

KECK GEOLOGY CONSORTIUM

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

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Students: *EMILY JOHNSON*, Whitman College, *BENJAMIN CARLSON*, Union College, *LUCY MINER*, Macalester College, *STEVEN ESPINOSA*, University of Texas-El Paso, *HANNAH HILBERT-WOLF*, Carleton College, *SARAH OLIVAS*, University of Texas-El Paso.

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Students: *KATHRYN KUMAMOTO*, Williams College, *EMILY CARBONE*, Smith College, *ERICA WINELAND-THOMSON*, Colorado College, *THAD STODDARD*, University of South Dakota, *NINA WHITNEY*, Carleton College, *KATHARINE*, *SCHLEICH*, The College of Wooster.

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Keck Geology Consortium: Projects 2011-2012

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INTRODUCTION

Iceland is unique geologically because it lies both on the Mid-Atlantic Ridge and above a hotspot. Over the course of Iceland's 15-million-year volcanic history, its rift systems have shifted. As the ridge system drifts away from the hotspot below, old rifts are abandoned and new rifts are created above the hotspot (Hardarson et al., 1997). At the beginning of a rift's lifespan, it is located directly above the plume, but it gradually becomes more distant from the plume as the rift drifts farther away. Large central volcanoes develop along these rifts, and the nature of these central volcanoes may change as the rift drifts farther from the hotspot. This is part of a larger project that seeks to determine whether central volcanoes change throughout the life of a rift zone, and if so, how.

The research for this project focuses on the Skagi-Snaefellsnes rift zone (active 15-7 Ma) in northwestern Iceland, and specifically the Hrafnfjordur central volcano. Hrafnfjordur (~14 Ma) is of particular significance because it formed during the beginning stages of the rift zone (Jordan, 2008). The purpose of this study is to examine the petrogenesis of the basaltic, intermediate and silicic rocks in the area. This information can be compared to the results of previous Keck projects, which studied central volcanoes that formed during later stages of the Skagi-Snaefellsnes rift.

GEOLOGY OF FIELD AREA

The field area stretches for 4 km along the southern shore of Hrafnfjordur. A sequence of lava flows rises steeply from sea level to over 300 m altitude. The flows in the area are nearly flat-lying and consist of basalts, basaltic andesites, andesites and dacites (Fig. 1). In the field, the flows were grouped into three different intervals (in stratigraphic order, from bottom to

