

KECK GEOLOGY CONSORTIUM

21ST KECK RESEARCH SYMPOSIUM IN GEOLOGY SHORT CONTRIBUTIONS

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Dr Andrew P. de Wet, Editor
Keck Director
Franklin & Marshall College

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster Pa, 17603

Dr Amy Rhodes,
Symposium Organizer
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The Biogeochemistry and Environmental History of Bioluminescent Bays, Vieques, Puerto Rico

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ROBERT WIEBE: Franklin and Marshall College

PAUL OLIN: Washington State University

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LYNNE STEWART: Oberlin College

Research Advisor: Steven Wojtal

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PO Box 3003, Lancaster Pa, 17603
Keckgeology.org

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MICHAEL BERNSTEIN: Amherst College

Research Advisor: Jack Cheney

INTRODUCTION

Iceland marks the expression of the Mid-Atlantic ridge above sea level and the intersection of this ridge with a mantle plume. This mantle plume, imaged by three-dimensional p-wave velocity models of the mantle, is thought to be responsible for Iceland's physiographic expression above sea level (Gudmundsson, 2000).

Volcanism in Iceland occurs in two types of volcanic zones; rift zones and flank zones. Rift zones represent sites of active tectonic rifting and thus the intersection of the Mid-Atlantic Ridge with Iceland. Flank zones, by contrast, represent off-rift zones. The products of rift zone volcanism are generally tholeiitic, whereas the products of flank zone volcanism are generally alkalic or transitional (Jónasson, 2007). Both rift and flank zones generate central volcanoes. Central volcanoes produce the silicic – intermediate rocks of Iceland in addition to large quantities of mafic material (Thordarson & Hoskuldsson, 2002).

Basalt is the dominant product of Icelandic volcanism. Approximately 12% of Icelandic volcanism is silicic. This project seeks to understand the petrogenesis of the silicic rocks. 2003 and 2004 Iceland KECK projects studied rhyolite petrogenesis of early (plume centered) and late (off-center, nearly abandoned) phases of the Skagi-Snaefellsnes rift. This rift was initiated 15 Ma and abandoned around 7 Ma. The results of their findings were equivocal. Major and trace element trends were found to be consistent with fractional crystallization and magma mixing trends were also observed.

To further the study of the silicic volcanics in the area and to add an intermediate location in the

paleorift history, the 2007 KECK project explored a transitional volcanic center along the abandoned Skagi-Snaefellsnes rift in the Westfjords of north-west Iceland. Using petrography and geochemistry, this project seeks to elucidate the mechanisms of rhyolite petrogenesis in Iceland's volcanic environment. The 2007 KECK Iceland data will also be examined in the context of the 2003 and 2004 KECK projects with the aim of working toward a deeper understanding of the relationship between rift drift and magma evolution in Iceland's dynamic tectonic environment.

METHODS

Fieldwork was conducted over a four-week period during the summer of 2007. Hand-sample lithology and field relations were used to characterize the volcanic stratigraphy and delineate distinct units. Thin sections of 25 samples were made by Amherst College and examined with a petrographic microscope. Also at Amherst, five thin sections were studied with a Zeiss EVO50 scanning electron microscope (SEM). Quantitative analyses of the minerals in these samples were performed with an Oxford INCA-Energy Dispersive Spectrometer (EDS). Clean chips of 19 samples, selected to characterize intra-unit as well as unit-to-unit variation, were sent for complete geochemical analysis by XRF and ICP-MS at Washington State University's Geo-Analytical Labs.

RESULTS

Unit Relations

Seven units of lava flows and two intrusive bodies were identified in the field and characterized

petrographically and geochemically. Units were distinguished based on hand sample lithology and field relationships, such as breaks in slope, cross cutting relations and superposition. The following chemical names were assigned to the units based on geochemical analysis: Unit 1, basalt; Unit 2, dacite; Unit 3, rhyolite; Unit 4, basaltic andesite to andesite; Unit 5, dacite to rhyolite; Unit 6, dacite; Unit 7 basalt to basaltic andesite; Intrusive 1, basalt; Intrusive 2, dacite. The following relative ages are hypothesized, oldest to youngest: Unit 1, Unit 2 and Unit 3, Unit 4, Unit 5, Unit 7, Intrusive 1 and Intrusive 2. Unit 6 is bracketed between Units 1 and 7, and lies stratigraphically adjacent to Unit 3 and Unit 4, therefore its exact position in the sequence is indeterminate.

