Laser Ablation ICP-MS of Siderophile and Chalcophile Elements in Mid-Ocean Ridge Glasses

Research Experience for Undergraduates
National High Magnetic Field Laboratory
Florida State University
Summer 2005

Evelyn Martinique Mervine
Dartmouth College
July 29th, 2005
Mentor: Dr. Vincent Salters

Abstract:

While geochemists have a good understanding of the behavior and concentrations of major elements and some trace elements in mid-ocean ridge basalts (MORBs), the behavior and abundances of most siderophile and chalcophile elements in MORBs is relatively poorly-understood. In this study the concentrations of many siderophile and chalcophile elements in MORBs were analyzed using Laser Ablation Inductively Couple Mass Spectrometry (LA-ICP-MS). Specifically, the concentrations of cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), germanium (Ge), arsenic (As), selenium (Se), molybdenum (Mo), palladium (Pd), silver (Ag), cadmium (Cd), rhenium (Re), and lead (Pb) were analyzed in MORB glasses. The concentrations of major and other trace elements, such as the Rare Earth Elements (REEs), were also measured for comparison purposes. Initially, twelve Indian ridge glasses were studied to develop the LA-ICP-MS method. Once the method was developed, two suites of glasses from the north mid-Atlantic ridge were analyzed to examine how siderophile and chalcophile elements behave during crystal fractionation. The relative compatibilities of siderophile and chalcophile elements were determined for these two suites of samples. Mo, Pb, Pd, and Zn were determined to be highly incompatible, Ga, Se, Cd, and Co were determined to be incompatible, and, finally, Ni and Cu were determined to be compatible in these samples. The relative compatibilities of Ag and Re could not be determined because there was insufficient data. Additionally, an ion microprobe was used to collect sulfur (S) concentration data in the mid-Atlantic samples. The concentration of S in these samples ranged from 0.207 to 0.314 weight percent, and S seemed to behave incompatibly.

Introduction:

For centuries, geologists only studied the major element chemistry of rocks and minerals and used this information primarily to classify rock into various categories. Thanks to the work of countless researchers and the development of new technologies, over the past hundred years geologists have come to understand that the chemistry of rocks is complex and that both major and trace elements are useful to study in rocks. Further, geologists have moved beyond simple classification of rocks and have developed techniques that use major and trace elements to glean information about the processes rocks undergo to reach the surface. Modern geochemists can even use the chemistry of rocks found on Earth's surface to obtain information about inner layers of the Earth which are currently inaccessible to scientific researchers.

However, while geologists appreciate that studying elements that are only present in trace amounts in rocks can provide a great amount of information on the history of that rock and on various Earth properties and cycles, many trace elements have yet to be fully studied and understood by geologists. Two major categories of elements, the siderophile and chalcophile elements, are particularly understudied. The behavior of most siderophile and chalcophile elements in rocks is poorly-understood in comparison to what is known about the behavior of major elements and selected trace elements, such as the rare earth elements (REEs).

While siderophile and chalcophile elements are present in only trace concentrations in most rocks, there is much that studying the behavior and abundances of these elements in rocks can potentially reveal about various processes. For example, comparing the behavior of siderophile and chalcophile elements with the well-constrained behavior of major and other trace elements during magma genesis can potentially reveal more about the petrogenesis of rocks. Studying siderophile and chalcophile elements in rocks can potentially give geologists information about the oxidation state of the mantle, the behavior of sulfur during magma genesis, the composition of the Earth's core, and dozens of other geochemical processes (Gaetani and Grove, 1 and Gebmann and Rubie, 1). While very few studies have examined the concentrations and behavior of siderophile and chalcophile elements, the studies that have been done so far indicate that there is a wealth of information that can be gleaned from these elements. For example, analysis of Zn, Cu, and Pb in mid-ocean ridge basalts indicates that the ratio of Zn / Pb can provide information about the source of these basalts in hydrothermal deposits (Doe, 1994).

