcite or secondary quartz surrounding the quartz plates. The tabular quartz was probably deposited as tridymite.

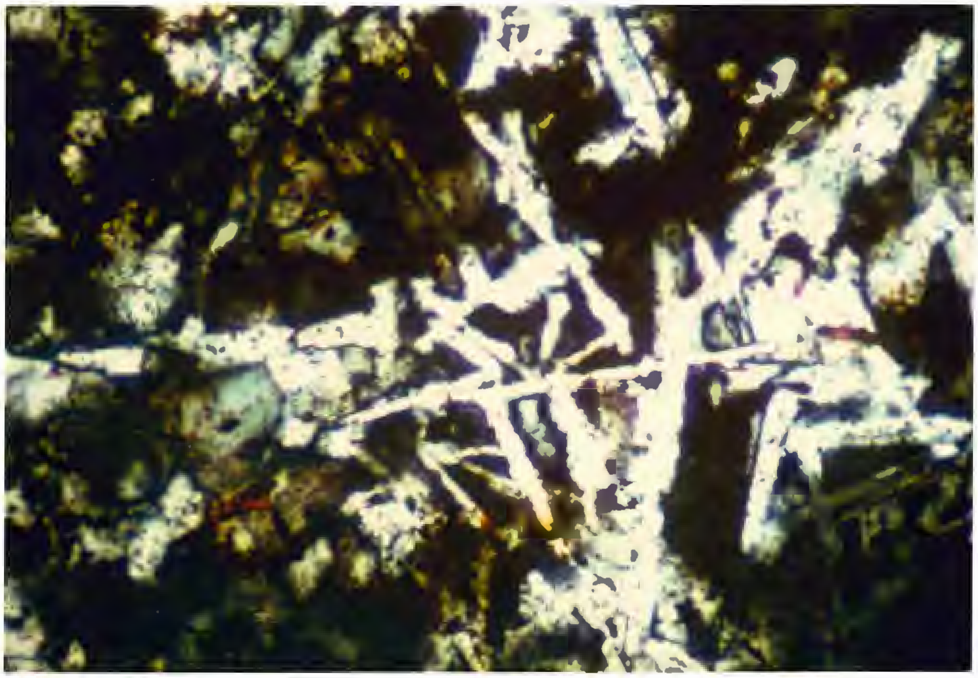


Figure 27. Typical texture of the Devil Track rhyolite. The light, elongate crystals are tabualr quartz, (tridymite paramorphs) the dark dusty brown mineral is alkali feldspar with hematite and the opaque blocks and scraps are probably magnetite. Sample GM-14, crossed nicols.

Anhedral opaque scraps are scattered throughout the rock and, along with the hematite staining on feldspars, give the rock its red color. Some of the scraps may be the result of alteration of mafic silicate minerals. Opaque outlines of original pyroxenes and rare possible fayalitic olivine pseudomorphs are present.

Small amounts of apatite, zircon and calcite also are present. Phenocrysts are extremely rare, but some plagioclase and quartz phenocrysts have been found. All phenocrysts observed have rounded and deeply embayed margins, and it is possible they are xenocrysts.

Quartz is estimated to make up 40% of the rock, alkali feldspar 55%, opaque scraps about 4% and other material less than 1%. The unit is aphanitic throughout but relatively coarser near the middle. The long axes of tabular quartz grains (tridymite paramorphs) were measured in thin sections as an indication of changes in grain-size (Figure 17). The quartz crystals vary in size from so small as to be barely recognizable near the base to 0.2 mm in the middle. The grain size distribution is similar to that of the Kimball Creek rhyolite even though none of the rocks from the Devil Track rhyolite are as coarse as those from the middle of the Kimball Creek.

Dark streaks are found in some talus of the Nipissing cliff near the base of this unit (Figure 28). The dark brown streaks, 2-15 mm long are narrow, curved and some are branching. They are subparallel and in one sample they form a folded foliation. Thin sectioning shows the streaks to be areas of high concentration of opaque scraps and hematite in a very fine-grained, spotted, possibly spherulitic groundmass. They may represent highly deformed fiamme.

The Devil Track rhyolite is overlain by the Croftville basalt flows near Grand Marais, and in the area of the Cascade River by sandstone. The sandstone has mud chips, but no obvious volcanic clasts.

Figure 28. Thin, dark streaks in very fine-grained pink rhyolite found near the base of the Devil Track rhyolite. SE 1/4, sec. 7, T.61 N., R.2 E.

Outlying outcrops

There are several bedrock exposures that lie near the Kimball Creek and Devil Track felsites that are not included in the map units but deserve mention here. Most are single outcrops that have not been correlated with any units. However, they lie stratigraphically close to the Devil Track and Kimball Creek felsites and may be genetically related.

Devil_Track_Lake_area

South of Devil Track Lake in the SE 1/4 sec. 35, T. 62 N., R.1 W. logging operations have uncovered an outcrop of porphyritic red rhyolite (DT-32). This outcrop lies south of and stratigraphically above the highest known outcrop that is certainly Kimball Creek felsite, and south of an outcrop in the NW 1/4 sec. 35 of fine-grained ophitic basalt believed to be part of the Red Cliff basalts. Thus the rhyolite lies in the same stratigraphic position as the Maple Hill rhyolite, the closest known outcrop of which is approximately 10 km to the east-southeast.

The rock is altered, fine-grained rhyolite with phenocrysts of magnetite, altered plagioclase, alkali feldspar and oxydized mafic silicates.

The groundmass is very fine-grained, brown-red alkali feldspar with interstitial quartz and abundant opaque scraps. The rock contains about 1% feldspar phenocrysts but lacks quartz phenocrysts which are abundant in the Maple Hill rhyolite. The rhyolite also lacks banding and spherulites which are common in the Maple Hill unit. This is interpreted to represent a separate flow, erupted at about the same time as the Maple Hill rhyolite.

Cascade_River_area

The Cascade River channel in the NW 1/4, sec. 36, T.62 N., R.2 W. has several exposures of rock unlike any others found in the field area. There is an outcrop of rhyolite 30 m south of, and about 8 m stratigraphically above exposures of the Kimball Creek rhyolite. The rock (ML-46) is dark rusty-red and composed entirely of fragments 0.5-7 mm across. There is no foliation to the rock and fragments are generally equidimensional, varying from sub-round to angular. The fragments are dark orange, red or brown and some are nearly opaque in plane-polarized light. All contain abundant opaque scraps and may have dark wavy bands created by concentrations of opaques. Some fragments contain roundish vesicles or parts of vesicles along the margins, and few of the fragments have straight-sided holes where phenocrysts might have existed. This rock is interpreted to be an unwelded lapilli tuff.

The next small isolated outcrops are approximately 35 m farther up-section. Two samples from this area are very dark-colored porphyritic rhyolites with less than 1% quartz and about 2% feldspar phenocrysts, but their groundmasses are very different. One (ML-23) has very fine-grained quartz, alkali feldspar and opaque scraps, whereas the other (ML-24c) has a spherulitic brown-red groundmass with no discernable crystals, but unusual curving red veins, some of which are filled with polycrystalline quartz. The rock having the veined groundmass contains small grains of native copper. An amygdaloidal basalt is just up-section from the rhyolites. Just down-section (upstream) from the rhyolites is a plagioclase-porphyritic, ophitic dibase.

This is the same area where Foster (1962) found what he called the "Cascade River ash flow tuff". Foster made no mention of the diabase but described the ash flow unit as having a firmly welded middle zone and an unwelded top. It is unclear whether the two rhyolites (ML-23, 24c) of this study are from Foster's welded or unwelded zone; in fact neither sample contains textures definitely of pyroclastic origin. Sample ML-24c with the grains of native copper could be from the mineralized zone interpreted by Foster (1962, 1963; Johnson and Foster, 1963) to be at the top of the unit.

The unwelded lapilli tuff is probably the rock type Foster interpreted to be the unwelded base of the "Cascade River ash flow tuff". The rock is exposed just above rhyolite believed to be near the top of the Kimball Creek rhyolite. This brings up the question of whether or not Foster's (1962) Cascade River unit is a separate deposit or the very top of the Kimball Creek rhyolite which is not exposed elsewhere. Unfortunately the phenocrysts have been weathered out leaving only rectangular holes, so phenocrysts cannot be used for correlation. If there is indeed an unwelded base and top, and a welded interior to the "Cascade River ash-flow tuff" as Foster (1962) suggested, then it must be a separate cooling unit, but since no definite evidence of the welded middle was found in this study, it is possible that the unwelded lapilli tuff (ML-46) is the top of the Kimball Creek rhyolite, or a still separate unit. Its larger grain-size than that of the Kimball Creek suggests the latter interpretation. The ophitic diabase is interpreted to be a dike.

Tait Lake area

In the NE 1/4, sec.10, T.61 N., R.3 W. in the Tait Lake quadrangle is an exposure of fine-grained, granophyric, porphyritic rhyolite (TL-29). It has alkali feldspar and abundant quartz phenocrysts surrounded by fine, radiating quartz crystals in optical continuity. The groundmass quartz shows granophyric intergrowths with dusty alkali feldspar. Although the exposure lies in a valley along strike with the

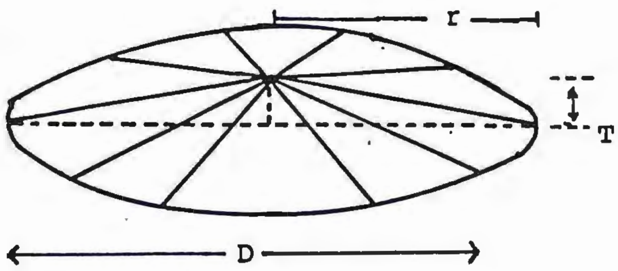
Kimball Creek rhyolite, the amount of quartz, the phenocryst assemblage and the groundmass texture are all different from the Kimball Creek rhyolite, thus it is not correlative. It is probably a shallow intrusion.

Felsite outcrops in the Tait River, in the E. 1/2, sec. 33, T.61 N., R.3 W. in the Lutsen Quadrangle have sheet joints common to the felsites in the area, allowing the Tait River to erode a small canyon. It is uncertain how many units are exposed in the canyon, but vesicular rhyolite talus was found near an area of extremely fine felsite, perhaps indicating a contact in the area even though none is exposed. Three of the samples from the canyon contain a network of tabular quartz crystals after tridymite in the groundmass. All felsites in this area have fairly abundant quartz phenocrysts, suggesting they are not correlative with either of the extensive rhyolite units in the Devil Track or Kimball Creek felsites, although they were erupted at nearly the same time as these larger units.

CHAPTER IV: DIMENSIONS

This discussion is an attempt to quantify the size of the felsites for comparison with other felsic volcanic units described in the literature. There are so many unknowns because of the poor exposure and truncation by Lake Superior that precise numbers cannot be determined, but by making some reasonable assumptions a realistic range of sizes can be calculated. One assumption made for all units is that the flows spread out uniformly in all directions and thus are approximately circular in plan. This is a reasonable assumption considering that the topography of the area during the middle Keweenawan probably consisted of a fairly flat lava plain with gentle slopes (White, 1960). However, if the flows in question traveled down valleys, or if there was significant ponding in a caldera or other low area, or the flows accumulated along linear fissures rather than a central vent, then the shapes of the units would be substantially different from the assumed shapes and the calculations are not valid. The volume calculations were made using the assumptions that a) the units that appear to be lava flows had a uniform thickness and thus approximated a short cylinder; and b) the units inferred to be welded tuffs thinned toward the edges and approximated short broad cones (Figure 35). These assumptions are made because ash flows typically thin toward the edges and rhyolite lavas usually have steep lobate margins and flat tops (Cas and Wright, 1987).

Units interpreted as ash flows:

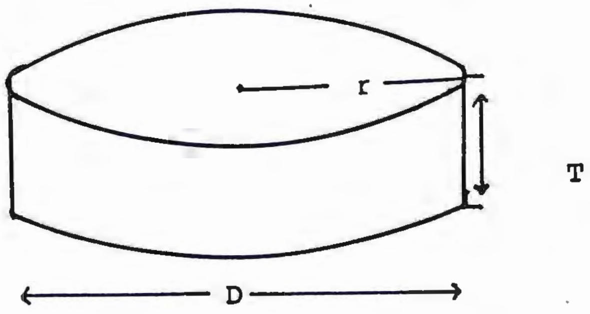


Aspect Ratio = Thickness / Diameter

Area Covered = πr^2

Volume = πr^2 T/3

Units interpreted as lava flows:



Aspect Ratio = T/D

Area Covered = πr^2

Volume = $\pi r^2 T$

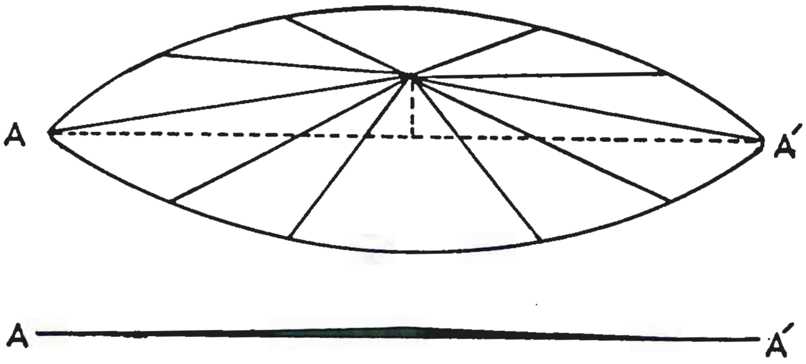
Figure 29. Diagram of the assumed original shapes of the units used in calculating the values in table 1.

These geometries are similar to those of rhyolite lavas and welded tuffs in Iceland (Walker, 1962).

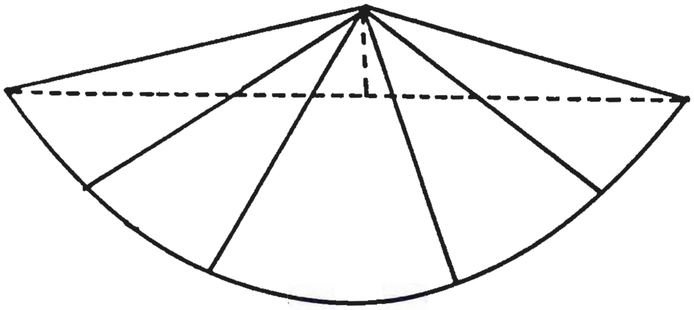
Another uncertainty is how the present erosion surface cuts the units. The calculations were made assuming the disks are cut through the center so that the greatest diameter of the circle is exposed (Figure 30). It is that unlikely the units are cut through their greatest diameter, so this assumption gives minimum figures.

Perhaps the largest uncertainty, though, is how much of the units are concealed under Lake Superior. Calculations are made using two alternative assumptions: a) the entire diameter of the unit is exposed on land (none of it is hidden beneath the lake); and b) only a radial section is exposed on land, and an equivalent portion lies beneath the lake. In table 1, part A shows the two measurable distances, thickness and approximate length of exposure on land, and the calculated areas, volumes and aspect ratios based on assumption A above. Part B of Table 1 shows the dimensions for each unit based on assumption B, that the units are centered at the shore of Lake Superior. Since the units appear to be the thickest at the lakeshore, it is possible that was originally near the center (Figure 30).

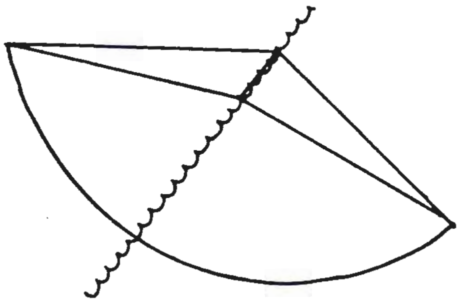
The aspect ratio of a volcanic unit is the ratio of thickness to extent (Walker, 1973, 1983) and is a useful indicator of the mobility of the flow.



I. Original extent of the rhyolites.



II. Up-dip half is eroded away.



III. Lake Superior conceals half the extent.
This is the assumed present situation.

Figure 30. Diagram of one possible interpretation of the origial shape, present erosion level and concealment under Lake Superor of the Devil Track and Kimball Creek rhyolites. The assumed original dimensions of the rhyolites, represented here by the cone in part one, are shown in table 1, part B.

Table 1

A) Minimum dimensions of the felsite units assuming the extent presently exposed was the original diameter.

Unit	Assumed shape*	Thickness (km)	Extent (km)	Aspect ratio	Area (km^2)	Volume (km^3)
Devil Track	b/co	0.2	42	1/210	1385	92
Maple Hill	s/cy	0.11	7.5	1/68	44	4.8
Kimball Creek	b/co	0.35	32	1/91	804	94
Kadunce icelandite	s/cy	0.2	20	1/100	314	63
Range Line icelandite	s/cy	0.04	23	1/575	415	17
Basal qtz latite	b/co	0.04	23	1/575	415	5.5

* b/co = broad cone, see figure 29
s/cy = short cylinder, see figure 29

B) Original dimensions of the units based on the assumption that one half of the original cross-section is now exposed, as shown in figure 30 for the rhyolites. The assumed shapes and thicknesses are the same as in part A.

	Radius (km)	Aspect ratio	Area (km^2)	Volume (km^3)
Devil Track	42	1/420	5540	370
Maple Hill	7.5	1/136	177	19.5
Kimball Creek	32	1/182	3216	375
Kadunce Icelandite	20	1/200	1250	25
Range Line icelandite	23	1/1150	1662	66
Basal qtz latite	23	1/1150	1662	22

Ash flows have aspect ratios which vary from about 1/400 for flows with relatively low mobility such as the Valley of Ten Thousand Smokes ignimbrite (Alaska), to 1/100,000 for very mobile flows such as the Taupo ignimbrite (Walker, 1983).

In figure 31 the values from part B are plotted on a graph of vertical to horizontal dimension along with known lava extrusions. The Devil Track and Kimball Creek rhyolites have diameters far larger than most rhyolites and even greater than many basalt flows.

In figure 32 the large rhyolite units are compared to various known ignimbrites on a plot of volume versus aspect ratio. The volumes and aspect ratios of the Devil Track and Kimball Creek rhyolites are about the same as or larger than many known ignimbrites. Figures 31 and 32 show that the dimensions of the two large rhyolites are close to those of some large ignimbrites and far larger than those of typical rhyolite lavas.

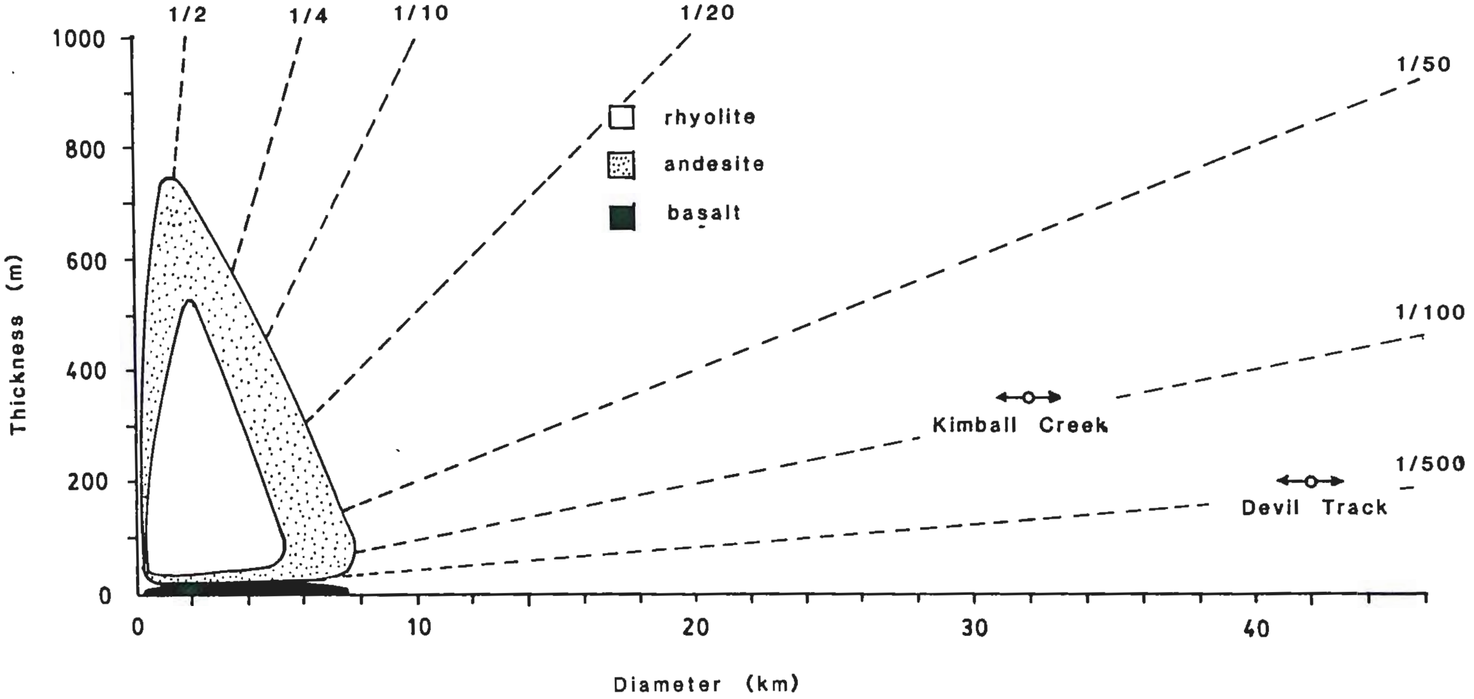
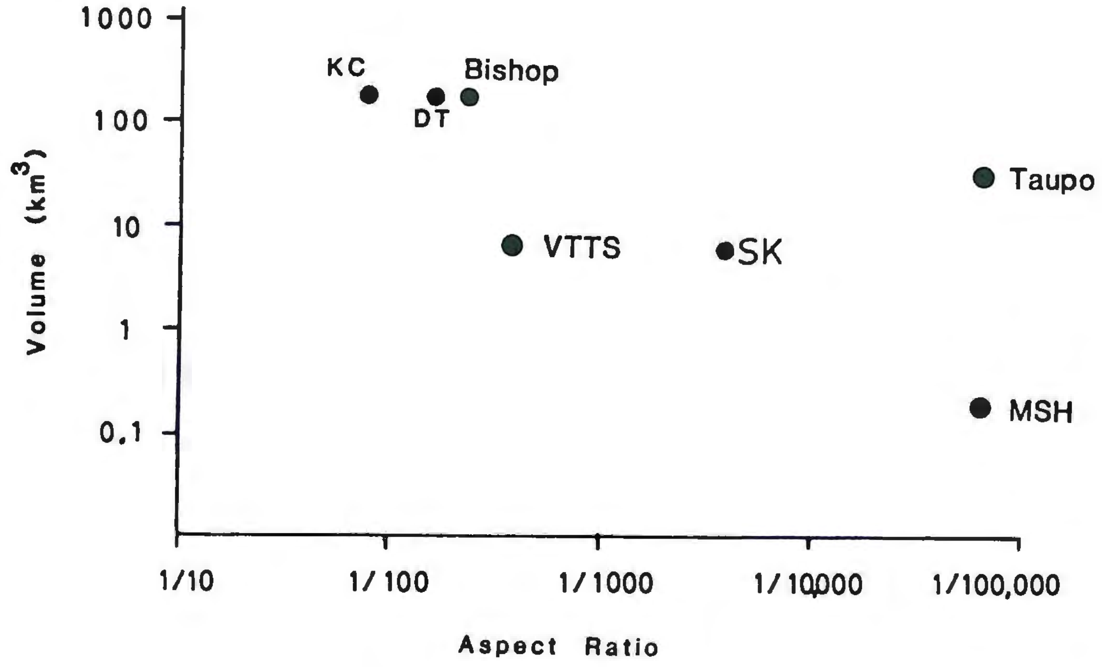


Figure 31. The dimensions of the Devil Track and Kimball Creek felsite units plotted with lava extrusions of different compostions. The dashed lines represent aspect ratios. The diameters of the Cook County units are minimum values shown in Table 1, Part A. After Walker, 1983.