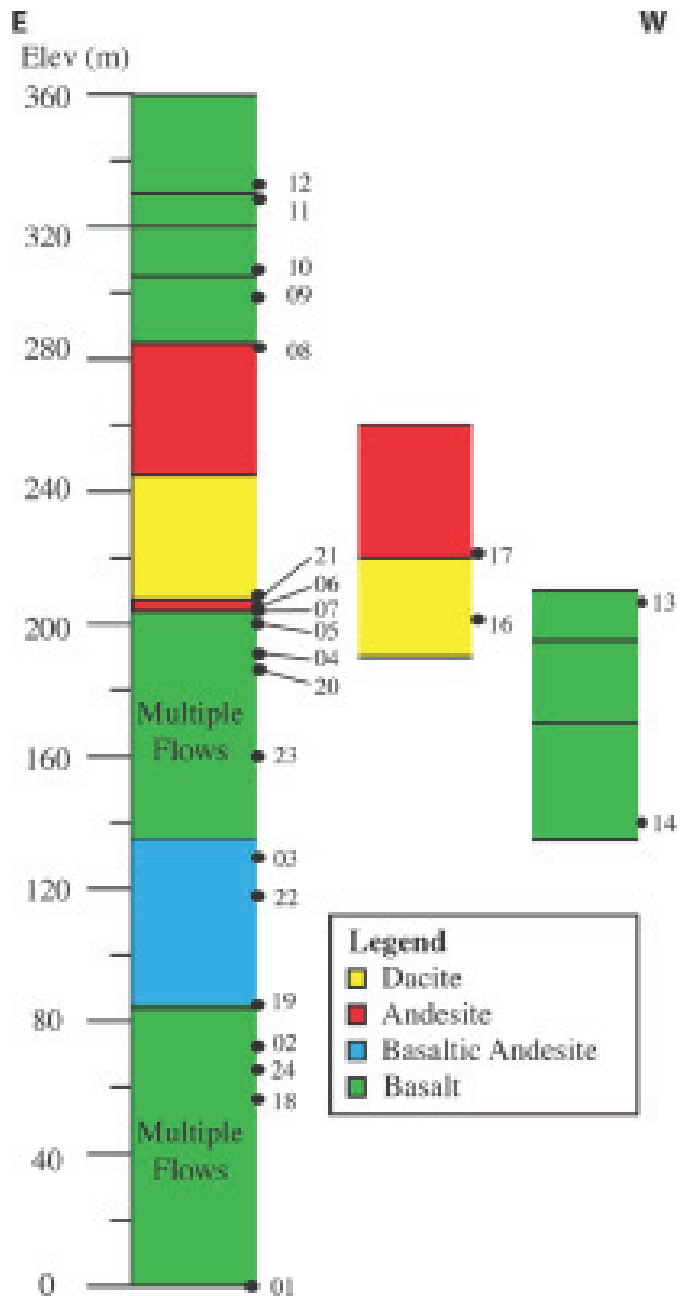


Figure 1. Stratigraphic section displaying rock type and sample numbers.

top): 1) lower basalts and basaltic andesite ; 2) andesite and dacite; 3) upper basalts. The lower basalt and basaltic andesite section comprises the lower ~200 m of the cliff and consists of at least six visibly distinct basalt flows and one thicker basaltic andesite flow; much of the area is covered, so it is possible that there are more flows. The andesite/dacite section makes up the next ~85 m of the cliff and consists of a thick andesite flow interrupted by a thick dacite flow. These are topped by the upper basalt section, which is approximately 300 m thick and consists of a series of thinner (10-15 m) basaltic flows.

PETROGRAPHY

Most of the basalts have intergranular-intersertal groundmass and are porphyritic (1-5% phenocrysts) with a phenocryst assemblage dominated by plagioclase but also including clinopyroxene, oxides and, in some flows, olivine (partially altered to iddingsite). Several of the lower basalt samples (02-EC-11, 18-EC-11, 20-EC-11, 05-EC-11, 07-EC-11) have a different groundmass texture that can be described as ophitic (Fig. 2).

In the ophitic samples, clinopyroxene grains up to 2.5 mm enclose randomly oriented plagioclase laths and olivine grains. Most of the basalts are relatively coarse-grained, with plagioclase laths of up to 0.4 mm in the groundmass. These samples also contain zeolites.

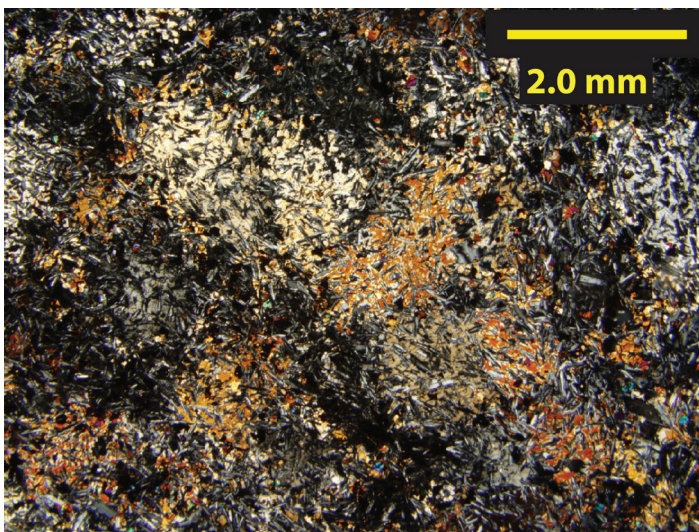


Figure 2. Photomicrograph of a lower basalt sample displaying ophitic texture (sample 18-EC-11).

The basaltic andesite flow, which occurs within the lower basalt section, exhibits the same mineralogy, intergranular-intersertal texture and coarse grain size present in most of the basalts, but its plagioclase phenocrysts have unusual resorption and regrowth textures. There are also resorption textures in plagioclase phenocrysts in two of the lower basalt samples.

