TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE, SOUTH-CENTRAL ALASKA
Faculty: JOHN GARVER, Union College, Cameron Davidson, Carleton College
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.

ORIGINS OF SINUOUS AND BRAIDED CHANNELS ON ASCRAEUS MONS, MARS
Faculty: ANDREW DE WET, Franklin & Marshall College, JAKE BLEACHER, NASA-GSFC, BRENT GARRY, Smithsonian

TROPICAL HOLOCENE CLIMATIC INSIGHTS FROM RECORDS OF VARIABILITY IN ANDEAN PALEOGLACIERS
Faculty: DONALD RODBELL, Union College, NATHAN STANSELL, Byrd Polar Research Center
Students: CHRISTOPHER SEDLAK, Ohio State University, SASHA ROTHENBERG, Union College, EMMA CORONADO, St. Lawrence University, JESSICA TREANTON, Colorado College.

EOCENE TECTONIC EVOLUTION OF THE TETON-ABSAROKA RANGES, WYOMING
Faculty: JOHN CRADDOCK, Macalester College, DAVE MALONE, Illinois State University
Students: ANDREW KELLY, Amherst College, KATHRYN SCHROEDER, Illinois State University, MAREN MATHISEN, Augustana College, ALISON MACNAMEE, Colgate University, STUART KENDERES, Western Kentucky University, BEN KRASUSHAAR

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: DAVID DETHIER, Williams College
Students: JAMES WINKLER, University of Connecticut, SARAH BEGANSKAS, Amherst College, ALEXANDRA HORNE, Mt. Holyoke College
DEPTH-RELATED PATTERNS OF BIOEROSION: ST. JOHN, U.S. VIRGIN ISLANDS
Faculty: DENNY HUBBARD and KARLA PARSONS-HUBBARD, Oberlin College

THE HRAFNJORDUR CENTRAL VOLCANO, NORTHWESTERN ICELAND
Faculty: BRENNAN JORDAN, University of South Dakota, MEAGEN POLLOCK, The College of Wooster
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.

SEDIMENT DYNAMICS OF THE LOWER CONNECTICUT RIVER
Faculty: SUZANNE O’CONNELL and PETER PATTON, Wesleyan University
Students: MICHAEL CUTTLER, Boston College, ELIZABETH GEORGE, Washington & Lee University, JONATHON SCHNEYER, University of Massachusetts-Amherst, TIRZAH ABBOTT, Beloit College, DANIELLE MARTIN, Wesleyan University, HANNAH BLATCHFORD, Beloit College.

ANATOMY OF A MID-CRUSTAL SUTURE: PETROLOGY OF THE CENTRAL METASEDIMENTARY BELT BOUNDARY THRUST ZONE, GRENVILLE PROVINCE, ONTARIO
Faculty: WILLIAM PECK, Colgate University, STEVE DUNN, Mount Holyoke College, MICHELLE MARKLEY, Mount Holyoke College
Students: KENJO AGUSTSSON, California Polytechnic State University, BO MONTANYE, Colgate University, NAOMI BARSHI, Smith College, CALLIE SENDEK, Pomona College, CALVIN MAKO, University of Maine, Orono, ABIGAIL MONREAL, University of Texas-El Paso, EDWARD MARSHALL, Earlham College, NEVA FOWLER-GERACE, Oberlin College, JACQUELYNE NESBIT, Princeton University.

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation
Keck Geology Consortium: Projects 2011-2012
Short Contributions—Northwestern Iceland Project

CRUSTAL MAGMATIC PROCESSES IN ICELAND’S OLDEST CENTRAL VOLCANO
Project Faculty: BRENNAN JORDAN, University of South Dakota, MEAGEN POLLOCK, The College of Wooster, JEANNE FROMM, University of South Dakota

THE HRAFNHFJÖRDUR CENTRAL VOLCANO: PETROGENESIS OF LAVAS IN THE EARLY STAGES OF AN ICELANDIC RIFT ZONE
EMILY CARBONE, Smith College
Research Advisor: Mark Brandriss

MAGMATIC PROCESSES OF THE HRAFNHFJÖRDUR CENTRAL VOLCANO, NORTHWEST ICELAND
KATHRYN KUMAMOTO, Williams College
Research Advisor: Reinhard Wobus

A GEOCHEMICAL AND PETROLOGIC ANALYSIS OF THE HRAFNHFJÖRDUR CENTRAL VOLCANO, WESTFJORDS, ICELAND
KATHARINE SCHLEICH, The College of Wooster
Research Advisor: Meagen Pollock

ORIGIN OF SILICIC VOLCANISM AT SAURATINDUR, NORTHWEST ICELAND
THAD STODDARD, University of South Dakota
Research Advisor: Brennan Jordan