VTTS = Valley of Ten Thousand Smokes, Alaska
MSH = Mount St. Helens eruption of May 18, 1980
KC = Kimball Creek rhyolite
DT = Devil Track rhyolite
SK = Skessa tuff, Iceland

Figure 32. Plot of volume versus aspect ratio for selected ignimbrites (Walker, 1983). The dimensions plotted for the Devil Track and Kimball Creek rhyolites are those shown in table 1, part B.

CHAPTER V: GEOCHEMISTRY

Introduction

The major goals of the geochemical study of the felsites are: 1) to describe the geochemical nature of the rocks, both major and minor elements; 2) to compare the chemistry of these units with that of other felsites; 3) to determine the effect of chemistry on the viscosity; 4) to investigate the evidence for any vertical variability; and 5) to propose possible petrogenetic models.

Geochemical diagrams and discussions are organized into three general sections, the first of which contains geochemical plots widely used to describe and classify rocks. The chemical data of the felsites and several other rhyolites were used to calculate viscosities, and the results are present in the second section. A computer program by Hardrock Software (1985) was used to calculate the viscosities. These data may be helpful in determining whether the chemistry had a large influence on the viscosity and thus on the depositional process, particularly when compared to the viscosities of deposits known to be large ash flows, rheoignimbrites and extensive lava flows. The analyses of the rhyolites used for comparison are listed in the appendix along with the trace element and averaged analyses of the Cook County felsites. The third section deals with the genesis of the magmas, specifically whether the felsite sequence can be accounted for by fractional crystallization.

Table 2

Symbols used on geochemistry figures.

∧	Devil Track rhyolite
∧	Average of 3 Devil Track rhyolite analyses
∧	Maple Hill rhyolite
•	Kimball Creek rhyolite
•	Average of 5 Kimball Creek rhyolite analyses
o	Kadunce icelandite
⊘	Range Line icelandite
r	Nockold's average rhyolite (Nockold, 1954)
L	LeMaitre's average rhyolite (LeMaitre, 1976)
I	Rhyolites in Iceland (Walker, 1966)
C	Peralkaline rheoignimbrites of the Canary Islands (Schmincke and Swanson, 1967)
W	Wagontire tuff, peralkaline rheoignimbrite, Oregon (Walker and Swanson, 1968)
T	Bracks rhyolite, peralkaline rheoignimbrite, Texas (Henry and others, 1988)
X	Cougar Point tuff, rheoignimbrite, SW Idaho (Bonnichsen and Citron, 1982)
■	Wall Mountain tuff, rheoignimbrite, Colorado (Chapin and Lowell, 1979)
+	Rhyolite lavas in SW Idaho (Bonnichsen, 1982)

Table 3.

Chemical Analyses

	MI-2	KC-1	KC-2	ML-12	DT-9	KC-17	DT-24	KC-18	KC-16	ML-1	GM-14	TL-27
SiO_2	62.60	64.32	59.26	70.80	70.00	68.88	69.10	70.80	71.52	73.00	72.23	74.00
TiO_2	1.09	1.11	1.78	0.54	0.53	0.48	0.55	0.54	0.38	0.38	0.45	0.38
Al_2O_3	12.01	12.64	12.39	12.70	12.70	12.77	12.30	12.15	11.56	11.80	11.38	12.10
Fe_2O_3	8.18	5.89	6.10	3.64	3.68	4.32	4.49	4.12	3.62	3.14	4.08	2.17
FeO	2.02	2.72	4.77	1.37	1.36	2.66	1.66	1.10	0.97	1.16	0.24	0.81
MnO	0.12	0.12	1.31	0.06	0.07	0.09	0.13	0.14	0.12	0.06	0.04	0.03
MgO	1.40	0.99	1.10	0.21	1.16	0.67	0.24	0.28	0.46	0.71	0.44	0.48
CaO	2.22	2.40	3.98	0.21	0.26	0.94	0.25	0.90	0.22	0.23	1.07	0.21
Na_2O	4.04	3.88	3.78	2.74	3.44	4.53	2.44	4.00	3.00	2.52	2.62	2.97
K_2O	4.15	4.12	3.24	6.32	5.30	3.45	6.41	4.92	7.04	5.57	5.50	5.43
P_2O_5	0.28	0.31	0.46	0.09	0.08	0.11	0.08	0.08	0.00	0.05	0.03	0.05
Total	98.02	98.50	98.17	98.66	98.58	98.90	97.65	99.03	98.89	98.62	98.08	98.63
Source	1	1	1	2	2	1	2	1	1	2	1	1
	Range Line icelandite	Kadunce Creek icelandite		Kimball Creek rhyolite					Maple Hill rhyolite	Devil Track rhyolite		

Sources:

1. Green, 1972b
2. Green, 1986.

Table 4.

Normative Minerals

	MI-2	KC-1	KC-2	ML-12	DT-9	KC-17	DT-24	KC-18	KC-16	ML-1	GM-14	TL-27
Quartz	18.63	21.31	16.61	30.16	27.64	26.33	29.71	32.21	27.37	35.61	33.52	34.92
Corundum	0.00	0.00	0.00	1.89	1.03	0.14	1.09	0.39	0.00	1.33	0.00	1.08
Orthoclase	24.53	24.35	19.15	37.35	31.32	20.39	37.88	20.39	41.60	32.92	32.50	32.09
Albite	34.18	32.83	31.98	23.18	29.12	38.33	20.65	33.85	20.28	21.32	22.17	25.13
Anorthite	2.39	4.91	7.28	0.45	0.77	3.94	0.72	3.94	0.00	0.82	3.05	0.72
Diopside	5.29	3.87	7.87	0.00	0.00	0.00	0.00	0.00	0.85	0.00	1.23	0.00
Hyperstene	1.03	0.67	2.03	0.52	2.89	2.32	0.60	0.70	0.75	1.77	0.53	1.20
Magnetite	3.74	5.94	8.84	2.98	3.08	6.34	4.18	2.44	2.42	2.83	0.00	1.61
Hematite	5.60	1.97	0.00	1.58	1.56	0.00	1.61	2.44	0.70	1.19	4.08	1.06
Ilmenite	2.07	2.11	3.38	1.03	1.01	0.91	1.05	1.03	0.72	0.72	0.59	0.72
Apatite	0.65	0.72	1.07	0.21	0.19	0.26	0.19	0.19	0.00	0.12	0.07	0.12
Acmite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.50	0.00	0.00	0.00

Several of the plots have data points that are averages from other selected volcanic fields. The analyses from rheoignimbrites in the Canary Islands (Schmincke and Swanson, 1967), Oregon (Walker and Swanson, 1968) and Texas (Henry and others, 1988) were chosen because of the well-developed flowage structures in the rocks as well as their peralkaline chemistry, which is thought to have the effect of lowering viscosities. Analyses from the Wall Mountain tuff in Colorado and the Cougar Point tuff in the Snake River Plain area in SW Idaho were chosen because the rocks are non-peralkaline ignimbrites yet have rheomorphic structures (Bonnichsen, 1982; Chapin and Lowell, 1979). There are also some rhyolites in SW Idaho which are probably very extensive and voluminous lava flows (Bonnichsen, 1982; Bonnichsen and Kauffman, 1987). Analyses from felsic rocks in Iceland (Walker, 1966) are used for comparison because of the general similarity between the North Shore Volcanic Group and Icelandic rocks (Green, 1977).

Primary crystallization of volcanic glass, which is crystallization while the deposit is still at magmatic temperatures (Green, in review; Lipman, 1965), often results in the formation of cristobalite, tridymite and/or feldspar and is not accompanied by major redistribution of elements. Rocks that have undergone primary crystallization, like the Devil Track and Kimball Creek rhyolites, may have compositions close to original magmatic compositions (Lipman, 1965). This is in contrast to rocks that have undergone secondary devitrification, occurring after initial cooling, which is accompanied by changes in alkali ratios. Noble (1965) suggested that cristobalite- or tridymite-bearing rocks are susceptible to sodium leaching, whereas quartz-bearing rocks are not. Glassy, porous margins of flows are especially susceptable to leaching of alkalis and silica by groundwater (Scott, 1970). Although the freshest possible samples of Devil Track and Kimball Creek felsite were chosen for analysis, they all are altered to some degree, probably both by deuteric- pneumatolytic processes and burial metamorphism. Some oxidation and kaolinization are ubiquitous and there probably has been some alkali and/or silica redistribution.

Geochemical Classification

Figure 33, Irvine and Baragar's (1971) alkali/silica diagram, is used to divide alkaline from subalkaline rocks below about 67 wt% SiO_2; above 67% the dividing line is not valid. The rocks in the study below 67% SiO_2 are all clearly subalkaline.

Although most samples are above 67% SiO_2, the graph is still useful as a basis of comparison between the Cook County felsites and other rhyolites. Sample KC-16 of the Maple Hill rhyolite is anomalously high in alkalies, similar to samples from the Canary Islands and Colorado. The Devil Track and Kimball Creek analyses plot in tight groups with the

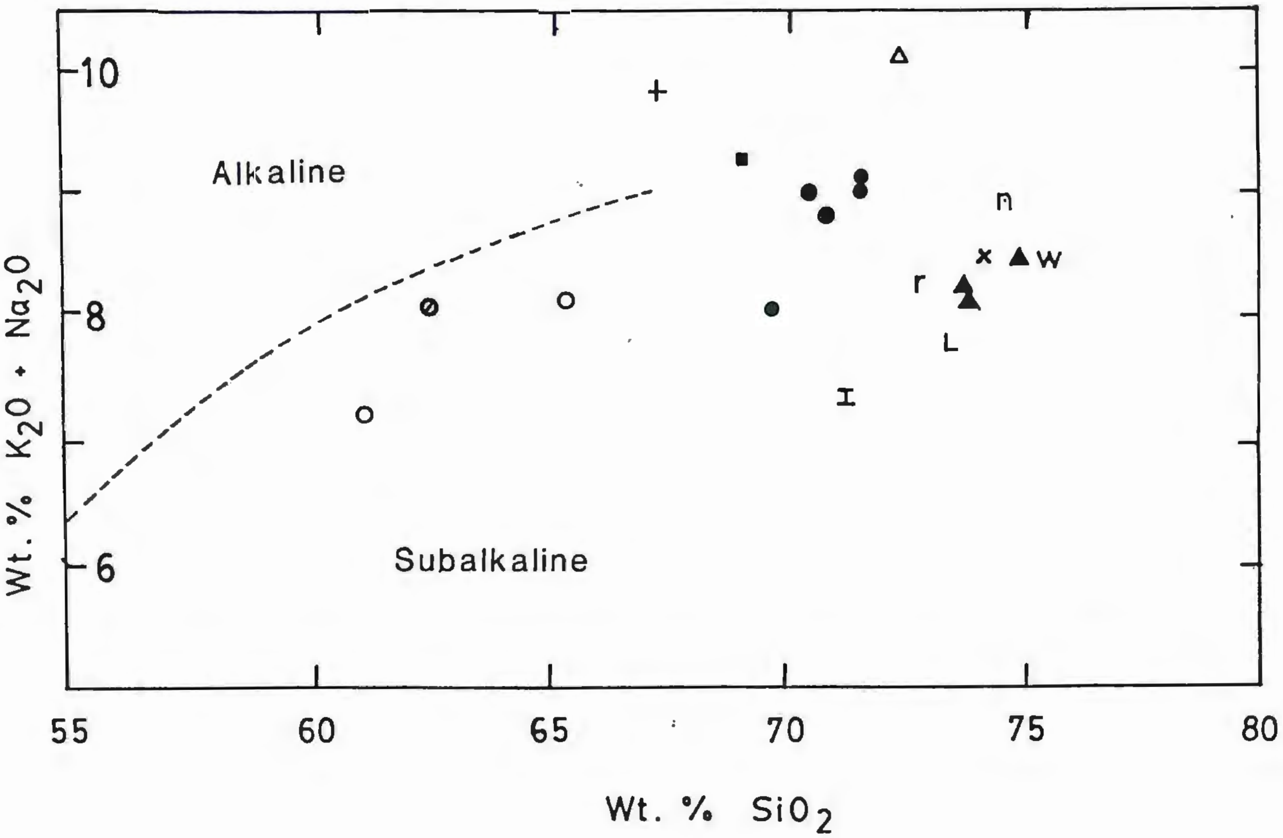


Figure 33. Felsites plotted on Irvine and Baragar's (1971) alkali / silica diagram with other selected rhyolites. Symbols are those shown in table 2.

Kimball Creek lower in SiO_2 and higher in alkalies than the Devil Track. The Devil Track plots near the Oregon and Nevada peralkaline rhyolites, and also near the Idaho and average rhyolites.

In Figure 34 the felsites are plotted on Irvine and Baragar's AFM diagram which subdivides subalkaline rocks into tholeiitic and calk-alkaline suites. The field outlined by the North Shore Volcanic Group is also shown (Green, 1972b). The division into tholeiitic and calc-alkaline generally is not applied to rhyolites but the three analyses from the intermediate units in this study are clearly in the tholeiitic field. The icelandites make up part of the iron-enrichment trend in intermediate rocks typical of tholeiitic suites such as the North Shore Volcanic Group.

In Figure 35 the felsites are shown on Irvine and Baragar's (1971) plot of normative plagioclase An composition versus color index. Color index is the sum of the percent of the mafic minerals in a rock, in this case the normative mafic minerals as calculated by the IGPET program. The Kimball Creek, Maple Hill, and Devil Track rhyolites plot in Irvine and Baragar's rhyolite field, whereas the Range Line icelandite unit and one of the two Kadunce icelandite samples plot in the dacite field. The other Kadunce icelandite sample

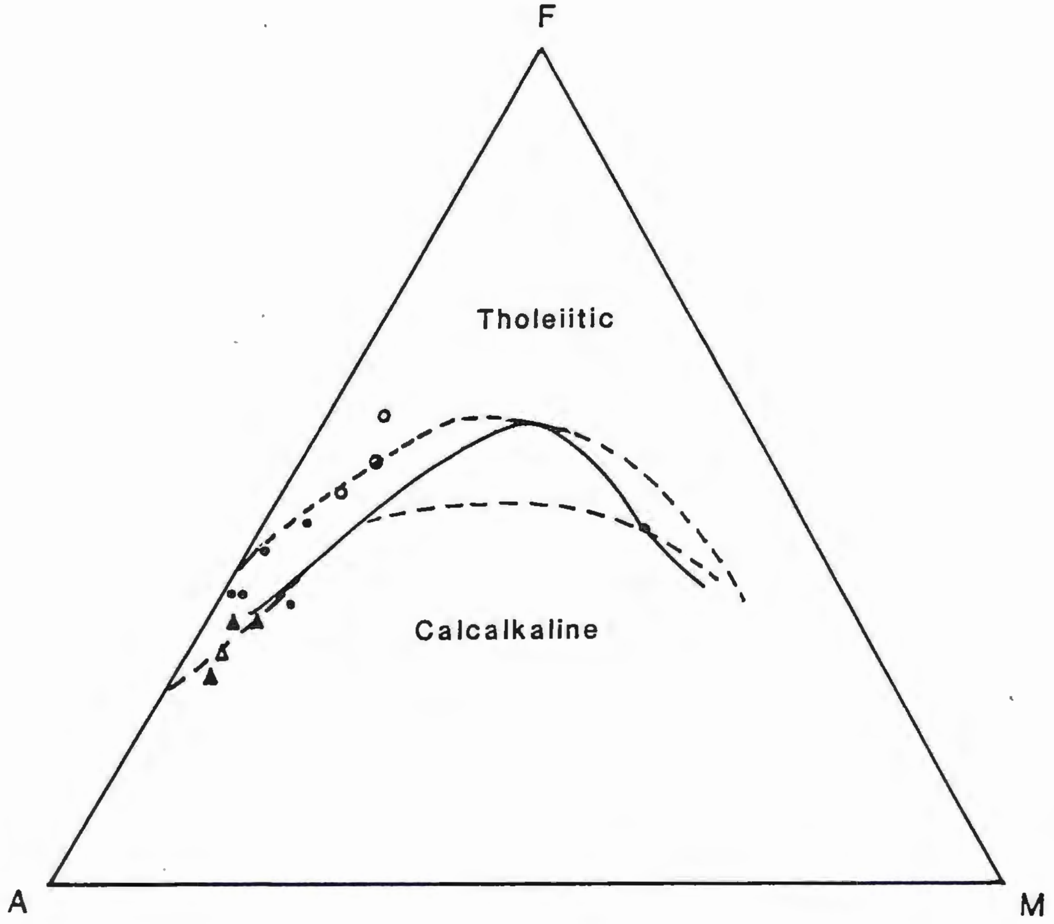


Figure 34. Felsites plotted on Irvine and Baragar's (1971) AFM diagram. The solid line divides calc-alkalkine from tholeiitic compositions, the dashed lines outline the area represented by the North Shore Volcanic Group (after Green, 1972b).

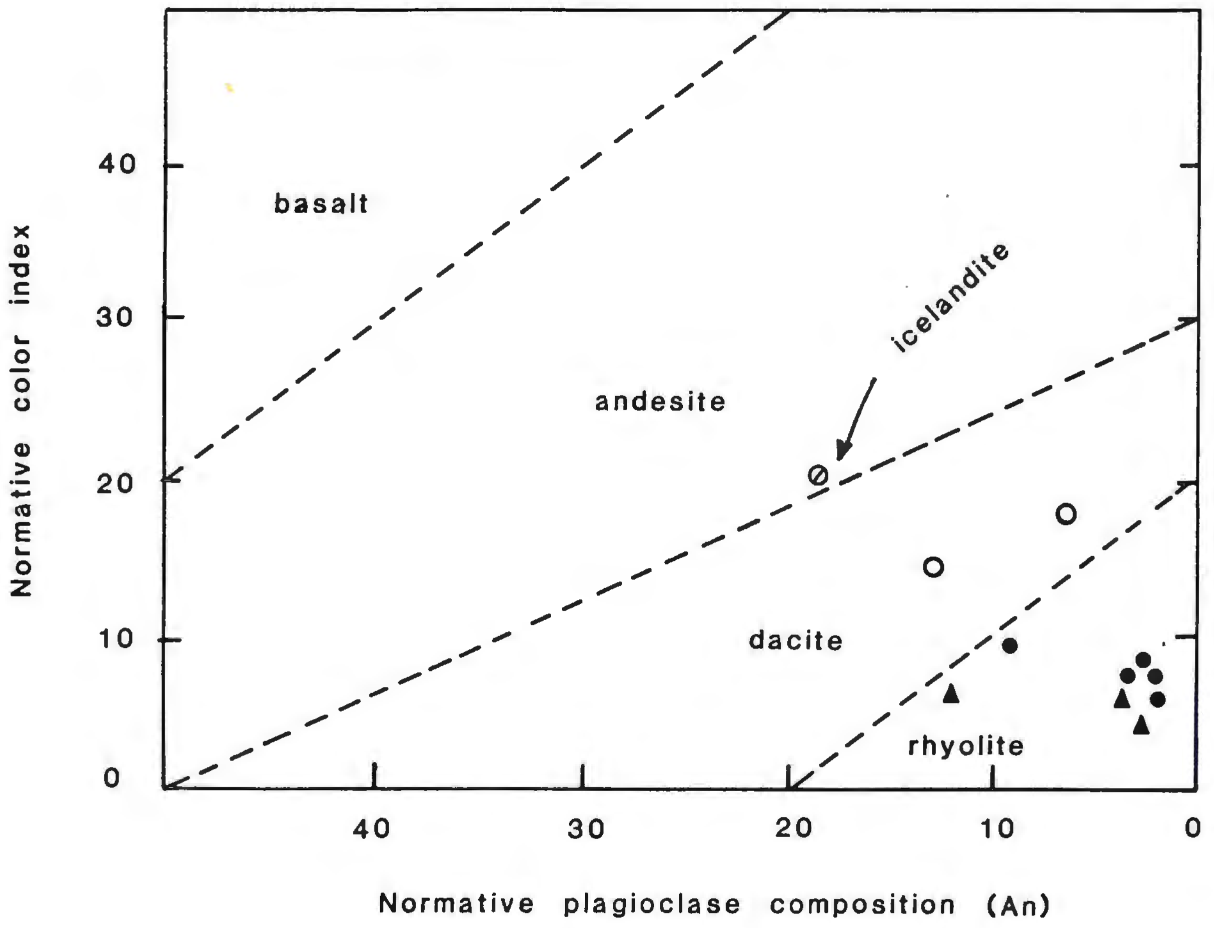


Figure 35. Felsites plotted on Irvine and Baragar's (1971) classification using plagioclase An composition verses color index. The values used here are normative values calculated using the IGPET program.

(KC-2) plots in the andesite field very close to the icelandite composition shown by Irvine and Baragar.

In the alkali versus silica plot of Middlemost (1980), the Devil Track and Maple Hill rhyolites plot clearly within the rhyolite field whereas all but one of the Kimball Creek anyalyses fall in the transitional rhyolite field of trachytic rhyolites (Figure 36). Irvine and Baragar's classification does not distinguish between dacite and trachyte however, and the two analyses that are dacites on Irvine and Baragar's plot are dacitic trachytes on the plot of Middlemost. One analysis (KC-2) of the Kadunce icelandite plots as andesite in the transitional field of between andesite and trachyandesite.