This objective of this study is to develop a technique for measuring the concentrations of select siderophile and chalcophile elements in mid-ocean ridge glasses using LA-ICP-MS. Specifically, this study examines the concentrations of the siderophile elements Co, Ni, Mo, Pd, and Re and of the chalcophile elements Cu, Zn, Ga, Ge, As, Se, Ag, Cd, and Pb. A technique for measuring the concentrations of these elements was developed on a set of glasses from the Indian Ridge. Once the method was developed, the concentrations of these samples were measured in two suites of glasses from the north mid-Atlantic ridge in order to examine how these elements behave during crystal fractionation.

Background-- Goldschmidt's Classification of the Elements:

Over seventy years ago, a brilliant young scientist named Victor Goldschmidt divided the periodic table into four categories: atmophile, siderophile, chalcophile, and lithophile elements (Henderson, 76). The suffix "-phile" comes from Greek and means "loving." Thus, the atmophile elements, for example, are literally the "atmosphere-loving" elements. Similarly, the siderophile elements are the "iron-loving" elements, the chalcophile elements the "sulfur-loving" elements, and the lithophile elements are the "rock-loving" elements. After coming up with this classification scheme in 1932, one of his first big scientific accomplishments, Goldschmidt went on to make a number of important discoveries and is now considered the father of modern geochemistry (Henderson, 76).

As the name suggests, the atmophile elements are those elements that are found in the Earth's atmosphere. They consist of the noble and covalently bonded gases. The siderophile elements consist of the metals near and including iron (Fe) in the periodic

table. The siderophile elements are transition metals and exhibit metallic bonding. The chalcophile elements are elements that tend to bond to sulfur as well as elements such as selenium (Se), tellurium (Te), antimony (Sb), and arsenic (As). Generally, chalcophile elements form covalent bonds. Lastly, the lithophile elements are elements that are concentrated in the Earth's crust and are the major constituents of rocks. Lithophile elements typically bond to oxygen in silicates and oxides and tend to form ionic bonds.

Goldschmidt developed his classification scheme through careful study of meteorites and sulfide ore smelting products (Reardon, 1). There are three main chemical phases found in meteorites: an iron-nickel alloy, a iron sulfide phase, and a silicate phase (Reardon, 1). In some meteorites, all three of these phases are believed to have existed simultaneously. Goldschmidt postulated that a detailed study of these phases as well as similar phases found in sulfide ore smelting products would provide a classification scheme for elements. As Goldschmidt suspected, the elements did fall into categories based on whether the elements preferred to be included in the iron-nickel, iron sulfide, or silicate phase, and Goldschmidt's classification of the elements was born (Reardon, 1). However, while the classification scheme has been around for over seventy years, the concentrations and behaviors of two of the four categories of elements, the siderophile and chalcophile elements, remains poorly understood in rocks.

Sample Selection:

Indian Ridge Samples:

The laser ablation technique was developed on twelve volcanic glass samples from the Indian ridge. The names of these samples are listed in Table 1. Six of the Indian

ridge samples were analyzed both with LA-ICP-MS and traditional solution ICP-MS so that the results could be compared.

North Mid-Atlantic Ridge Samples:

Once the laser technique was developed and tested on the Indian ridge samples, twenty-nine samples from the north Atlantic mid-ocean ridge were analyzed using LA-ICP-MS. These samples were borrowed from the Smithsonian's volcanic glass collection. Selecting samples from the Smithsonian's volcanic glass collection was ideal as there is major and some trace element data available for most of these samples. Having this data available allowed the behavior of siderophile and chalcophile elements to be easily compared to the well-understood major and other trace elements.

These twenty samples come from the north Atlantic mid-ocean ridge and represent one suite of fifteen samples and a second suite of fourteen samples. The samples in each suite are related to each other through crystal fractionation. The samples were selected by examining the major element concentrations in the PETDB database. Tables 2 and 3 list the Smithsonian samples along with the longitude, latitude, depth, and major elemental concentrations of the samples. Table 2 provides the information for the first suite of samples while Table 3 provides the information for the second suite of samples.