The andesitic samples also have an intergranular-intersertal groundmass, but they are only sparsely porphyritic (<1% phenocrysts) and are much finer grained (0.01-0.02 mm plagioclase laths in the groundmass) and the phenocrysts are not resorbed. The groundmass contains more glass and flow texture, including bands and swirls of darker and lighter material, which could be a product of flow banding or mixing.

The dacites have a similar texture to the andesites but show no flow textures or bands in the groundmass. There is no olivine visible in the andesites or dacites, and the dacites contain phenocrysts of hornblende.

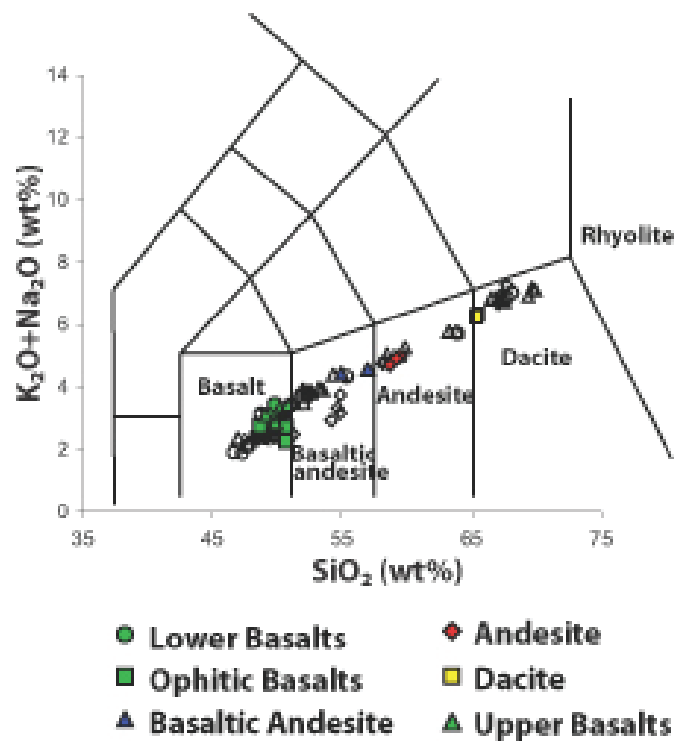


Figure 3. Alkali vs. silica diagram overlain on classification diagram of LeBas et al., 1986. Black-and-white symbols represent samples from nearby field areas in this project.