Geochemical influence on viscosity

Chemical composition of a volcanic deposit is one of the most important factors influencing the viscosity of the lava or glass and therefore how easily rheomorphic flow can occur. Field and experimental evidence indicates that Na, K, Ca, Mg and Fe have the effect of decreasing viscosity by inhibiting the polymerization of SiO_4 tetrahedra, whereas Si and Al increase viscosity (Chapin and Lowell, 1979; Ekren and others, 1984; Peterson, 1979; Schmincke and Swanson, 1967; Shaw, 1972; Walker and Swanson, 1968). Rheomorphism commonly is associated with ash of peralkaline composition such as the

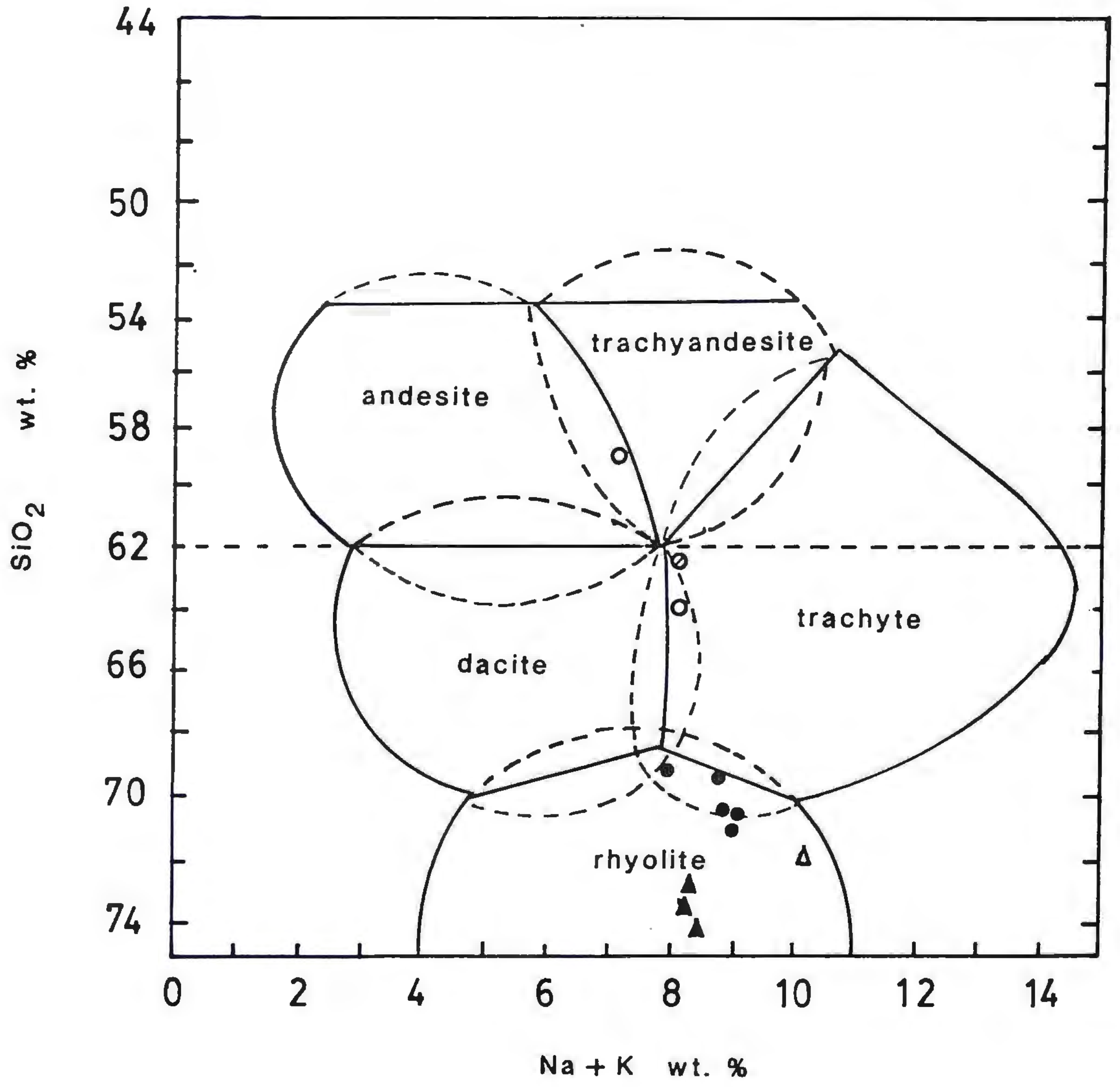


Figure 36. Felsites plotted according to the alkali / silica classification of Middlemost (1980).

rheoignimbrites in the Canary Islands, Trans-Pecos Texas and central Oregon. The high alkalies, and particularly Na/K ratios greater than 1, are thought to have contributed to the decreased viscosities in some of these rocks (Walker and Swanson, 1968).

The viscosity calculations represented in Figure 38 are meant to be used only for comparison of the effects of major-element compositions on relative viscosities and not as an accurate estimate of the viscosities. The effects of temperature and volatile content on viscosity are significant and may have had an even greater effect than differences in major element composition (Bonnichsen and others, 1988; Chapin and Lowell, 1979; Ekren and others, 1984; Friedman and others, 1963).

Figure 37 shows viscosity of selected rhyolites calculated for 900^{o} C without volatiles, after the method of Shaw (1972), plotted against percent silica. The fairly linear trend of increasing viscosity with increasing silica shows the strong dependence of viscosity on composition, particularly silica content. Because the temperature and volatile content (no volatiles) are constant, the spread of analyses away from the linear trend is due to the effects of components other than silica. The Wall Mountain tuff, for example, has a very high Al content which increases the viscosity relative to other samples with similar SiO_2 contents. Another example is sample KC-17 from the Kimball Creek rhyolite which has unusually low

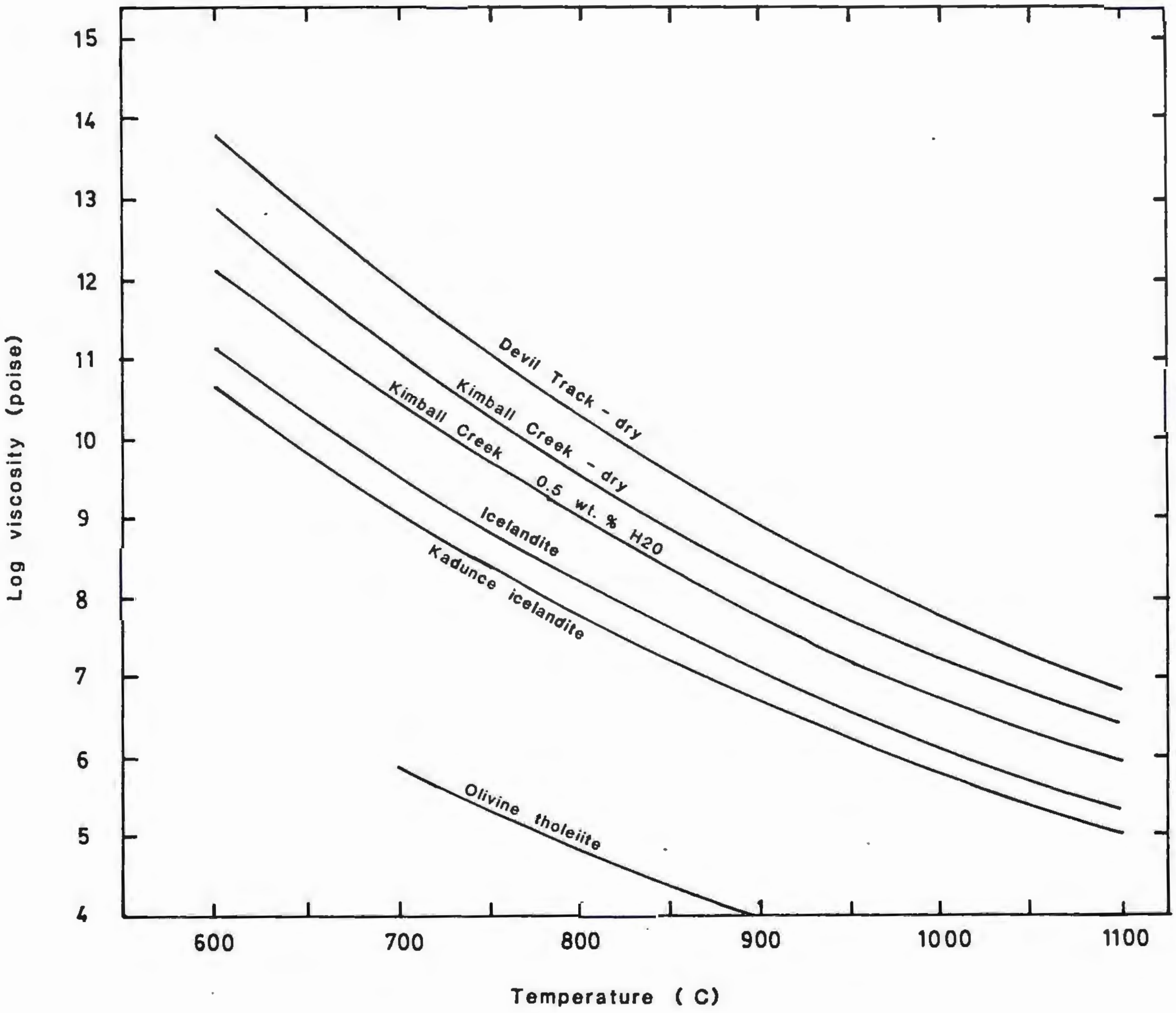


Figure 37. Graph of silica content versus log viscosity for the Cook County felsites and other rhyolites. Symbols used are those shown in table 2. Units interpreted as lava flows are underlined.

calculated viscosity due to the high iron, total alkalies and Na/K ratio.

The Devil Track and Kimball Creek rhyolites have compositions giving low viscosities relative to some other rhyolites as a result of their high iron and alkali contents. The Kimball Creek has lower silica as well, giving lower viscosities than all rocks used for comparison except the Canary Island rheomorphic peralkaline rocks. This indicates that the compositions of the Devil Track and Kimball Creek were favorable for rheomorphism. If there were major changes in the Na/K ratio or total alkali content during alteration, then the original compositions may have been more favorable for rheomorphism than the observered compositions. The compositions give viscosities that are relatively low for rhyolites yet are still several orders of magnitude greater than the viscosities of intermediate lavas such as the icelandites.

The strong influence of temperature and water content on viscosity is shown in Figure 38, which plots temperature versus viscosity for the Devil Track and Kimball Creek felsites. An increase in temperature of 100^{o} C or the addition of 0.5 wt. % water decreases the viscosity by two orders of magnitude.

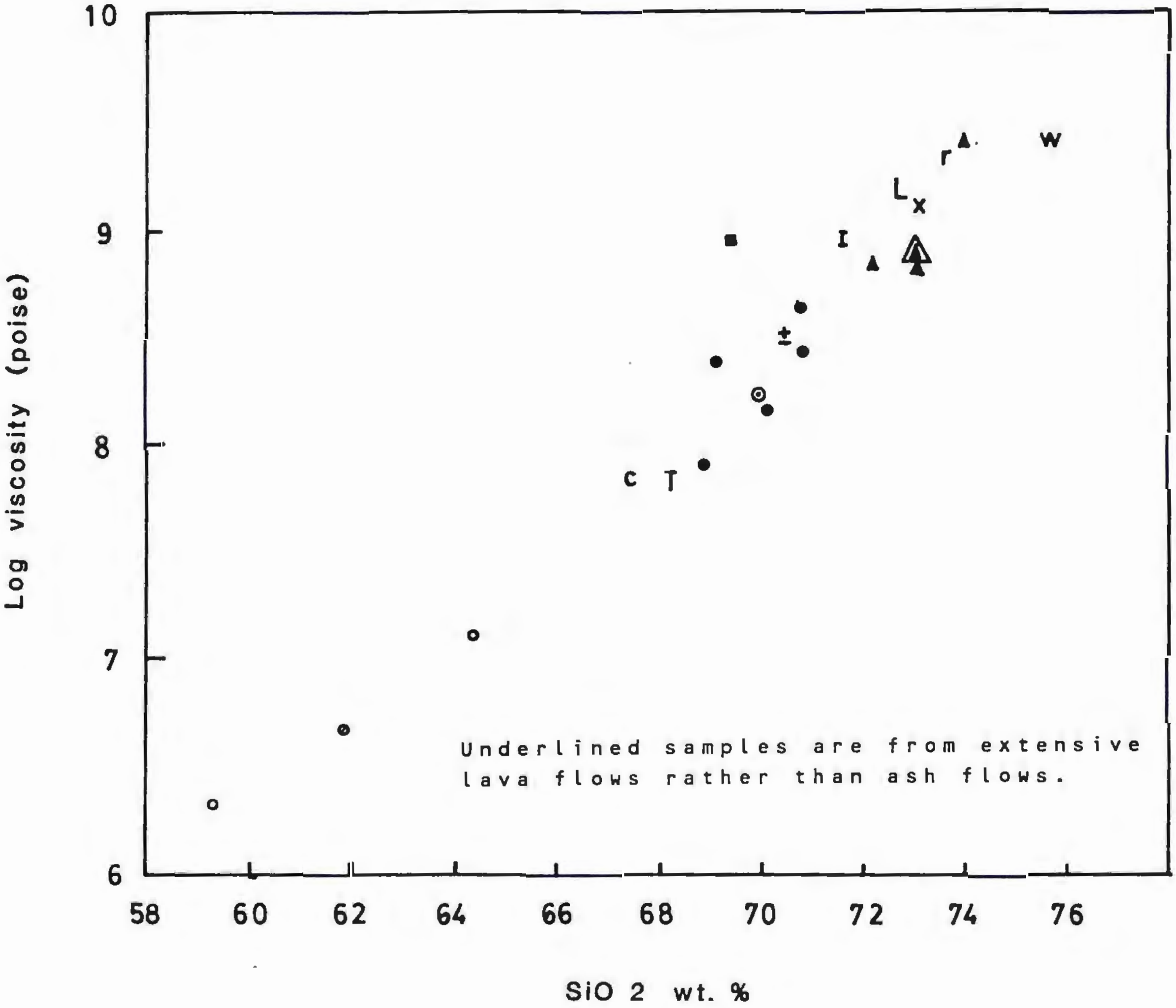


Figure 38. Graph of viscosity change with temperature for the felsites. The viscosities were calculated according to the method of Shaw (1972) using "Hardrock software". The olivine tholeiite basalt is the average of four samples from the North Shore Volcanic Group (Green, 1972b).

Several of the rhyolites shown in Figure 37, such as the Wall Mountain tuff in Colorado, the Wagontire tuff in Oregon and the Devil Track rhyolite have compositions giving high viscosities yet the rocks show evidence of high mobility during rheomorphic flow. The temperatures of these rhyolites must have been high to account for the lowered viscosities. The conclusion that a high temperature is the most important variable, more important than composition, allowing rhyolite to have low viscosities has been reached by many who have worked with rheoignimbrites and extensive rhyolite lava flows (Bonnichsen and Kauffman, 1987; Bonnichsen and others, 1988; Chapin and Lowell, 1979; Christiansen and Hildreth, 1988; Ekren and others, 1984).

Chemical variation in the sequence

Figure 39 is a plot of major elements versus stratigrapy in the felsite sequence. The trend in elemental composition with stratigraphy in the Kimball Creek felsite sequence is toward more felsic compositions upward, specifically decreasing TiO_2, $FeO+Fe_2O_3$, MnO, MgO, CaO and increasing SiO_2 upward (Figure 37). This trend, at least for most components, extends across the Red Cliff basalts upward into the Maple Hill and Devil Track rhyolites, which may represent an evolving magmatic system of which the Red Cliff basalts are not a part. This would imply different source regions and vents for the felsites and the intervening basalts, which is

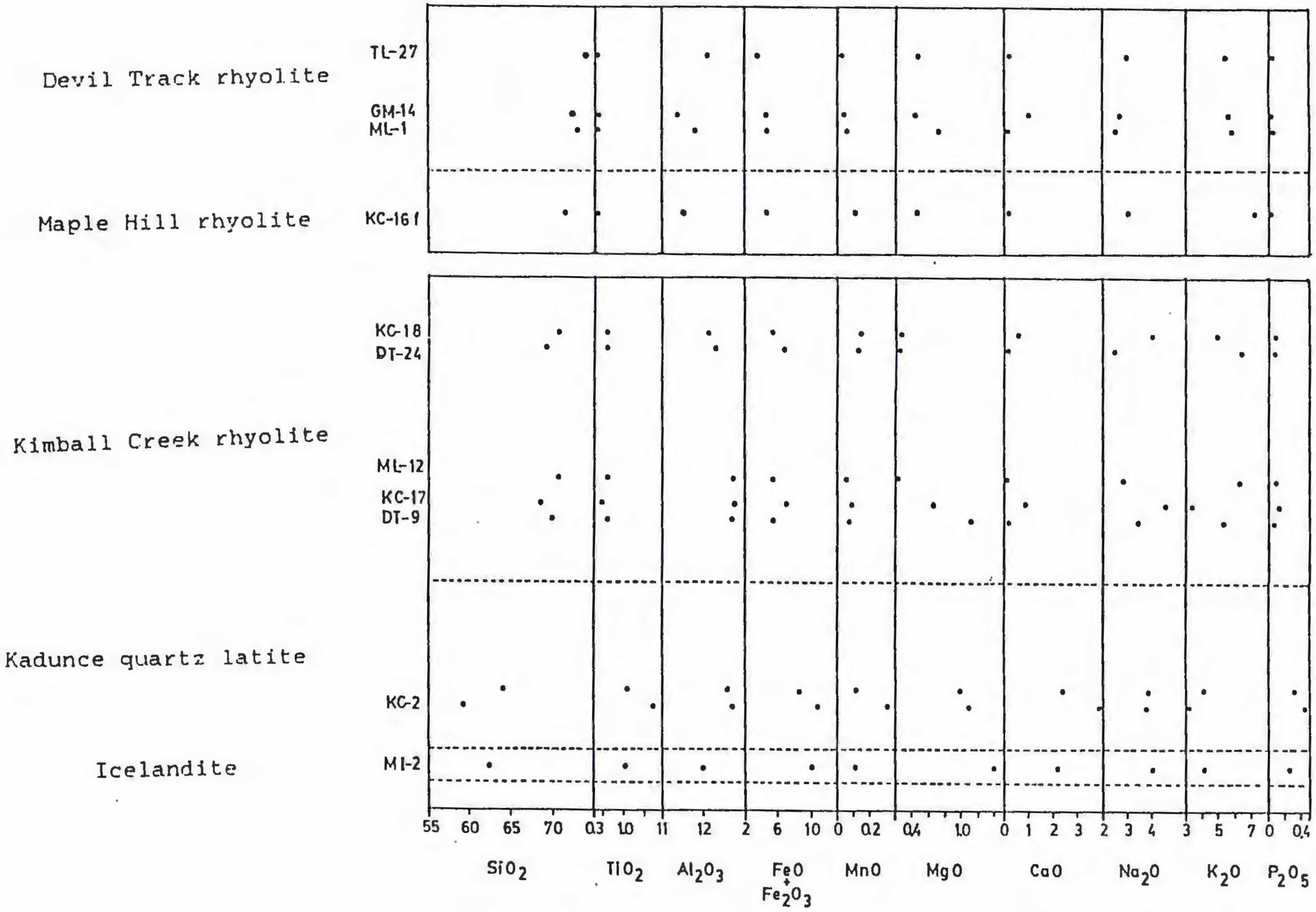


Figure 39. Major element composition of the felsites plotted against approximate stratigraphic position. Subtle trends within units may be masked by overlapping effects of chemical variations along strike.

feasible because they may have flowed far from their sources. The hypothesis that the felsites are part of an evolving magmatic system is tested in the section on petrogenesis.

Many large ignimbrites show a compostional trend vertically through the unit. The trend is usually toward more mafic compositions upward in the ash flow, which is the inverse of the zoning in the magma chamber from which the ash-flow was erupted (Hildreth, 1979). Unfortunately, the present chemical data for the felsites are insufficient to determine chemical trends within individual units for the following reasons: a) the analyses are from different positions along strike so the effects of lateral and vertical compositional variation may overlap and cannot be distinguished; b) the stratigraphic position of some of the isolated western outcrops cannot be accurately determined; c) there are too few chemical analyses to make any solid conclusions.

Petrogenesis

It is possible that the overall trend in the Kimball Creek-Devil Track felsite sequence of generally more mafic older flows overlain by increasingly felsic flows is the result of fractional crystallization of a parent magma. To test the hypothesis that the felsite units are genetically related as an evolving magmatic suite, fractional crystallization models were tested. Various geologically feasible assemblages of minerals were chosen as the crystallizing phases and entered into the IGPET program, which uses the least squares approximation method of Bryan and others (1969) to determine if the chosen daughter magma could be produced by the removal of the mineral assemblage from the indicated parent magma. Use of the IGPET program allows many parent/daughter and mineral assemblage combinations to be tested rapidly. All trials that had successful results with the major element modeling are presented in Appendix 7 together with the trace element results. A model in which the sum of the squares of the residuals is less than one is considered geologically feasible, the lower the number the closer the "fit".

Because no minerals in the felsites have been analysed, microprobe mineral analyses of other Minnesota Keweenawan rocks were used (Green, 1986). The analysed minerals are from intermediate rocks and are probably good approximations of the compositions of the minerals crystallizing from the parent magmas of the Cook County suite. No analyses of alkali feldspar are available however, so analyses were chosen from Deer, Howie and Zussman (1966). Average analyses of the units were used in the parent/daughter combinations and the compositions of the icelandites are assumed to be the parent magmas. Mineral analyses are presented in Appendix 5.

The first series of models tested made up a progressive fractionation scheme in which the parent icelandite composition underwent fractional crystallization to produce a magma of the composition of the Kimball Creek rhyolite. Magma of Kimball Creek composition then underwent further fractional crystallization of a different mineral assemblage to produce the Maple Hill rhyolite, which similarly gave rise to the Devil Track rhyolite. This scenario implies that the magma system was closed; that there was no magma added to the chamber. Thus the original parent eventually fractionated to produce each composition represented by the erupted felsites.

The second set of models tested whether each felsite composition could have been produced by fractionation directly from the parent icelandite composition. This would imply that the magma chamber was replenished with icelandite magma after each fractional crystallization and eruptive event, or that fractionation of icelandite magma took place in a different chamber for each eruptive unit. The more-felsic flows higher in the sequence would have been the result of removal of a higher proportion of parent icelandic magma by crystal fractionation. In this case the assemblage of minerals crystallizing remains constant compared to the step-wise fractional crystallization in which the steps from the composition of one unit to the next may have different minerals crsystallizing.

Another model tested is fractional crystallization of the Kimball Creek rhyolite to produce the Devil Track rhyolite. The results of these tests are discussed below.