Analysis:

Laser Ablation Method Development:

The LA-ICP-MS method for analyzing siderophile and chalcophile elements in mid-ocean ridge basalts was developed using the twelve Indian ridge samples. All of the experimentation and LA-ICP-MS data collection was done in the Geochemistry

Department at Florida State University. The samples, which consisted of glass chips approximately 1-3 mm in width and 0.25-1 mm in thickness, were mounted in epoxy on a metal slide, which was polished to reveal a fresh, smooth glass surface for ablation.

Once the samples were polished, they were placed in the sample holder in the LSX-200 laser used for the ablation of the samples. Each sample slide held six samples, which were analyzed on two separate days. Argon gas was used to pick up the ablated sample and carry this sample to the mass spectrometer. The argon gas flowed through a teflon tube to the Finnigan MAT Element 1 mass spectrometer, which ionized the sample, separated the ions with a magnetic field, and counted the ions so that concentrations could be calculated.

During the experimentation with the Indian ridge samples, various track and spot analyses were used to ablate the sample. The best signal was obtained by using a 5-spot analysis that ablated the sample for fifty to ninety seconds depending on how many elements were measured. One important observation that was made is that the different sizes of spots do not provide comparable data, even though correcting the other elemental ratios by dividing them by the concentration of the major element calcium (Ca) or iron (Fe) should correct for the differences in the abundance of material being ablated. Thus, 5-spot analyses were used throughout this study. The glass reference material NIST SRM 612 was analyzed with 5-spot analyses and was measured before and after each set of six Indian ridge samples. Additionally, blank measurements were taken at the beginning, end, and after every two to three glass samples. Representative blank counts are provided in Table 4.

Firing on Residual Aprons:

The Indian ridge samples were used to determine how firing on the residual apron around a previous laser hole affects data quality. The residual apron consists of sample fall-out and forms around every laser hole. Around the 5-spot laser hole a fairly large residual apron was observed, about 5-10 times the diameter of the 5-spot hole, which is 80-100 μm in diameter. Figure 2 is an image of a sample showing several laser holes and their residual aprons. Figures 3 and 4 are scanning electron microscope images of a laser hole and the surrounding apron debris.

Several aprons, both aprons that were several days old and fresh aprons formed by laser holes made only minutes before, were fired on. While firing on a residual apron hole did affect the initial signal and caused spikes in the concentrations of most elements, delaying data collection for 10 seconds after the laser began firing produced a normal, smooth signal. By incorporating this delay into the data collection method, it was discovered that laser holes can be made very close together and still produce reliable, high-quality data. Once the delay was incorporated into the method, the data collected from holes fired on residual aprons was comparable to the data collected from holes fired on a fresh glass surface.

Comparison with Solution ICP-MS:

The concentrations determined for six of the Indian ridge samples with the LA-ICP-MS method were compared with concentrations determined with traditional solution ICP-MS. Glass chips of six Indian ridge samples analyzed with LA-ICP-MS were dissolved using HF-HCl-HNO_3 digestion. 50-100 mg of each glass sample was dissolved in approximately 4 mL of 3:1 concentrated HF:HNO_3. Hydrofluoric acid removes

silicates, the bulk of the glass samples. Once dissolved, the samples were sonicated for 30 minutes then dried down and re-dissolved in 6 N HCl, which converts the fluorides to chlorides. Next, the samples were dried down again and re-dissolved in concentrated HNO_3. The samples were dried down one last time and then were picked up once again in concentrated HNO_3, which was diluted with quartz distilled H_2O so that the sample concentrations were 1000 ppm. The samples were then diluted once more so that the sample concentrations were approximately 100 ppm, the concentration needed to be introduced into the mass spectrometer. This solution was introduced into the Finnigan MAT Element 1 mass spectrometer to determine the concentrations of elements in solution. A standard solution made with BHVO was also measured to determine solution concentrations, as given in the 2004 paper by Willbold and Jochum.

