Geochemical Variations of Basalts Erupted along the Reykjanes Ridge

Senior Thesis

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Approved by

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Abstract

The Reykjanes Ridge is the section of the Mid-Atlantic Ridge just south of Iceland, and is the seaward extension of the Reykjanes Peninsula on Iceland. Reykjanes, meaning smoky peninsula, describes the steam from geothermal hot springs on the peninsula. This section of mid-ocean ridge shallows from the south, near the Charlie Gibbs Fracture Zone, towards Iceland, and this effect is ascribed to the presence of a mantle plume beneath Iceland. It is unknown whether the plume represents a compositional anomaly, a thermal anomaly, or both. Distinct variations in the geochemistry of basalt erupted along the Reykjanes Ridge towards Iceland have been described by previous workers (e.g., Schilling, 1973; Jones et al., 2014) and may reflect the presence of the plume beneath Iceland, but could also reflect interaction of magma with thickened Icelandic crust. Publication of a new compilation of geochemical data for mid-ocean ridge basalts by Gale et al. (2013) allows geochemical variations along the ridge to be re-examined using whole-rock data that have been filtered to exclude analyses of poor quality and that have been corrected for interlaboratory bias. The data used for this research are analyses of samples from 57°N to 64°N taken from this compilation of Mid-Ocean Ridge Basalt (MORB) analyses by Gale et al. (2013). The database includes major oxide data, trace element data and isotope data for 302 samples along with the latitude, longitude and depth at which the samples were collected. These analyses are plotted on variation diagrams to assess the role of crystallization and of other processes in controlling the composition of basalts erupted along the ridge. The analyses are also plotted against latitude in order to establish changes in magma geochemistry over the length of the ridge. Significant variations in major oxide and trace element composition occur as the ridge approaches Iceland, with a distinct change in composition occurring at 60.5°N. In order to further understand how specific groups of elements changed over the length of the ridge, the data was normalized to the average composition of normal mid-ocean ridge basalt, primitive mantle, and CI chondrite (for rare earth elements only). The results from this research shows that variations in major oxides are consistent with control by crystallization, and there is remarkable similarity between whole rock and volcanic glass analyses. Trace element data show considerable variations in samples collected along the ridge, but do not provide convincing evidence for variation with assimilation of thickened crust.It is concluded that the mantle plume reflects a compositional anomaly, but it is not clear that there is also a thermal anomaly.

Acknowledgements

I would first like to thank my advisor, Dr. Michael Barton for his counseling, guidance, and for inspiring me to delve deeper into petrology. Dr. Barton has a vested interest in his students along with the advancement of Earth Sciences education. I have had the privilege of working in his research group for three years and am very thankful for his mentorship.

PhD candidate Jameson Scott has also been instrumental in my research. He spent many hours helping me get started with graphing software and data interpretation. He is also studying the Reykjanes Ridge with a focus on volcanic glasses.

I want to thank Shell Exploration and Production Company for funding my research throughout the Shell Undergraduate Research Experience during the summer of 2014. I was able to complete much of this research during that time.

Last but certainly not least I would like to thank my academic major advisor, Dr. Anne Carey, who has strongly influenced my academic path. Before stepping foot on campus, she was the first person that I spoke with from the School of Earth Sciences regarding my major. Since that moment she has never ceased to be an excellent advisor.

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Introduction

Studies of mid-ocean ridge basalt are essential for understanding the origin and evolution of oceanic crust. The composition of basalt erupted along ridges reflects the composition of the mantle source region, the degree of melting in the mantle, the effects of intracrustal evolutionary processes such as crystallization, and the effects of post-eruptive processes such as seawater interaction (Sun and McDonough, 1989). The mid-ocean ridge contains the youngest oceanic crust, since that is where oceanic crust is formed. This crust is slowly created over time through injection of magma along the ridge axis and intrusion of magma beneath the axis, and older crust is transported away from the ridge (Langmuir, 2007). Therefore, samples of basalt from mid-ocean ridges provide the best estimates of the composition of newly accreted oceanic crust because such samples have not had time to become altered through interaction with seawater.

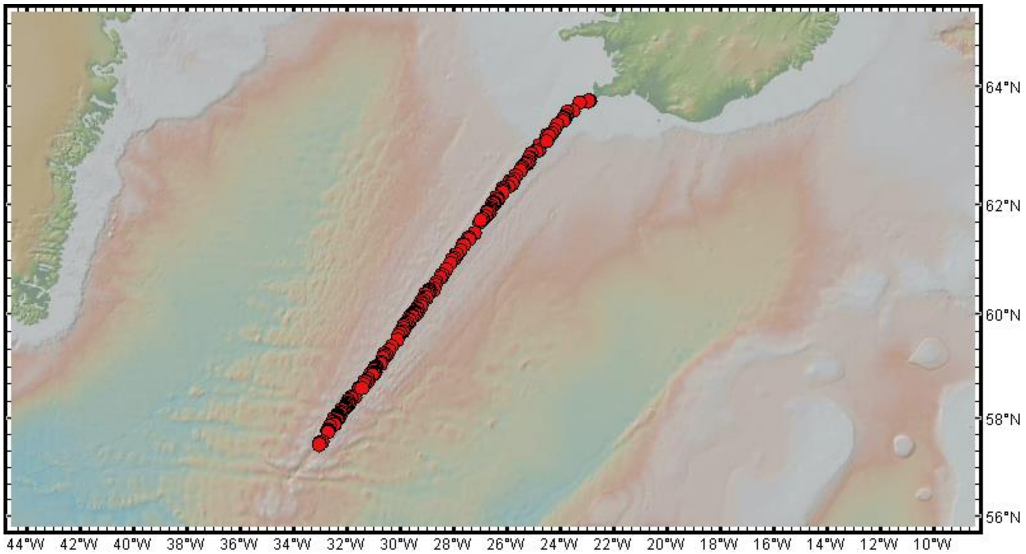

Figure 1: Each red dot denotes a sample obtained from the ridge. Samples were taken from 57°N to 63°N. No samples were taken beyond 63°N because the ridge becomes very shallow and samples are subject to increased weathering. Note the V-shaped ridges.
Figure generated with GeoMapApp: http://www.geomapapp.org

The Reykjanes Ridge is different from other ridges because it intersects Iceland, the only part of a mid-ocean ridge that is exposed above sea-level. Thickened crust, increase in temperature and the potential influence of heterogeneous mantle sources from the Iceland mantle plume contribute to the ridge's unique characteristics (Schilling et al., 1982). The plume's influence should extend well beyond the actual boundary of the Iceland itself. Therefore, a study of basalts erupted along the Reykjanes Ridge should reveal the systematic changes in chemistry as the ridge approaches the plume beneath Iceland. The purpose of this research is to understand the effects of interaction between mid-ocean ridges and mantle plumes on basalt geochemistry along with the evolution and generation of oceanic crust. This research will contribute to an ongoing study of the igneous petrology of Iceland being performed by Dr. Michael Barton's research group at The Ohio State University.

Geologic Background

Iceland is a volcanic island centered on a divergent plate boundary: the Mid-Atlantic Ridge. The eastern edge of the North American Plate and the western edge of the Eurasian Plate make up the western and eastern halves of Iceland, respectively. On Iceland itself, the ridge is offset by transform faults and is cut into segments before reaching the north coast and extending offshore to join with the Kolbeinsey Ridge. The spreading rate in Iceland averages 1.8 cm/yr (calculated using the method described by DeMets et al, 2010).

The plate margin extends offshore to the south from the Reykjanes Peninsula to join with the Mid-Atlantic Ridge. The Reykjanes Ridge is that segment of the Mid-Atlantic Ridge between the Reykjanes Peninsula and the Charlie Gibbs Fracture Zone, a transform fault located at latitude 52.5° N. Along the Reykjanes Ridge there are multiple active volcanoes and seamounts due to active rifting and mantle decompression (White, 1995). Indeed, there are seamounts along the entire length of the ridge but they lie beneath the ocean's surface.

Most scientists agree that a mantle plume lies beneath Iceland and is the cause of extensive volcanism throughout the region. The plume accounts for the thickened volcanic crust that

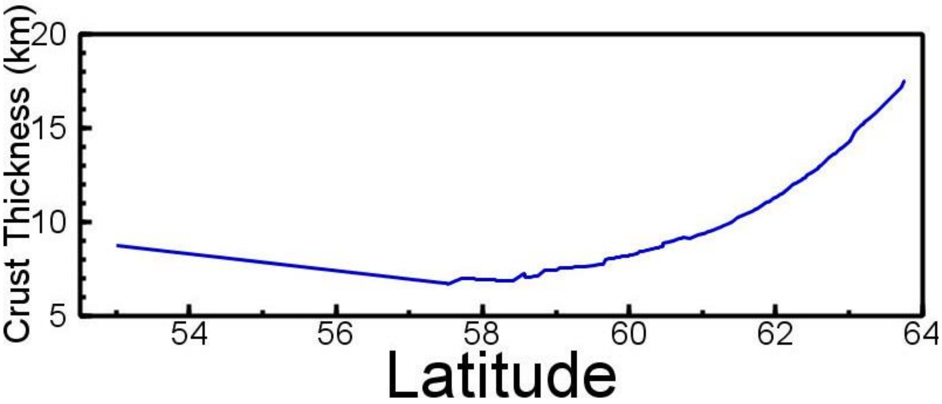

Figure 2: Diagram showing crustal thickness increasing with latitude towards Iceland. The cause of this increased thickness is ascribed to a mantle plume (Scott et al., 2010).

underlies Iceland. It also accounts for the heat that provides renewable geothermal energy for the inhabitantsof Iceland. The mantle plume theory describes the plume as being deep and narrow, with its base postulated to lie either in the lower mantle or at a thermal boundary layer between the upper and lower mantle near 660 km depth (Shen, 1998). The plume has a higher temperature than the surrounding mantle and probably contains higher concentrations of water, thus lowering the melting point of the mantle, enhancing melt productivity, and increasing volcanic activity (Kovalenko, 2006). The plume theory also explains the uplift and thickened crust that is necessary for Iceland's existence along the ridge (White, 1995).

V-shaped ridges (Figure 1) extend outward from the ridge, representing variations in crustal thickness resulting from temporal fluctuations in melt production (e.g. Schilling, 1982; White, 1995; Jones et al., 2002; Jones et al., 2014). The variability in production of magma for the formation of V-shaped ridges is attributed to fluctuations in the mantle plume, with hot patches moving upwards and spreading radially through the asthenosphere, eventually being drawn up into the melting region when passing beneath the Reykjanes Ridge (Jones et al., 2014).

Methods and Samples

The data used for this research is from a global catalog of analyses of ridge basalts published by Gale et al. (2013). The samples have been filtered to exclude analyses of inferior quality and the data accounts for uneven sampling through the use of ridge segment average values. Location and segment means effectively reduce the bias that uneven sampling presents (Gale et al., 2013). This research uses that database as a source of analyses for examination and interpretation of geochemical variations in basalts erupted along the ridge. Each sample extracted from the database has analyses for major oxides and trace elements. Other essential information such as sample depth, latitude, longitude and spreading rate are also included in the database. This database has been instrumental in this research because it provides petrologic and geochemical information for a large number of samples from selected ridge segments.

The Gale et al. (2013) data for the Reykjanes Ridge consists of 302 sample analyses. This research uses 228 of those analyses, eliminating samples that were exposed to increased weathering near the surface of the water or on Iceland itself. These data were analyzed with Excel and the Cohort statistical analysis and plotting program. By plotting oxide and element concentrations on variation diagrams (typically, oxide and element concentrations plotted against the concentration of MgO) it is possible to assess whether the observed variations are consistent with those expected to result from crystallization of basalt melts. All oxides and elements were plotted against MgO because this oxide is removed from the melt by crystallization of olivine so that the MgO contents of magmas produced by crystallization of olivine-bearing assemblages will decrease in a steady and predictable way. Thus, trends produced by plotting the concentrations of other oxides and elements against MgO can be used to determine whether a suite of magma compositions is related by crystallization, or whether other processes must have occurred during magma evolution.