Trace Elements

As an independent test of the fractionation models some trace elements were modeled for parent/daughter pairs that had good results for the major elements as indicated by low calculated residuals. Trace elements modeled were Sc, Cr, Sm, Eu, Th and Ni, although data for Ni are not available for the icelandite units. The trace element abundances were averaged for each unit for use in the calculations (Appendix 4). The theoretical trace element abundance in the daughter was calculated using the equation of Arth (1976):

$$C_d = C_i F'^{(D_s - 1)}$$

where

C_d = Concentration of a trace element in the daughter magma.

C_i = Concentration of the trace element in the parent magma.

F' = Fraction of liquid remaining after fractional crystallization.

D_s = Bulk distribution coefficient for an element
$= W^x K^{x/l} + W^y K^{y/l} + \ldots$

where

$K^{x/i}$ = solid/liquid partition coefficient for the given element in mineral x.

W^x = Weight fraction of each mineral x in the crystallizing assemblage.

The weight fraction of the crystallizing phases and the fraction of liquid remaining are from the results of the major element modeling. Concentrations of the trace element in the parent and daughter are from the chemical analyses, and the partition coefficients used for felsic rocks are from Allegre (1977), Cox and others (1979), Cullers (1981), Hanson (1977), and Leeman (1976), and are presented in Appendix 6. A sample calculation for Eu partitioning during fractionation of Kadunce icelandite to produce the Kimball Creek rhyolite is given below. Results from the IGPET calculations for the major element modeling for this combination are shown in Appendix 7.

$$C_d = Ci\ F'^{(Ds-1)}$$

$$Ds = (0.57)(2.1) + (0.23)(0.87) + (0.2)(0) - 1$$
$$Ds = 1.40 - 1 = 0.40$$
$$Cd = (2.91)\ (0.715)^{(0.40)}$$
$$= 2.54$$

The percent difference between the calculated value and the observed value is given by:

$$\frac{\text{Difference between calculated and observed}}{\text{Observed value}} \times 100 = \%\ \text{diff.}$$

$$= \frac{2.78 - 2.54}{2.78} \times 100 = 8.6\%\ \text{difference}$$

Considering the uncertainties in the analytical trace element values and in the assumed distribution coefficients, trace element models with less than 20% difference between the calculated value and the observed value are considered to be good results.

Results

The major element models show that fractionation could have taken place in a step-wise fashion from either icelandite parent to produce the Kimball Creek and Maple Hill (numbers 1-6 on Table 5), but not the Devil Track rhyolite. Fractionation of plagioclase, augite, and magnetite with or without olivine, from either icelandite parent could produce the composition of the Kimball Creek. This model is especially important because those are the phenocrystic phases in the icelandite units. Trace element modeling for these combinations also showed good results, suggesting the Kimball Creek originated by fractional crystallization of icelandite magma.

From the composition of the Kimball Creek rhyolite further fractional crystallization of the assemblages a) plagioclase and magnetite; b) quartz, plagioclase and magnetite; or c) alkali feldspar, quartz and magnetite, could produce the composition of the Maple Hill rhyolite. Using the phenocryst

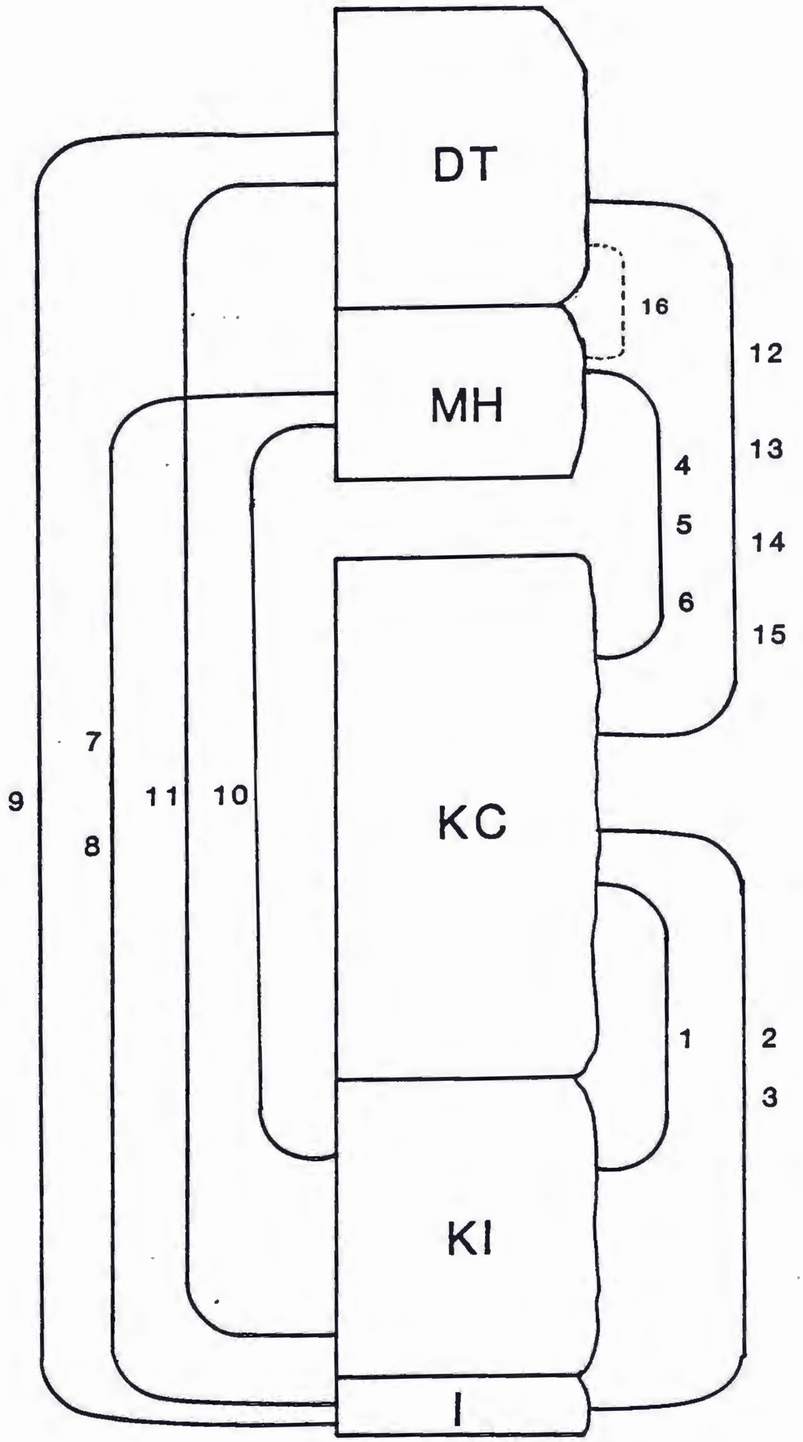


Figure 40. Diagram of a stratigraphic column of the felsites showing the parent/daughter pairs used in the petrogenetic modeling. The daughter is the stratigraphically higher of each pair. Abreviations and numbers correspond to those in Table 5. The dashed line joining the MH/DT pair indicates melting rather than fractional crystallization.

Table 5.

Number	Parent	Daughter	Fractionating minerals	Sum of residuals	Trace elements within 30 % diff.
1 #	KI	KC	plag, cpx, mag	.241	Sc, $\underline{\text{Sm}}$, $\underline{\text{Eu}}$, $\underline{\text{Th}}$, n*
2 #	I	KC	plag, cpx, mag	.291	Sc, Cr, (Sm), $\underline{\text{Th}}$, (Eu), n*
3	I	KC	plag, cpx, mag, ol	.261	Sc, $\underline{\text{Cr}}$, $\underline{\text{Th}}$, (Sm), (Eu), n*
4	KC	MH	plag, mag	.875	Cr, Ni, (Th)
5	KC	MH	qtz, plag, mag	.227	Cr, $\underline{\text{Eu}}$, (Th)
6	KC	MH	qtz, kfsp, mag	.156	Cr, (Eu), (Th)
7 #	I	MH	plag, cpx, mag	.652	(Cr), (Eu), (Th), n*
8	I	MH	plag, cpx, mag, ol	.514	$\underline{\text{Cr}}$, (Eu), Th, n*
9	I	DT	plag, cpx, mag, ol	.622	$\underline{\text{Cr}}$, $\underline{\text{Th}}$, n*
10 #	KI	MH	plag, cpx, mag	.243	(Sm), $\underline{\text{Eu}}$, Th, n*
11 #	KI	DT	plag, cpx, mag	.433	(Eu), $\underline{\text{Th}}$, n*
12	KC	DT	plag, mag	.248	Th
13	KC	DT	qtz, plag, kfsp, mag	.248	(Cr), $\underline{\text{Ni}}$
14	KC	DT	qtz, plag, kfsp, cpx, mag	.164	$\underline{\text{Ni}}$
15	KC	DT	plag, kfsp, mag	.170	Ni
16*	MH	DT	kfsp, qtz, mag	.160	$\underline{\text{Sm}}$, (Th)

Abreviations: # = models with phenocryst assemblage the same as that observed in the parent
* = assimilation of phenocrysts rather than fractional crystallization
I = Icelandite
KI = Kadunce icelandite
KC = Kimball Creek rhyolite
MH = Maple Hill rhyolite
DT = Devil Track rhyolite
qtz = quartz
plag = plagioclase
kfsp = alkali feldspar
cpx = clinopyroxene (augite)
mag = magnetite
ol = olivine

$\underline{\text{Sm}}$ = Less than 10 % difference between calculated and observed

(Sm) = 20% - 30% difference

Table 5. Results of fractional crystallization modeling. The numbers in the first column coincide with those shown in Figure 40.

assemblage observed in the Kimball Creek rhyolite (plagioclase, alkali feldspar, magnetite and augite) did not have positive results; at least one of the minerals had to be melted in order to produce the daughter Maple Hill composition. Three of the six trace elements modeled had fairly good results. It is possible the Kimball Creek fractionated to create the Maple Hill, but the results do not give strong evidence for or against these models.

The next step in the modeling, fractionation of the Maple Hill to create the Devil Track, did not give any positive results even though all possible combinations of the observed phenocryst assemblage (plagioclase, alkali feldspar, quartz and magnetite) were tried. In each model one or more minerals had to be melted to produce the Devil Track.
Other evidence that the Devil Track magma did not originate by fractional crystallization of the Maple Hill magma is their apparent difference in temperature. The phenocryst assemblage in the Maple Hill indicates a much lower temperature than is indicated by the aphyric nature of the Devil Track. One possible interpretation is that the Maple Hill magma was heated, causing increased convection within the magma, stirring of the quartz, feldspar, and magnetite crystals that had settled, and melting of these minerals to produce the Devil Track rhyolite.

The next set of models tested were fractionating the icelandite parent directly to the Maple Hill and Devil Track rhyolites (numbers 7-11 in Table 5). Fractionating plagioclase, augite and magnetite, with or without olivine, could produce the Maple Hill or Devil Track. In these trials only 2 or 3 of the 5 trace elements modeled showed positive results.

The results of the two sets of models for the production of the Devil Track felsite sequence are too similar to determine whether the sequence was produced by direct fractionation of the icelandite parent or from the Kimball Creek rhyolite, but the models provide a close enough fit to suggest the Kimball Creek and Devil Track felsite sequences may be genetically related. Magma mixing or assimilation of wall rocks or xenocrysts could have affected the composition of the daughter magmas and may account for the poor fit of the trace elements.

The last set of models tested fractionation of the Kimball Creek to produce the Devil Track (numbers 12-15 in Table 5). Low residuals were achieved for some models, but fractionation of the phenocryst assemblage in the Kimball Creek (plagioclase, alkali feldspar, clinopyroxene and magnetite) does not fit because one or more of the minerals would have to be melted to produce the Devil Track. Trace element models did not give positive results either since only 1 of the 6 elements calculated had less than 20% difference between the calculated and the observed values. It is more likely that the Devil Track originated by fractional crystallization directly from the icelandite parent or originated from the Maple Hill rhyolite by heating and melting of quartz, feldspar and magnetite crystals.

CHAPTER VI:

VOLCANOLOGICAL INTERPRETATIONS

Introduction

All the units in this study are too fine-grained to have been hypabyssal intrusions so they must have originated as ash flows, lava flows, or air-fall deposits. Distinguishing welded tuffs from lava flows is a common problem compounded in situations where the ash was strongly welded and crystallized and/or flowed as a viscous liquid (Bonnichsen and Kauffman, 1987; Ekren and others, 1984; Smith, 1960). The diagnostic features of these types of deposits are reviewed below.

Problems with the interpretion of felsic volcanic units arise because of variability within lava flows and ash flows, and because some diagnostic features may or may not be found in either. The variability in both types of deposits is due to differences in 1) the magnitude of eruptions (rate of eruption, volume of lava or ash) and 2) the physical properties of the material, especially the viscosity, which is determined largely by temperature and chemical composition, including volatile content.

Rhyolite lava flows are typically quite viscous and flow about 1-2 km or less from their vents. The result is usually short, thick flows with aspect ratios of about 1/8, and rarely less than 1/50 (Walker, 1973). The movement of the viscous lava generally produces complexly folded flow bands that may vary in attitude with position in the flow. The center generally has laminar fluidal banding; the upper part has steep, contorted and discontinuous banding. Ramp structures are common and foliation surfaces may have linear markings (Christiansen and Lipman, 1966). Movement also commonly causes autobrecciation resulting in breccia zones 2-10 m thick enveloping the more massive or foliated central part of the flow (Bonnichsen and Kauffman, 1987; Christiansen and Lipman, 1966; Ekren and others, 1984). Pumiceous and glassy zones, vitrophyres, rootless dikes and breccia zones may be present locally in the centers of flows (Bonnichsen and Kauffman, 1987; Fink, 1983). Most lava flows have highly vesicular tops, blunt, lobate flow margins and some have giant gas cavities. Phenocrysts generally are intact, except perhaps where autobrecciation was intense.

Distinguishing lavas from ash flows may be difficult not only because the features of some hot ash flows overlap with features characteristic of lava flows, but also because some unusual rhyolite lavas travel great distances. The most-important variables affecting the distance a lava flow can travel are the viscosity, the effusion rate, total volume of material, and the slope and form of the topography. High effusion rates generally produce extensive, simple units whereas lower rates result in complex sequences of shorter flow units (Walker, 1973; Malin, 1980). There are extensive rhyolite lavas in the Snake River Plain area in Idaho with long dimensions of at least 40 km (Ekren and others, 1984; Bonnichsen and Kauffman, 1987). Some of these lava flows had a relatively low silica content, 70% SiO_2 compared to 72-74% for most rhyolites, and are inferred to have been erupted at unusually high temperatures, about 900-1100 °C, decreasing the viscosity by three orders of magnitude. The relatively low viscosity probably combined with a very high eruption rate to allow the flows to travel great distances (Bonnichsen and Kauffman, 1987). There are also extensive rhyolite lava flows in Yellowstone National Park, Wyoming which have maximum dimensions of 25 - 32 km, leading Christiansen and Hildreth (1988) to point out that size, extent, and aspect ratio alone can not be used to distinguish lavas from tuffs.

The distinguishing features of pyroclastic rocks were first well described by Smith (1960) and Ross and Smith (1961). Smith wrote the following concerning the recognition of welded tuffs (Smith, 1960, p. 820-821):

> No single criterion is in itself infallible. The ultimate criteria are those that establish that the rock is or was composed of vitric, at least in part, pyroclastic materials, chiefly glass shards and pumiceous fragments, and that these have been deformed and welded while still hot. The writer has found that the most pertinent observations are usually made at or near the base of the unit in question.

Other features common to ash flows are widespread broken phenocrysts, rock fragments, gas escape structures, and vertical and lateral zonations. Ash flows, particularly large ones, usually have a vertical chemical zonation resulting from the progressive evacuation of vertically zoned magma chambers (Hildreth, 1981; Smith, 1979). They also may have zonation of physical features imparted during deposition and cooling, such as foliations, varying degrees of welding and crystallization and lithophysal zones (Ross and Smith, 1961). Ash flows may also exhibit vertical and lateral sorting, with dense particles such as rock fragments and crystals concentrated closer to the vent and lower in the flow whereas lighter objects such as fine ash and pumice are concentrated upward in the flow and further from the vent (Fisher and Schmincke, 1984). Ash flows generally thin gradually toward the flow margins and have smooth top surfaces.

Another useful criterion for recognizing ash flows is their large extent and deposition over topographic highs as a result of their very high mobility. The large extent in relation to thickness gives low aspect ratios (thickness/extent), generally less than about 1/400 (Walker 1983) except where they form a deep caldera fill. Large ash flows commonly travel tens of kilometers and may travel as far as 225 kilometers from their vents (Cass and Wright, 1987).

The diagnostic features of ash flows, specifically fragmental textures, may be obscured in hot flows, especially if they are 50-100 meters or more thick. Large, hot flows may weld to a compact glass in which shards and pumice fragments are so compressed they resemble fluidal banding in rhyolite lavas. Crystallization may further obscure fragmental textures by crystals growing across pyroclast boundaries. The situation may be even further complicated if the hot glass is of low enough viscosity to allow viscous flow during or after emplacement of the ash flow. Such deposits, known as "rheoignimbrites", contain many of the flow structures common to felsic lavas such as flow bands, folds, lineations, ramp structures and lineated vesicles. They each may have resorbed phenocrysts and similar crystallization products, spherulites, lithophysae or vapor-phase crystallization that precipitates tridymite or cristobalite. Rheoignimbrites in effect become lavas and only at the top, the bottom and the distal edges may they give evidence of a pyroclastic origin.

Examples of welded tuffs with rheomorphic structures are found in the Canary Islands (Schmincke and Swanson, 1967), Nevada (Hoover, 1964), Texas (Price and others, 1986), Colorado (Chapin and Lowell, 1979), and Idaho (Bonnichsen and Citron, 1982; Ekren and others, 1984). Some of these controversial deposits have been interpreted as both lavas and ash flows.

A third but less-likely possible origin of the Devil Track and Kimball Creek felsites is that they originated as ash falls. Ash falls are generally fine-grained, bedded, extensive deposits which have low aspect ratios and are generally cool during deposition and thus show clear pyroclastic textures and no welding. However, there are exceptional ash falls which were deposited at high temperatures and resemble both lava flows and ash flows. Pantelleritic air-fall tuffs in the Canary Islands were not only hot enough to weld throughout their thickness, but were of low enough viscosity to flow after emplacement (Wolff and Wright, 1981). Thus they may resemble rheoignimbrites in their physical characteristics.

It is unlikely the Devil Track and Kimball Creek felsites were ash falls because they lack bedding and, furthermore, the transportation and deposition of ash over such large areas at the high temperatures that evidently existed in these units requires that the ash traveled in ash flows which conserve heat well.

The interpretations of most units in the Devil Track and Kimball Creek felsites are difficult not because they have much conflicting evidence, but because they lack many features diagnostic or typical of either lava flows or pyroclastic rocks. Since definite criteria are lacking, the final interpretation cannot be made on one detail but must take all features into account. The general format for the interpretation of each unit is: 1) consideration of the dimensions of the unit, 2) review and evaluation of the evidence for a lava flow origin and the problems with that interpretation, 3) the same for a pryroclastic origin and finally, 4) the favored interpretation and its implications.

Basal quartz latite

The lowest unit in the Kimball Creek felsite, the basal quartz latite, has an extent of at least 7 km and aspect ratio of 1/175 for the definite outcrops, which is more typical of pyroclastic flows than lava flows. If the westernmost outcrop is of the same unit, then the 23 km extent and aspect ratio of about 1/625 is that of a high aspect ratio ignimbrite.

The unit has some features suggestive of a lava flow and some of a pyroclastic flow. The lineated vesicles in the lowest 1 m appear similar to vesicles in lava flows sheared by movement of the lava. Although much of the unit lacks any visible structures in outcrop, there are vertical bands in some areas in the upper part of the unit, perhaps similar to the vertical flow bands common to rhyolite lavas or rheoignimbrites (Cass and Wright, 1987).

There are problems with the lava flow interpretation however, such as the extent of the unit and the lack of flow breccias. Although the top of the unit is not exposed and may contain valuable information, flow bands and vesicles are not as common in the available exposures as would be expected in a rhyolite lava flow.

The pyroclastic flow interpretation is supported by two samples that have weathered surfaces showing vague tabular, angular fragments. In thin section the fragments closely resemble fiamme, some of which are bent around phenocrysts (Figure 8). The abundant rock fragments concentrated near the base of the unit are consistent with the typical zonation of ash flows.

Stratigraphically above the highest definite outcrop of the basal quartz latite is an outcrop of unwelded ash. Because only one isolated exposure of this rock type was found, it is unknown how thick or extensive the rock is. It may be a separate unwelded ash flow or air-fall unit or it could be the unwelded top or bottom zone of a larger ash flow. The phenocrysts are similar to those of the underlying quartz latite which would permit it to be the unwelded top zone of the basal quartz latite ash flow.

There are problems with the pyroclastic interpretation as well. Most of the groundmass is homogeneous and lacking in visible pyroclasts. The unit also lacks an unwelded basal zone, broken phenocrysts, and zonation of devitrification and crystallization features.

Although there is not overwhelming evidence for either interpretation, the ash flow interpretation is favored because of the presence of probable fiamme, the low aspect ratio of the unit, and the concentration of rock fragments near the base. It is interpreted to have been deposited by a hot ash flow that became welded all the way to the base of the deposit, then underwent viscous flow which could have developed the vertical flow bands. Gas exsolving from the glass near the base formed vesicles lineated parallel to the direction of flow. Compaction and flow of the deposit probably deformed shards and pumice lapilli to the extent that much of the unit became homogeneous glass lacking recognizable pyroclasts.

Range line icelandite

The Range line icelandite unit has no evidence of being a pyroclastic flow but has some features indicative of a lava flow origin. Because ash flows of intermediate compositions tend to be less crystallized than rhyolitic ash flows (Smith, 1960) and this unit is holocrystalline, lacking any evidence of secondary devitrification, it is likely that crystallization of the groundmass was largely from a melt and not from glass. The phenocrysts are commonly in clusters that probably would not have remained intact during an explosive pyroclastic eruption. The lineated and spherical vesicles and amygdules that are progressively more abundant higher in the unit are consistent with a lava flow.

The only problem associated with the lava flow interpretation is the large extent of the unit, apparently at least 27 km. Although all exposures of this unit are similar and there is no evidence of its being a series of separate lava domes or short flows, that possibility cannot be ruled out. If the unit is a series of shorter lava flows erupted along a fissure, then the present erosion level must be approximately parallel to the length of the fissure, which would be unlikely. No flow bands or breccia zones have been documented, but these are generally lacking in less-viscous intermediate lava flows (Cass and Wright, 1987).