Laser Ablation of Mid-Atlantic Ridge Samples:

Once the method was developed on the Indian ridge samples, the concentrations of siderophile and chalcophile elements in the mid-Atlantic ridge samples were measured. Again, the standard reference glass material NIST SRM 612 was measured and blank measurements were taken. The reference material was measured at the beginning and end of the day's analysis as well as after every sample slide. Blanks were measured after every standard measurement and also periodically during sample measurement, generally after every three to four ablations. For each sample, two to three ablations were done on a single glass grain so that the results could be averaged. Unfortunately, only seven of the twenty-nine samples on loan from the Smithsonian were measured before the laser head on the LSX-200 burned out. Data was collected for samples VG 3342, VG 3348, VG 3350, VG 3355, VG 3356, VG 3976, and VG 3978. As

the laser has not yet been repaired, data has not yet been collected for the remaining samples.

Ion Microprobe Measurements:

In addition to the LA-ICP-MS data, an ion microprobe was used to determine the sulfur concentration in eight of the twenty-nine mid-Atlantic ridge samples. The samples were analyzed on the ion microprobe at Florida International University (FIU). The samples were shipped down to FIU in Miami, and the data was collected in Tallahassee using a remote internet link. S concentration data was collected for samples VG 3342, VG 3348, VG 3349, VG 3350, VG 3355, VG 3356, VG 3976, and VG 3978.

Results and Discussion:

As a large amount of data was collected and there is still much work to be done before this data can be fully interpreted and understood, only a selection of the data collected during this eight-week internship will be presented in this paper. A full analysis of the implications of the concentrations of siderophile and chalcophile elements measured in this study is beyond the scope of this paper and should not be carried out until data is collected for all twenty-nine mid-Atlantic ridge samples. Thus, only some general observations on the trends observed in the data will be given below.

The sample concentrations were calculated by comparing the counts measured in the samples with those measured in the standard NIST SRM 612. The standard concentration values for all elements except Se and Pd were taken from the 2004 paper by Pearce et al. (Pearce, 138). The preferred average values reported in this paper were used for all sample concentration calculations. There were no concentration values

reported for the elements Se and Pd, so the concentration of these elements in the SRM 612 standard was estimated to be 40 ppm in all calculations.

Once the concentrations of the elements were calculated, the REEs were examined to double-check that these samples do indeed represent a suite related through crystal fractionation. The REEs all showed typical crystal fraction trends and plotted incompatibly against the major elements. A spider diagram of the REEs for the seven mid-Atlantic ridge samples analyzed is given in Figure 5. The figure shows that samples with higher MgO content contained lower concentrations of REEs while the samples with lower MgO content contained higher concentrations of the REEs. The behavior of the REEs shows that these samples are clearly represent a suite of samples related through crystal fractionation.

Once the REEs were analyzed, the concentrations of the siderophile and chalcophile elements were plotted against the major elements to look for crystal fractionation trends. Trends could be determined for all elements except Ag and Re. Possibly, measuring the concentrations of these elements in the remaining mid-Atlantic ridge samples will shed light on the behavior of these two elements. Most of the siderophile and chalcophile elements behave incompatibly. The relative compatibility of the siderophile and chalcophile elements measured was determined to be, from most highly incompatible to least incompatible: Mo, Pb, Pd, Zn, Ga, Se, Cd, Co, Ni, and Cu. Table 5 summarizes the relative behavior of the chalcophile and siderophile elements measured in this study. Mo, Pb, Pd, and Zn were determined to be highly incompatible elements while Ga, Se, Cd, and Co were determined to be incompatible elements. Ni and Cu were the only two elements that showed compatible trends. Figure 6 gives a few

examples of the graphs used to determine the relative compatibilities of the siderophile and chalcophile elements. The graphs show that chalcophile Pb and Zn show incompatible behavior while chalcophile Cu shows compatible behavior.

The compatible behavior of Cu is very surprising as there is no known explanation for this behavior. While the compatibility of Ni makes sense as Ni is incorporated into olivine, the behavior of Cu is befuddling and suggests the presence of a sulfide melt or, perhaps, of a melt of a composition yet undiscovered in geochemistry.

