KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FIFTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2012
Amherst College, Amherst, MA

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ISSN# 1528-7491

The Consortium Colleges The National Science Foundation ExxonMobil Corporation

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Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation

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MAGMATIC PROCESSES OF THE HRAFNFJÖRÐUR CENTRAL VOLCANO, NORTHWEST ICELAND

KATHRYN KUMAMOTO, Williams College
Research Advisor: Reinhard Wobus

INTRODUCTION

Iceland is geologically unique since it is the only place on Earth where a mid-ocean ridge and a hotspot intersect. The interaction between the two features has caused high levels of volcanic activity in the area, resulting in an abnormally thick crust. The hotspot is most often interpreted as a warm buoyant mantle plume (e.g. Jónasson, 2007), but others propose that old subducted plates cause the increased melt generation (e.g. Hofmann and White, 1982).

There is a recurring process in Iceland whereby the rift expression of the Mid-Atlantic Ridge forms centered over the hotspot. However, the ridge is drifting northwest of the stationary hotspot at a rate of 1-3 cm/yr, weakening the connection between the ridge and the hotspot. To keep the two systems tied together, however, the ridge system eventually abandons the off-center rift in favor of forming a new rift re-centered over the hotspot, a phenomenon known as rift jumping (Sigurdsson et al., 1978). The mechanism and impacts of this process are still poorly understood.

In an effort to learn more about rift-jumping, the abandoned 15-7 Ma Skagi-Snaefellsnes rift in northwest Iceland was examined. Southern Skagi volcanoes (active 7-8 Ma) show evidence for magma mixing between basalt and high-silica rhyolite, as well as between basalt and low-silica rhyolite, creating a spectrum of intermediate and more silicic lavas (Jordan and Duncan, 2004). Petrogenesis of rocks from the Arnes central volcano (10 Ma), on the other hand, appears to be dominated by continuous fractional crystallization of a single basaltic parent magma (Jordan and Olin, 2008). Rocks from the southern flank of the Hrafnfjörður central volcano (14 Ma) are also proposed to have formed from fractional crystallization, though nearby volcanic rocks of Leirufjordur show evidence of magma mixing in addition to fractional crystallization (Jordan and Olin, 2008).

This project focuses on the core of the Hrafnfjörður central volcano (Fig. 1). Studying the geochemistry, petrology, and field context of the rocks erupted from this volcano provides new insights on the early life of the Skagi-Snaefellsnes Rift.