Petrography

A summary of outcrop, hand sample and petrographic characteristics for all units is presented in Table 1. The basalt intrusion has similar phenocryst assemblage and textures to other basalts, but differs in groundmass and grain size, likely due to its intrusive character. The dacite intrusion contains 10-15% glass, 5% phenocrysts with plagioclase > clinopyroxene and Ti-Fe oxides in a cryptocrystalline, nearly vitric matrix, and plagioclase laths and phenocrysts similar to those found in Unit 3. Clinopyroxene

inclusions occur in plagioclase. Ti-Fe oxides occur as inclusions in both plagioclase and clinopyroxene.

Chemical analyses of minerals were determined by EDS for the major phenocryst minerals of 5 samples chosen as representative of the range of compositions of the rocks in the area. Average An content ranges from An₁₂ in the rhyolite to An₅₇ in the basaltic andesite. Average Mg# of pyroxenes ranges from 62 in the basaltic andesite to 3 in the rhyolite. The pyroxenes in these rocks are coexisting pigeonites and augites (Robinson, 1980). Anomalously, the feldspars in the basalt from Unit 1 average An₄₁ and the pyroxenes Mg# 51.

GEOCHEMISTRY

Rocks in the seven units range in composition from basalt to rhyolite. The rocks are subalkaline and tholeiitic. A series of Harker variation diagrams (Fig. 1) illustrates the behavior of compatible and incompatible elements with increasing silica content.

Samples are enriched relative to both N-type MORB and E-type MORB (Fig. 2). The REE diagram exhibits a stacking of similarly patterned lines for basalts through rhyolites across units and samples. Such stacking is suggestive of fractionation in this sub-al-

Unit Number	Outcrop & weathering	Hand sample Description	Thin-section textures and modes where applicable	Phenocrysts and abundance
Unit 1 basalt	Tan-orange brown color	Dense, very dark colored, aphanitic	Cryptocrystalline matrix with microlites of plagioclase. Pilotaxitic.	<1-1.5% plag (4-2.7mm)>cpx and TiFe oxides.
Unit 2 dacite	Pervasive; buff-grey-tan color	Dark grey-green groundmass, plag phyric	Cryptocrystalline, altered matrix with microlites and plag-cpx-TiFe oxide glomerophyrs and plag cumuloephyrs.	10% plag>>cpx subequal with TiFe oxides.
Unit 3 rhyolite	Platy joints on cm scale. Stained red or orange-grey	Medium dark-light grey color, variably fine-coarser aphanitic	Cryptocrystalline, microlites and laths. Weakly trachytic texture. glomerophytic. 15% TiFe oxide, 35% cpx, 50% plag.	Inclusions range from <1% to 3% of plag phenocrysts
Unit 4 basaltic andesite	Slightly platy with vertical jointing. Yellow-brown and tan-brown color	Medium-light grey color, aphanitic. Flow banded	cryptocrystalline and microcrystalline. Intragranular and trachytic. Cryptocrystalline interflows. 15% TiFe oxide, 20-30% cpx, 55-65% plag.	Inclusions: 3-10% abundance. Phenocrysts <1% plag (.17-1.86mm)
Unit 5 dacite & rhyolite	Red to light grey, red, brown and orange. Massive. Internal flow structures and breccias	Dark to medium grey color. Matrix supported breccias: pebble to small cobble	Crypto-microcrystalline with plagioclase laths and microlites. Trchytic texture. Resorbed glomerophyrs.	8% plag (0.3-1.5mm) > cpx.
Unit 6 dacite	Pervasive; variably tan-brown, red, pale-green, green	Heavily altered and friable. Porphyritic.	Cryptocrystalline matrix, flowbanded and altered.	20-25% plag (2.8-0.2mm) >> cpx subequal with TiFe
Unit 7 basalt, b. andesites	Red-brown thinly stacked flows	Dark-medium grey color, aphanitic and aphyric	Cryptocrystalline with pilotaxitic texture and microlites. One microcrystalline sample: 8% TiFe, 45% cpx, 47% plag	<1% plag (1.1-0.3mm) > cpx

Note: Plag = plagioclase. Cpx = clinopyroxene. Unless otherwise indicated, plagioclase phenocrysts have lamellar twins and are concentrically zoned.