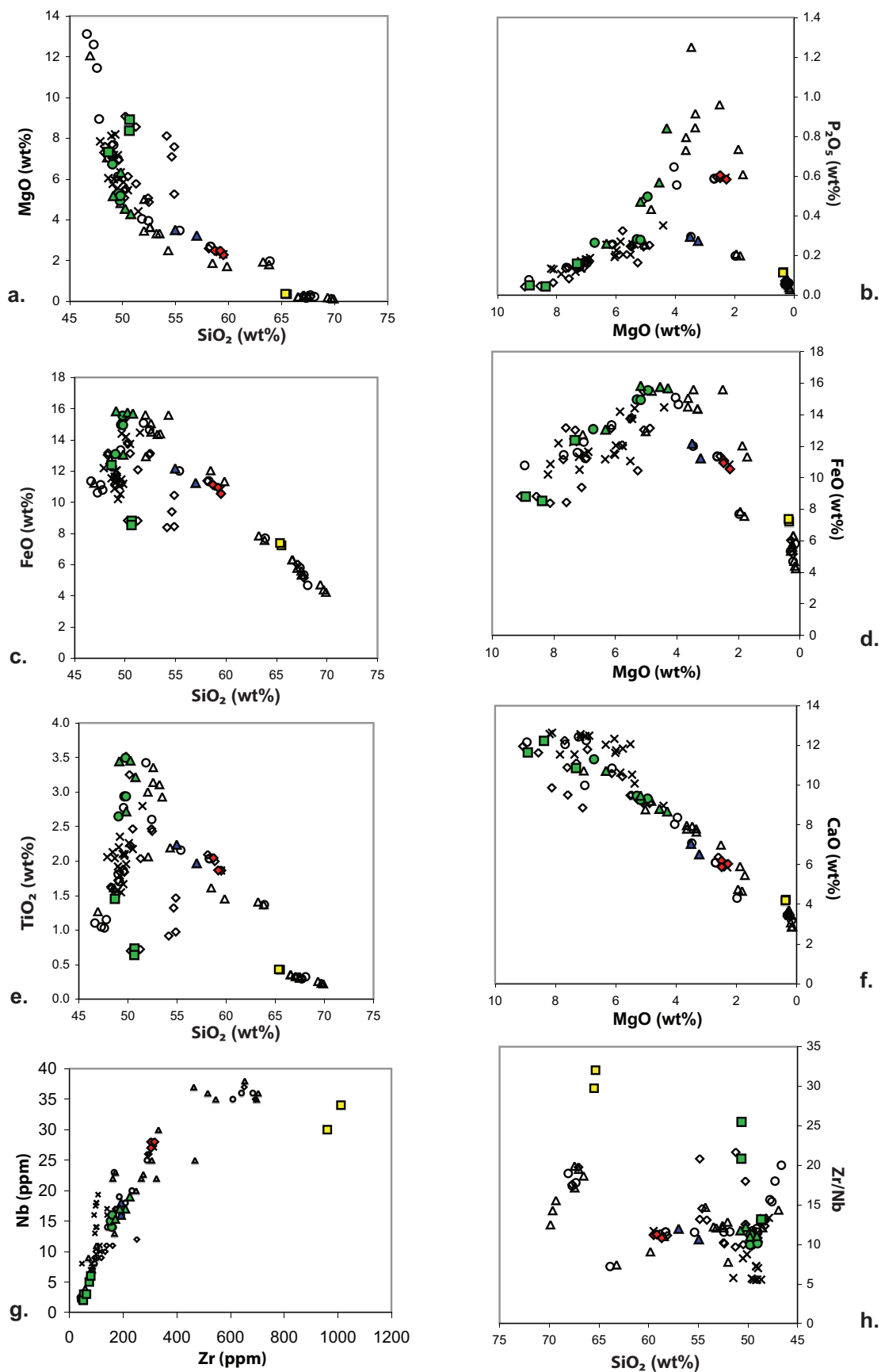


Figure 5. (a-f) Harker and Fenner diagrams illustrate what is interpreted as a plagioclase, olivine, oxide and clinopyroxene fractional crystallization trend. (g) A straight-line trend through the origin in a Zr vs. Nb diagram. (h) Dacites and ophitic basalts display anomalously high Zr/Nb ratios.

GEOCHEMISTRY

Whole Rock Geochemistry

Twenty samples were analyzed by XRF at Wooster College for major and minor element and trace element abundance (samples 02-EC-11 and 05-EC-11 are included only in trace element data). The rock compositions of the suite plot along a trend of increasing alkali versus silica (Fig. 3), and can be classified as basalt, basaltic andesite, andesite and dacite (LeBas et al., 1986).

The ophitic basalts are compositionally distinct from the other basalts; they are poorer in the incompatible elements P, Nb, Zr (HFSE) but not in K, Rb or Ba (LIL). They are also poor in the major element oxides TiO_2 , FeO and MnO but have higher concentrations of Ni, Al_2O_3 , MgO and CaO.

The non-ophitic basalts, basaltic andesites and andesites all have relatively similar Zr/Nb ratios (10-12). The ophitic basalts have a higher and wider range of Zr/Nb ratio values (13-26), resembling those characteristic of neovolcanic zones (Hardarson, 1997). The dacites also have a much higher Zr/Nb ratio (30-32) than any of the other samples.

When plotted vs. silica on Harker diagrams and vs. MgO on Fenner diagrams, the non-ophitic basalts and andesites follow tight, curved trends of depletion in FeO, MgO and CaO; enrichment followed by depletion in P_2O_5 and TiO_2 ; and depletion followed by enrichment in Al_2O_3 . The basaltic andesite samples consistently plot slightly off of these trends. Though the dacite samples plot along most of the trends, there is a wide compositional gap between the andesites and dacites in each diagram. Several trace element diagrams between strongly incompatible elements (Zr vs. Y, Zr vs. Nb, Y vs. Nb) exhibit straight-line trends, and the trend passes through the origin in the Zr vs. Nb diagram, characteristic of fractional crystallization. These trace element trends exclude the dacites, which plot separately.