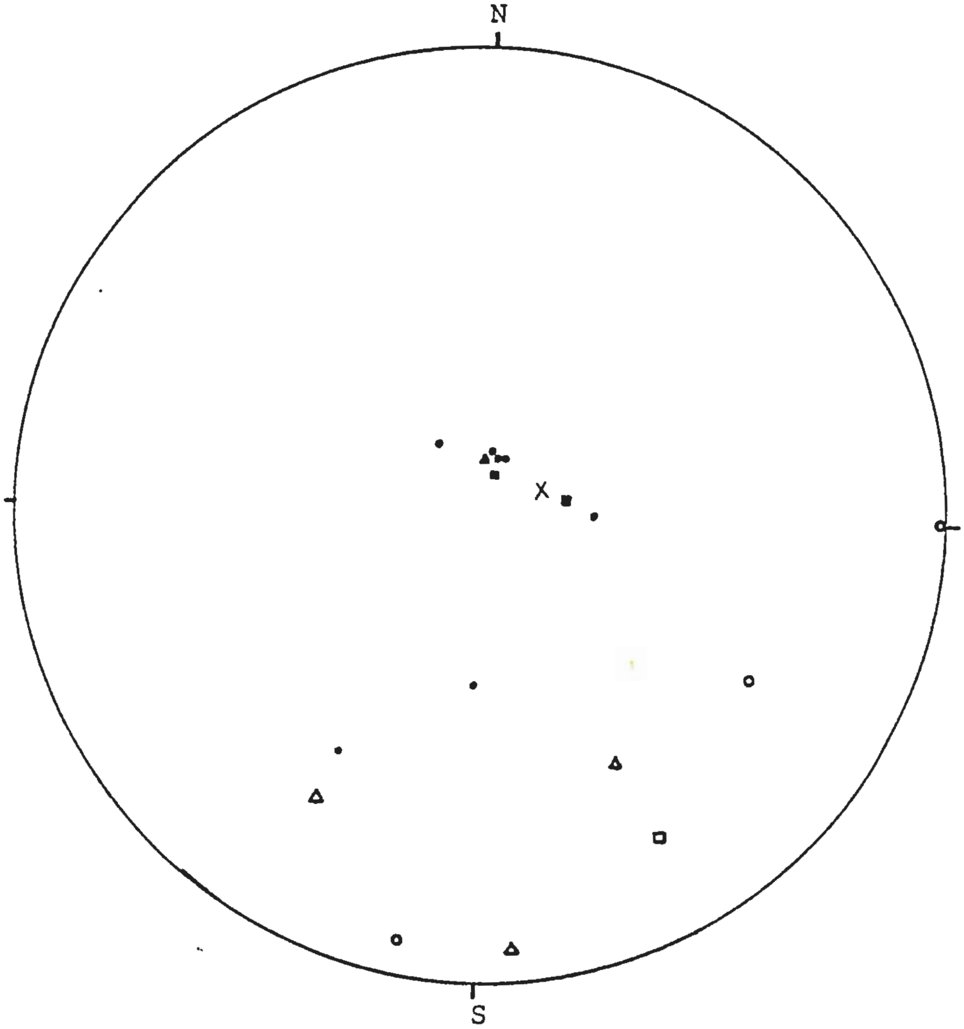
Kadunce Icelandite

Although of uncertain extent, this unit appears to have a lower aspect ratio than most felsic and intermediate lava flows, approximately 1/100, but maybe as high as 1/75.

There is no evidence to suggest the Kadunce icelandite is a pyroclastic unit but there are indications it is a lava flow. The groundmass is holocrystalline, composed primarily of plagioclase, alkali feldspar and quartz with no spherulites, lithophysae or any relict pyroclasts. Long slender plagioclase phenocrysts (0.4 mm x 5 mm) and clusters of phenocrysts are unbroken, all of which are consistent with the lava-flow interpretation. Near the top of the unit the rock is highly vesicular with thin strands of rock between vesicles suggesting the chilling of a frothy, viscous liquid.

Interpretation of structures in the lowest three units

The structural features measured in the three lower units of the Kimball Creek felsite are plotted on a stereographic projection in Figure 41. Most of the measured sheeting joints plot fairly close together and close to the attitude of the only exposed contact in the area. The similarity of the attitudes of most sheeting joints to that of the contact indicate that the joints are roughly parallel to the base of the flow and reflect the attitude of the unit. The vesicle lineations are variable but have generally southerly trends and plunges between 4° and 25°. After accounting for the 12° dip of the units, 2 of the vesicle lineations indicate a flow direction toward the southeast, 2 to the north and 1 each to the east-southeast and southwest. Data are too limited to determine whether the variable pattern reflects flow away from a central area or local variations in flow direction due to minor topographic features.



× Pole to flow contact at base of quartz latite

■ Sheet joints in the quartz latite

□ Vesicle lineations in the quartz latite

▲ Sheet joints in the Range Line icelandite

△ Vesicle lineations in the Range Line icelandite

● Sheet joints in the Kadunce icelandite

○ Vesicle lineations in the Kadunce icelandite

Figure 41. Stereographic projection of structural features in the lower three units of the Kimball Creek felsite sequence.

Kimball Creek rhyolite

Introduction

The interpretation of the Kimball Creek rhyolite, like all the extensive felsite units in this study, is problematic due to the scarcity of evidence for either a lava flow or an ash flow origin. The majority of exposures of the unit are homogeneous, fine-grained rhyolite without recognizable internal stratigraphy or structures. The uniform, holocrystalline groundmass is likewise lacking any textures diagnostic of either a lava- or ash-flow origin and few broken phenocrysts were found. The rare exposures near the top and bottom of the unit, however, contain valuable information about emplacement.

Dimensions

The aspect ratio for that part of the unit exposed on land is much smaller than aspect ratios of rhyolite lavas, but is typical of ignimbrites. With at least 32 km of strike length, the unit is more extensive than typical rhyolite lava flows. However, the original extent of the rhyolite was probably much greater than the 32 km now exposed on land and perhaps larger than the assumed 64 km value in Table 1-B, so the aspect ratio of the original deposit was probably smaller than 1/182. The calculated minimum volume of the unit (Table 1-A) is also far greater than can be expected in a rhyolite lava flow but is reasonable for a large ignimbrite.

There may be reason to believe the original extent of the deposit was larger than even the extrapolated value of 64 km. The unit appears to thin toward the west but is still at least 150 m thick at the Cascade River, the western-most known exposure, which suggests the unit does not pinch out near the Cascade, but probably extends well beyond the known 32 km strike length. There also may have been a large volume of rhyolite contained in unexposed intra-caldera deposits and there is no way of knowing how much of the unit is concealed under Lake Superior. The volume calculations also ignore the high density of the Kimball Creek in comparison to most ignimbrites that contain appreciable pore space, as high as 20% in densely welded rocks and up to 50% in poorly welded rocks (Cass and Wright, 1987; Peterson, 1979). Although the initial porosity of the deposits is uncertain, anhedral quartz, deposited in cavities after the units had cooled, makes up only a few percent of the rocks indicating they were of low porosity. The calculated dimensions are thus minimum figures and there is no indication of how large the deposit could have been.

Evidence of extrusion as lava

The only evidence of a lava flow origin for the Kimball Creek rhyolite is the presence of flow structures: folded bands and lineations near the top and bottom of the unit. However, flow structures can be found in either lava flows or rheoignimbrites so these structures are not diagnostic of origin. There are other problems associated with the lava flow interpretation, such as the lack of flow bands in the middle of the unit and lack of breccias. Exposures within 5-10 m of the base of the deposit and 40 m of the top of the unit are flow-banded but not brecciated. However, breccia zones may be only 2-10 m thick and have sharp boundaries with massive rhyolite in lavas (Bonnichsen and Kauffman, 1987; Christiansen and Lipman, 1966) so may be concealed at the base or top of the Kimball Creek. Spherulites, lithophysae, rootless dikes and vesicles, which are common to felsic lava flows, are scarce or completely missing from the Kimball Creek rhyolite.

Evidence favoring explosive eruption

Unfortunately, the very base of the Kimball Creek rhyolite is not exposed, but rock within 5-10 m of the base contains informative features. There are abundant wavy, subparallel light-colored streaks forming a foliation which is folded. The light streaks are set in a groundmass so fine that in thin section only some microlites are visible and much of the rock is too fine to be identifiable. A possible interpretation of this outcrop is that the groundmass was a dense vitrophyre and the light streaks were firmly welded and compressed pyroclastic fragments (fiamme), now accentuated by weathering. Dense vitrophyres are common near the bases of large pyroclastic flows. The folding could have been caused by viscous flow of the hot glass during and/or after deposition from an ash flow. Another interpretation of the streaks and veinlets is given later with the discussion of the Devil Track rhyolite.

Phenocrysts make up about 5-7% of the rock at the base compared to 2-3% in the rest of the unit, and although rock fragments are rare in the unit, several were found at the lowest exposure. This observation is consistent with the description of many other ignimbrites which commonly are graded with respect to crystals and rock fragments (Fisher and Schmincke, 1984). Other evidence of a pyroclastic origin is the presence of occasional broken phenocrysts.

Another outcrop with possible evidence of origin is found just south of Devil Track Lake near the top of the deposit. The rock has alternating layers of fragment-rich and fragment-poor rock, perhaps suggesting segregation of fragments during flow in a pyroclastic flow. The light-colored angular fragments found in the rock at this location resemble pumice fragments completely flattened to form a foliation. This rock closely resembles rock found exposed in the Cascade River, 10 km to the west, presumably at about the same stratigraphic position, although the fragments are not as definite.

The most-convincing evidence of a pyroclastic origin is found at the highest known outcrop of the Kimball Creek rhyolite at the shore of Lake Superior. The dark red fragments found at this location are almost certainly fiamme. The fragments are elongate with an internal foliation parallel to the long axis of the fragment. This suggests flattening of pumice and elimination of all pore spaces to create a eutaxtic texture. Compaction caused fragments near phenocrysts to be bent around the phenocrysts.

In the area south of Devil Track Lake, the lower of the two rhyolite exposures has a texture that hints at being made up partly of fragments. The outcrop just to the south and stratigraphically higher has more-distinct fragments and the highest known outcrop at the shore of Lake Superior has even more-definite fragments. These exposures suggest that there is a progressive transition upwards from no visible fiamme in the middle of the unit, to highly deformed fiamme, to flattened but less-deformed fragments near the top. This transition is accompanied by a change in the groundmass quartz from plates decreasing in size upward from the middle of the unit, to anhedral quartz higher in the unit where crude fragments are visible, to an extremely fine-grained groundmass having almost no visible crystals near the top of the unit.

The transition of decreasing grain size and decreasing fragment deformation upward is believed to be the result of: a) increasing lithostatic pressure downward, deforming pyroclasts and homogenizing the glass and b) the relatively fast cooling near the top of the unit in relation to the middle where high temperatures were maintained much longer, allowing coarser primary crystallization in the middle of the ignimbrite sheet.

Another feature observed at the highest-known outcrop, possibly indicative of a pyroclastic origin, is a small area of slightly coarser-grained rhyolite with abundant cavities. This rock may be part of a de-gassing structure near the top of the unit. De-gassing structures are common in ignimbrites and are usually pipes but occur in a wide variety of shapes. They may form during movement of the ash flow and seem to resist mechanical mixing (Cass and Wright, 1987).

There are problems associated with the ash-flow interpretation as well. There are fewer rock fragments and broken phenocrysts than expected in an ash flow.

Favored interpretation

The favored interpretation of the Kimball Creek rhyolite is that it was a very large, hot ash flow. This interpretation is made on the basis of its large extent and small aspect ratio, the transition of decreasing grain size and more recognizable pyroclastic fragments upward from the middle of the unit, the possible fiamme and vitrophyre near the base, the presence of fiamme near the top and lack of many features common to lava flows. However, there are problems with this interpretation and some of the features of this unit are also consistent with a lava-flow origin.

The very high temperature of the magma, well conserved during eruption, and relatively high alkalies and iron, and low silica for a rhyolite, resulted in low viscosity of the shards which allowed compaction to homogeneous dense glass that underwent viscous flow. The insulation of the thick deposit maintained a high temperature long enough for the glass to weld thoroughly and most of it to crystallize completely to alkali feldspar and tridymite.

Maple Hill rhyolite

The Maple Hill rhyolite contains abundant structures suggestive of viscous flowage, such as lineated vesicles, flow bands, folds and folded vesicle trains. A nearly complete section of the unit is exposed in the Nipissing cliff at the lakeshore and no pyroclastic fragments are present even near the top where pyroclastic textures probably would have been preserved had they been present. The high vesicularity near the top is locally suggestive of a frothy liquid (Green, 1970).

The Maple Hill rhyolite is interpreted to have originated as a lava flow that traveled relatively far, at least 7.5 km. For the lava flow to have traveled so far the rate of eruption must have been great and/or the viscosity of the lava must have been relatively low. The differential movement and shearing within the viscous, flowing rhyolite developed flow bands, folds and aligned phenocrysts and vesicles parallel to the banding. The variation of the orientation of the banding within the unit is consistent with banding in rhyolite lava flows elsewhere (Bonnichsen and Kauffman, 1987; Christiansen and Lipman, 1966). The lack of broken phenocrysts is also consistent with a lava flow origin.

The rhyolite cooled quickly near the top and bottom, causing much of the liquid to quench to glass, which subsequently devitrified to spherulites and a dense aphanitic groundmass. Yet in the middle of the unit the rhyolite retained its heat longer, allowing the growth of some fine-grained tridymite, alkali feldspar and mafic minerals.

Special mention should be made of the recumbent folds exposed in the Nipissing Cliff near the top of the unit. The axis of one fold is N.35° E., and that exposed 40 m west is oriented N.10° W. If they are part of the same fold, then the flow direction at this location was about S.12° W., perpendicular to the fold axes.

Devil Track Rhyolite

Introduction

Problems of interpreting the origin of the Devil Track rhyolite are much the same as those associated with the Kimball Creek rhyolite, specifically the almost complete lack of original textures or structures indicative of a mode of deposition. The two rhyolites are similar in composition, volume, texture, grain size, flow structures and probably also in origin. Some differences between the two voluminous rhyolites are that the Devil Track is aphyric, and more homogeneous in that it lacks vertical zonation and observed fragmental textures. However, there is probably considerable valuable information missing because of the lack of exposures near the top of the unit.

Evidence

The only features that may indicate the rhyolite was lava are the thin bands and lamellae which are commonly contorted; these undoubtedly were produced by flowage. The very large extent, the low aspect ratio, the absence of breccia zones, and abundant vesicles are not consistent with a lava flow origin.

Evidence of a pyroclastic origin includes the large extent, the small aspect ratio, and the few possible pyroclasts found near the base of the unit. Although the pyroclastic interpretation is favored, there is not overwhelming evidence and the lava interpretation cannot be excluded.

Interpretation

The Devil Track rhyolite is interpreted to have been deposited by a very large, hot ash flow. During and after emplacement, the thick deposit quickly collapsed to dense hot glass in the middle and lower parts of the unit. The material was evidently of low enough viscosity to flow an undetermined distance, producing corrugated lineations, bands, and folds in banding. The temperature within the body of the deposit remained high long enough for the glass to completely crystallize to tridymite and alkali feldspar, further obliterating pyroclastic textures, similar to the Kimball Creek rhyolite.

Discussion

This section discusses some aspects of the ash flow interpretation of the two large rhyolite units of the Devil Track and Kimball Creek felsite sequences. Some structures in these units are not necessarily evidence for either type of eruptive style, but can be explained by the ash flow model. The discussion is arranged in inferred chronological order from eruption to crystallization. However, it is likely that several of the processes occured contemporaneously.

Temperature

Ash flows that do not entrap much air may lose a remarkably small amount of heat between eruption and emplacement, and emplacement temperatures may be as high as magmatic temperatures (Boyd, 1961; Walker, 1983). Ekren and others (1984) showed that emplacement temperatures of rheomorphic welded tuffs in Idaho could have been as high as 1100° C based on co-existing magnetite and ilmenite. The emplacement temperatures of the Devil Track and Kimball Creek rhyolites were probably as high as those in the Idaho tuffs and perhaps even higher because no other tuffs have been reported that had the nearly complete crystallization that occurred in the Cook County rhyolites. The tabular quartz in the Devil Track and Kimball Creek rhyolites is interpreted to have crystallized as stable tridymite that subsequently inverted to quartz (Green, 1970, 1972b). Although tridymite can crystallize in a metastable condition below 870° at one atmosphere, crystallization of tridymite does indicate a high-temperature environment (Deer, Howie and Zussman, 1980). Other evidence of high temperatures are the presence of resorbed feldspar phenocrysts in the Kimball Creek rhyolite, and the lack of phenocrysts in the Devil Track indicate temperatures at or above the feldspar liquidus.

The Devil Track and Kimball Creek rhyolites have chemical compositions that may have produced relatively low-viscosity liquids yet composition could not have been the major factor giving the apparently low viscosities. Many workers suggest temperature is the important variable controlling viscosity in extensive rhyolite lava flows and rheomorphic welded tuffs (Bonnichsen and Kauffman, 1987; Bonnichsen and others, 1988; Chapin and Lowell, 1979; Christiansen and Hildreth, 1988; Ekren and others, 1984). The temperature of the Devil Track and Kimball Creek rhyolites must have been unusually high to allow the material to be of low enough viscosity to flow on very gentle slopes. Ignimbrites emplaced at very high temperatures are strongly welded throughout most of their thickness and have been called "high-grade ignimbrites" by Walker (1983).

It has been proposed that superheating of rhyolite magma can occur by the injection of basalt into or adjacent to a felsic magma chamber (Ekren and others, 1984; Walker, 1962,

1983) and that the superheating can trigger explosive felsic eruptions (Sparks and Sigurdsson, 1977). Although no mixed magmas have been found in the Devil Track or Kimball Creek rhyolites, this mechanism could explain their very high temperatures because the North Shore Volcanic Group is dominantly basaltic.

Juvenile_particle_size

One possible reason why there are no visible fiamme in the Devil Track and the majority of the Kimball Creek rhyolite, in spite of a pyroclastic origin, may be that the unit had little coarse (lapilli-sized) material. In fact, there is evidence near the top of the Kimball Creek rhyolite unit that few large pyroclasts were present at that location. The pyroclastic fragments in the exposure at the shore of Lake Superior are present only in one small area of the outcrop; the rest of the outcrop has very few visible fragments and is microcystalline. This small area of concentrated fiamme probably represents a "pumice swarm" created by concentration during flow (Smith, 1960). More fragments are present in the exposure south of Devil Track Lake but much of the rock similarly is devoid of visible fragments. Fine ash would lose its identity more readily during welding and crystallization than coarser pyroclasts; the scracity of pyroclastic textures in the Devil Track and Kimball Creek may be partly due to a dominance of very fine ash.

Deposition and welding

There is some uncertainty about depositional processes for rheoignimbrites, but a model that may account for some features in the Devil Track and Kimball Creek rhyolites is similar to that described by Chapin and Lowell (1979) for the emplacement of the Tertiary Wall Mountain Tuff in Colorado. The Devil Track and Kimball Creek rhyolites, like the Wall Mountain Tuff, were hot enough to undergo primary welding, which occurs when glass fragments weld and collapse during deposition in the laminar boundary layer. The resulting deposit shows megascopic primary flow structures such as lineations, banding and a foliation, which may be folded. This is in contrast to cooler ash-flow tuffs deposited as loose ash that welds after emplacement, which is secondary welding. A model for the emplacement of the Devil Track and Kimball Creek rhyolites, slightly modified from that of the Wall Mountain Tuff (Chapin and Lowell, 1979) is as follows: As the glassy particles were agglutinating and depositing, there was laminar shearing of the compacting and welding mass, which formed bands and a foliation. Gas escaping from the collapsing mass was concentrated along shear planes. Lineations and primary flow folds were developed in the bands by motion within the layer. Motion ceased after possible secondary flow due to gravitational spreading or readjustments around topographic highs.

The major factors influencing the degree of welding of a pyroclastic deposit are the viscosity of the glass, the load pressure, and the rate of cooling (Riehle, 1973; Smith, 1960; Walker, 1983). Although the distinction between liquid and low viscosity glass is arbitrary at such high temperatures, the particles may not have resembled rigid glass shards as much as liquid droplets that coelesced into a pool and thus lost their individual boundaries during deposition and welding. This may explain the scarcity of preserved pyroclastic textures. The presence of sparse vesicles in the Devil Track are evidence that the liquid was of low enough viscosity to revesiculate after deposition.

If there were any particles rigid enough to maintain their own boundaries, as there were at least near the top of the Kimball Creek rhyolite, then they would have been firmly welded shortly after deposition. If the ash was emplaced at about 900^{o} C with 0.5 weight percent water, then it would have been firmly welded in most of the unit within a day after emplacement (Cass and Wright, 1987). The temperature would have remained above the welding temperature in the middle of the units for another several hundred years (Figure 42; Jaeger, 1968). The firmly welded fiamme near the top of the Kimball Creek rhyolite are evidence that the glass was of high enough temperature and low enough viscosity to be completely compressed under low lithostatic pressure in that unit and the same was probably true in the Devil Track rhyolite. Lower in the units any rigid fragments must have been extremely firmly welded and fused to a homogeneous dense glass, as described by Peterson (1979).

Rheomorphic Structures

Many rheoignimbrites have been described containing a wide variety of flow structures (Chapin and Lowell, 1979; Deal, 1973; Ekren and others, 1984; Lock, 1972; Noble, 1968; Parker, 1972; Price and others, 1986; Schmincke, 1974; Schmincke and Swanson, 1967; Sparks and Wright, 1979; Walker and Swanson, 1968; Wolff and Wright, 1980), but only those structures found in the Devil Track and Kimball Creek rhyolites will be reviewed here. The Kimball Creek rhyolite has definite rheomorphic structures only near the top and bottom, whereas the Devil Track has them throughout the vertical section exposed along the shore of Lake Superior. This indicates that in the Devil Track many layers were in motion, not necessarily all at once, but the unit does not appear to have been carried passively along by a mobile horizon near the base. The flowage probably further deformed the pyroclasts and contributed to the homogenization of the glass.