Table 1: Abbreviated summary of unit characterizations, excluding intrusive bodies.

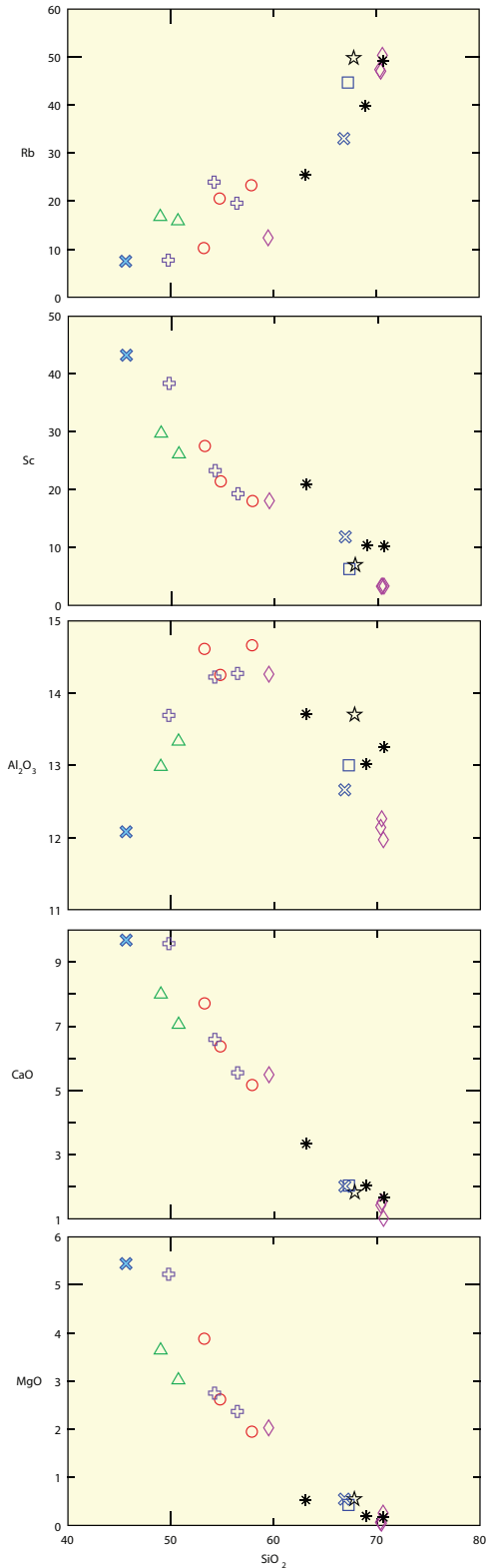


Figure 1: Harker variation diagrams. Note the different compatibilities of major (MgO , CaO , Al_2O_3) and trace (Sc , Rb) elements with increasing silica content. Symbol Key: Unit 1 – empty triangles. Unit 2 – empty square. Unit 3 – empty diamond. Unit 4 – empty circles. Unit 5 – asterisks. Unit 6 – empty five-pointed star. Unit 7 – empty Greek cross. Intrusive 1 – filled x . Intrusive 2 – empty x .

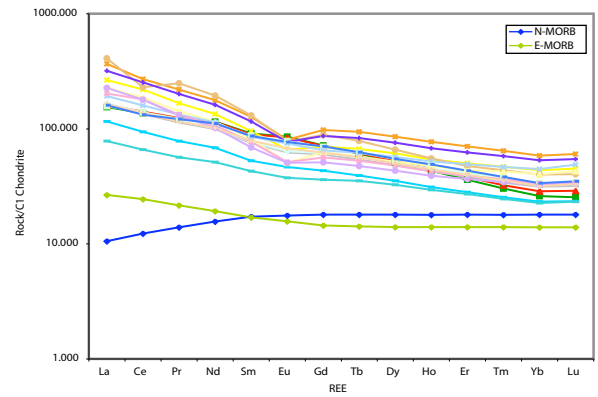


Figure 2: Chondrite-normalized REE diagram showing the trace element patterns for all samples. Note the stacking of similar patterns. N-type MORB and E-type MORB presented for comparison.