GEOCHEMICAL ANALYSIS OF TERTIARY DIKES HRAFNHFJÖRDUR CENTRAL VOLCANO, NORTHWEST ICELAND: IMPLICATIONS FOR DIKE ORIGIN
NINA WHITNEY, Carleton College
Research Advisor: Cameron Davidson

PETROLOGIC AND GEOCHEMICAL CHARACTERIZATION OF BASALTIC AND INTERMEDIATE MAGMAS IN AN ABANDONED TERTIARY RIFT, NORTHWEST ICELAND
ERICA WINELAND-THOMSON, Colorado College
Research Advisor: Jeff Noblett

Keck Geology Consortium
Pomona College
185 E. 6th St., Claremont, CA 91711
Keckgeology.org
INTRODUCTION

Iceland is located at an intersection between the Icelandic mantle plume and the Mid-Atlantic Ridge. Rifting that represents the mid-ocean ridge spreading axis has shifted eastward in several jumps to newer rift systems in relation to the mantle plume (Hardarson et al., 1997). This relocation is due to the westward movement of the plate boundary and can be observed through two extinct rifts: the Skagi-Snaefellsnes rift zone and an extinct rift formed along a NE-SW strike off shore of the northwest of Iceland.

Hrafnfjordur is the oldest of the central volcanoes investigated in the four Iceland Keck projects to date. This volcano represents the early, hotspot-centered phase of the rift zone. This 2011 Keck project seeks to understand the origin(s) and process(es) of the formation of lavas in the Hrafnfjordur central volcano that erupted heterogeneous igneous rocks. This study will address the following questions: 1) what is the nature and origin(s) of the source magma(s); and 2) how do the individual units relate to one another including possible magma mingling/mixing, and/or fractional crystallization.

In Iceland rift zone volcanoes produce tholeiitic basalts, but the flank zone volcanoes, produce alkaline and transitional basalts (Saemundsson, 1979). More than 90% of the volcanic rocks found on Iceland are of basaltic composition, where the other 10% are of intermediate and silicic composition (Beloussov and Milanovsky, 1977). The processes that formed these silicic rocks, either fractional crystallization or magma mixing are of great interest and are much debated.

The thermal state of the crust has a large influence on the genesis of the silicic magma; the silicic magmas formed within or close to the rift zone are generated by crustal melting whereas those formed in flank zones are generated by fractional crystallization (Martin and Sigmarsson, 2007). Fractional crystallization is dominant in cooler crust, and crustal melting with warmer crust. The silicic rocks in Iceland are characterized as dacites, trachytes, low-alkali rhyolites and alkalic rhyolites. The trachytes and alkalic rhyolites are produced from the volcanoes in the flank zones and the dacites and low-alkali rhyolites are mostly found in the rift zones. Overall, these silicic rocks are Fe-rich and Ca-poor in comparison to silicic rocks in general, which indicates that these rocks were generated in magma low in water pressure (Jonasson, 2007).

The Tertiary basalts are very diverse. Martin and Sigmarsson (2007) propose three distinct potential mantle components in order to explain this diversity: depleted upper mantle source, enriched mantle plume and recycled oceanic crust. The recycled oceanic crust is most likely to have a variable composition forming garnet pyroxenite or ecgolite at depth and would undergo partial melting, which would yield either ne-normative alkali basalts or qz-normative basalts. As the melt mixes with lherzolite, the initial melt becomes diluted in incompatible elements before reaching the surface. Pyroxenites in the mantle source help to explain the diverse range in composition of basalts in the off-rift volcanic zones, ranging from alkali basalts through transitional alkali basalts. Since the farthest area away from the plume center has the lowest mantle temperature, the ne-normative pyroxenite melts would be least diluted by lherzolite and thus, incompatible elements. There is evidence that the most alkaline basalts, those closer to the periphery of the off-rift volcanic zones, represent melts of distinct pyroxenitic lithology’s. Individual volcanic systems are very diverse and there seems to be a correlation between them and the heterogeneity of the magma. Mantle melts having both diverse characteristics tend to have similar isotope ratios at the surface.
plagioclase are 0.5 x 1.5 mm on average. Of the 6.5% phenocrysts in this thin section, 1.5% are olivine, 2% are clinopyroxene and 3% are plagioclase. A subophitic texture exists.

The andesite unit is characterized by a very dark-gray fresh surface and a very fine-grained aphanitic groundmass. It is typically a cliff former of variable thickness. Phenocrysts present are plagioclase, clinopyroxene and orthopyroxene and range from 0.2 x 0.3 mm to 1.3 x 2.3 mm. The samples show a trachytic texture of the feldspars in thin section and there are at least two grains of quartz, which appear to be xenocrysts based on the presence of rounded edges as well as reaction rims that consists of some opaques and minor clinopyroxenes. Also, a unique plagioclase xenocryst is present, which is partially resorbed with an albitic rim.