METHODS

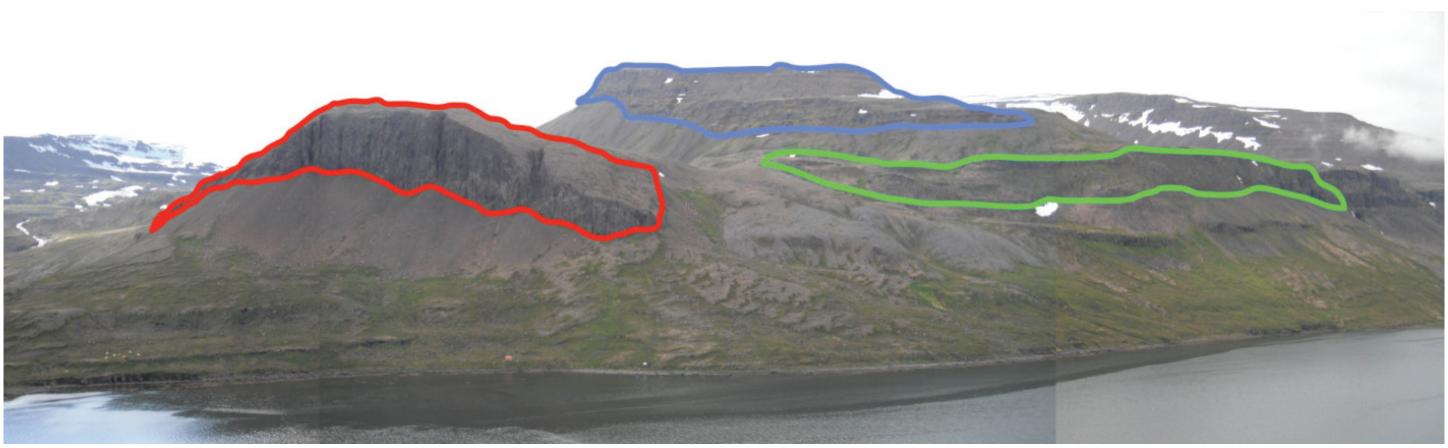

Figure 1: A panorama of the field area, as viewed looking south across Hrafnfjordur. The grass-covered slopes contain most of the basalt and basaltic andesite outcrops. The dacite cliff is the rounded structure on the left, with the outcrop outlined in red. The andesite cliff exposure is outlined in green on the right. The exposed upper basalts are outlined in blue.

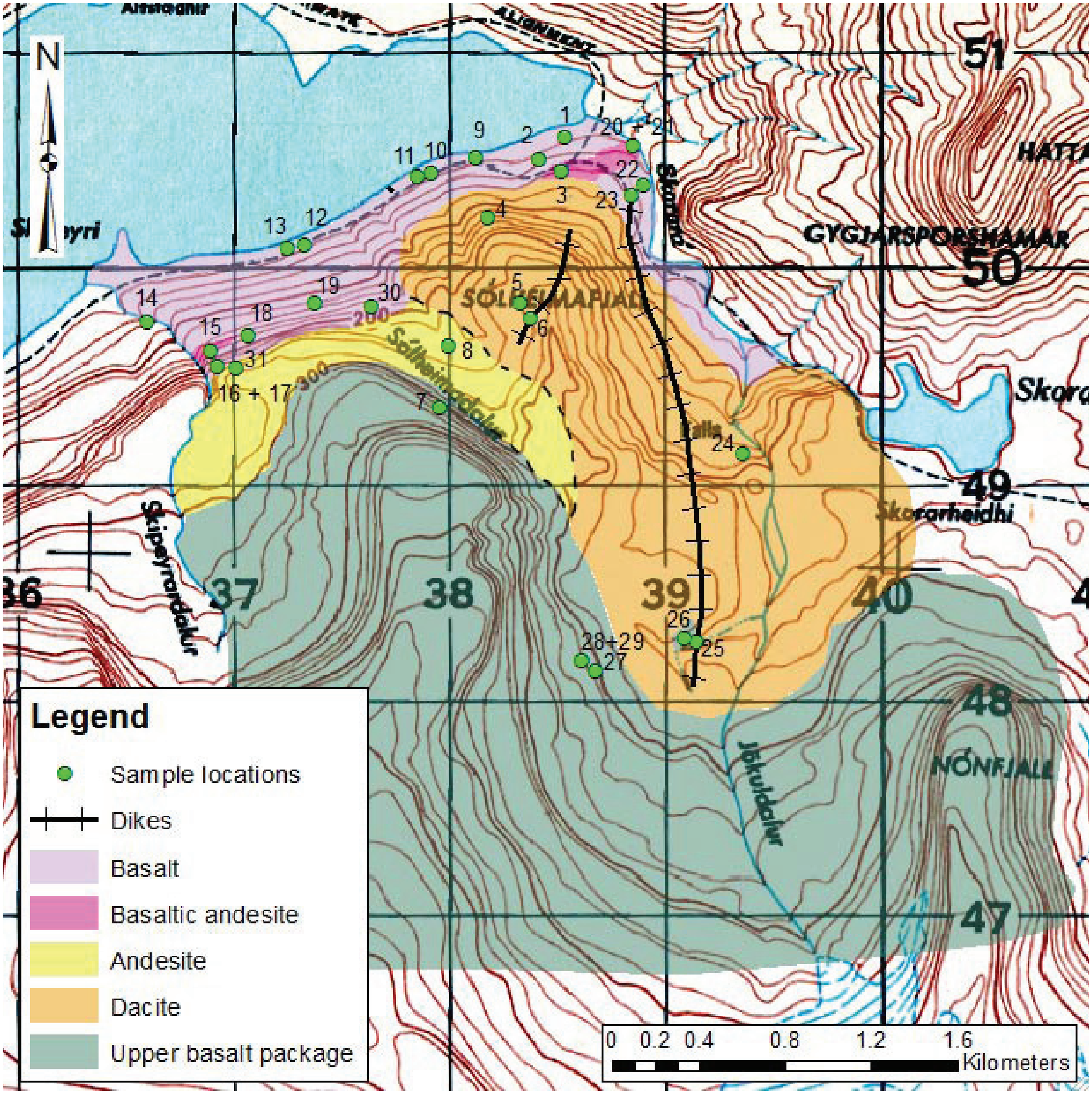

Figure 2: The geologic map of the study area, marking all sample locations.