Plagioclase compositions

Plagioclase phenocrysts and groundmass plagioclase

laths in samples of the basalt (18-EC-11), basaltic andesite (03-EC-11 and 19-EC-11), and andesite (06-EC-11) were analyzed by SEM at Smith College.

Representative plagioclase phenocrysts in the basalt have compositions of An₇₀₋₇₅. Phenocrysts in the andesite have compositions of An₃₀₋₄₀. Plagioclase laths in the two intermingling groundmass colors mentioned above were determined to be of similar composition when analyzed with the SEM. Therefore, there is no evidence of chemical differences between the two groundmass colors. In the basaltic andesite samples, plagioclase phenocrysts, which exhibit resorption textures as described above, have a wide variety of compositions, even within the same crystal. The plagioclase crystal shown in Figure 3, from basaltic andesite sample 03-EC-11, shows petrographic and geochemical evidence of a complex history of resorption and regrowth.

INTERPRETATION AND CONCLUSIONS

As mentioned above, the basalts plot in two distinct compositional groups that correspond with two very

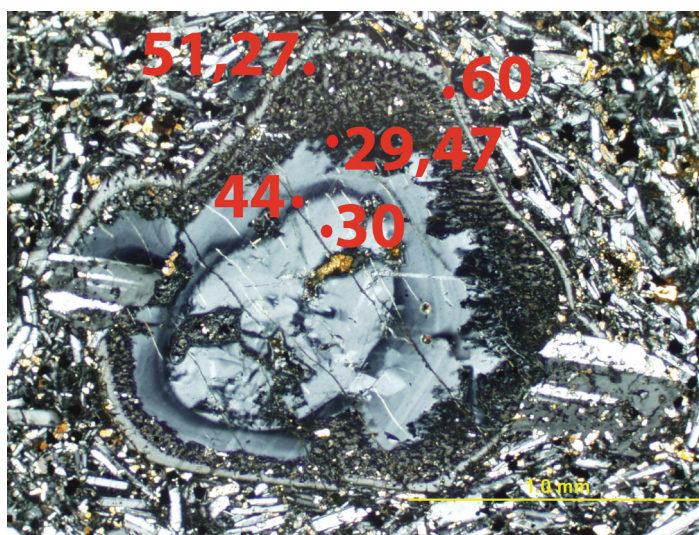


Figure 4. Photomicrograph of a plagioclase phenocryst in basaltic andesite sample 03-EC-11. Percent anorthite compositions are labeled. The center core has a relatively sodic composition and has been resorbed to such a degree that its euhedral shape has been rounded. It is surrounded by a calcic overgrowth that shades gradually into a more sodic composition through normal zoning. This sodic zone shows more resorption texture, and the holes are filled in with more a more sodic composition. The entire crystal is surrounded by a final calcic rim.

different groundmass textures. The unusual texture and chemistry of the ophitic basalts may be due to either a cumulate texture or an origin from a distinct source. A cumulate texture may have formed through expulsion of interstitial liquid during clinopyroxene growth. This could explain the large concentrations of incompatible elements because they would be more concentrated in the liquid than in the crystals, and it would also explain the anomalously high Zr/Nb ratio because zirconium is more incompatible than niobium in clinopyroxene (Kamber and Collinson, 2000). However, the ophitic basalts are not low in all incompatible elements. As mentioned above, they are low in high field strength elements but not in large-ion lithophile elements. This would be unusual in a cumulate because large-ion lithophile elements are mobile in aqueous fluids. Regarding the Zr/Nb ratio, Hardarson et al. (1997) note that the Zr/Nb ratio is generally unaffected by low-pressure fractional crystallization and low-temperature alteration, indicating that the Zr/Nb ratio of the interstitial liquid should not be significantly different from the Zr/Nb ratio of the crystals. In addition, a study of another volcanic suite in Iceland containing ophitic basalts found that the texture is a consequence of the lava's initial chemical composition rather than chemical variation due to fractional crystallization (Robinson et al., 1982). These ophitic basalts were chemically distinct from the other basalts in the study because they were Mg-rich olivine tholeiites. Similarly, the ophitic basalts in this study are more magnesium-rich and contain much larger amounts of olivine than the other basalts. For all of these reasons, it seems more likely that the ophitic basalts originated from a source distinct from the source of the other basalts. The abundance of large-ion-lithophile elements likely results from the presence of a potassium-rich zeolite.