The middle basalt flows are characterized by a medium-gray color on fresh surfaces, relatively coarse-grained aphanitic groundmass that appears shiny with few to no vesicles. Phenocrysts present are plagioclase, olivine and clinopyroxene and range from 0.2 x 2.2 mm to 1.3 x 1.0 mm. Of the 18% phenocrysts in thin section, 9% are plagioclase, 6% are olivine and 3% are clinopyroxene. The olivine crystals, which are most abundant, are very fresh and show no indication of weathering or any mineral reaction rims.

FIELD SITE OVERVIEW

The field site is located in the Westfjords region in the northwest of Iceland on the North side of the Hrafnojfordur. The field site for this study is approximately 7.5 km² with 553 m of vertical relief from sea level to the top of the highest peak, Mánafell. A basic stratigraphic section was defined in the field using the descriptions of outcrop and hand sample characteristics. There are significant areas of cover that obscure the volcanic units, although there is a greater amount of exposed areas to covered areas. Units defined in the field are as follows. To the west of Mánafell: an andesite, a lower basalt, a basaltic andesite and then an upper basalt. To the east of Mánafell: the same units plus a rhyolite between the andesite. Subsequent study of thin sections and geochemistry led to redefining the units. Thus, the final units are as follows: lower basalt, andesite, middle basalt, then dacite and lastly upper basalt.

PETROGRAPHY

The lower basalt unit consists of typically medium-gray color and is porphyritic with a relatively fine aphanitic groundmass. In thin section, this unit is characterized by an abundance of plagioclase phenocrysts including many yellow weathered crystals as well as olivine and clinopyroxene phenocrysts. The
Figure 2. Harker and Fenner diagrams illustrating major element variations of all samples. The samples in the Harker diagrams show curvilinear trends with a notable break-in-slope at 52.5 wt.% SiO$_2$. In the CaO/Al$_2$O$_3$ graph, CaO/Al$_2$O$_3$ decreases as SiO$_2$ increases. In the Fenner diagrams, the samples plotted against TiO$_2$ and FeO* on the Y-axis show two breaks-in-slope at approximately 8 and 4 wt.% MgO. The CaO graph shows a break-in-slope at approximately 7 wt.% MgO and reveals a different inflection. And CaO/Al$_2$O$_3$ decreases as MgO decreases.
Dacite flows show a fresh surface color of either a dark gray or pink and the groundmass is typically aphanitic with visible groundmass plagioclase. Flow banding is prominent. Plagioclase is the only phenocryst present and averages 0.3 x 0.7 mm. Many minerals are very weathered; the pyroxenes have weathered to iron oxides and clays and the opaques are not euhedral.

The samples collected from the upper basalt flows have a fresh surface color of light to medium gray and a relatively coarse aphanitic groundmass with a few vesicles. Under thin section, this unit tends to have olivine as the phenocrysts and small plagioclase, pyroxenes and opaques as the groundmass. The only phenocrysts present are olivine, which constitute approximately 12%. This unit is micro-gabbroic with a subophitic texture.

**GEOCHEMISTRY**

The degree of weathering is important in this study since hydrothermal alteration is very common in Icelandic lavas. The Hutchison Weathering Index measures the degree of alteration of lavas (Hutchison, 1974). The lavas of this study fall between 67.6 and 76.7. These numbers indicate that the weathering levels are acceptable, not low enough to be rejected. The andesite has the greatest amount of weathering and the middle basalt the least. The basalts generally have about the same level of weathering.

![Figure 3. Spider plot showing the abundances of elements normalized to N-MORB from Saunders and Tarney (1984) and Sun (1980). The samples resemble N-MORB basalts from 1 to 10 times enrichment.](image)