It is useful to divide sample locations into segments along the ridge based on latitude. Comparison of the compositions of magmas erupted in the various segments allows changes in magma composition as the ridge approaches Iceland to be readily identified. By observing change in composition over the course of the ridge, the extent of the plume's effect on basalt chemistry can be determined. The grouping of samples into segments followed the approach adopted for glasses from the Reykjanes Ridge described by Jameson Scott.

Normalized plots were also generated in order to compare data from the Reykjanes Ridge with data from elsewhere, and to facilitate comparison of samples collected from different segments of the ridge. Trace element data were normalized to the composition of an average "normal" mid-ocean ridge basalt (N-MORB – composition from Gale et al., 2013) and to an estimate of Earth's primordial mantle composition (from Sun and McDonough, 1989). Rare-earth elements were normalized to values for the CI Chondrite (reported by McDonough and Sun, 1995).

This research focuses on whole rock analyses. Each sample was collected by dredging the ocean floor for basalt along the ridge. Analyses of basaltic glasses have been used by Jameson Scott as part of his study of the pressures of partial crystallization of magmas erupted along the Reykjanes Ridge. The glass analyses are compared with whole rock analyses in this study in order to analyze consistency between whole rock and glass analyses.

Results

Whole rock major oxides all show trends on variation diagrams consistent with crystallization of olivine (ol) plagioclase (plag) and clinopyroxene (cpx). The decrease in CaO and Al_2O_3 with decreasing MgO indicate crystallization of clinopyroxene and plagioclase along with olivine (Kelley and Barton, 2007). The changes in slope on the plots of CaO and Al_2O_3 versus MgO indicates that pyroxene and plagioclase began to crystallize along with olivine when the MgO content of the melt decreased to ~8.4wt.%

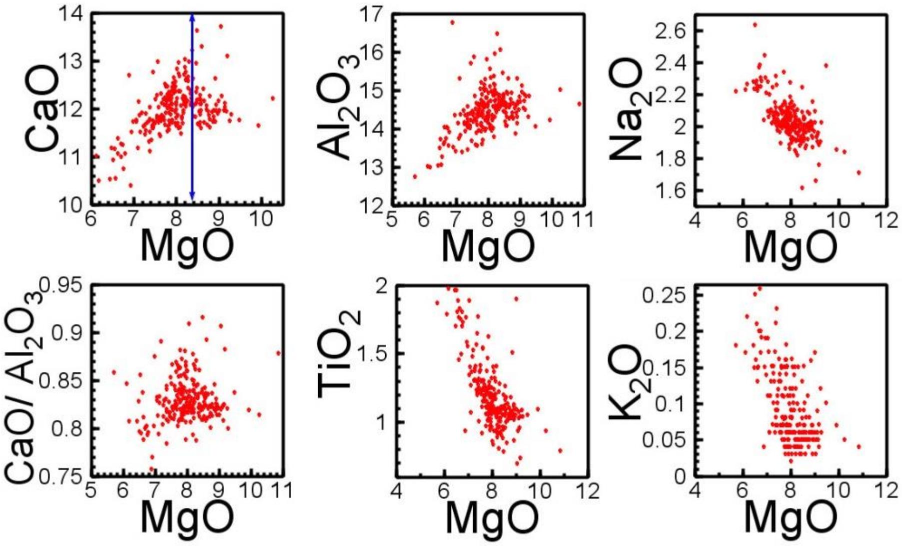

Figure 3: Whole-rock major oxides plotted against MgO show trends consistent with those expected for crystallization. The vertical blue line on the CaO diagram shows where CaO began to be removed from the melt.

Distinct changes in magma geochemistry occur as the ridge approaches Iceland. This change occurs at approximately 60.5° N latitude (Figure 4). The change in FeO/TiO_2 can be interpreted to indicate the magmas erupted along the northern part of the ridge are more evolved than those erupted along the southern part of the ridge. The increases in K/Ti and K/P along the northern end of the ridge suggest a change in mantle composition from which the basalts are ultimately derived: the mantle beneath the northern part of the ridge appears to be enriched in elements such as K relative to the mantle beneath the southern part of the ridge. The decrease in Na_8 (Na_2O values normalized to 8 wt.%MgO to minimize the effects of crystallization) suggests higher degrees of melting of the mantle beneath the northern part of the ridge. The variations in K/Ti, K/P and Na_8 with latitude are therefore consistent with a change in both the composition and temperature of the mantle as Iceland is approached.

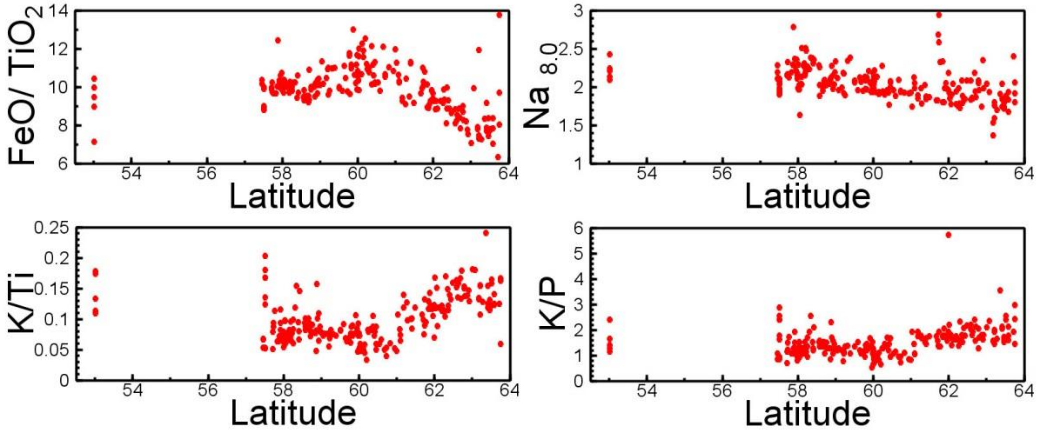

Figure 4: Incompatible element ratio trends correlate with thickened crust suggesting a compositionally and thermally anomalous source (plume) accounts for geochemical variations.

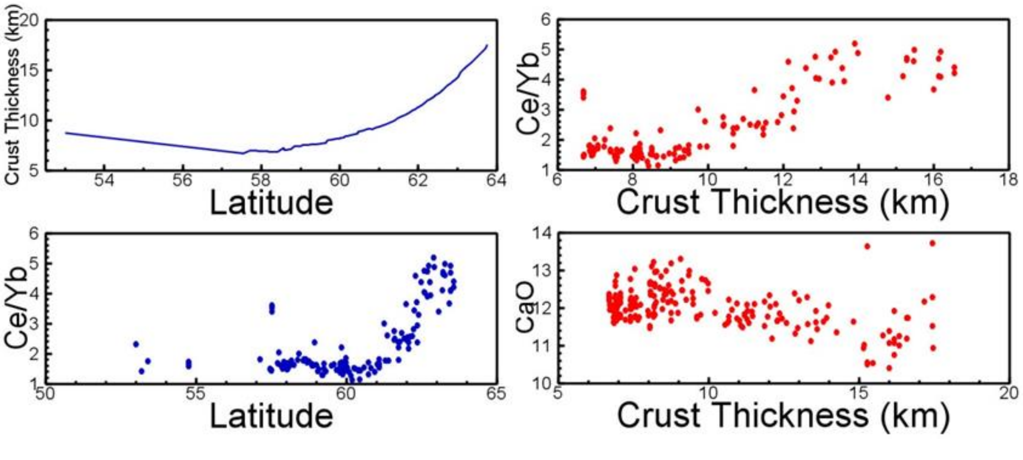

Figure 5: Crustal thickness increases significantly towards Iceland. CaO trend is inconsistent with assimilation of thickened crust. Light rare earth elements are significantly affected by plume anomaly.

A plot of Ce/Yb versus latitude supports other evidence that the mantle beneath the northern part of the ridge is enriched in highly incompatible elements relative to the mantle beneath the southern part of the ridge. Crustal thicknesses have been estimated for the Reykjanes Ridge by Scott and co-workers (2013), and the results of that study indicate that at latitudes south of ~61^{0}N crustal thickness is 6-9 km, considered the normal range for mid-ocean ridge crust (White, 1992), At latitudes >~61^{0}N, crustal thickness increases to 10-16 km. Therefore, the changes in geochemistry correlate with changes in crustal thickness (Figure 6). The thickness of oceanic crust is related to the flux of magma from the underlying mantle, with thicker crust reflecting a higher magma flux and higher magma productivity in the mantle source region of the basalts. The changes in geochemistry and the change in crustal thickness from south to north along the ridge therefore support the proposal that a thermal plume occurs in the mantle beneath Iceland. Note that CaO contents (Figures 5 and 6) show a negative correlation with crustal thickness. This decrease in CaO correlates with a change in latitude and is similar to trends shown by FeO/TiO_2 (Figure 4) and MgO (Figure 6). The changes indicate that basalt magmas erupted north of 60.5^{0}N have undergone more extensive intracrustal crystallization than those erupted to the south of 60.5^{0}N. This suggests that ascending magmas have greater opportunity to pond and crystallize in thicker crust.

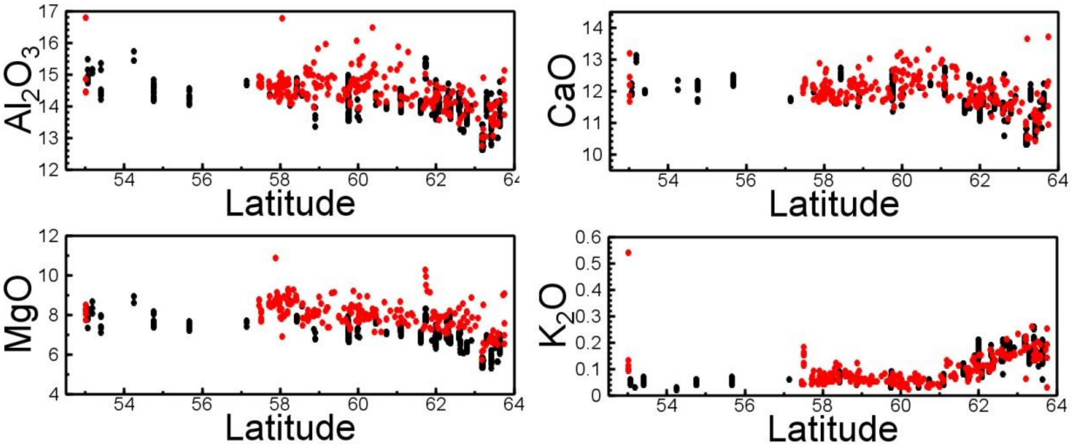

Figure 6: Whole rock data (red) superimposed over glass data (black). Both datasets exhibit change in trend at 60.5°N. Whole-rock MgO is greater than glass MgO due to the presence of olivine phenocrysts in whole-rock samples.

Major oxide analyses for the volcanic glasses used in studies of the pressures of partial crystallization (Scott et al., 2012; 2013) are very consistent with the whole rock data, although the whole-rock samples contain higher percentages of MgO due to the presence of olivine phenocrysts. The glass data therefore support evidence from the whole-rock analyses that a change in mantle source region from “normal MORB” mantle in the south to “plume” mantle in the north occurs at 60.5°.

Results from normalization diagrams all show enrichment in large–ion lithophile elements, incompatible elements (such as Nb, Ta, Zr, Hf), and light rare-earth elements closer to the plume anomaly. The latitude at which enrichment occurs in the normalized plots coincides with the latitude of significant variation found in figures 4, 5, and 6 (60.5°N). See appendices for all normalized diagrams.