Our goals in the field were to identify and map the different rock units on a 1:25,000 topographic map and to obtain samples for future chemical and petrographic analysis. GPS points and compass bearings allowed us to plot our sample sites on a field map as well (Fig. 2). Of the 32 samples originally collected, 22 were cut for petrographic thin sections, 5 were cut for polished thin sections, and 20 were prepared for X-Ray fluorescence (XRF) major and trace element analysis. Thin sections were prepared by Vancouver GeoTech, five polished sections were prepared by Wagner Petrographic, XRF analysis was completed at the College of Wooster, and SEM analysis was performed at Smith and Williams Colleges.

FIELD RELATIONS AND PETROGRAPHY

The flows from the Hrafnfjörður volcano are stratified, with basalts and basaltic andesites generally on the bottom close to the shore of the fjord, Hrafnfjörður, and more silicic rocks forming cliffs above (Fig. 2). Above the cliffs is another package of extensive plateau basalts, but these basalts are believed to have originated elsewhere and are not the focus of this project. Covered slopes also make up a significant portion of the landscape, but for the purposes of a geologic map, units were extrapolated beneath these areas.

My project focuses on the southeastern portion of the fjord, bounded on each side by rivers. The most noticeable features are the imposing cliffs rising to the south of the shoreline. The cliffs are composed of dacite on the eastern side and andesite on the western side. Both of these intermediate-silica rocks are very fine-grained, with crystals on the order of tens and hundreds of microns for the andesite and dacite respectively. Scattered phenocrysts of plagioclase and clinopyroxene are also present. EDS with the SEM at Williams College showed the presence of plagioclase, clinopyroxene, an exsolution intergrowth of ilmenite and magnetite, and quartz in the groundmass of both samples. Crystals tend to be aligned, indicating a flow direction. In addition, the andesite exhibits some banding of darker and lighter minerals. The relationship between the two intermediate silica cliffs is unclear in the field and will be discussed later.

Below the cliffs is a series of layered basalts. In the field, each individual flow is about 3-4 meters thick with varied lateral extent, horizontally jointed, and locally vesicular. The lateral extent of the basalt flows is masked by grass, but I extrapolated their breadth using changes in slope. In general, these basalts are fine-grained with 1-2% phenocrysts, predominantly euhedral to subhedral plagioclase though a few clinopyroxene phenocrysts can be observed in thin section. Clusters of phenocrysts are also present in some rocks, possibly representing a cumulate formed in the magma chamber prior to eruption. Other constituents of the basalts include minor altered olivine and opaque oxides, mostly ilmenite-magnetite intergrowths, as well as rare apatite and zircon crystals in the groundmass. The basalts vary in texture from intergranular to subophitic or ophitic (Fig. 3).

Some phenocrysts in the basalts also exhibited disequilibrium textures. Spongy cellular plagioclase grains as well as resorbed plagioclase and clinopyroxene crystals are present in both ophitic and intergranular units. Other plagioclase grains are zoned, with