On an AFM plot (Fig. 1), the samples reveal a tholeiitic trend and there are no outliers. When plotted on Harker diagrams (Fig. 2), the data reveal curvilinear trends with sharp breaks-in-slope at 52.5 wt.% SiO2 content. P2O5, TiO2 and FeO* are oxides that are representative of this trend, suggesting a possible change in fractionating minerals. In the CaO/Al2O3 vs. SiO2 graph (Fig. 2), CaO/Al2O3 decreases with increasing SiO2, suggesting that clinopyroxene plays an important role in fractionation. Three Fenner diagrams (Fig. 2) comparing MgO to CaO, TiO2 and FeO* wt.% also have breaks-in-slope, which suggests the crystallization of a sequence of minerals out of the magma. These diagrams typically show an almost horizontal, unchanging slope with little increase in other elements as MgO decreases from 14 to 8 wt.%, suggesting a modest amount of olivine-dominated crystallization. At 8 wt.% MgO, TiO2 and FeO* begin to rise more dramatically with decreasing MgO suggesting the addition of other minerals to the fractionating assemblage. At approximately 4 wt.% MgO, TiO2 and FeO* begin to decline with decreasing MgO. This point of the change in slope indicates the crystallization of an iron-titanium oxide, titanomagnetite and/or ilmenite phase in the FeO* and TiO2 graph. The CaO graph reveals a slightly different trend, where CaO is nearly constant with decreasing MgO until about 6.5-7 wt.%. This trend suggests that one or more calcic minerals must be crystallizing to keep CaO from increasing but not enough to cause it to decrease. The graph of CaO/Al2O3 vs. MgO indicates which calcic minerals are crystallizing, and specifically the process of plagioclase and clinopyroxene minerals in the melt. In this graph, CaO/Al2O3 decreases with decreasing MgO, suggesting that clinopyroxene plays a significant role in the crystallization process. All of these phases were observed in thin section.

Spider plots show the enrichment of incompatible elements normalized against lavas in specific tectonic settings. Figure 3 presents a spider plot normalized against N-MORB, suggesting two points. Firstly, the patterns are generally flat at 1 to 10 times N-MORB enrichment, with the more primitive lavas being near 1. Secondly, the more primitive samples are relatively parallel to each other. The less incompatible
elements cross each other and do not reveal the same trend as the primitive basalts. Some of the elements are influenced by fractionating phases, such as Sr. The general enrichment of the incompatible elements suggests an E-MORB signature.

DISCUSSION

The volcanism in Iceland is due to a combination of mid-ocean ridge and mantle plume activity. Tectonic classification diagrams indicate tectonic settings where the lavas erupted. It is by considering different sources, such as N-MORB, E-MORB and OIB, that the tectonic settings can be evaluated. The source, OIB, is typically a mantle plume signature. In the ternary diagram of Ti/100 vs. Zr vs. Y*3 (Fig. 4) the samples primarily plot in an ocean floor tectonic setting with a few plotting in an island arc setting. This pattern is repeated on four other tectonic classification diagrams. The island arc component is an anomaly and could suggest variation in the mantle source. These plots are consistent with the spider plots and suggest that these samples come from an N-MORB setting. The enrichment in highly incompatible elements raises the possibility that these lavas might come from two or more sources, with a small amount of enriched material present in this magmatic system, suggesting an E-MORB signature and thus indicating a minor plume component.

Fractional crystallization is strongly supported as a plausible mechanism to relate the spectrum of volcanic rocks to one another. The break-in-slope on the Harker diagrams represents the crystallization of oxides, with a change from mafic mineral fractionation to a trend controlled more by plagioclase. The break-in-slope on the Fenner diagrams suggests specific sequence of minerals fractionating out of the magma, which is consistent with the observed petrography. Further testing of the fractionation model with Pearce element ratios is in progress. At least a little assimilation is required by the presence of the quartz xenocrysts.

While the plots mentioned previously show plausibility that all rocks are related by fractional crystallization, other plots demonstrate that some lavas lie off of the main trend and cannot be related in that way. For example, when considering a plot of Zr vs. SiO₂ including the regional data (Fig. 5), it appears that two andesite samples are not connected and cannot have followed a single fractionation path. The sample with the higher SiO₂ wt.% content and the sample with the lower SiO₂ wt.% content plot on different trends. The lower silica andesite plots amongst those with lower SiO₂ wt.% content and higher Zr ppm content whereas
the higher silica andesite plots with higher SiO₂ wt.% content and lower Zr ppm content samples and solely amongst the regional data. This suggests that the two trends represent two distinct fractionation trends, caused by varying fractionation assemblages reflecting different depths of crystallization, and segments of some trends could reflect magma mixing.

CONCLUSIONS

Major, minor and trace element data reveal the complexity of the evolution of the lavas. The Harker and Fenner diagrams support the process of fractional crystallization whereas the SiO₂ vs Zr graph does not support the fractionation along a single path from a common source. The spider plots and tectonic classification diagrams all support that the magma is derived as an N-MORB source. Some signature of an enriched (hot spot) source is present in the highly incompatible elements suggesting multiple sources may be involved. The data supports both a fractional crystallization and magma mixing relationship among the diverse lavas.

REFERENCES


Martin, E. & Sigmarsson, O., 2007, Crustal thermal state and origin of silicic magma in Iceland: the case of Torfajökull, Ljósufjöll and Snaefells-

jökull volcanoes: Contributions to Mineralogy and Petrology, v. 153, p. 593-605.