Discussion

The mantle plume's effect on Reykjanes basalt chemistry can be seen on plots of composition versus latitude and on the normalized plots (appendices A, B and C). Incompatible elements and the light rare earth elements become increasingly enriched in erupted magmas as the ridge approaches Iceland, with the enrichment beginning at 60.5° N. These results clearly indicate a change in the composition of the mantle source region as the ridge approaches Iceland. The mantle beneath Iceland (plume mantle) is enriched in incompatible elements relative to normal MORB mantle.

Thickening of the oceanic crust also begins at approximately ~61° N, and is attributed to an increase in the extent of mantle melting and hence magma productivity based on the correlation of Na_8 with latitude. Therefore, variations in geochemistry along the ridge correlate with crustal thickness and with latitude. An obvious explanation for the correlation between magma composition and crustal thickness is that the plume is hotter than the normal MORB-like mantle underlying the southern part of the ridge. According to this hypothesis, the amount of melt produced in the mantle beneath the ridge increases as the ridge approaches Iceland. However, this is not the only explanation for the increased magma productivity associated with the plume. It is likely that the plume is richer in water than the surrounding mantle based on the measurements of water contents of magmas erupted along the Reykjanes Ridge and on Iceland (Nichols et al., 2002). An increase in H_2O along the ridge towards Iceland is also consistent with the behavior of K_2O; H_2O and K_2O are both highly incompatible elements and should exhibit nearly identical behavior during melting and crystallization. Thus the Iceland plume may represent a "wet-spot". The effect of water on the melting of mantle lithologies is well known from experimental studies (e.g., Green, 1973), and hydrous mantle lithologies melts at significantly lower temperatures than the equivalent anhydrous lithologies. Therefore, melting of hydrous mantle will produce a greater volume of melt than melting of anhydrous mantle at the same pressure and temperature. The decrease in Na8 with latitude along the Reykjanes Ridge possibly reflects an increase in the amount of water in the source region and a resulting increase in the amount of melting as the ridge approaches Iceland. The relative roles of temperature and water content in controlling the geochemistry of magmas erupted along the Reykjanes Ridge cannot be determined from this study. Future work may show that the Iceland plume is both hotter and wetter than the surrounding mantle, in addition to being compositionally distinct from that mantle (e.g., Kovalenko 2006).

Conclusions

Several conclusions can be drawn from this study of the Reykjanes Ridge basalts. The first and most straightforward of these is that whole-rock compositional data are consistent with compositional data for glasses. This indicates that conclusions drawn from whole-rock data apply to glass data (liquid compositions), and vice-versa.

The second conclusion is that geochemical variations are consistent with crystallization dominating magma evolution along the ridge. The third conclusion to be drawn from this research is that there are significant and systematic variations in major and trace element geochemistry as the ridge approaches Iceland, with onset of compositional change occurring at 60.5°N. This latitude could represent the southernmost limit of the Iceland mantle plume's effect on the ridge. This suggests that the plume's influence on basalt composition extends several hundred kilometers from Iceland itself.

Suggestions for Future Research

These geochemical variations are ascribed to the presence of a mantle plume beneath Iceland. The plume reflects a compositional anomaly, but it is not clear that there is also a thermal anomaly. In order to determine the nature of the plume and its role in influencing magma compositions, more research needs to be done. The use of geothermometers to determine the temperature of crystallization of magmas erupted along the ridge, and examination of magma temperatures versus latitude might help establish whether the plume represents a thermal anomaly as well as a compositional anomaly. Efforts to calculate the pre-eruptive temperatures of magmas erupted along the ridge are currently underway at Ohio State.

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Appendix A: Normal Mid-Ocean Ridge Basalt Normalized Diagrams