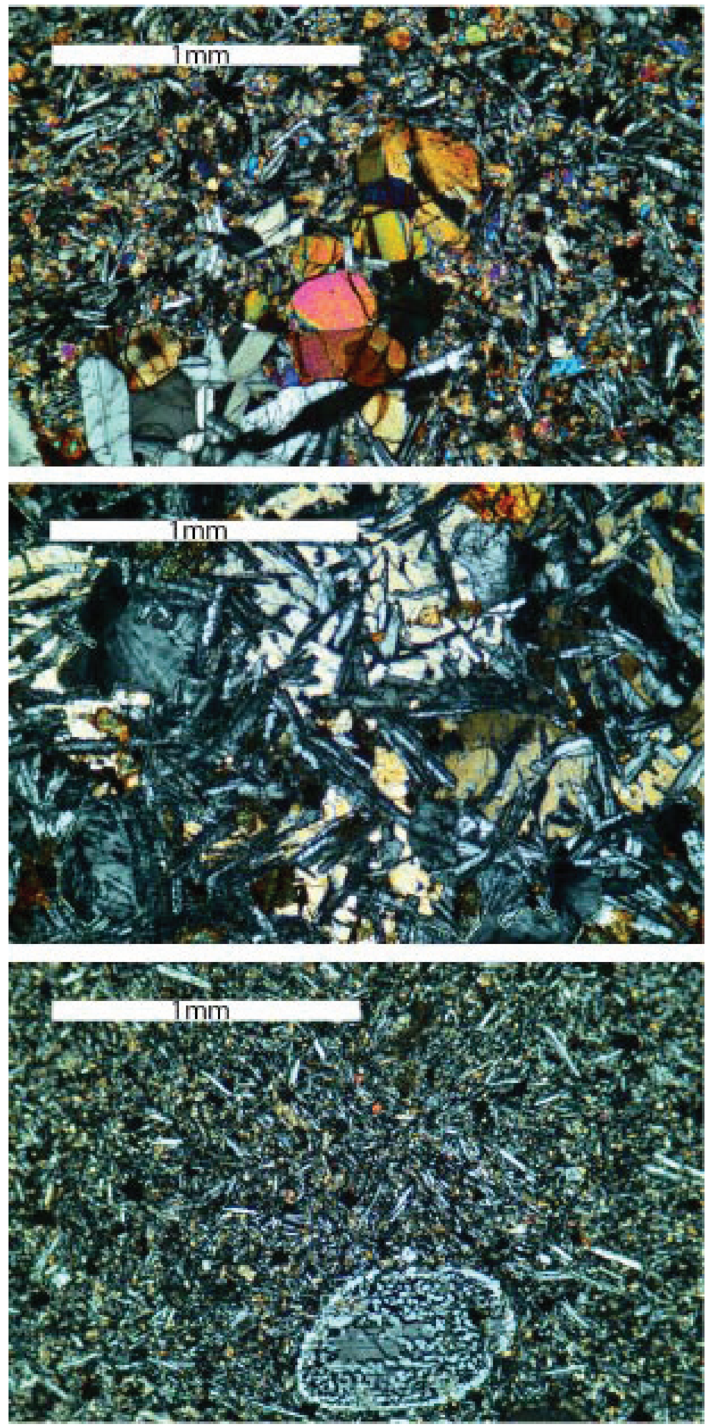

Figure 3: Photomicrographs of various basalt textures. The top picture shows an intergranular texture, and the middle shows an ophitic texture. The bottom picture is intergranular with a grain of spongy, cellular plagioclase.