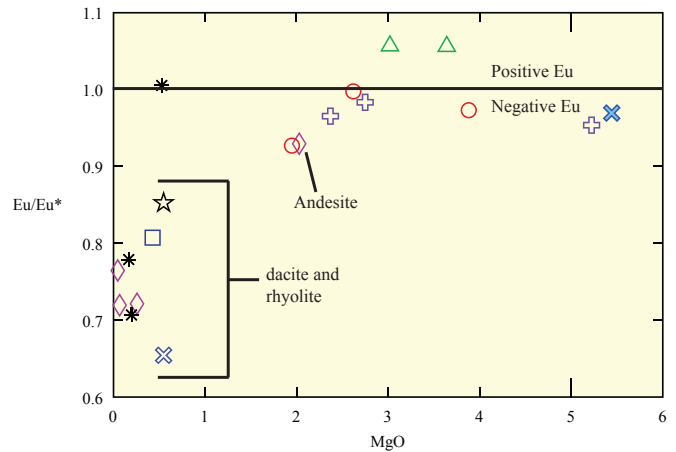


Figure 3: Plot of Eu enrichment relative to MgO content. Eu^* represents the europium value that would be predicted from the abundance of adjacent REE. Eu/Eu^* values less than 1 indicate a negative Eu anomaly. Note the negative Eu anomaly in the dacite and rhyolite samples. See Figure 1 for symbol key.

kaline data series (Pearce, 1996). Incompatible element spider diagrams (not shown) show negative Sr, P and Ti anomalies (Sun & McDonough, 1989). In a plot of Eu/Eu^* versus MgO , a negative Eu anomaly is observable in the rhyolite and dacite samples (Fig. 3).

DISCUSSION

Harker variation diagrams (Fig. 1) show Unit 1 to be an outlier of the other flows. Data corroborating this finding include $Mg\#$; the pyroxene $Mg\#$ in

the basalt of Unit 1 is 51 whereas the Mg# is 62 in Unit 4 basaltic andesites, and 57 in Unit 3 andesite. The high magnesian content of the pyroxenes in more primitive Unit 1 basalts, as compared to less magnesian pyroxenes in more evolved units, precludes a simple liquid line of descent between Unit 1 and the other, more evolved units. The plagioclase phenocrysts in this sample of Unit 1 exhibit textural disequilibrium and mixing texture. It is possible that recharge of an evolved magma by a more primitive magma occurred. If true, the lower An plagioclase and lower Mg# clinopyroxene may have been at equilibrium before injection and began to resorb after recharge. The progression in Mg# among the rest of the data, from the most magnesian basaltic andesites to the least magnesian rhyolites is consistent with a genetic linkage among those other six units.

The decrease in CaO and Sc with increasing SiO₂ content as shown in the Harker variation diagrams (Fig. 1) is consistent with the removal of early forming pyroxene. In addition to MgO, CaO and Sc, the following elements also behaved compatibly with increasing silica content: FeO, TiO₂, MnO, P₂O₅, Sr and V. The compatibility of V is consistent with titanomagnetite fractionation. As expected, Rb behaves incompatibly, increasing in concentration with increasing silica content. In addition to Rb, the following elements also behaved incompatibly with increasing silica content: Na₂O, K₂O, Nb, Zr, Hf, Ta, REE with the exception of Eu, Ba, U, Rb, Th, Pb and Ta. The variation diagram for Al₂O₃ (Fig. 1) behaves differently; Al₂O₃ content increases with increasing silica content then subsequently decreases. Early clinopyroxene removal from the melt may account both for the decrease of CaO and the modest initial increase of Al₂O₃. The Eu anomalies in the dacite and rhyolite samples of Figure 3 suggest plagioclase fractionation. Later plagioclase removal may account for the continued decrease in CaO and the subsequent decrease in Al₂O₃.

Brophy (2008) has presented a model for distinguishing between fractionation of MORB under moderate p_{H₂O} and partial melting of hydrated basalt crust as processes responsible for the origin

of silicic magmas. The Brophy model is based on liquid SiO₂ content controls on REE partition coefficients and posits that these effects are manifest in trace element versus SiO₂ relationships. These relationships provide a means to distinguish between fractionation and melting. In plots of La, Y, and Yb versus liquid SiO₂ our data were consistent