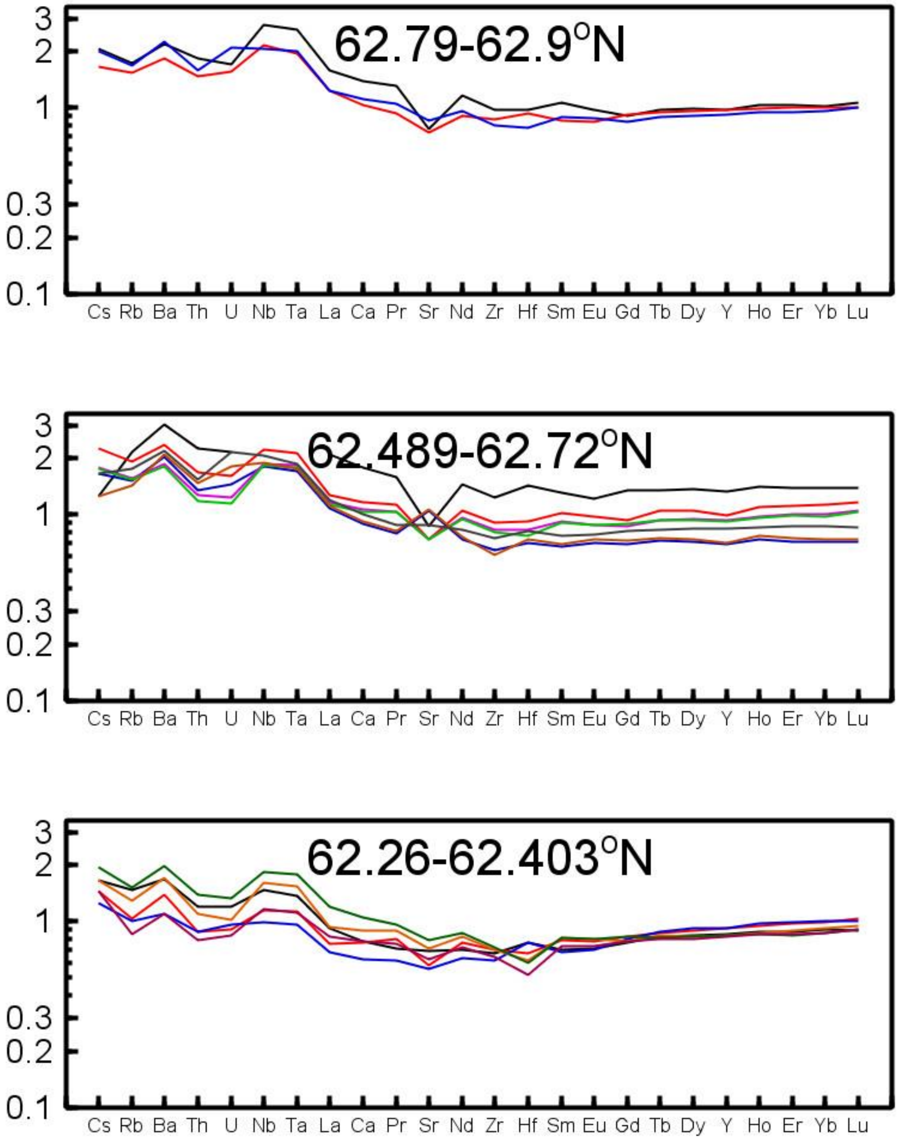

Figure A1: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

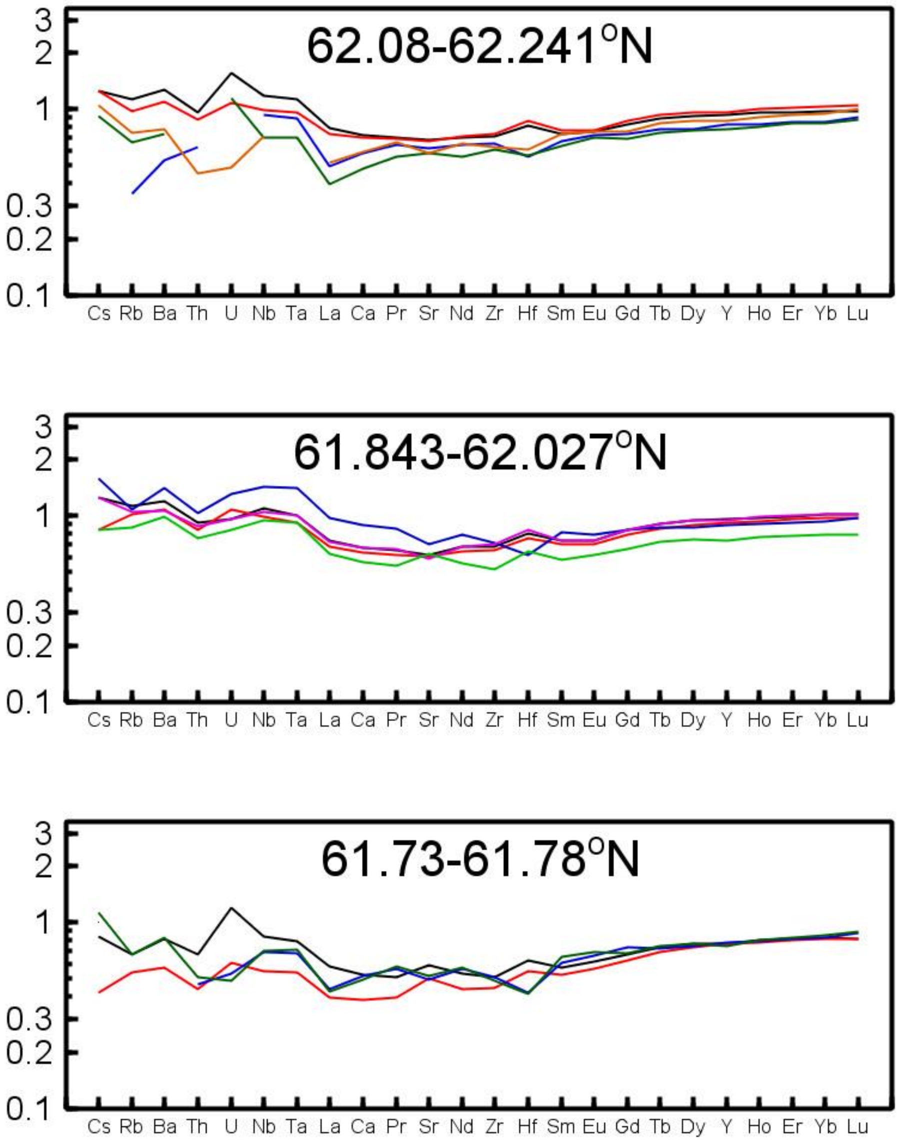

Figure A2: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

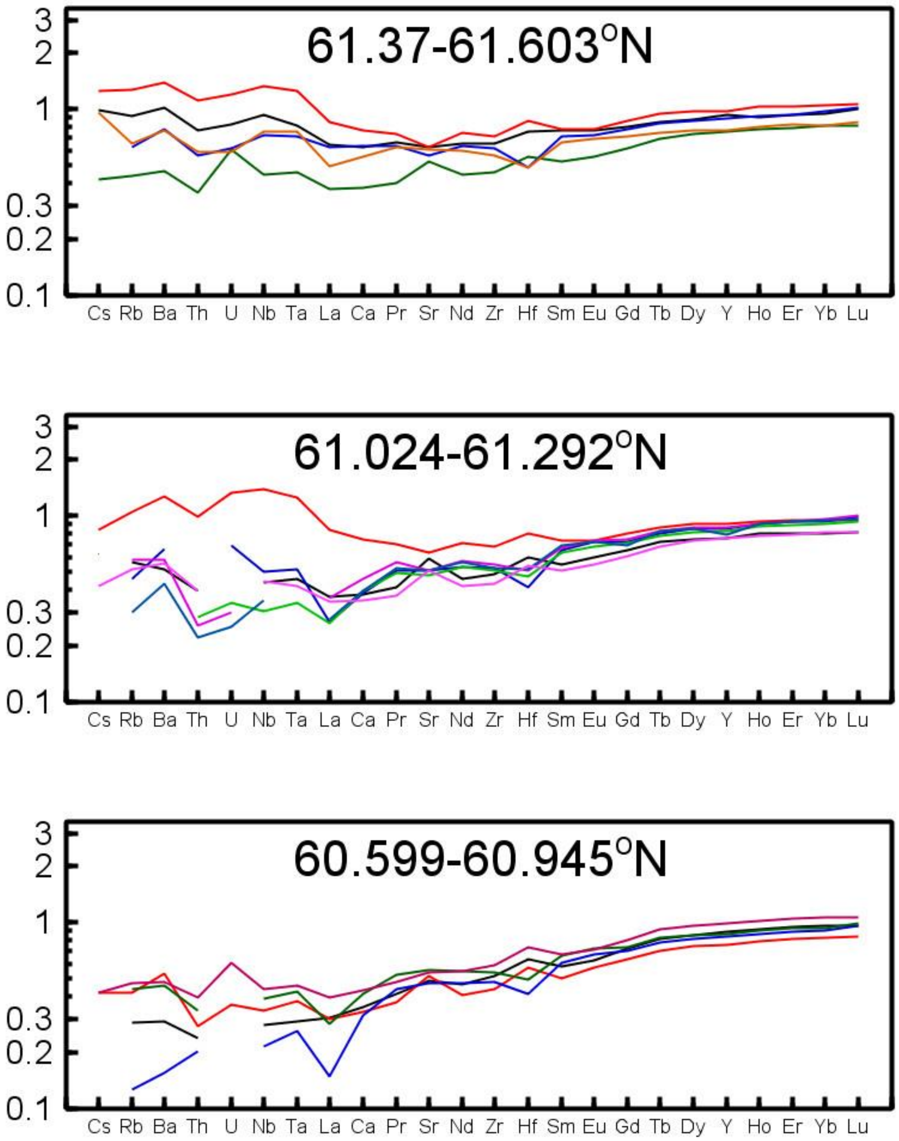

Figure A3: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

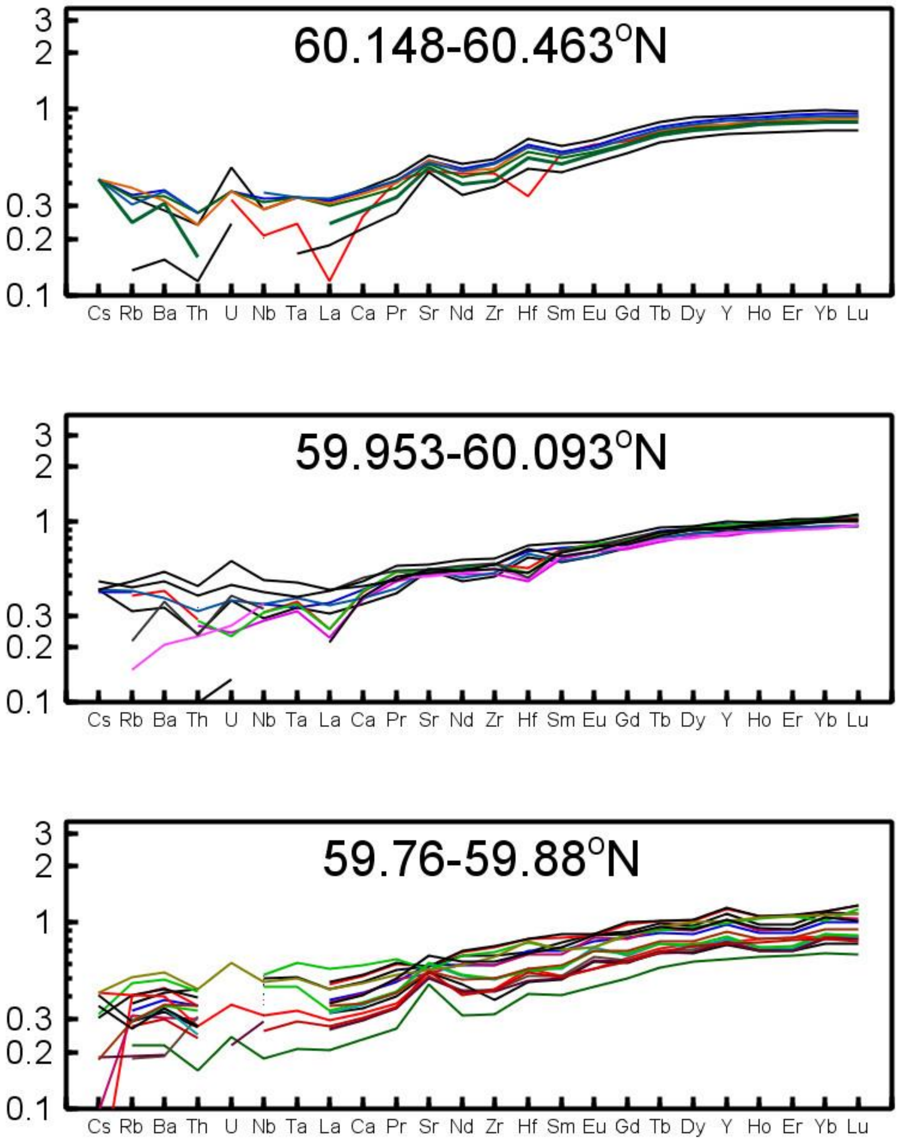