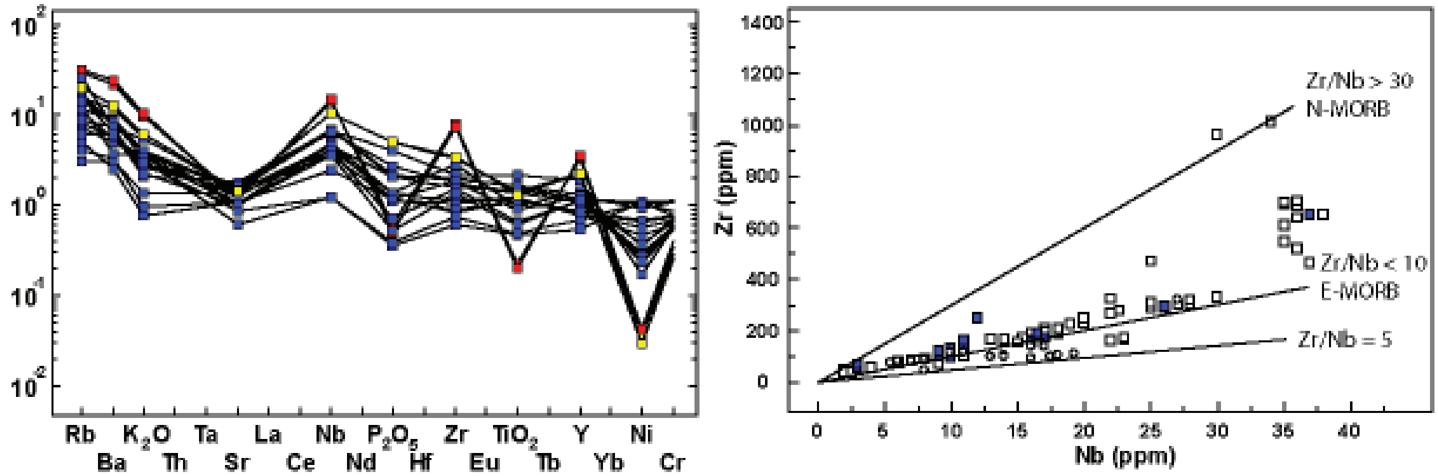

Figure 4: On the left, a MORB-normalized element variation diagram shows enrichment of dacites (red) and andesites (yellow) compared to basalts (blue) in my field area (after Bevins et al., 1984). The Zr/Nb diagram (after Wood, 1979) on the right shows that the rocks from Hrafnfjörður are enriched in plume material, though they are not pure E-MORB. Blue squares represent rocks from the field area; white squares represent data from the rest of the volcano; white circles represent dikes from the area.

more sodic rims. Some clinopyroxene crystals are also zoned.

GEOCHEMISTRY

XRF major and trace element analyses were carried out on 20 samples from the field area. As with most Icelandic rocks, all samples follow a tholeiitic trend when plotted on an AFM diagram. A spider diagram shows that the samples are enriched in incompatible elements compared to MORB (after Bevins et al., 1984). A Zr-Nb plot indicates the significance of mantle plume influence in the development of the primary magma: all data points plot below the Zr/Nb=30 line that defines N-MORB composition, and most of them are very close to the Zr/Nb=10 line defining E-MORB composition (Wood et al., 1979) (Fig. 4).

Harker diagrams versus SiO_2 generally show a change in slope at around 50% SiO_2. This is true of Al_2O_3, CaO, FeO, MgO, TiO_2 and some trace elements. Therefore, it is more instructive to examine variation diagrams using wt% MgO as the independent variable. For instance, there is a strong inflection point in TiO_2 versus MgO at 4.5 wt% MgO, with titanium initially increasing with decreasing MgO but then abruptly decreasing below 4.5 wt% MgO. P_2O_5 versus MgO has a similar shape to TiO_2 versus MgO, but the inflection point is closer to 3.5 wt% MgO. CaO/Al_2O_3 versus MgO shows four high-Mg samples aligned with the top of a trend of decreasing CaO/Al_2O_3 with decreasing MgO.

DISCUSSION

Interpreting the Stratigraphy: Multiple vents or erosion?

The relation between the two intermediate-silica cliff-forming units is unclear in the field. The andesite is a well-defined flow, and the basaltic flows above and below it are visible without any covered intervals. The dacite was sampled at the bottom of the exposed outcrop, but a talus slope continues down from the outcrop for about 40 meters of elevation, and I hypothesize that the dacite continues beneath the talus. Whether or not this is the case, the lower boundary of the dacite outcrop is stratigraphically lower than the bottom of the andesite cliff to the west. The relationship between the eroded top of the dacite and the upper flow boundary of the andesite is harder to interpret due to recent glacial erosion, but it appears that they may be at a similar elevation. This means that either the andesite flow and lower basalt flows terminate against the dacite, or that the dacite terminates against the basalt-andesite pile after it had been eroded, with the dacite filling in a topographic low. If the former is true, the andesite and the west-