The most-convincing evidence of flowage in the Devil Track and Kimball Creek rhyolites is the presence of folds in the bands and lamellae. There are folds in the Kimball Creek rhyolite at the important outcrop on the shore of Lake Superior where fiamme form a foliation which is tightly folded

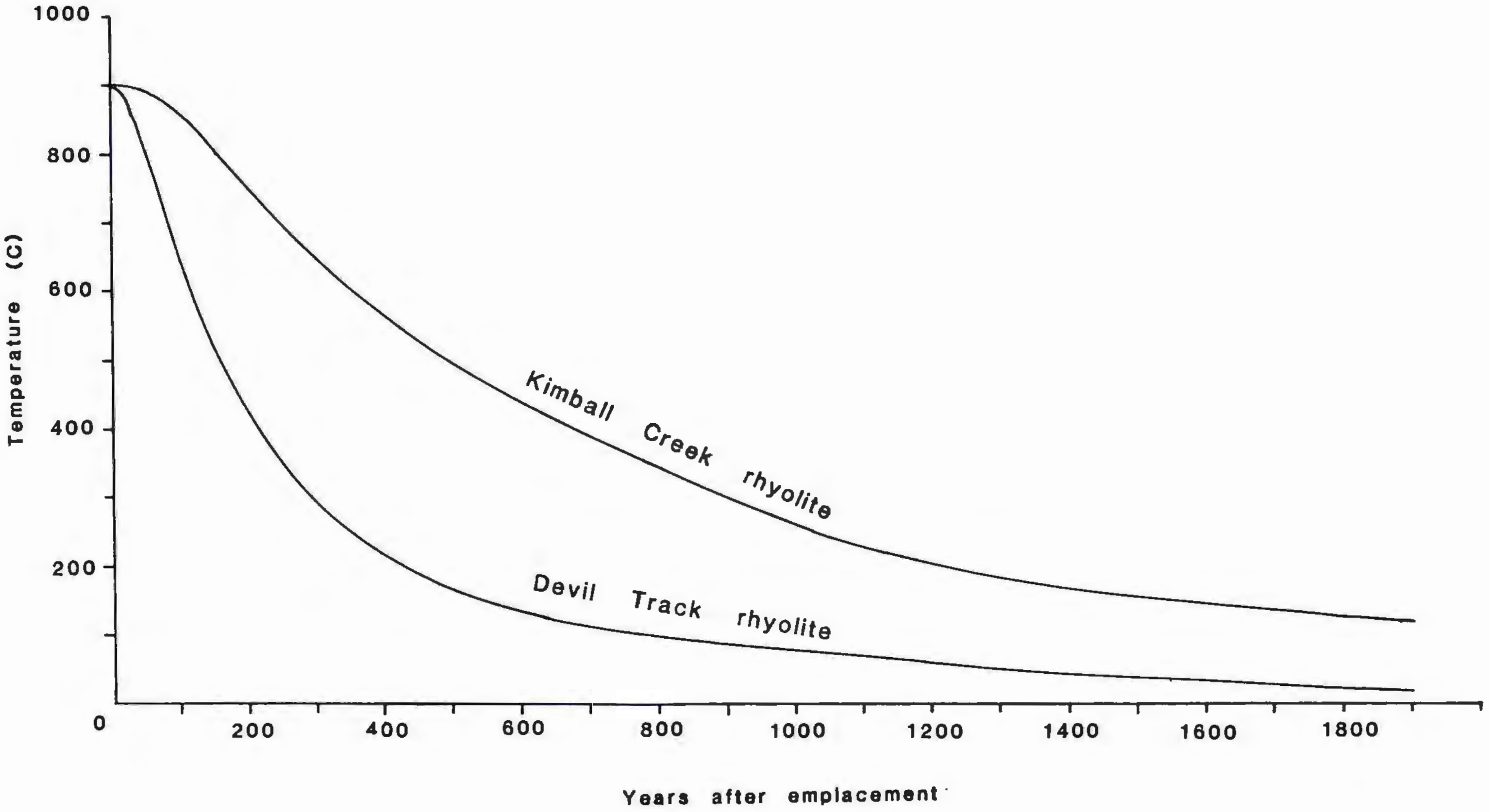


Figure 42. Temperature at the center of the rhyolites in relation to the time after emplacement assuming an initial temperature of 900° C. Calculations are by the method of Jaeger, 1968.

(Figure 22). Folded bands and lamellae are also common at the exposure at the stratigraphically lowest known outcrop in the Kimball Creek, and also an exposure in the Cascade River near the top of the unit that has lineations on the folded joint surfaces. Folds in the Devil Track vary from 5 cm across in fine lamellae to folds in bands and joints covering outcrops several meters across.

Another common rheomorphic feature observed in the rhyolites is the presence of lineations on foliation planes. In their paper on rheomorphic welded tuffs, Wolff and Wright (1980, p.16) stated: "Well developed lineations approach a "rodding" type fabric of closely-spaced parallel ridges, a few millimeters wide and tens of centimeters long, on the foliation surface". This description closely matches the lineations near the top of the Kimball Creek and throughout the Devil Track rhyolite, although some are up to 5 cm wide. Wolff and Wright (1980) went on to say the lineations in rheomorphic welded tuffs in the Canary Islands have a mean orientation parallel to the slope and thus to the direction of movement. Lineations measured in the Kimball Creek rhyolite at the outcrop near the shore of Lake Superior have a fairly consistent orientation with strikes about N.80° W. (Figure 43) that probably shows the trend of the direction of movement at that location, but not the sense of direction, since their plunges are near zero. In the exposures of Devil Track rhyolite along the shore of Lake Superior the measurement of 15 areas of lineations have a consistent orientation of about

N 80° W., which probably reflects the trend of the direction of movement for that unit at that location (Figure 44).

The light gray streaks and small quartz veinlets in the Kimball Creek and Devil Track rhyolites, especially prominent in the stratigraphically lowest exposures of both units, are less-definite flow structures, but also may have been partly produced by flow. The Wall Mountain tuff has "abundant light gray streaks that vary from a few millimeters to many centimeters in length" (Chapin and Lowell, 1979, p. 138) and the Apache Leap tuff has similar streaks (Peterson, 1979). Chapin and Lowell concluded the streaks were too abundant to have been extremely flattened pumice and may have been created by gas trapped along foliation planes causing crystallization of the glass. The streaks and veinlets in the Cook County rhyolites may be of similar origin.

Another possible explanation of the streaks and quartz veinlets is that shearing of the glass as it became more brittle may have opened up tension cracks. Sheridan (1979) concluded that tension cracks in ash flows dip in the downstream direction and indicate laminar flow during the last stages of movement as the glass became increasingly viscous. The quartz veinlets in the Cook County rhyolites, especially the en echelon quartz veins near the base of the Kimball Creek rhyolite, are probably tension cracks that were filled with

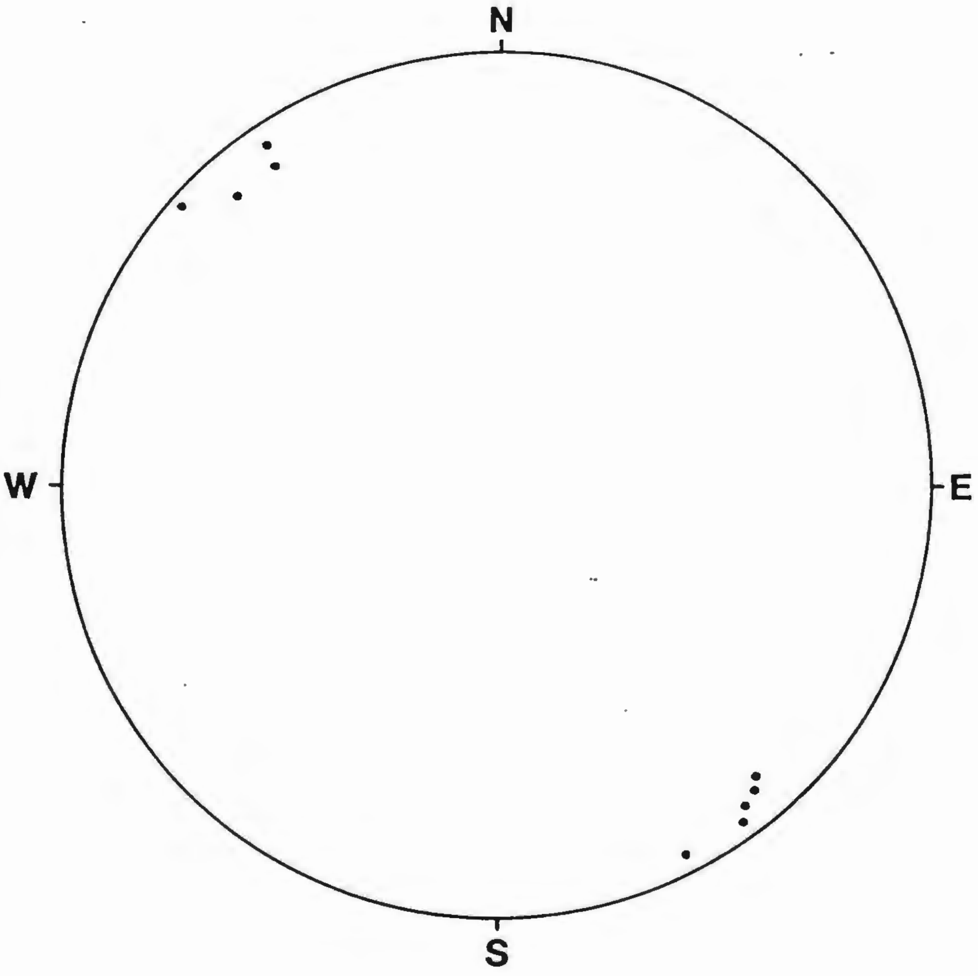


Figure 43. Stereograph of corrugated lineations in the Kimball Creek rhyolite in SW 1/4, sec. 10, T.61 N., R.2 E.

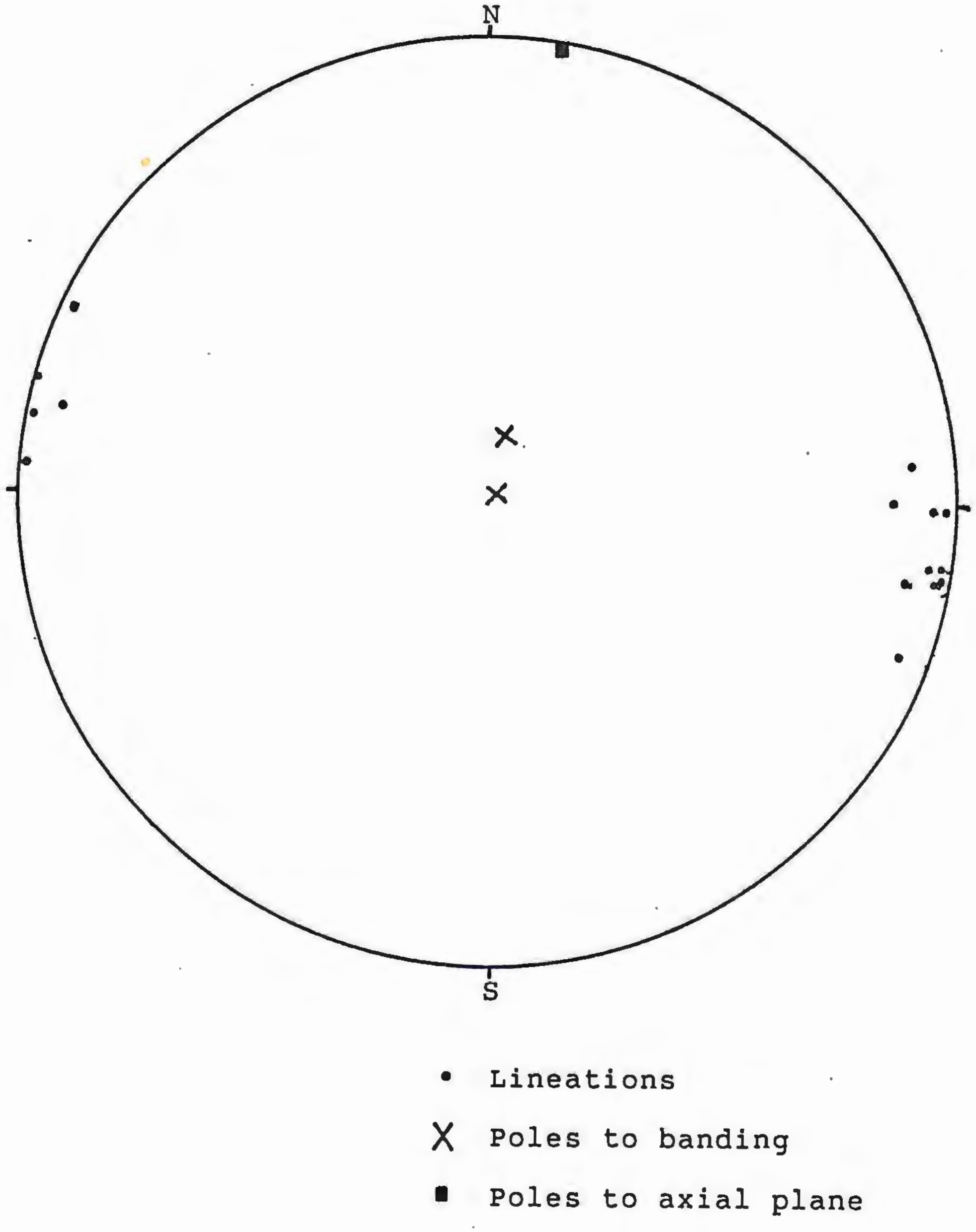
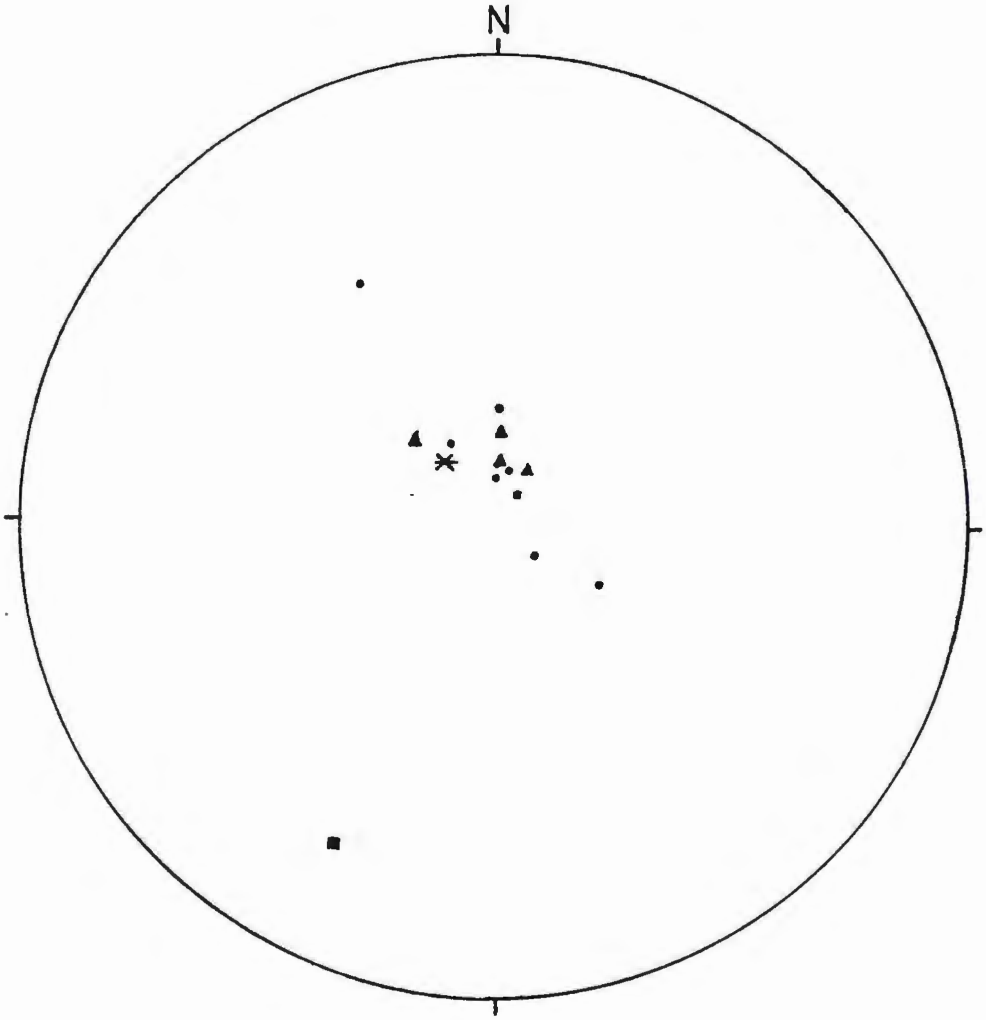


Figure 44. Stereographic projection of corrugated lineations, banding and axial planes of folded bands in the Devil Track rhyolite.

quartz by volcanic gases or after burial of the unit. Continuous horizontal partings or flow planes coated with gas-phase silica minerals have been reported in rheoignimbrites in the Canary Islands (Schmincke, 1974; Schmincke and Swanson, 1966, 1967).

Foliations are common in strongly welded tuffs (Fisher and Schmincke, 1984) and have been considered a post-emplacement compaction feature by many. However, Chapin and Lowell (1979) considered the foliation in the Wall Mountain Tuff to be a primary flow feature because of the lineations on the foliation surfaces and folding of the foliation. The foliation in the Wall Mountain tuff is parallel to flow bands and is interpreted to have formed by gas being trapped along shear planes during deposition. The presence of lineations on sheeting joint surfaces in the Devil Track and Kimball Creek rhyolites indicate there was movement along those planes and their similar attitude to the local stratigraphic units (Figures 45, 46) indicates the shearing was generally parallel to the bottom of the unit. Parallelism of sheeting joints and flow bands indicates that the shearing created planes of weakness along which the joints later formed.



● Poles to sheeting joints in the Kimball Creek rhyolite.

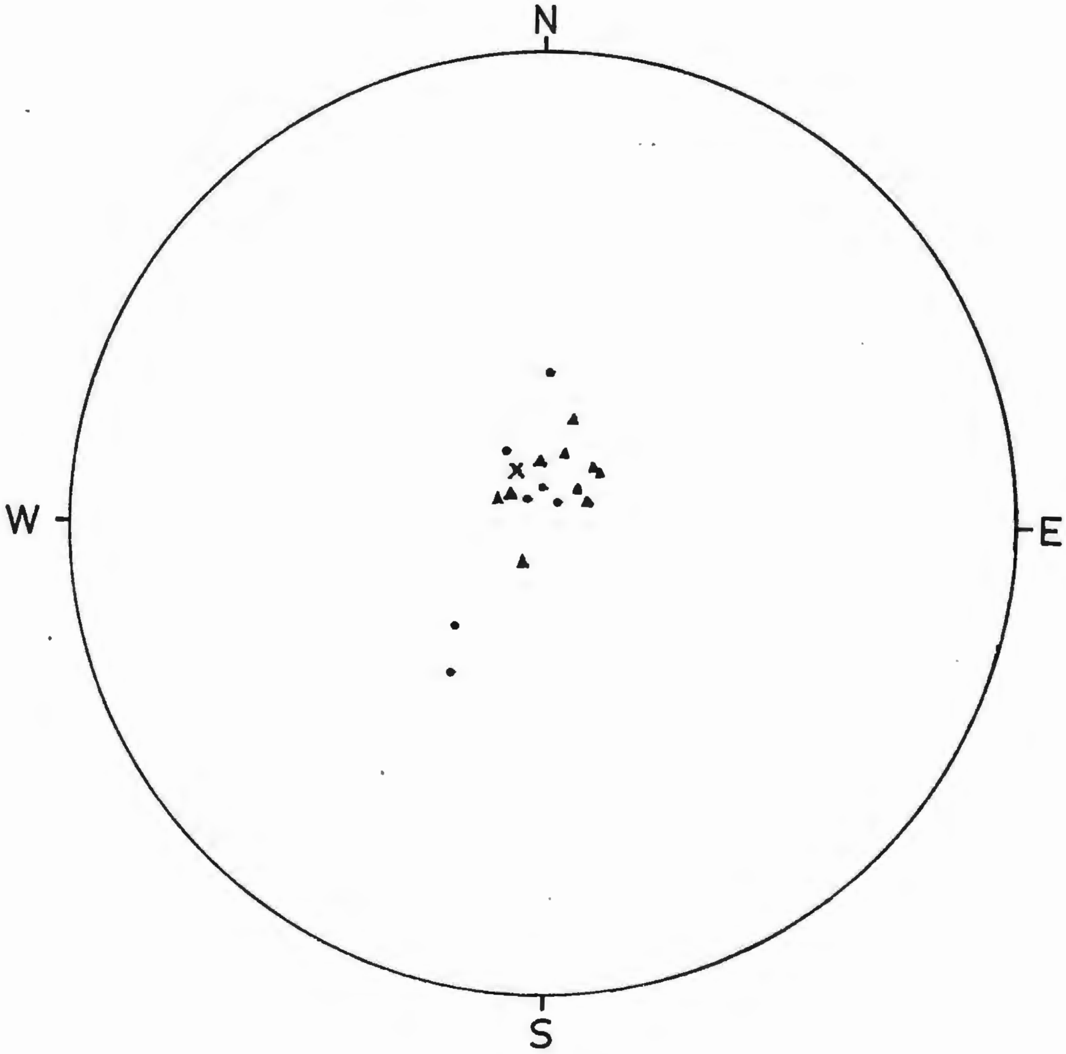
Rocks above the rhyolite in the Cascade River area:

■ Lineated vesicles

▲ Poles to sheeting joints

✳ Pole to contact between lava flows

Figure 45. Stereographic projection of sheeting joints in the Kimball Creek rhyolite and structures in the units just above the Kimball Creek in the Cascade River area.



● Poles to sheeting joints along shore

▲ Poles to sheeting joints inland

× Pole to bedding in sedimentary rock above the Devil Track rhyolite.

Figure 46. Stereographic projection of sheeting joints in the Devil Track rhyolite.

It is unknown how far the Devil Track and Kimball Creek rhyolites, or any other rheoignimbrites, moved by rheomorphic flow after deposition from the ash flows. It is also unknown whether the flowage was dominantly laminar or turbulent, because none of the exposures are large enough to trace the flow structures for more than a few meters. If there was much turbulent flow or movement along ramp structures that carried material upward in the flow, then the movement may have disturbed vertical compositional zonations if they were present. The movement probably also contributed to the destruction of any pyroclasts.

Cooling and Crystallization

The Devil Track and Kimball Creek rhyolites quickly became densely welded in much of the units and as a result, porosity was low. In the absence of cavities to accommodate major vapor-phase crystallization, the crystallization took place predominantly in firmly welded glass; this has been called primary crystallization (Green, in review; Lipman, 1965). Primary crystallization is enhanced in low-viscosity glass with high alkalis, Na/K ratios, and dissolved volatiles (Lofgren, 1982; Ross and Smith, 1961; Schmincke and Swanson, 1967) and these factors plus the high temperature facilitated complete crystallization within the Devil Track and Kimball Creek rhyolites. These rhyolites are unusual because devitrification usually creates spherulites with cristobalite and alkali feldspar rather than tridymite (Ross and Smith, 1961). Lithophysae, which are common in densely welded zones of ash flows (Cass and Wright, 1987), are absent. The unusual nature of the crystallization was probably due to the very high temperatures. The crystallization obliterated any remaining pyroclastic textures by crystals growing across pyroclast boundaries and may even have destroyed some flow structures in the middle of the Kimball Creek rhyolite where they are scarce.