Figure A4: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

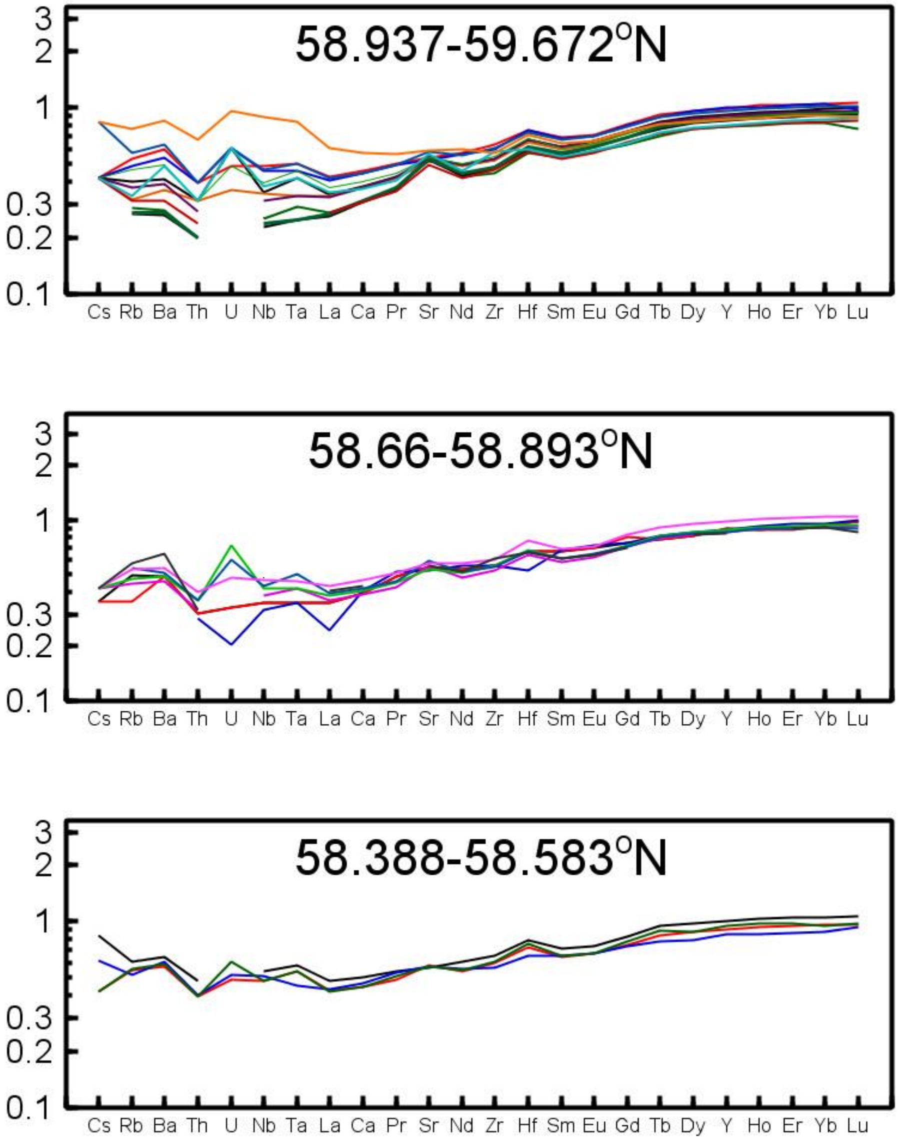

Figure A5: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

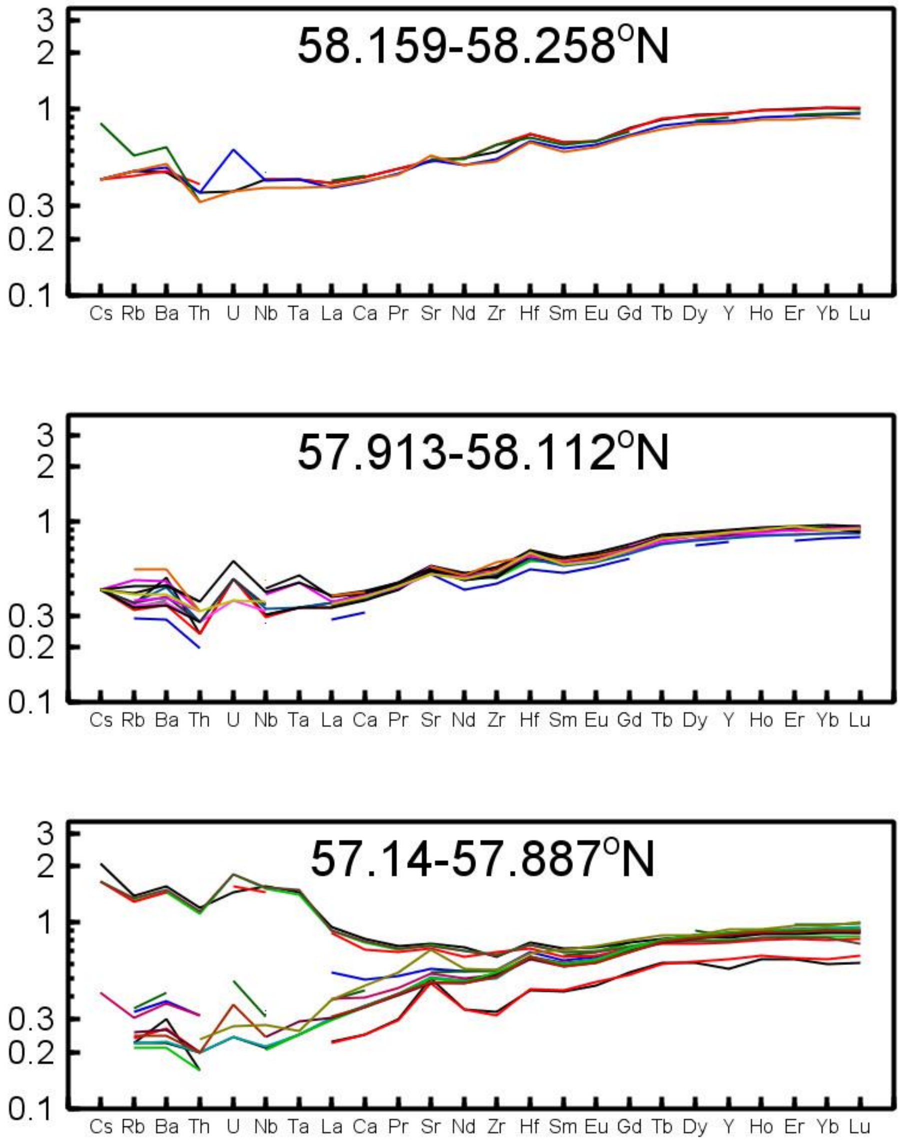

Figure A6: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

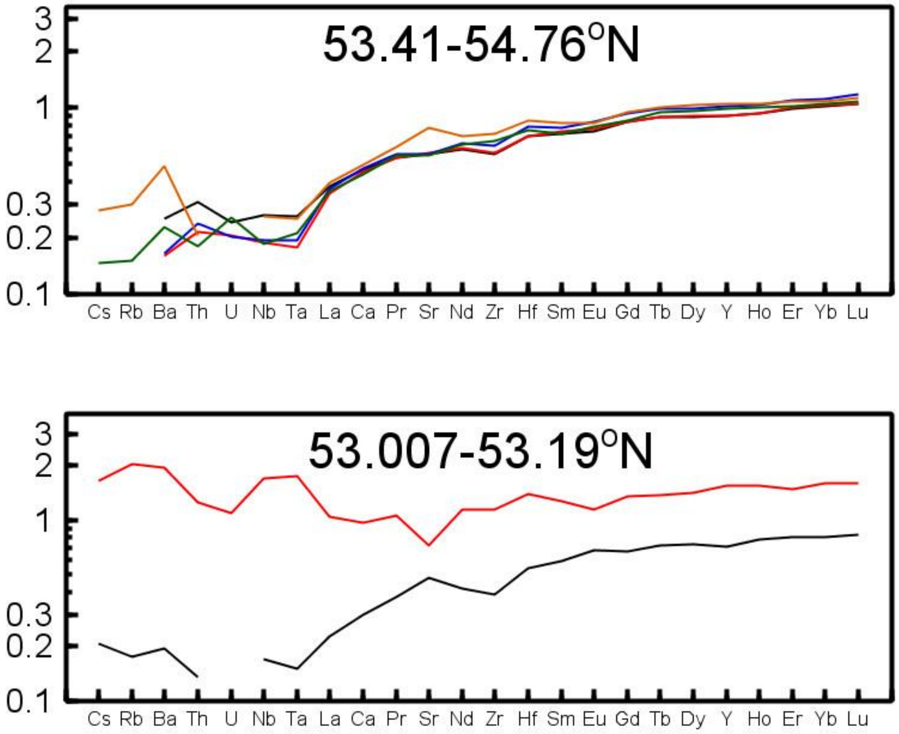

Figure A7: Normal Mid-Ocean Ridge Basalt (NMORB) Normalized Trace Element Patterns.