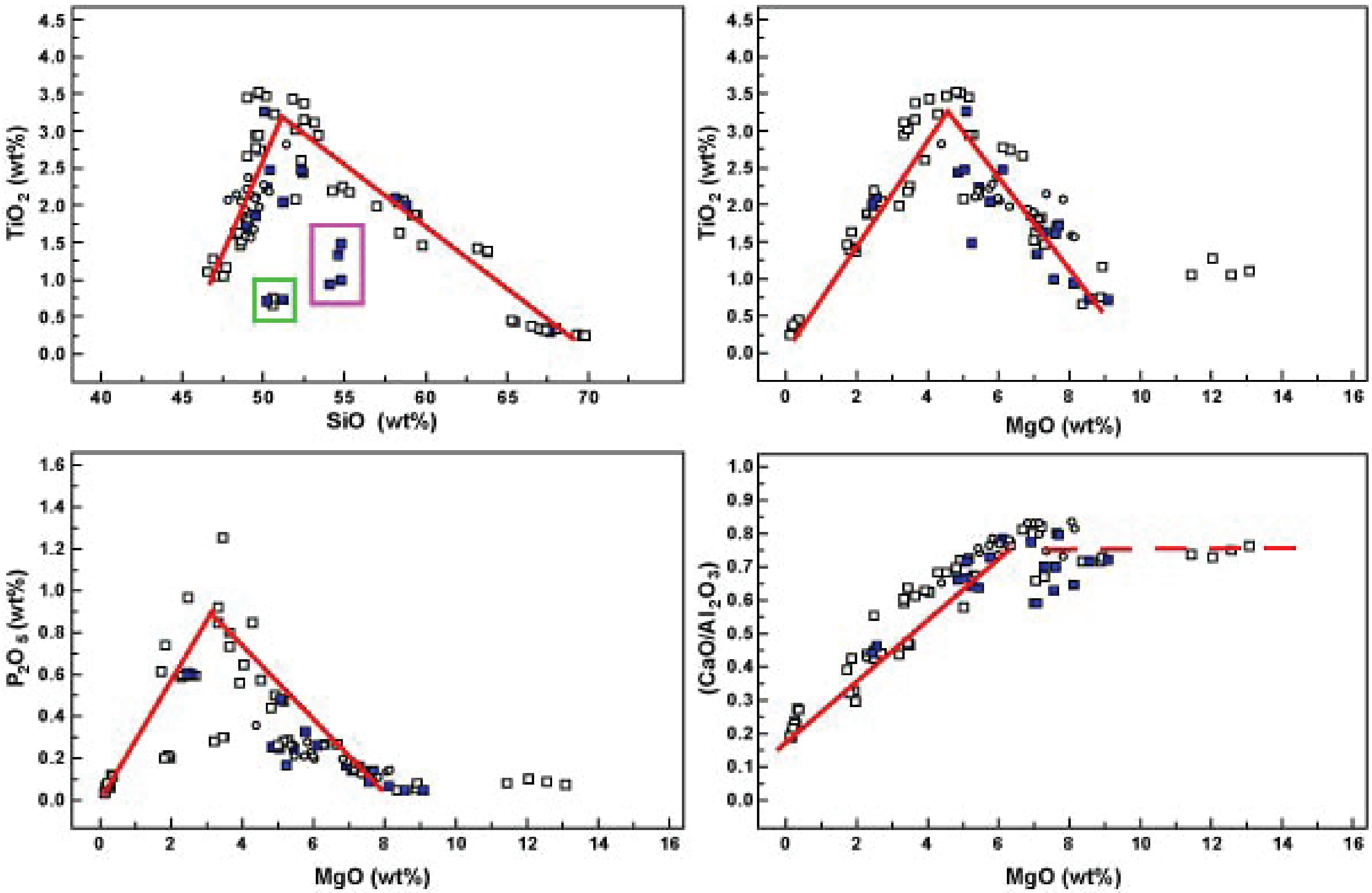

Figure 5: Harker diagrams illustrating fractional crystallization. Blue squares represent rocks from the field area; white squares represent data from the rest of the volcano from this trip; white circles represent dikes from the area. The red lines highlight the fractional crystallization trend, and the dashed red line is a potential crystallization trend. The pink box encloses samples formed due to the mixing of magmas within the Hrafnfjörður system, and the green box encloses samples that may have mixed with an unidentified magma source.

ern lower basalts probably erupted from a vent to the west, toward the tip of the peninsula. Following the same logic, the dacite and eastern lower basalts would have erupted from a vent to the east. If, however, the dacite terminates against an eroded lava pile, all of the lavas could have erupted from a single vent to the west.

Petrogenesis: Fractional crystallization or otherwise

In general, rocks from Hrafnfjörður follow a fractional crystallization trend. For instance, the inflection point in the variation diagrams for wt% TiO_2 versus MgO represents the crystallization of ilmenite at 4.5 wt% MgO, now seen in thin section as a magnetite-ilmenite exsolution texture. Apatite, on the other hand, separated at 3.5 wt% MgO, at the inflection point on the graph of P_2O_5 versus MgO (Fig. 5).