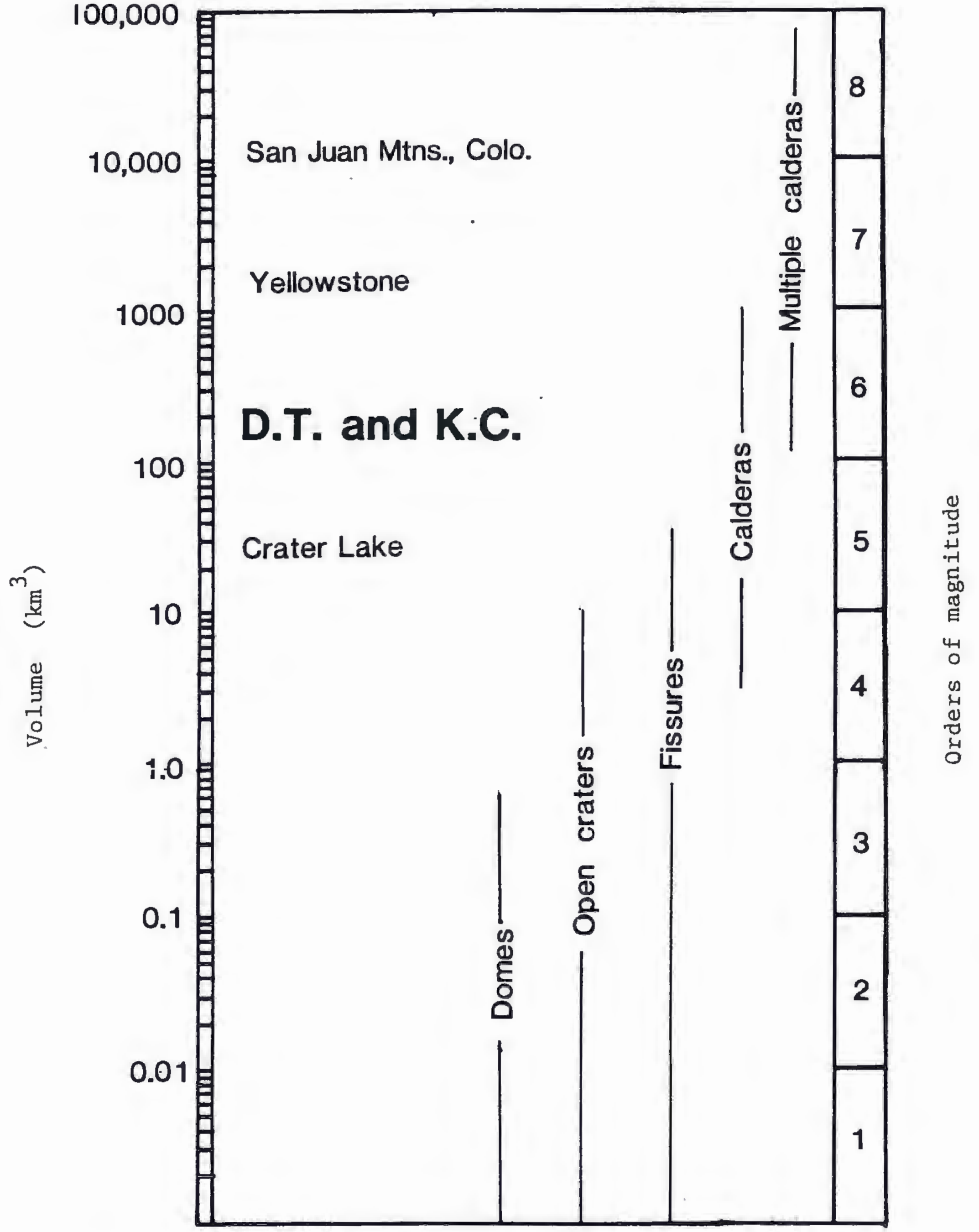
The majority of the crystallization was primary, but vapor-phase deposition during cooling certainly accounts for the tridymite paramorphs seen in diktytaxitic cavities and perhaps accounts for some of the groundmass crystallization as well. The passage of gas through the flows resulted in at least partial oxidation of most mafic minerals, and perhaps redeposited and oxidized iron in the groundmass, imparting the red color (Smith, 1960). Quartz could have been deposited in cavities and tension cracks at this stage or by groundwater after burial.

Peterson (1979) described the progressive flattening of pumice downward in the Apache Leap tuff in Arizona and attributed this to increasing lithostatic pressure and lower viscosity of the glass due to sustained high temperatures downward in the deposit. A curve of the flattening ratios of pumice is not linear however; breaks in the flattening curve were caused by short breaks in the deposition of ejecta, thus allowing the top of the deposit to cool for a short time before continued deposition. Although the absence of pumice in the Devil Track and Kimball Creek prevents use of this type of analysis, the measurement of grain-size variation within the units probably expresses the thermal history of the body of the unit. Since the Devil Track and Kimball Creek rhyolites are coarser-grained in the middle than near the top and bottom, it can be assumed that each unit cooled as a single cooling unit. This analysis cannot determine whether they were single- or multiple-flow cooling units. If they are multiple-flow cooling units, then the successive ash flows had to have had similar compositions and were deposited fast enough to prevent significant cooling between eruptions. The graph of grain size and stratigraphic position for the Devil Track shows one break in slope and a grain size generally smaller than that observed in the Kimball Creek rhyolite (Figure 17). This may indicate deposition was not continuous in the Devil Track but may have pulsated due to eruption of two or more ash flows. However, no mesoscopic evidence of multiple eruptive pulses is present.

Caldera and Vent Area

Most pyroclastic deposits larger than 10 km^3 that can be linked to a source area have associated calderas. Simple cone collapse structures erupt a maximum of about 100 km^3 of material, and most erupt less than 50 km^3 (Smith, 1960). The eruptions that created the Devil Track and Kimball Creek rhyolites, each containing more than 90 km^3 of rock, may have been associated with foundering of the roof of a magma chamber and the development of a caldera. As shown in Figure 47, the Devil Track and Kimball Creek each have volumes equal to deposits erupted from calderas and multiple calderas. Ignimbrites with volumes in the range of 100 km^3, about the size of these rhyolites, have calderas with diameters of about 10 km (Smith, 1960). However, the stratigraphy adjacent to the rhyolites gives no indication of a caldera and nowhere in the North Shore Volcanic Group are there rocks similar to the caldera-collapse breccias described in the western United States (Lipman, 1976). The absence of any coarse deposits may suggest that the available exposures of rhyolite are not proximal deposits and the great thickness of the Devil Track and Kimball Creek cannot be attributed to ponding in a caldera. Perhaps the source vent system has been eroded away or is concealed at depth or under Lake Superior.

Another interpretation is that the rhyolites were erupted directly from great depths and did not reside in high level magma chambers, thus there was no caldera formation associated with their eruptions (Ekren and others, 1984; Whitney and Stormer, 1986).



DT = DevilTrack   KC = Kimball Creek

Figure 47. Plot of volumes of ash flow fields, their associated vent morphologies and relative orders of magnitude (after Smith, 1960).

Co-ignimbrite ash-fall

Voluminous eruptions of ash not only produce ash flows but also ash clouds that subsequently settle as co-ignimbrite ash-fall deposits that can equal the ash flow in volume (Sparks and Walker, 1977; Walker, 1983). Wind may transport fine ash great distances, so air-fall deposits commonly extend well beyond the limits of the associated ash flow. Rheoignmibrites require a high temperature during deposition so must result from low eruption columns that entrap little air and lose little fine ash (Walker, 1983). Thus it could be expected that there would not be major air-fall deposits above rheoignimbrites. The few detailed descriptions of rheoignimbrites do not mention associated air fall deposits yet it seems likely that eruptions of the magnitude that produced the Devil Track and Kimball Creek rhyolites were violent enough that some ash was lost and later settled as airfall. No exposures of ash have been found above either rhyolite but it could have been eroded shortly after deposition or perhaps it is now concealed.

Even though it may have been a minor amount of ash, it is still of interest whether there are any preserved ash layers in Keweenawan rocks elsewhere that may be correlative with these rhyolites. The only ash reported so far in the North Shore Volcanic Group that could possibly be of air-fall origin is a tuffaceous interflow sandstone with well-preserved angular shards found by M.Jirsa (1980) at Two Harbors, Minnesota. Correlations between the Northeast and Southwest limbs of the North Shore Volcanic Group, across the Beaver Bay Complex, have not yet been possible, but the ash at Two Harbors lies in the upper part of the North Shore Volcanic Group sequence as do the Devil Track and Kimball Creek rhyolites. Unfortunately the shards in the Two Harbors rock have been replaced by secondary minerals and probably do not retain their original composition.

CHAPTER VII:

SUMMARY AND CONCLUSIONS

The Devil Track and Kimball Creek felsites are very large volcanic units with little evidence of origin. Determining their origin has been a major objective of this study. Distiguishing between extensive low-viscosity rhyolite lava flows and rheoignimbrites can be difficult because they commonly have similar physical features and dimensions. The only definite single criterion for the recognition of ash flows is the presence of pyroclastic textures. Since pyroclastic textures can be destroyed in hot ash flows that are densely welded and crystallized, which is probably the case for some of the units in this study, all features of the unit in question must be taken into account when an interpretation is made.

The lowest unit in the Kimball Creek felsite, the basal quartz latite, has features typical of lavas such as flow bands and some lineated vesicles, yet lacks a basal breccia zone. The extent of 23 km, with a thickness of only 40 m, and aspect ratio of 1/575 (maximum) gives the unit dimensions more typical of ash flows than felsic lava flows. Evidence of a pyroclastic origin are the sparse fiamme and possible unwelded top zone with definite shards. The unit is interpreted to have been an ash flow that was deposited at a very high temperature, allowing the glass to compact to a very firmly welded mass that flowed under its own weight and momentum.

The flowage and compaction created flow bands and homogenized the glass so that pyroclastic textures were destroyed in much of the unit.

The 40-m thick Range Line icelandite unit has a very large extent, at least 23 km, and low aspect ratio (1/575), indicating a very mobile flow. Evidence of extrusion as lava are: the vesicles increasing in abundance upward in the unit with very vesicular rock near the top and a holocrystalline groundmass containing no evidence of pyroclastic textures or secondary devitrification. The unit is interpreted as a lava flow. Although the unit is not well exposed, it is homogeneous and there is no evidence that it is made up of several lava flows along strike. For the lava to flow such a great distance it must have had a high effusion rate and/or low viscosity. The modal composition, the relatively high iron, and low alumina in both of the icelandite units are similar to icelandites described by Carmichael (1964).

The 200-m thick Kadunce icelandite is only exposed in the eastern part of the field area and it is uncertain how far west the unit extends; it does not reach as far west as the Cascade River, and thus is less than 32 km in known length. Its aspect ratio is approximately 1/100. The unit has plagioclase phenocrysts, commonly in clusters, a holocrystalline groundmass and lacks any evidence of devitrification or pyroclastic textures. There is an increase in the percent of plagioclase phenocrysts near the top but it is uncertain whether the change is gradual or abrupt near the top of the unit. The very vesicular rock exposed within a few meters of the top of the unit supports a lava flow origin.

The youngest unit is the Kimball Creek rhyolite which, with an extent of at least 32 km and aspect ratio of 1/91, has dimensions typical of large ash flows. The bulk of the unit is homogeneous rhyolite dominated by tabular quartz crystals, which are paramorphs of tridymite, and subhedral alkali feldspar. Phenocrysts are plagioclase and alkali feldspar and some magnetite. There are some radial clusters of both quartz and alkali feldspar but no well-developed spherulites or lithophysae. The majority of the unit lacks any suggestion of pyroclastic textures. There are also no breccia zones, and very few flow bands or vesicles, all of which are common in rhyolitic lavas. Rock exposed near the top and bottom, however, contains evidence of flowage and some fiamme as well.

The lowest known exposure has an extremely fine-grained, dense groundmass with abundant light streaks and quartz veinlets that are locally folded. This exposure is interpreted to represent a devitrified basal vitrophyre. The light streaks and quartz veinlets are relict tension cracks created during viscous flow and later filled with quartz. Near the top of the unit there are possible fiamme which are concentrated in bands, perhaps as a result of segregation in an ash flow. The highest known exposure has fiamme forming bands that are folded and contorted. The highly flattened nature of the pumice fragments at this exposure, only about 40 m below what is now the top of the unit, indicates the glass was of fairly low viscosity and was easily deformed.

The Kimball Creek rhyolite is interpreted to have been a large, very hot ignimbrite. The high temperature at the time of eruption was well conserved and was the primary reason the glass had a low enough viscosity to flow during and/or after deposition. The compaction and flowage obliterated pyroclast outlines, created lineations and flow bands which are locally folded. The low viscosity allowed the pyroclasts to collapse into a densely welded mass and facilitated crystallization. Primary crystallization produced a holocrystalline groundmass of tridymite and alkali feldspar and destroyed any remaining pyroclastic textures. The progressively coarser grain size toward the middle of the unit is the result of slower cooling in the middle and indicates the unit was a single cooling unit.

Petrogenetic modeling of both major and trace elements gives evidence that the Kimball Creek rhyolite magma originated by fractional crystallization of plagioclase, augite and magnetite from an icelandite parent represented by the underlying icelandite lava flows.

The Maple Hill rhyolite has abundant flow features such as lineated vesicles, vesicles concentrated into folded bands, abundant flow bands and folds. Rock near the top of the unit is very vesicular and contains no suggestion of pyroclastic textures, which indicate a lava flow origin rather than a pyroclastic origin. This flow also had exceptional mobility for a rhyolitic lava since it extends at least 7.5 km, giving an aspect ratio of 1/68.

The Maple Hill may have originated by fractional crystallization from a parent magma of the composition of the Kimball Creek rhyolite or of the composition of the icelandite units.

The Devil Track rhyolite is homogeneous aphyric rhyolite with little evidence of either a pyroclastic or lava flow origin. The great extent, at least 42 km, and low aspect ratio (maximum of 1/120) indicate a very mobile flow, probably an ash flow. Lineations, bands and lamellae which are locally folded were undoubtedly created by flow. A few dark fragments that could be pyroclasts were found near the base of the unit in very fine-grained rock. This unit is interpreted to have been deposited by a large, hot ash flow. Evidence of a high temperature of eruption are: a) the almost complete lack of phenocrysts indicating a temperature above the liquidus; b) the apparently stable crystallization of tridymite; c) flowage of the glass requiring a low viscosity and thus a high temperature because the composition is not unusual for a rhyolite. Temperatures as high as 900-1000 °C or more and resultant low viscosity allowed the ash-flow to collapse to a densely welded mass, flow, and crystallize as did the Kimball Creek rhyolite.

The Devil Track magma may have formed by fractional crystallization directly from an icelandite parent magma, or by melting of alkali feldspar, quartz and magnetite crystals into a magma of the composition represented by the Maple Hill rhyolite. Injection of basaltic magma into or near-by the magma chamber containing Maple Hill magma could have caused an increase in temperature. The increase in temperuature may have resulted in stiring and melting of settled crystals, increased vesiculation and eventual eruption of the aphyric Devil Track at a very high temperature.

The nearly complete primary crystallization of the Devil Track and Kimball Creek rhyolites to alkali feldspar and tridymite is very unusual and is probably the the result of very high temperatures. Many workers consider temperature to be the most important varaible influencing the viscosity of rhyolites and thus whether or not rheomorphic flow can occur in an ash flow. The Devil Track and Kimball Creek rhyolites add support to this hypothesis since they have evidence of rheomophic flow and high temperatures.

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Appendix 1

Average chemical compositions of the felsites

	Icelandite	Kadunce Icelandite	Kimball Creek rhyolite	Maple Hill rhyolite	Devil Track rhyolite
SiO_2	62.60	61.79	69.92	71.52	73.08
TiO_2	1.09	1.45	0.53	0.38	0.40
Al_2O_3	12.01	12.52	12.52	11.56	11.76
Fe_2O_3	8.18	6.00	4.09	3.62	3.13
FeO	2.02	3.75	1.63	0.97	0.74
MnO	0.12	0.72	0.10	0.12	0.04
MgO	1.40	1.00	0.51	0.46	0.54
CaO	2.22	3.19	0.51	0.22	0.51
Na_2O	4.04	3.83	3.43	3.00	3.54
K_2O	4.15	3.68	5.37	7.04	5.50
P_2O_5	0.28	0.39	0.09	0.00	0.04

Sample	I-A	KI-A	KC-A	MH-A	DT-A
Group #	1.00	2.00	3.00	4.00	5.00
Qual	0	0	0	0	0
Key	1	2	3	4	5
Ref	0	0	0	0	0
SiO2	64.34	63.62	71.14	72.59	73.84
TiO2	1.12	1.49	0.54	0.39	0.40
Al2O3	12.34	12.89	12.74	11.73	11.88
FeO	9.65	9.43	5.41	4.29	3.60
MnO	0.12	0.12	0.10	0.12	0.04
MgO	1.44	1.44	0.52	0.47	0.55
CaO	2.28	2.29	0.52	0.22	0.52
Na2O	4.15	4.16	3.49	3.04	3.58
K2O	4.27	4.27	5.46	7.15	5.56
P2O5	0.29	0.29	0.09	0.00	0.04
Total	100.00	100.00	100.00	100.00	100.00

Appendix 2.

Trace element abundances of the felsites.

File name A:LGCMAJ .ROC

Sample	DT-9	DT-24	ML-1	ML-12	TL-27A	KC-17	KC-18	GM-14	MI-2	KC-1	KC-2	KC-16
RB	180.00	160.00	120.00	190.00	130.00	0.00	146.00	0.00	0.00	130.00	120.00	129.00
SR	70.00	50.00	30.00	80.00	40.00	0.00	90.00	0.00	0.00	190.00	290.00	90.00
Y	70.00	120.00	60.00	80.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZR	650.00	640.00	600.00	650.00	600.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NB	50.00	40.00	60.00	40.00	50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BA	1120	1100	1550	1140	1440	0	440	0	0	1040	910	2040
LI	40.00	10.00	10.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B	50.00	50.00	40.00	0.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SC	7.20	9.30	4.90	0.00	4.10	0.00	6.70	0.00	18.40	13.20	19.00	3.70
V	4.00	14.00	6.00	0.00	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CR	6.00	0.00	5.00	0.00	4.00	1.00	6.00	.00	11.00	2.10	2.80	4.00
CO	5.00	3.00	2.00	0.00	2.00	3.15	15.40	73.00	6.32	14.00	0.00	14.40
NI	3.00	4.00	4.00	0.00	4.00	0.00	30.00	40.00	0.00	0.00	0.00	20.00
CU	16.00	16.00	6.50	0.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ZN	140.00	140.00	130.00	0.00	110.00	73.00	0.00	0.00	120.00	0.00	0.00	0.00
AS	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SE	0.00	0.00	0.00	0.00	0.00	7.50	0.00	4.50	0.00	0.00	0.00	0.00
MO	0.00	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SB	0.80	0.70	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CS	2.20	2.50	2.70	0.00	1.20	3.30	4.30	3.80	2.40	4.00	3.90	3.60
LA	84.90	111.00	56.30	0.00	38.00	76.20	95.70	29.40	81.50	54.40	63.50	84.20
CE	206.00	256.00	138.00	0.00	220.00	169.00	134.00	77.00	183.00	130.00	137.00	178.00
ND	60.00	100.00	43.00	0.00	30.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SM	12.30	21.00	8.00	0.00	6.40	18.20	17.60	8.66	17.90	13.30	0.00	14.70
EU	1.80	3.40	1.40	0.00	0.80	2.99	2.92	2.29	3.88	2.66	3.15	2.49
YB	8.20	14.00	5.60	0.00	6.70	8.90	7.82	2.36	9.00	6.36	6.37	7.38
LU	1.24	2.00	0.99	0.00	1.12	1.38	1.17	0.25	1.30	0.94	0.98	1.11
HF	18.00	24.00	23.00	0.00	20.00	18.90	17.80	6.30	19.00	14.40	11.90	22.80
TA	2.00	2.00	2.00	0.00	1.00	0.00	4.40	0.00	3.30	0.00	0.00	3.90
PB	12.00	22.00	12.00	0.00	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TH	15.00	17.00	10.00	0.00	17.00	15.30	14.40	2.36	11.60	12.20	9.60	15.70
U	3.60	7.80	3.30	0.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO*	4.99	6.15	4.25	4.93	2.94	6.65	4.88	4.01	9.65	8.20	10.63	4.29
F/F+M	0.811	0.962	0.857	0.959	0.859	0.908	0.946	0.900	0.872	0.892	0.906	0.904
Rb/Sr	2.571	3.200	4.000	2.375	3.250	0.000	1.622	0.000	0.000	0.684	0.414	1.433
K/Rb	248	341	391	280	352	0	284	0	0	269	232	460
K/Ba	39.9	49.6	30.3	46.7	31.8	0.0	94.1	0.0	0.0	33.6	30.6	29.1
den	2.38	2.39	2.36	2.37	2.34	2.41	2.38	2.36	2.48	2.46	2.53	2.36

Appendix 3.

Chemical composition of the rhyolites used for comparison.

```
File name A:OTHER .ROC
Sample        NOCKOL  LE MAT  ICELAN  CANARY  OREGON  BRACKS  COLORA  COUGAR  ID LAV
Group #        22.00  116.00   58.00   10.00    2.00    4.00    4.00    8.00    7.00
Qual               0       0       0       0       0       0       0       0       0
Key                0       0       0       0       0       0       0       0       0
Ref                0       0       0       0       0       0       0       0       0

SiO2           74.33   74.06   73.65   68.99   76.46   69.13   70.49   74.65   71.23
TiO2            0.22    0.28    0.31    0.98    0.06    0.58    0.46    0.37    0.63
Al2O3          13.57   13.50   13.27   13.47   12.22   13.09   15.46   12.47   13.43
FeO             1.89    2.49    3.11    4.88    2.34    5.67    1.73    2.69    4.07
MnO             0.03    0.06    0.08    0.20    0.00    0.22    0.44    0.04    0.07
MgO             0.32    0.40    0.33    0.50    0.01    0.24    0.33    0.24    0.57
CaO             1.14    1.16    1.65    0.72    0.30    1.29    1.02    0.93    1.96
Na2O            3.02    3.61    4.46    5.72    4.34    4.79    3.33    2.68    2.94
K2O             5.40    4.37    3.03    4.45    4.24    4.93    5.95    5.87    4.98
P2O5            0.07    0.07    0.11    0.09    0.02    0.06    0.79    0.06    0.13
Total         100.00  100.00  100.00  100.00  100.00  100.00  100.00  100.00  100.00
```

NOCKOL = Nockold's average rhyolite (Nockold, 1954)
LE MAT = LeMaitre's average rhyolite (LeMaitre, 1976)
ICELAN = Rhyolites in iceland (Walker, 1966)
CANARY = Peralkaline rheoignimbrites of the Canary Islands (Schmincke and Swanson, 1967)
OREGON = Peralkaline Wagontire tuff, Oregon (Walker and Swanson, 1968)
BRACKS = Peralkaline Bracks rhyolite, Texas (Henry and others, 1988)
COLORA = Wall Mountain tuff, Colorado (Chapin and Lowell, 1979)
COUGAR = Cougar Point tuff, Idaho (Bonnichsen and Citron, 1982)
ID LAV = Rhyolite lava flows in SW Idaho (Bonnichsen, 1982)

Appendix 4.