Appendix B: Primitive Mantle Normalized Diagrams

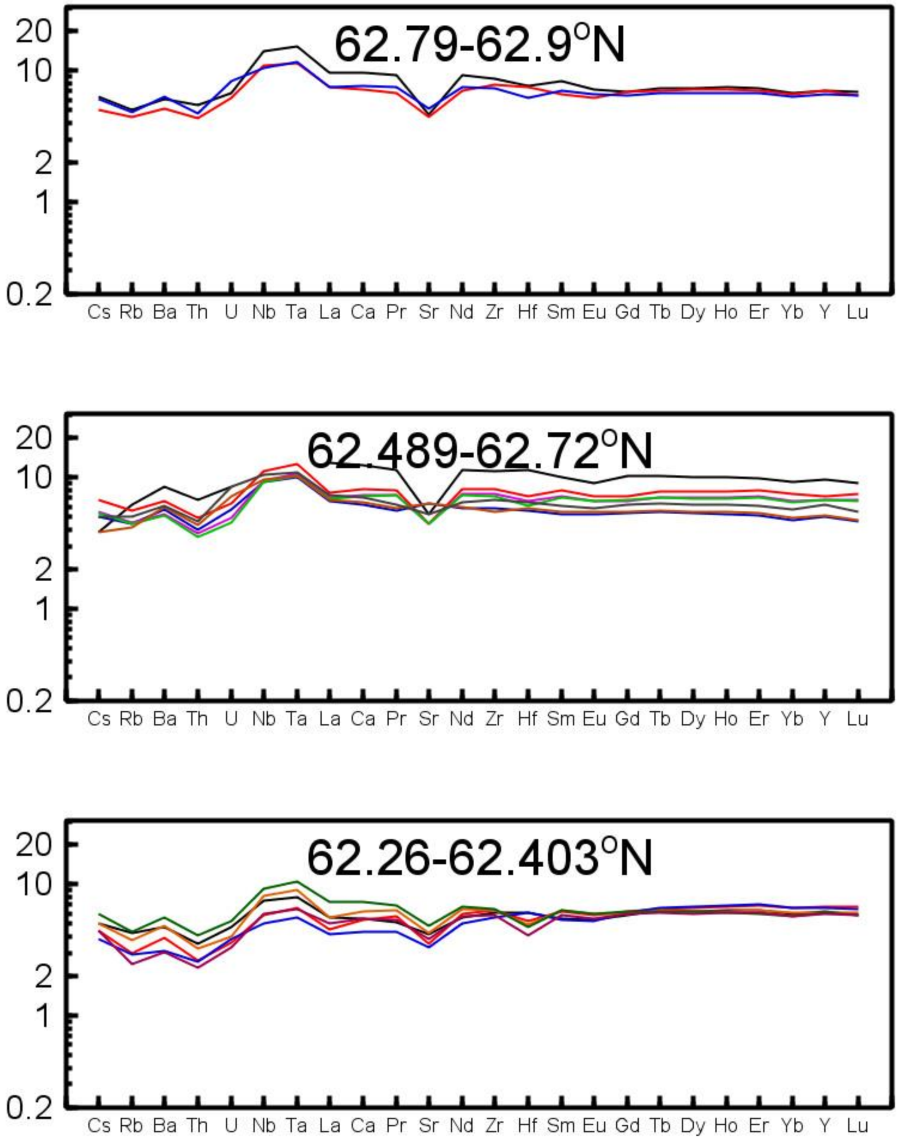

Figure B1: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

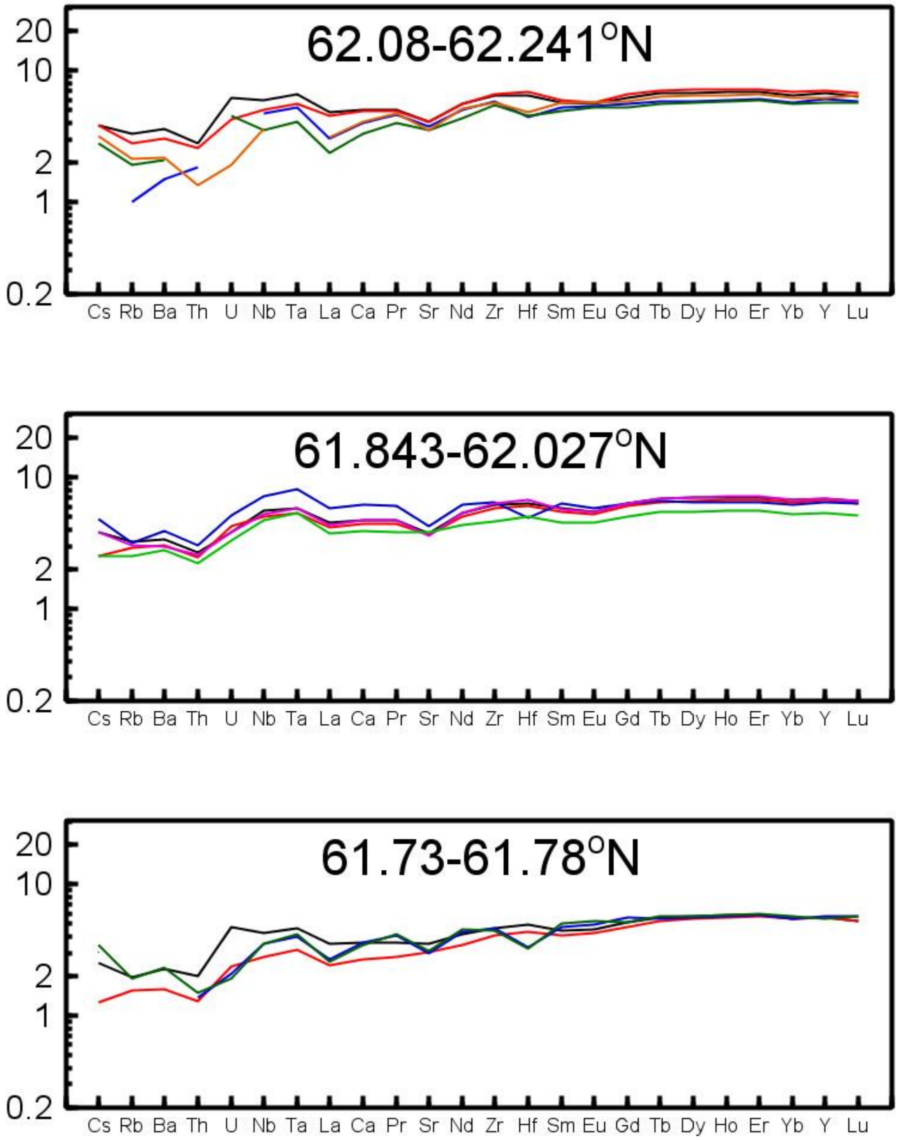

Figure B2: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

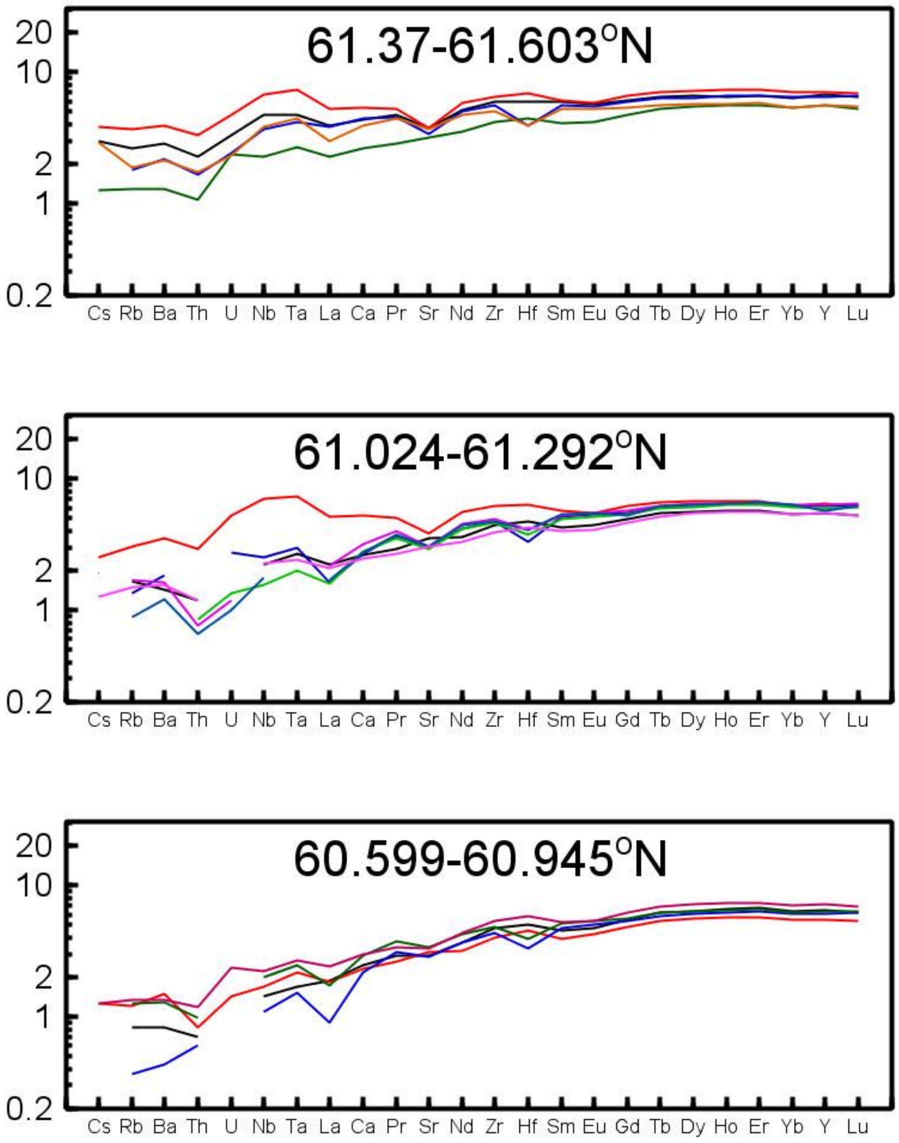

Figure B3: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

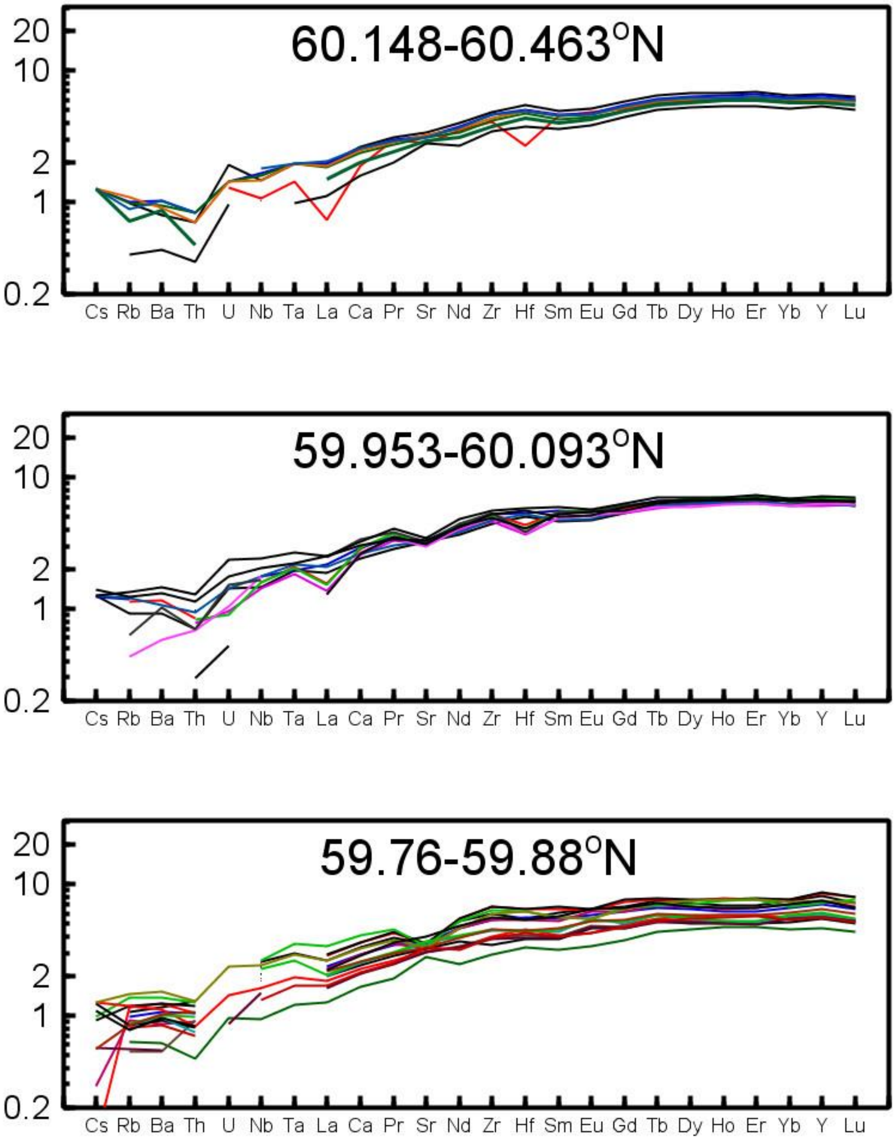

Figure B4: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

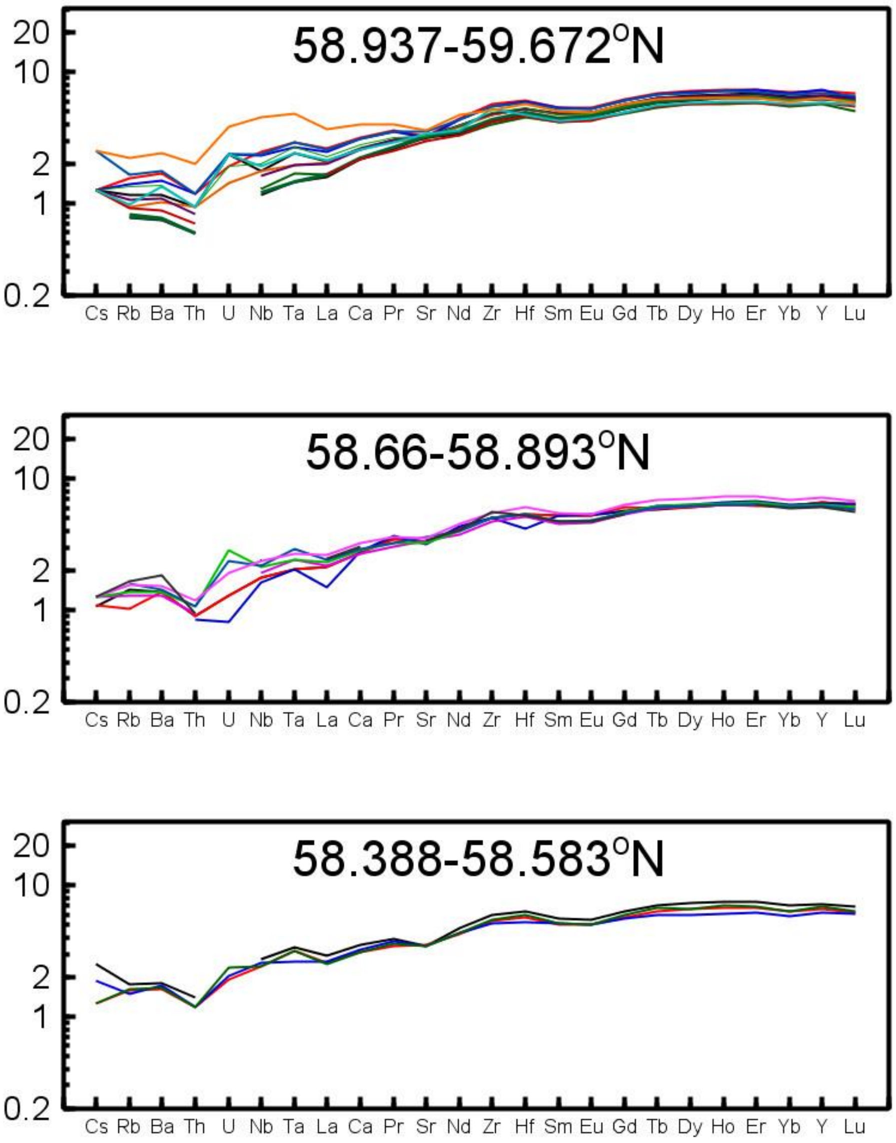

Figure B5: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

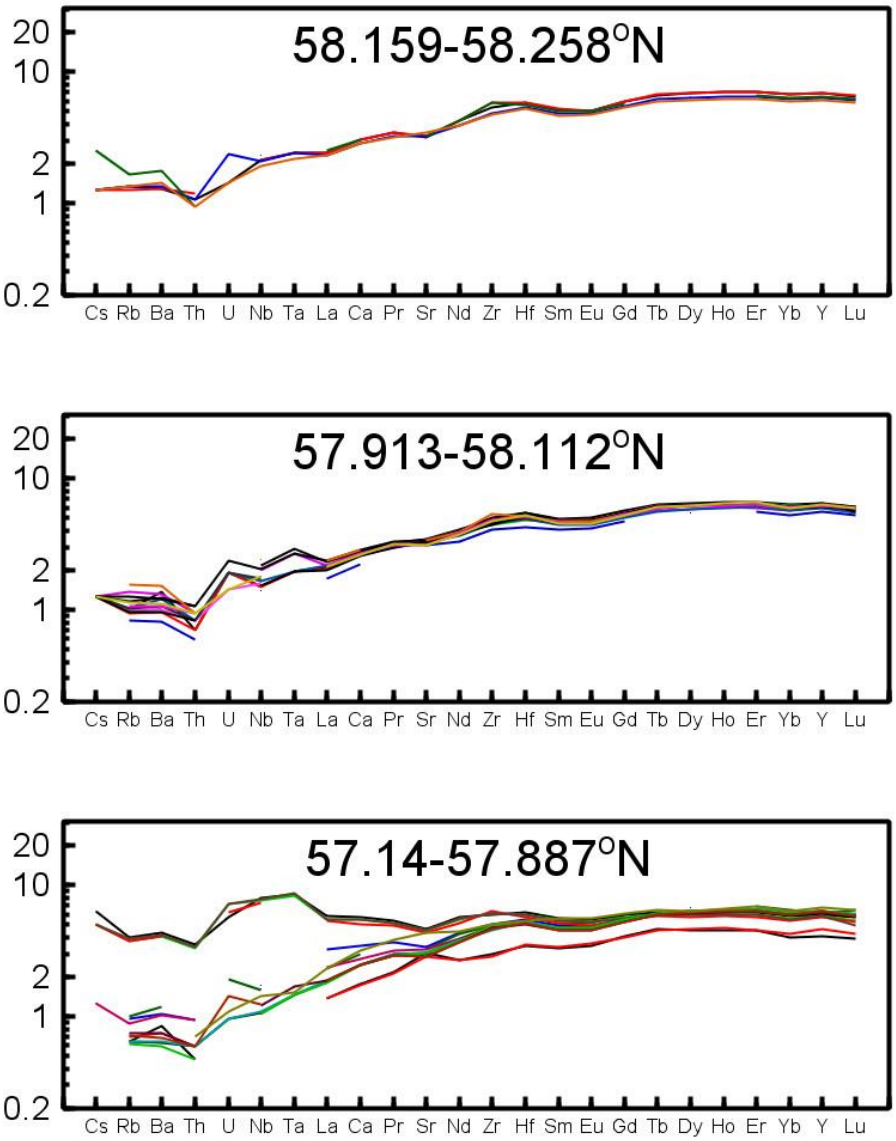

Figure B6: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

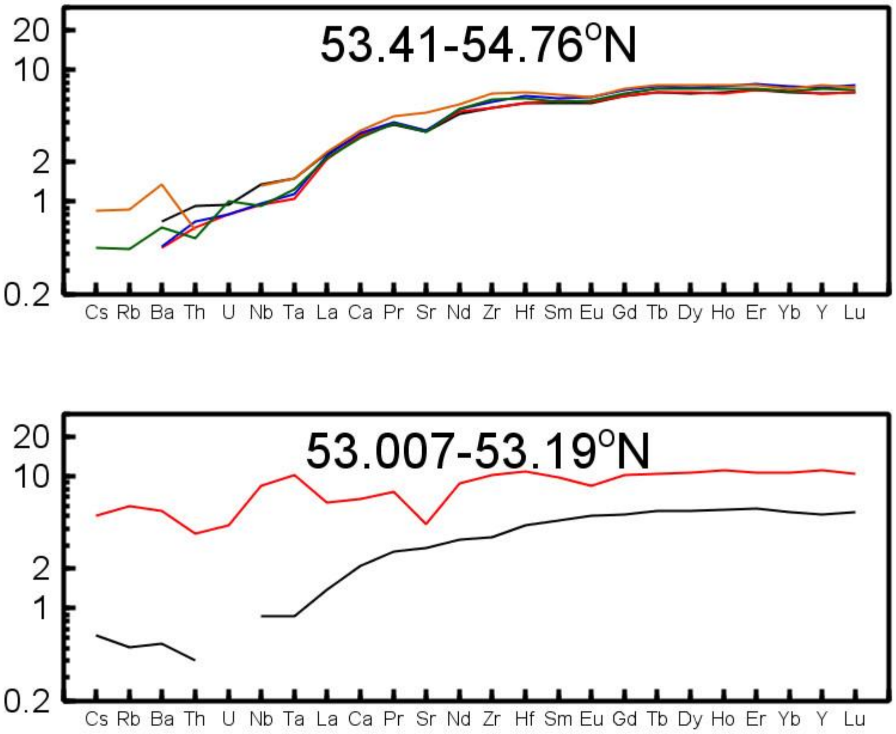

Figure B7: Primitive Mantle (PRIMMANT) Normalized Trace Element Patterns.