Finding the fractionation point of the two major minerals, plagioclase and clinopyroxene, is a bit more complex, though. If the high-Mg samples are anomalous, then there is no significant inflection point in the wt% CaO/Al_2O_3 versus MgO chart (Fig. 5). This would mean that plagioclase and clinopyroxene fractionated over the compositional range of all samples and, therefore, that the initial fractionation point is not contained within the data set. If, however, we assume that the four high-Mg samples are not anomalous, then the inflection point in the CaO/Al_2O_3 versus MgO chart at about 8 wt% MgO would mark the crystallization of both plagioclase and clinopyroxene; otherwise, there would be an additional inflection point in the chart. Previous studies have shown this same flat behavior at high wt% MgO in Iceland (e.g. Johnson, 2005), so it is probable that this is the case at Hrafnfjörður. This trend would include the fractionation of olivine, though little is present in these samples.

Not all samples lie on the fractionation trend, however, so an additional explanation is required. Magma mixing is a likely mechanism for some of these off-trend samples, particularly a low-titanium cluster at 55% SiO_2 (boxed in pink in Fig. 5). These basaltic andesites contain spongy cellular plagioclase and zoned pyroxene crystals, evidence of disequilibrium crystallization and resorption. If initial equilibrium crystallization were interrupted by the introduction of a magma source with a different composition, these textures would be expected (e.g. Andersson and Ekland, 1994).

The dacite samples exhibit off-trend behavior as well, notable in Figure 4 in the Zr-Nb diagram. They also do no lie on any evident magma mixing trend. Therefore, another mechanism must be utilized. Crustal melting is the most likely mechanism, since this would produce a more silicic magma enriched in incompatible elements like zirconium (e.g. Meganck, 2004).

There is one more major group of basaltic samples that lie distinctly removed from the main fractionation trend (boxed in green in Fig. 5), and they are too depleted or enriched in elements to be explained by magma mixing within the bounds of observed Hrafnfjörður chemistries. These samples represent an ophitic basalt flow located directly beneath the andesite cliff. In terms of major and minor elements, it is particularly depleted in iron, titanium, and phosphorus and is slightly enriched in aluminum, calcium, and magnesium. This unit contains less than 1% opaque crystals, hence the low abundance of iron and titanium. It is possible that it crystallized as a cumulate, explaining the low abundance of some incompatible elements since they would be removed with the interstitial liquid. In addition, if it can be assumed that iron-titanium oxides crystallize late, iron and titanium would have been removed with the interstitial liquid as well, explaining the lack of opaque oxides. However, cumulates are usually depleted in LILEs, adn this is not the case for these samples. A more likely petrogenetic mechanism for this unit is magma mixing with at least one source outside of the known magma compositions of Hrafnfjörður. There are a number of large spongy cellular plagioclase phenocrysts, 1-3mm in diameter. These phenocrysts are larger than any other observed phenocrysts at Hrafnfjörður, and I hypothesize that they came from another source of magma. In addition, as noted above, the texture indicates a disequilibrium in the melt, most likely due to mixing with an unsampled magma.

CONCLUSION

Evidence from bulk chemistry suggests fractional crystallization as the dominant mechanism for petrogenesis at the Hrafnfjörður central volcano. Magma mixing and crustal melting also take place at a much lower frequency. Placing this in the context of other studies from the Skagi-Snaefellsnes Rift, fractional crystallization appears to be the most important mechanism early in the rift's life, while magma mixing becomes increasingly important as the rift ages. The complete story of Hrafnfjörður is more complex, however, and future work with more detailed chemical analyses and radiometrically dated samples would be constructive.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Bud Wobus, for his insights, ideas, and support; my project directors, Brennan Jordan and Meagen Pollock, for all their help in the field, in the lab, and with the technology; Mark Brandriss for his help with the SEM at Smith; Jeanne Fromm for her support in the field with the identification of volcanics as well as local plants; Emily Carbone for the hours we spent working out where our maps overlapped; and the rest of my Keck group for being excellent field assistants and wonderful people.

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