The concentration of S, a chalcophile element present in much large concentrations than the other siderophile and chalcophile elements measured in this study, was determined using the ion microprobe at FIU. The concentration of S in eight of the twenty-nine mid-Atlantic ridge samples was determined. The concentration of S in the samples ranged from 0.207 to 0.314 weight percent. When plotted against the concentrations of major elements, sulfur seemed to behave like an incompatible element. Figure 7 shows the concentration of S plotted against the concentrations of MgO and CaO. Like many of the other chalcophile elements, S seems to behave incompatibly.

Future Work:

Much more work needs to be done before the behavior of siderophile and chalcophile elements in mid-ocean ridge glasses is fully understood. However, while the data in this study does need further analysis in order to be fully understood, the initial results and conclusions are very exciting and, in the case of certain elements such as Cu, unexpected. Clearly, there is much that the siderophile and chalcophile elements can reveal about the composition of mid-ocean ridge glasses, the petrogenesis of volcanic glasses, and the composition of the Earth's mantle and core. Some of our basic

assumptions about the petrogenesis of glasses and the composition of the mantle may very well be wrong or may need to be modified, depending on what the siderophile and chalcophile elements reveal.

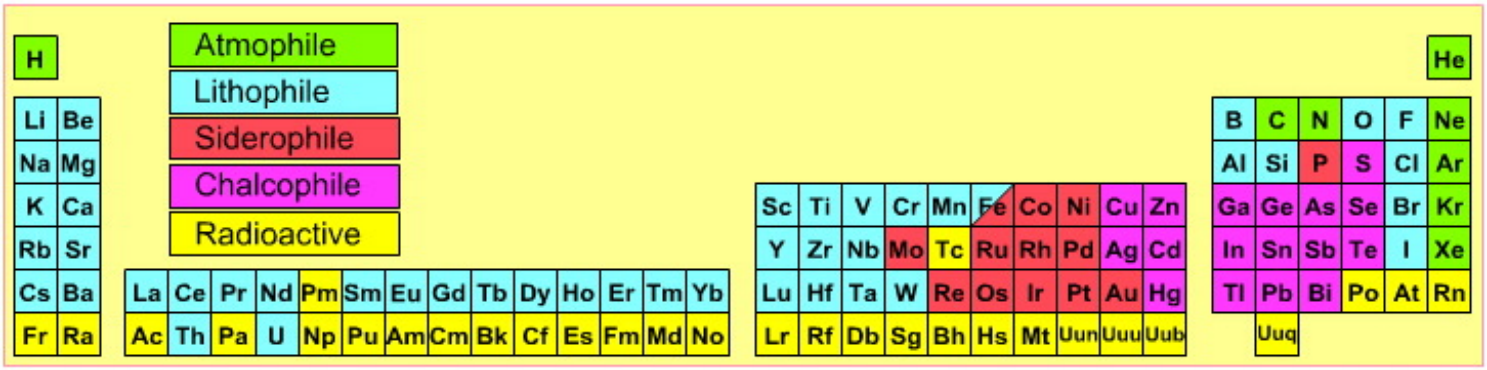
For this study, the next step is to determine the concentrations of siderophile and chalcophile elements as well as S content for all twenty-nine samples in the two mid-Atlantic ridge suites. If the samples all follow crystal fractionation trends, the results presented in this paper will be verified and work can begin on understanding why these crystal fractionation trends occur.

Acknowledgements:

This research was done as part of a Research Experience for Undergraduates (REU) summer program and was funded by the National Science Foundation. I sincerely thank everyone in the Geochemistry Department and the Center for Integrating Research and Learning at the National High Magnetic Field Laboratory at Florida State University for their support, knowledge, and patience. In particular, I would like to thank Dr. Vincent Salters, who supervised the research, and Dr. Michael Bizimis, who assisted with the mass spectrometry. I would also like to Mr. Timothy O'Hearn at the Smithsonian Institution for preparing the samples for loan and for a wonderful tour of the Smithsonian's rock and mineral collections.