Appendix C: Rare Earth Elements Normalized Diagrams

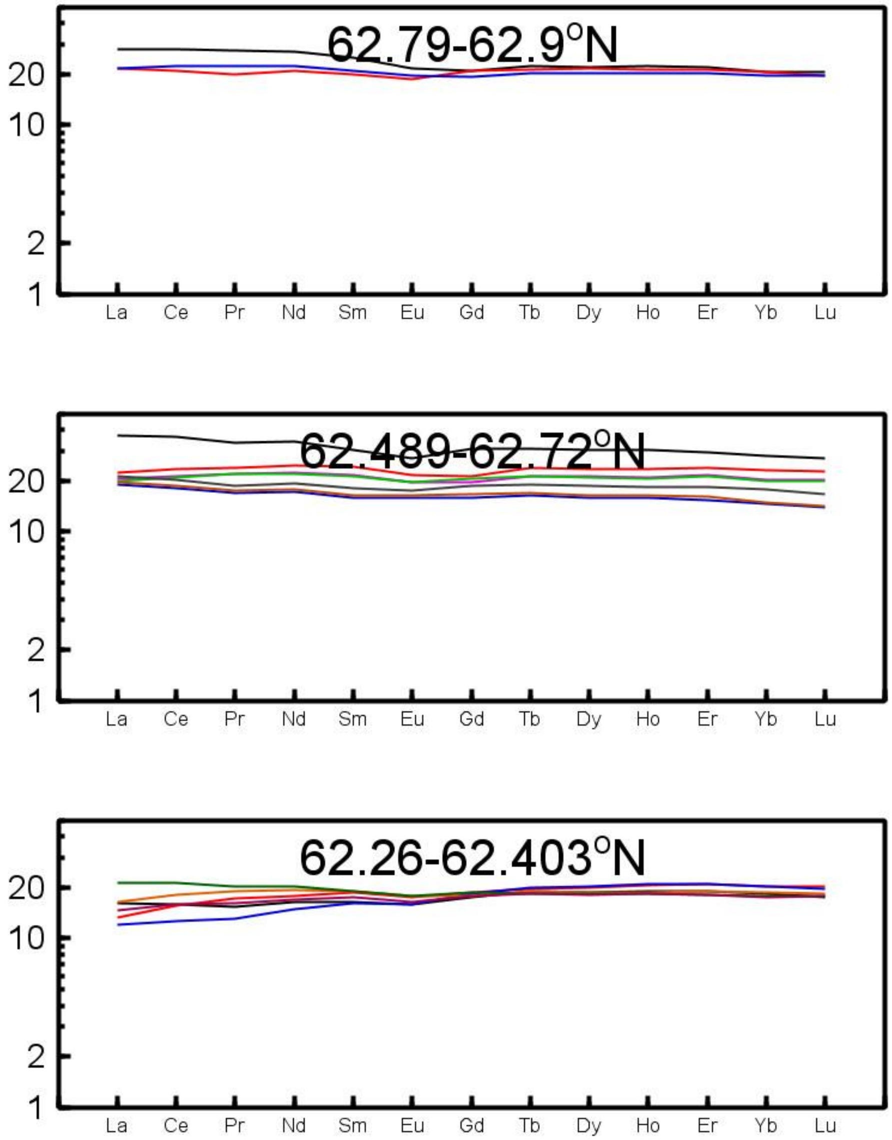

Figure C1: Rare Earth Element (REE) Normalized Trace Element Patterns.

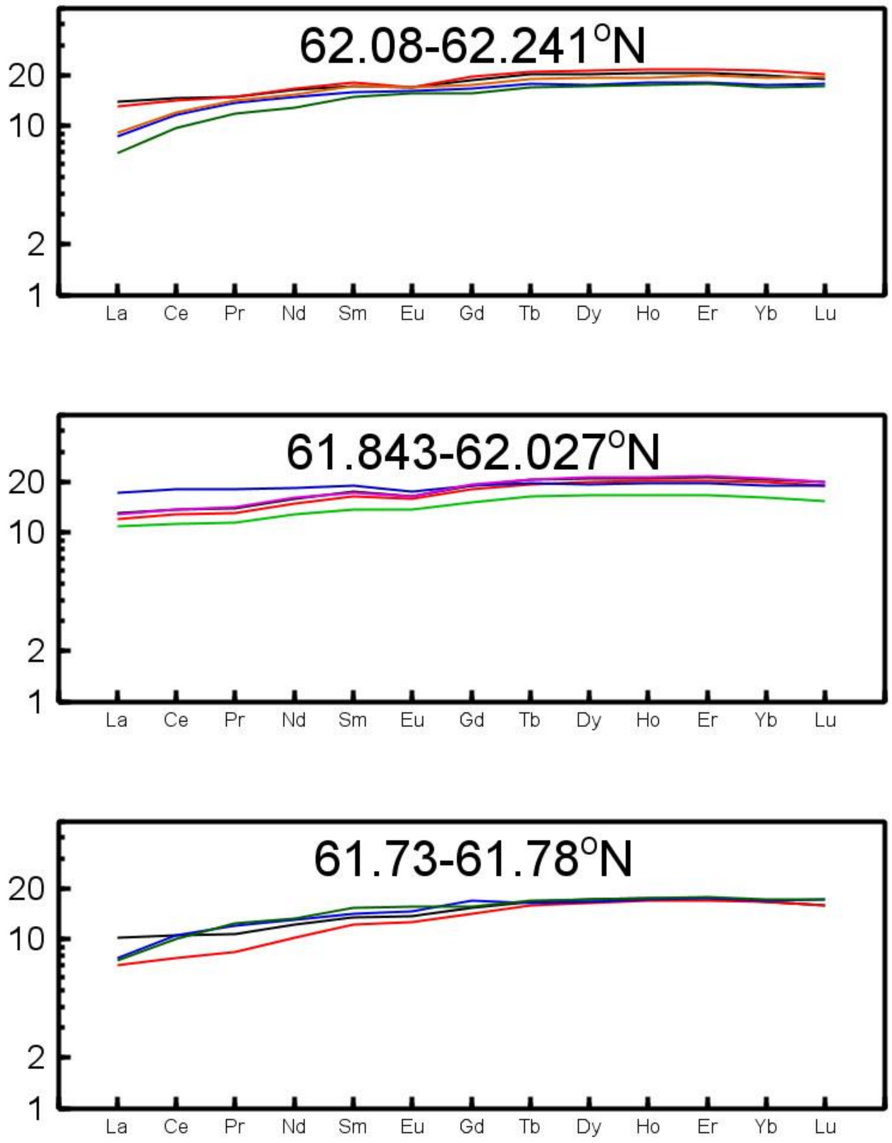

Figure C2: Rare Earth Element (REE) Normalized Trace Element Patterns.

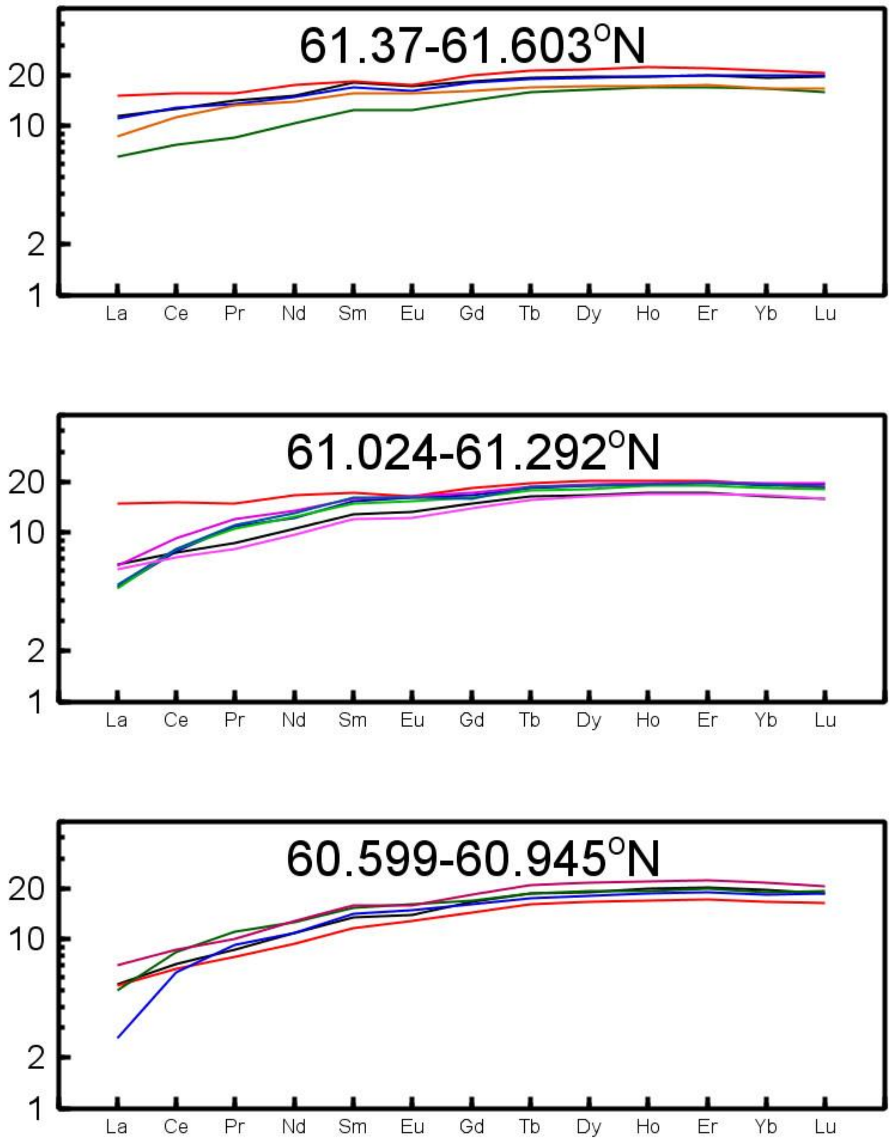

Figure C3: Rare Earth Element (REE) Normalized Trace Element Patterns.