Average trace element analyses of the felsites.
Data were used in the petrogenetic modeling.

Devil Track rhyolite		Maple Hill rhyolite		Kimball Creek rhyolite	
Sc	4.16	Sc	3.70	Sc	7.75
Cr	4.50	Cr	4.00	Cr	3.50
Ni	4.00	Ni	20.00	Ni	3.66
Sm	10.63	Sm	14.70	Sm	17.28
Eu	1.50	Eu	2.49	Eu	2.78
Th	14.83	Th	15.70	Th	15.43

Range Line icelandite		Kadunce icelandite	
Sc	16.10	Sc	18.40
Cr	2.45	Cr	11.00
Ni	n/a	Ni	n/a
Sm	13.3	Sm	17.90
Eu	2.91	Eu	3.88
Th	10.9	Th	11.60

n/a = no analysis available

Appendix 5.

Compositions of the minerals used in the petrogenetic models.

File name TOM .MIN

Sample	NL-1P	NL-1 C	NL-1CB	NL-1CL	OKF-46	OKF-46	OKF-46	NE-2-3	F-237M	F-237O	SIO2	OR-47	OR-68	OR-21	
Group #	1.00	1.00	1.00	1.00	2.00	2.00	2.00	3.00	3.00	4.00	0.00	0.00	0.00	0.00	
Qual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Key	1	3	2	2	1	1	2	5	5	3	0	0	0	0	
Ref	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
SIO2	57.92	51.85	48.87	49.13	62.28	58.30	48.96	0.11	0.45	29.87	100.00	65.22	64.70	63.69	
TIO2	0.00	0.00	0.85	0.77	0.00	0.00	0.66	16.20	7.94	0.08	0.00	0.00	0.00	0.00	
Al2O3	26.35	1.46	1.38	1.07	22.94	26.05	0.66	3.07	0.23	0.00	0.00	20.10	19.73	21.83	
FeO	0.44	16.93	19.19	21.10	0.47	0.47	25.62	76.30	90.64	67.35	0.00	0.07	0.07	0.16	
MnO	0.00	0.00	0.44	0.48	0.00	0.00	0.56	0.58	0.35	1.69	0.00	0.00	0.00	0.14	
MgO	0.09	12.22	11.33	8.95	0.05	0.09	4.29	3.21	0.02	0.40	0.00	0.00	0.00	0.14	
CaO	8.55	17.19	17.63	18.21	4.85	7.40	18.94	0.23	0.23	0.52	0.00	0.85	0.34	2.75	
Na2O	6.45	0.31	0.31	0.29	8.84	7.29	0.33	0.11	0.13	0.08	0.00	5.58	3.42	7.55	
K2O	0.60	0.04	0.00	0.00	0.58	0.40	0.00	0.00	0.00	0.00	0.00	8.18	11.73	3.75	
FeO*	0.44	16.93	19.19	21.10	0.47	0.47	25.62	76.50	90.64	67.35	0.00	0.07	0.07	0.16	
F/F+M	0.830	0.381	0.634	0.707	0.904	0.839	0.859	0.960	1.000	0.994	X 1.701412E+38	1.000	1.000	0.683	
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
Source	1	1	1	1	1	1	1	1	1	1	2	2	2	2	
den	2.43	2.85	2.92	2.94	2.38	2.42	2.98	5.03	5.45	3.89	2.24	2.32	2.31	2.35	
	Plagioclase	Augite		Augite	Plagioclase	Plagioclase	Augite	Magnetite with Ti	Magnetite	Olivine	Quartz	Alkali feldspar	Alkali feldspar	Alkali feldspar	

1. Green, 1986
2. Deer, Howie and Zussman, 1980

Appendix 6.

Partitioning coefficients used in petrogenetic modeling.

Element	Quartz	Alkali Felds.	Plagio.	Augite	Olivine	Magnetite
Sc	0.001 Cull.	.06 Cull.	0.06 Cull.	15.0 Cull.	.02 Alle.	1.0 Alle.
Cr	0.001 Cull.	0.00 Cox	0.01 Leem.	10.0 Leem.	1.8 Alle.	10.0 Alle.
Ni	0.0 Cull.	0.0 Cox	0.26 Alle.	3.5 Carr.	15.0 Carr.	5.0 Carr.
Sm	0.001 Cull.	0.02 Hans.	0.10 Hans.	1.70 Hans.	0.01 Leem.	0.0 Alle.
Eu	0.001 Cull.	1.10 Hans.	2.10 Hans.	0.87 Cull.	0.01 Alle.	0.0 Alle.
Th	0.001 Cull.	0.02 Cull.	0.02 Cull.	0.013 Cull.	0.0 Cull.	0.0 Cull.

Sources

Alle. = Allegre and others, 1977
Carr = Carr, IGPET program
Cox = Cox and others, 1979
Cull. = Cullers and others, 1981
Hans. = Hanson, 1977
Leem. = Leeman, 1976

Appendix 7.

Petrogenetic models with favorable results.

Numbers correspond to those in Table 5 and Figure 40.

1.

```
The Parent lava is KI-A
  Coef      %
  0.158   0.568 BKF-46PR
  0.056   0.202 NE-2-302
  0.064   0.230 NL-1C9
  0.715         KC-A is the daughter
       SiO2    TiO2   Al2O3  FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
KC-A  71.14    0.54  12.74   5.40   0.10   0.52   0.52   3.49   5.46   0.09
KI-A
OBS   63.62    1.49  12.89   9.42   0.12   1.44   2.29   4.16   4.27   0.29
CALC  63.80    1.35  12.99   9.46   0.13   1.28   2.28   3.92   4.00   0.07
DIF   -0.07    0.14  -0.05  -0.04  -0.01   0.16   0.01   0.24   0.28   0.22
 Sum of squares of residuals=   0.241
```

1. KI-KC plag cpx mag

Element	Obs.	Calc.	% diff.
Sc	7.75	6.55	15.50
Cr	3.50	0.80	77.14
Ni	n/a		
Sm	17.28	15.85	8.30
Eu	2.78	2.55	8.30
Th	15.43	15.17	1.70

2.

```
The Parent lava is I-A
  Coef       %
  0.136    0.515 GKF-46PR
  0.057    0.215 NE-2-302
  0.071    0.269 NL-1 C
  0.734          KC-A is the daughter
        SiO2    TiO2   Al2O3   FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
KC-A   71.14    0.54   12.74   5.40   0.10   0.52   0.52   3.49   5.46   0.09
I-A
OBS    64.34    1.12   12.34   9.64   0.12   1.44   2.28   4.15   4.27   0.29
CALC   64.43    1.32   12.76   9.60   0.11   1.44   2.28   3.80   4.09   0.07
DIF    -0.04   -0.20   -0.21   0.05   0.02  -0.00   0.00   0.36   0.17   0.22
 Sum of squares of residuals=   0.291
```

2. I-KC plag mag cpx

Element	Obs.	Calc.	% diff.
Sc	7.75	6.67	13.94
Cr	3.50	3.34	4.57
Ni	n/a		ERR
Sm	17.28	20.83	-20.54
Eu	2.78	3.52	-26.62
Th	15.43	15.74	-2.01

3.

```
The Parent lava is I-A
  Coef       %
  0.071    0.265 NL-1CS
  0.138    0.518 GKF-46PR
  0.044    0.164 NE-2-302
  0.014    0.052 F-2370
  0.731          KC-A is the daughter
        SiO2    TiO2   Al2O3   FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
KC-A   71.14    0.54   12.74   5.40   0.10   0.52   0.52   3.49   5.46   0.09
I-A
OBS    64.34    1.12   12.34   9.64   0.12   1.44   2.28   4.15   4.27   0.29
CALC   64.45    1.16   12.70   9.64   0.15   1.33   2.31   3.80   4.07   0.07
DIF    -0.04   -0.04   -0.18   0.01  -0.03   0.11  -0.03   0.35   0.19   0.22
 Sum of squares of residuals=   0.261
```

3. I-KC plag cpx mag ol

Element	Obs.	Calc.	% diff.
Sc	7.75	6.77	12.65
Cr	3.50	3.80	-8.57
Ni	n/a		ERR
Sm	17.28	20.94	-21.18
Eu	2.78	3.45	-24.10
Th	15.43	15.74	-2.01

```
4. The Parent lava is KC-A
     Coef       %
     0.127    0.858 GKF-46PR
     0.021    0.142 NE-2-302
     0.862          MH-A is the daughter
          SiO2    TiO2   Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
   MH-A  72.59    0.39   11.73   4.29    0.12    0.47    0.22    3.04    7.15    0.00
   KC-A
   OBS   71.14    0.54   12.74   5.40    0.10    0.52    0.52    3.49    5.46    0.09
   CALC  70.50    0.67   13.10   5.37    0.12    0.48    0.82    3.75    6.23    0.00
   DIF    0.25   -0.13   -0.18   0.03   -0.02    0.04   -0.30   -0.26   -0.77    0.09
    Sum of squares of residuals=   0.875
```

4. KC-MH plag mag

Element	Obs.	Calc.	% diff.
Sc	3.70	8.74	-136.22
Cr	4.00	3.28	18.00
Ni	4.00	3.70	7.50
Sm	10.63	19.79	-86.17
Eu	1.50	2.47	-64.67
Th	14.83	17.85	-20.36

```
5. The Parent lava is KC-A
     Coef       %
     0.138    0.605 GKF-46PR
     0.026    0.114 NE-2-302
     0.064    0.281 SIO2
     0.773          MH-A is the daughter
          SiO2    TiO2   Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
   MH-A  72.59    0.39   11.73   4.29    0.12    0.47    0.22    3.04    7.15    0.00
   KC-A
   OBS   71.14    0.54   12.74   5.40    0.10    0.52    0.52    3.49    5.46    0.09
   CALC  71.14    0.72   12.31   5.37    0.11    0.45    0.85    3.58    5.60    0.00
   DIF    0.00   -0.18    0.21   0.03   -0.01    0.07   -0.33   -0.09   -0.14    0.09
    Sum of squares of residuals=   0.227
```

5. KC-MH qtz plag mag

Element	Obs.	Calc.	
Sc	3.70	9.65	-160.81
Cr	4.00	3.37	15.75
Ni	20.00	3.92	80.40
Sm	14.70	22.00	-49.66
Eu	2.49	2.59	-4.02
Th	15.70	19.90	-26.75

```
6.  The Parent lava is KC-A
      Coef        %
      0.205     0.619 OR-21
      0.094     0.285 SIO2
      0.032     0.097 NE-2-302
      0.670             MH-A is the daughter
            SiO2    TiO2    Al2O3   FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
    MH-A  72.59     0.39   11.73    4.29    0.12    0.47    0.22    3.04    7.15    0.00
    KC-A
    OBS   71.14     0.54   12.74    5.40    0.10    0.52    0.52    3.49    5.46    0.09
    CALC  71.14     0.78   12.43    5.36    0.13    0.44    0.72    3.59    5.56    0.00
    DIF    0.00    -0.24    0.15    0.05   -0.03    0.07   -0.20   -0.10   -0.09    0.09
     Sum of squares of residuals=   0.156
```

6. KC-MH k-spar qtz mag

Element	Obs.	Calc.	% diff.
Sc	14.70	25.70	-74.83
Cr	2.49	3.16	-26.91
Ni	20.00	3.92	80.40
Sm	14.70	22.00	-49.66
Eu	2.49	2.59	-4.02
Th	15.70	19.90	-26.75

```
7.  The Parent lava is I-A
      Coef        %
      0.074     0.202 NL-1CL
      0.225     0.613 GKF-46PR
      0.068     0.185 NE-2-302
      0.638             MH-A is the daughter
            SiO2    TiO2    Al2O3   FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
    MH-A  72.59     0.39   11.73    4.29    0.12    0.47    0.22    3.04    7.15    0.00
    I-A
    OBS   64.34     1.12   12.34    9.64    0.12    1.44    2.28    4.15    4.27    0.29
    CALC  64.00     1.40   12.94    9.59    0.15    1.19    2.60    3.96    4.69    0.00
    DIF    0.14    -0.28   -0.30    0.06   -0.03    0.25   -0.32    0.19   -0.43    0.29
     Sum of squares of residuals=   0.652
```

7. I-MH plag mag

Element	Obs.	Calc.	% diff.
Sc	3.70	6.69	-80.81
Cr	4.00	3.01	24.75
Ni	n/a		ERR
Sm	14.70	23.40	-59.18
Eu	2.49	3.15	-26.51
Th	14.83	18.10	-22.05

8.

```
The Parent lava is I-A
  Coef       %
  0.231    0.617 BKF-46PR
  0.070    0.186 NL-1CL
  0.048    0.127 NE-2-302
  0.026    0.070 F-2370
  0.626          MH-A is the daughter
        SiO2    TiO2   Al2O3   FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
MH-A   72.59    0.39   11.73   4.29    0.12    0.47    0.22    3.04    7.15    0.00
I-A
OBS    64.34    1.12   12.34   9.64    0.12    1.44    2.28    4.15    4.27    0.29
CALC   64.05    1.07   12.86   9.66    0.18    1.09    2.55    3.98    4.61    0.00
DIF     0.12    0.05   -0.26  -0.02   -0.06    0.35   -0.27    0.18   -0.34    0.29
 Sum of squares of residuals=   0.514
```

8. I-MH plag cpx mag ol

Element	Obs.	Calc.	% diff.
Sc	3.70	7.38	-99.46
Cr	4.00	3.82	4.50
Ni	n/a		ERR
Sm	14.70	23.90	-62.59
Eu	2.49	3.13	-25.70
Th	15.70	18.44	-17.45

9.

```
The Parent lava is I-A
  Coef       %
  0.140    0.519 NL-1P
  0.046    0.170 NL-1 C
  0.058    0.216 NE-2-302
  0.026    0.095 F-2370
  0.723          DT-A is the daughter
        SiO2    TiO2   Al2O3   FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
DT-A   73.84    0.40   11.88   3.59    0.04    0.55    0.52    3.58    5.56    0.04
I-A
OBS    64.34    1.12   12.34   9.64    0.12    1.44    2.28    4.15    4.27    0.29
CALC   64.58    1.24   12.53   9.63    0.11    1.16    2.39    3.51    4.10    0.03
DIF    -0.09   -0.12   -0.09   0.01    0.02    0.27   -0.10    0.64    0.16    0.26
 Sum of squares of residuals=   0.622
```

9. I-DT plag cpx mag ol

Element	Obs.	Calc.	% diff.
Sc	4.16	10.16	-144.23
Cr	4.50	4.10	8.89
Ni	n/a		ERR
Sm	10.63	22.16	-108.47
Eu	1.50	3.58	-138.67
Th	14.83	16.00	-7.89

```
10.  The Parent lava is KI-A
       Coef       %
       0.248    0.644 GKF-46PR
       0.064    0.167 NL-1 C
       0.073    0.190 NE-2-302
       0.615          MH-A is the daughter
            SiO2    TiO2   Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
     MH-A  72.59    0.39   11.73   4.29   0.12    0.47    0.22    3.04    7.15    0.00
     KI-A
     OBS   63.62    1.49   12.89   9.42   0.12    1.44    2.29    4.16    4.27    0.29
     CALC  63.39    1.42   13.22   9.44   0.12    1.32    2.46    4.09    4.34    0.00
     DIF    0.09    0.07   -0.16  -0.02   0.01    0.12   -0.18    0.07   -0.26    0.29
      Sum of squares of residuals=   0.243
```

10. KI-MH plag cpx mag

Element	Obs.	Calc.	% diff.
Sc	3.70	6.94	-87.57
Cr	4.00	0.70	82.50
Ni	n/a		ERR
Sm	14.70	18.24	-24.08
Eu	2.49	2.28	8.43
Th	14.83	17.55	-18.34

```
11.  The Parent lava is KI-A
       Coef       %
       0.184    0.581 GKF-46PR
       0.057    0.179 NL-1CS
       0.076    0.240 NE-2-302
       0.673          DT-A is the daughter
            SiO2    TiO2   Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
     DT-A  73.84    0.40   11.88   3.59   0.04    0.55    0.52    3.58    5.56    0.04
     KI-A
     OBS   63.62    1.49   12.89   9.42   0.12    1.44    2.29    4.16    4.27    0.29
     CALC  63.95    1.55   12.53   9.42   0.10    1.27    2.26    4.06    3.85    0.03
     DIF   -0.13   -0.06    0.18   0.00   0.03    0.18    0.02    0.10    0.43    0.26
      Sum of squares of residuals=   0.346
```

11. KI-DT plag cpx mag

Element	Obs.	Calc.	% diff.
Sc	4.16	9.07	-118.03
Cr	4.50	0.78	82.67
Ni	n/a		ERR
Sm	10.63	16.80	-58.04
Eu	1.50	1.84	-22.67
Th	14.83	15.29	-3.10

12.

```
The Parent lava is KC-A
  Coef       %
  0.033    0.598 GKF-46PC
  0.022    0.402 F-237M
  0.940          DT-A is the daughter
        SiO2   TiO2   Al2O3  FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
DT-A   73.84   0.40   11.88  3.59   0.04   0.55   0.52   3.58   5.56   0.04
KC-A
OBS    71.14   0.54   12.74  5.40   0.10   0.52   0.52   3.49   5.46   0.09
CALC   71.37   0.56   12.04  5.40   0.05   0.52   0.73   3.61   5.24   0.04
DIF    -0.09  -0.02   0.35   0.00   0.06   0.00  -0.21  -0.12   0.22   0.05
 Sum of squares of residuals=   0.248
```

12. KC-DT plag mag

Element	Obs.	Calc.	% diff.
Sc	4.16	8.02	-92.79
Cr	4.50	2.90	35.56
Ni	4.00	2.16	46.00
Sm	10.63	18.31	-72.25
Eu	1.50	2.74	-82.67
Th	14.83	16.40	-10.59

13.

```
The Parent lava is KC-A
  Coef       %
  0.143    0.658 OR-47
  0.006    0.029 GKF-46PR
  0.036    0.163 SiO2
  0.033    0.151 NE-2-302
  0.783          DT-A is the daughter
        SiO2   TiO2   Al2O3  FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
DT-A   73.84   0.40   11.88  3.59   0.04   0.55   0.52   3.58   5.56   0.04
KC-A
OBS    71.14   0.54   12.74  5.40   0.10   0.52   0.52   3.49   5.46   0.09
CALC   71.14   0.85   12.43  5.34   0.05   0.53   0.56   3.66   5.53   0.03
DIF     0.00  -0.31   0.15   0.06   0.05  -0.01  -0.04  -0.17  -0.07   0.06
 Sum of squares of residuals=   0.165
```

13. KC-DT K-spar plag qtz mag

Element	Obs.	Calc.	% diff.
Sc	4.16	9.45	-127.16
Cr	4.50	3.09	31.33
Ni	4.00	3.88	3.00
Sm	10.63	21.90	-106.02
Eu	1.50	2.93	-95.33
Th	14.83	19.66	-32.57

14.

```
The Parent lava is KC-A
  Coef       %
  0.005    0.021 GKF-46PR
  0.154    0.660 OR-47
  0.040    0.173 SIO2
  0.033    0.143 NE-2-302
  0.001    0.004 NL-1 C
  0.768          DT-A is the daughter
       SIO2    TIO2    Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
DT-A  73.84    0.40   11.88   3.59    0.04    0.35    0.32    3.58    5.56    0.04
KC-A
OBS   71.14    0.54   12.74   5.40    0.10    0.52    0.52    3.49    5.46    0.09
CALC  71.14    0.85   12.44   5.34    0.05    0.54    0.57    3.65    5.53    0.03
DIF    0.00   -0.31    0.15   0.06    0.05   -0.02   -0.05   -0.16   -0.07    0.06
 Sum of squares of residuals=   0.164
```

14. KC-DTplag K-spar qtz mag cpx

Element	Obs.	Calc.	% diff.
Sc	4.16	9.47	-127.64
Cr	4.50	2.85	36.67
Ni	4.00	3.93	1.75
Sm	10.63	22.40	-110.72
Eu	1.50	2.95	-96.67
Th	14.83	20.00	-34.86

15.

```
The Parent lava is KC-A
  Coef       %
  0.011    0.099 GKF-46PR
  0.074    0.653 OR-47
  0.028    0.248 NE-2-302
  0.889          DT-A is the daughter
       SiO2    TiO2    Al2O3  FeO     MnO     MgO     CaO     Na2O    K2O     P2O5
DT-A  73.84    0.40   11.88   3.59    0.04    0.35    0.32    3.58    5.56    0.04
KC-A
OBS   71.14    0.54   12.74   5.40    0.10    0.32    0.32    3.49    5.46    0.09
CALC  71.13    0.81   12.39   5.35    0.05    0.38    0.38    3.69    5.55    0.04
DIF    0.00   -0.27    0.18   0.06    0.05   -0.06   -0.06   -0.20   -0.08    0.06
 Sum of squares of residuals=   0.170
```

15. KC-DT plag K-spar mag

Element	Obs.	Calc.	% diff.
Sc	4.16	8.42	-102.40
Cr	4.50	2.94	34.67
Ni	4.00	3.55	11.25
Sm	10.63	19.39	-82.41
Eu	1.50	2.80	-86.67
Th	14.83	21.20	-42.95

```
16. The Parent lava is MH-A
   Coef       %
 -0.181   0.402 SIO2
 -0.012   0.026 NE-2-302
 -0.258   0.572 OR-21
   1.451          DT-A is the daughter
       SIO2    TIO2   Al2O3  FeO    MnO    MgO    CaO    Na2O   K2O    P2O5
DT-A  73.84    0.40  11.88   3.59   0.04   0.55   0.52   3.58   5.56   0.04
MH-A
OBS   72.59    0.39  11.73   4.29   0.12   0.47   0.22   3.04   7.15   0.00
CALC  72.59    0.40  11.58   4.28   0.02   0.72   0.04   3.24   7.10   0.06
DIF   -0.00   -0.01   0.08   0.01   0.11  -0.25   0.19  -0.20   0.05  -0.06
 Sum of squares of residuals=   0.160
```

16. MH-DT melting qtz K-spar mag

Element	Obs.	Calc.	% diff.
Sc	4.16	2.60	37.50
Cr	4.50	3.04	32.44
Ni	4.00	14.46	-261.50
Sm	10.63	10.17	4.33
Eu	1.50	2.16	-44.00
Th	14.83	10.86	26.77