Figures:

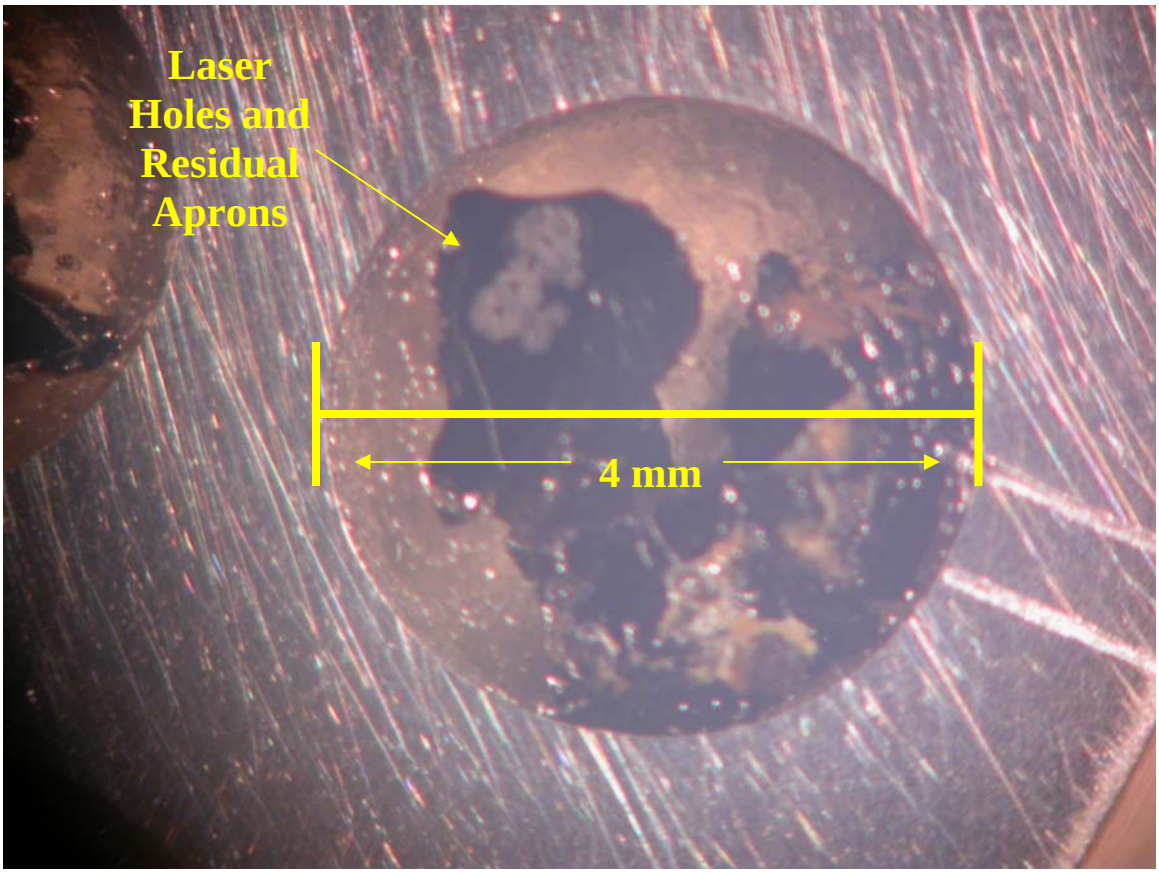
Figure 1: Goldschmidt's Classification of the Elements



This periodic table shows the division of the periodic table into Goldschmidt's four categories of elements: atmophile, lithophile, siderophile, and chalcophile. This table also displays the radioactive elements.

Table Source: http://www.meta-synthesis.com/webbook/35_pt/pt.html

Figure 2: Laser Holes and Surrounding Residual Aprons on a Sample Slide



This is microscope image of the laser holes and residual aprons that were made in a grain in one of the Indian ridge samples. The diameter of the circle is approximately 4 mm. The diameter of the laser holes in approximately 100 μm, and the diameter of the residual aprons ranges from approximately 500 μm to approximately 1000 μm. Note that on this slide newer laser holes were fired on top of the residual aprons of older holes and that the aprons are overlapping.