Hardarson et al. (1997) argue that a wide range of Zr/Nb ratio values indicates either a depleted plume source directly above a plume or a mixture with N-MORB in a dying rift zone. This central volcano was located nearly above the plume and was not associated with a dying rift zone, so it is likely that the wide range of Zr/Nb ratios in the ophitic basalts indicate a source of depleted plume material. Within each of the two basalt groups in my area, the different flows may be related through fractional crystallization, mixing or

a combination of both. The resorbed plagioclase phenocrysts in some of the ophitic basalt samples indicate that their origin involved some degree of mixing. The non-ophitic basalts plot on fractional crystallization trends with the andesites. The curved trends in the Harker and Fenner diagrams described above (FeO, MgO, CaO, P_2O_5 , TiO_2 , Al_2O_3) are all plausible fractional crystallization trends for plagioclase, olivine, Fe-Ti oxides and clinopyroxene (Fig. 5).

The basaltic andesites display petrographic and geochemical evidence of magma mixing. The petrographic resorption and regrowth textures, along with the wide variation of chemical composition in separate zones within one crystal, indicate a complex mixing history. The cores of resorbed plagioclase phenocrysts in these basaltic andesite samples are compositionally similar to the unresorbed phenocrysts in the andesite samples. The outer equilibrium zones of the crystals (Fig. 3) are more calcic than the andesite phenocrysts but more sodic than the compositions of phenocrysts in the basalt samples. This is consistent with an origin of the basaltic andesites by mixing of basaltic and andesitic magmas from the area. The geochemical data also support an origin through mixing of basalt and andesite. The basaltic andesite samples plot slightly off of several of the perceived fractional crystallization trends (Fig. 5) that the rest of the data follow. They plot on mixing lines between the andesite and a hypothetical basalt within the non-ophitic compositional array on trace element diagrams. In these diagrams, the basaltic andesite plots two thirds of the distance down the mixing line between the basalts and andesites, suggesting that the mixture is roughly two parts andesite and one part basalt.

The andesites may have formed through fractional crystallization or mixing, though there is more evidence for fractional crystallization. There is no petrographic evidence for mixing. None of the plagioclase phenocrysts exhibit resorption textures, and the lack of compositional difference between the different colors of groundmass suggests that the groundmass texture was a result of flow banding rather than mixing. Geochemical data, however, provide some evidence of fractional crystallization. The andesites plot on fractional crystallization trends in Harker, Fenner

and trace element diagrams with the non-ophitic basalts (Fig. 5). These chemical trends may also be due to mixing between the basalts and dacites, but this hypothesis is not consistent with trace element data because the dacites plot off of hypothetical mixing lines with the basalts, basaltic andesites and andesites.

Martin and Sigmarsson (2007) suggest two possible mechanisms for the formation of silicic magmas in Iceland: crustal melting and fractional crystallization. The dacites generally fit along some of the fractional crystallization trends listed above (FeO vs. SiO_2 , FeO vs. MgO , P_2O_5 vs. MgO , CaO vs. MgO , MgO vs. SiO_2) but plot off of others (Nb vs. Zr, Y vs. Zr, TiO_2 vs. SiO_2). The large compositional gap between the andesites and dacites in most diagrams is unusual in a fractional crystallization trend and thus supports the crustal melting hypothesis. In addition, the high Zr/Nb ratio of the dacite samples makes it unlikely that the dacites are genetically related to the basalts and intermediates in the area.

Through this study it can be concluded that the most likely methods of origin for this suite of rocks involves fractional crystallization, mixing, and at least two separate sources, one of which may be depleted plume for the basalts; mixing between the lower basalts and the andesite for the basaltic andesite; fractional crystallization for the andesite; and crustal melting for the dacite. Though more data would be necessary to determine the petrogenetic story more precisely, it is apparent from this study that many complex processes are at work in this early stage of the rift zone. This study also suggests that central volcanoes in the earliest stage of rifting produce basalts derived from depleted plume material, much like plume-centered neovolcanic zones in Iceland.

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