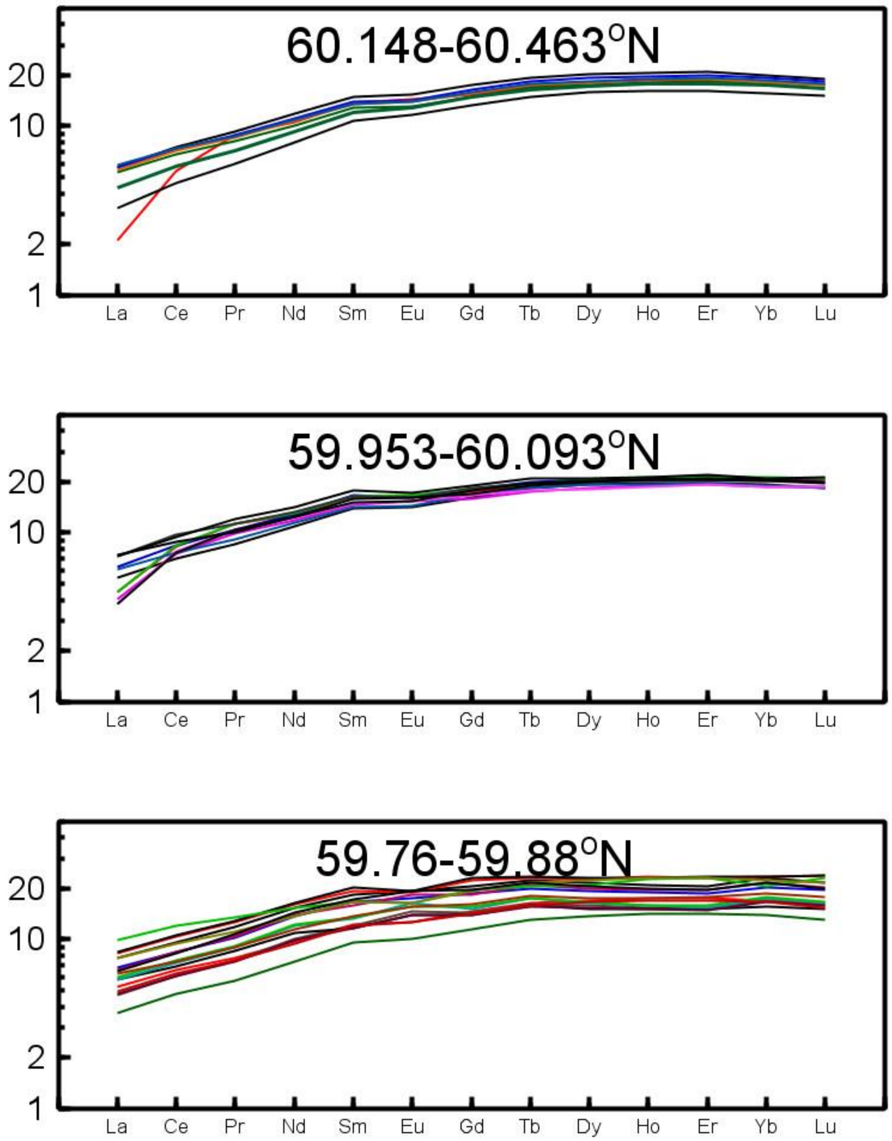

Figure C4: Rare Earth Element (REE) Normalized Trace Element Patterns.

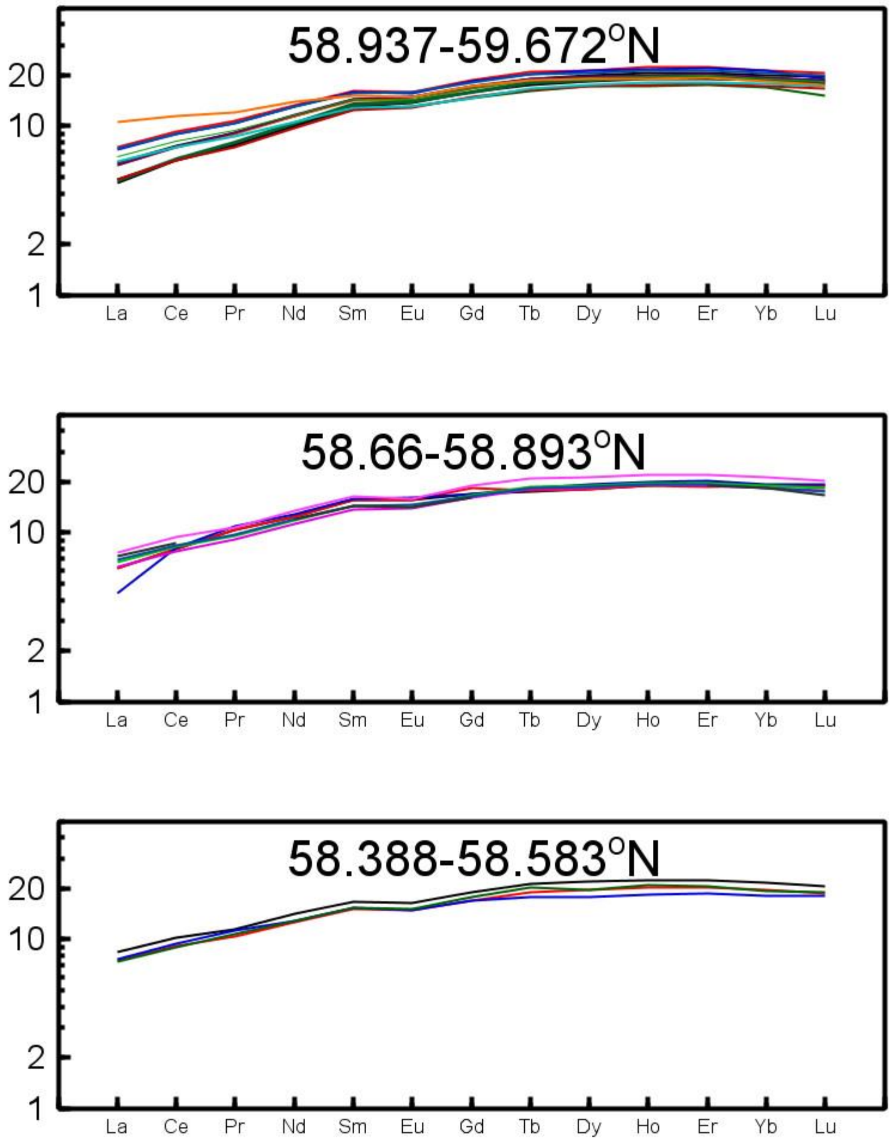

Figure C5: Rare Earth Element (REE) Normalized Trace Element Patterns.

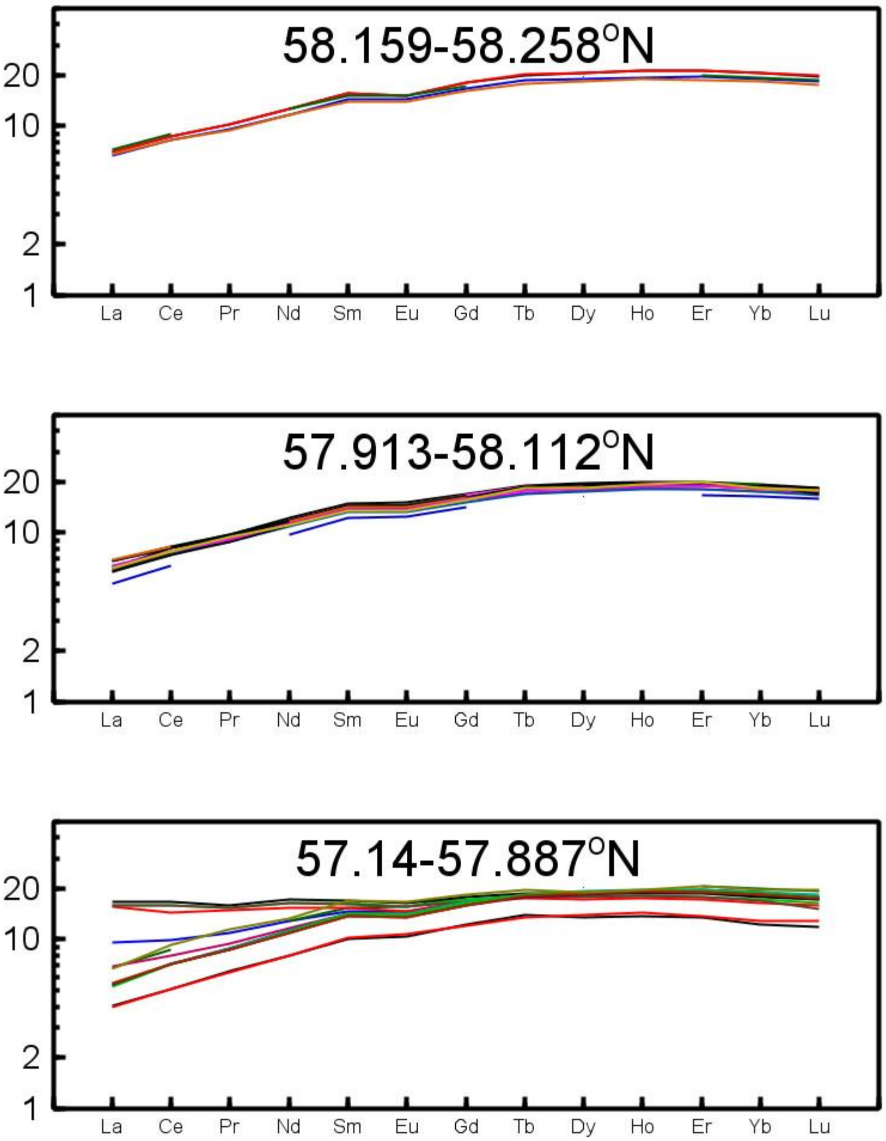

Figure C6: Rare Earth Element (REE) Normalized Trace Element Patterns.

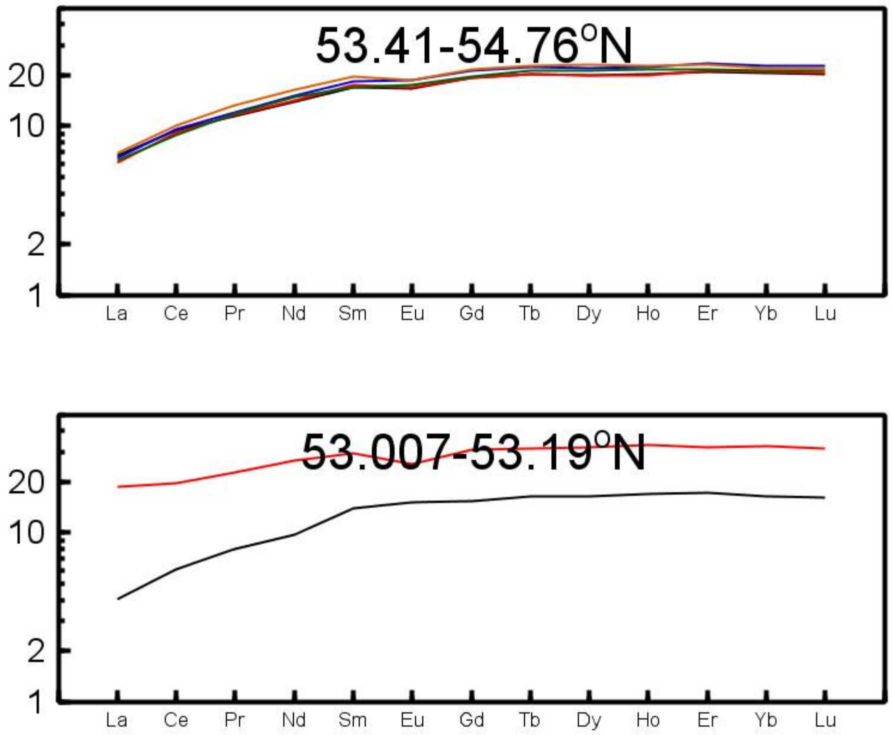

Figure C7: Rare Earth Element (REE) Normalized Trace Element Patterns.