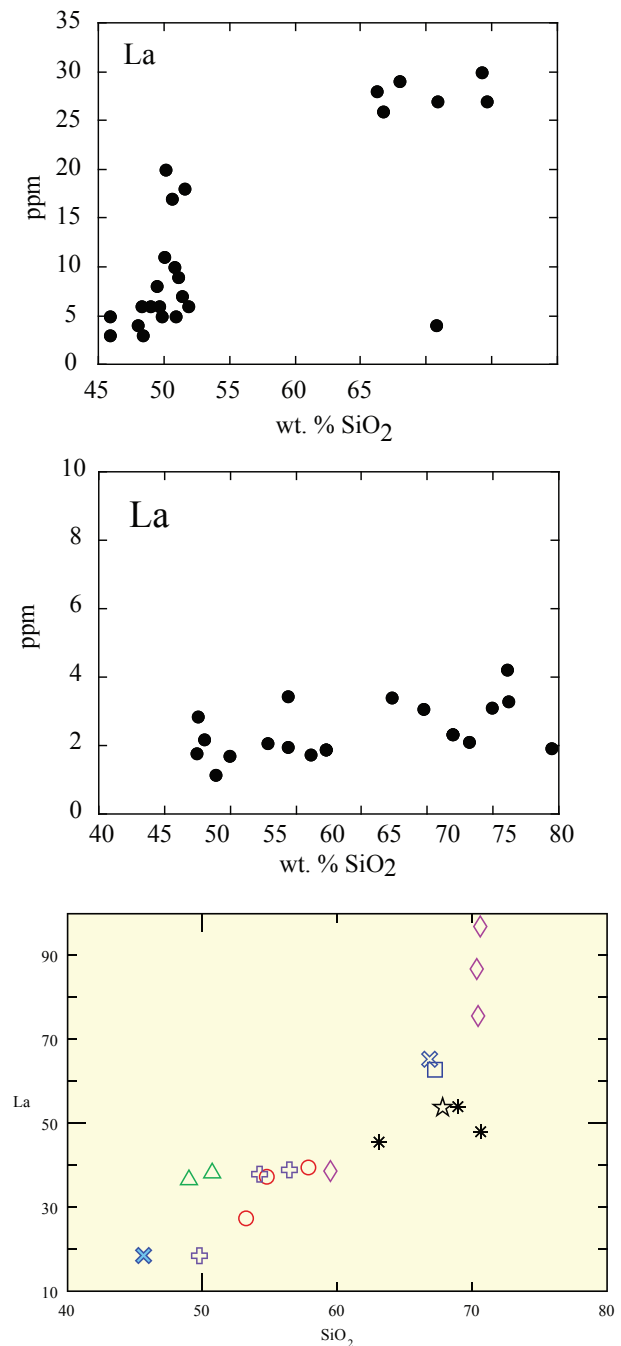


Figure 4: La-SiO₂ diagrams. The top two, after Brophy (2008), model fractional crystallization (top) and partial melting (middle). The diagram at the bottom presents our data. The trend is consistent with the fractional crystallization model. See Figure 1 for symbol key.

with fractional crystallization (Fig. 4). A plot of the Zr/Hf ratio with increasing La (ppm) (not shown) yields a completely horizontal trend, demonstrating that the ratio of these incompatible elements is unchanged with increasing concentration, a phenomenon consistent with fractional crystallization. A plot of Rb versus Hf (not shown) presents a co-linear relationship consistent with fractional crystallization and inconsistent with a partial melting model of a hydrothermally altered basalt crust (Geist et al., 1995). The stacked arrangement of the REE data in Figure 2 is also consistent with fractionation in this sub-alkaline data series (Pearce, 1996). The data permit a model of ~65% fractionation from the most primitive basalt in this data set to the most evolved rhyolite. Because we do not see a basaltic parent in this suite, we stipulate that the fractionation corroborated by the data is from a later stage.

CONCLUSION

Considering the model for extended fractional crystallization of MORB under moderate pH_2O conditions by Brophy (2008) in conjunction with the observation that REE trends and the co-linear variation of the Rb/Hf ratio are inconsistent with a partial melting model of hydrothermally altered basalt crust, we conclude that the basaltic andesites through rhyolites in this study are related by fractional crystallization.

Taking the above as true we describe the nature of the fractionation. The data permit a model of ~65% fractionation from the most primitive samples present to the most evolved. Sc trends are consistent with clinopyroxene fractionation. The negative Eu anomaly in the dacites and rhyolites is consistent with plagioclase fractionation. SiO_2 enrichment and associated TiO_2 and V trends are consistent with Ti-magnetite precipitation.

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