Figure 3: SEM Image of a Laser Hole and Surrounding Residual Apron

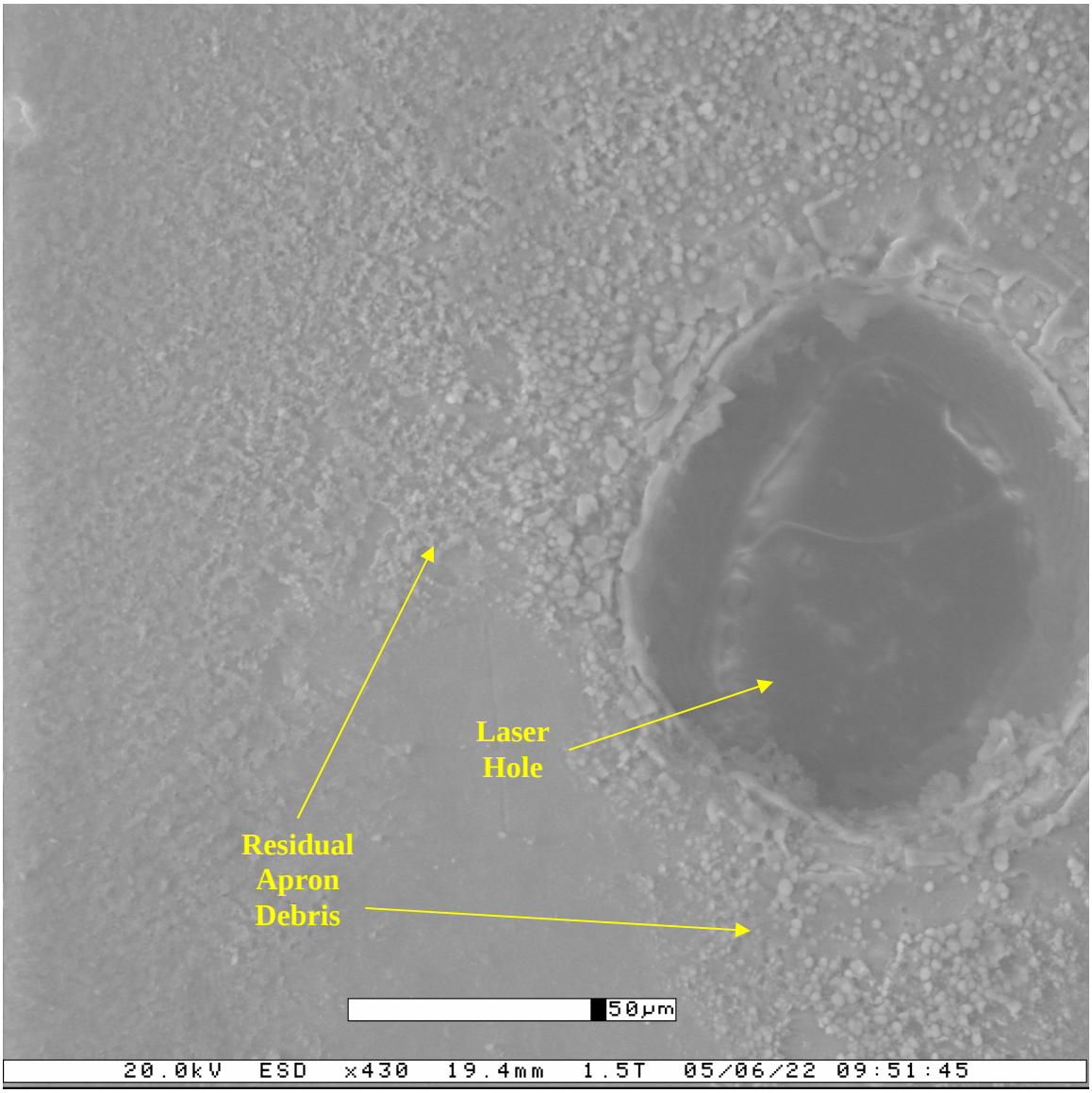


Figure 4: SEM Image of Laser Hole and Surrounding Residual Apron

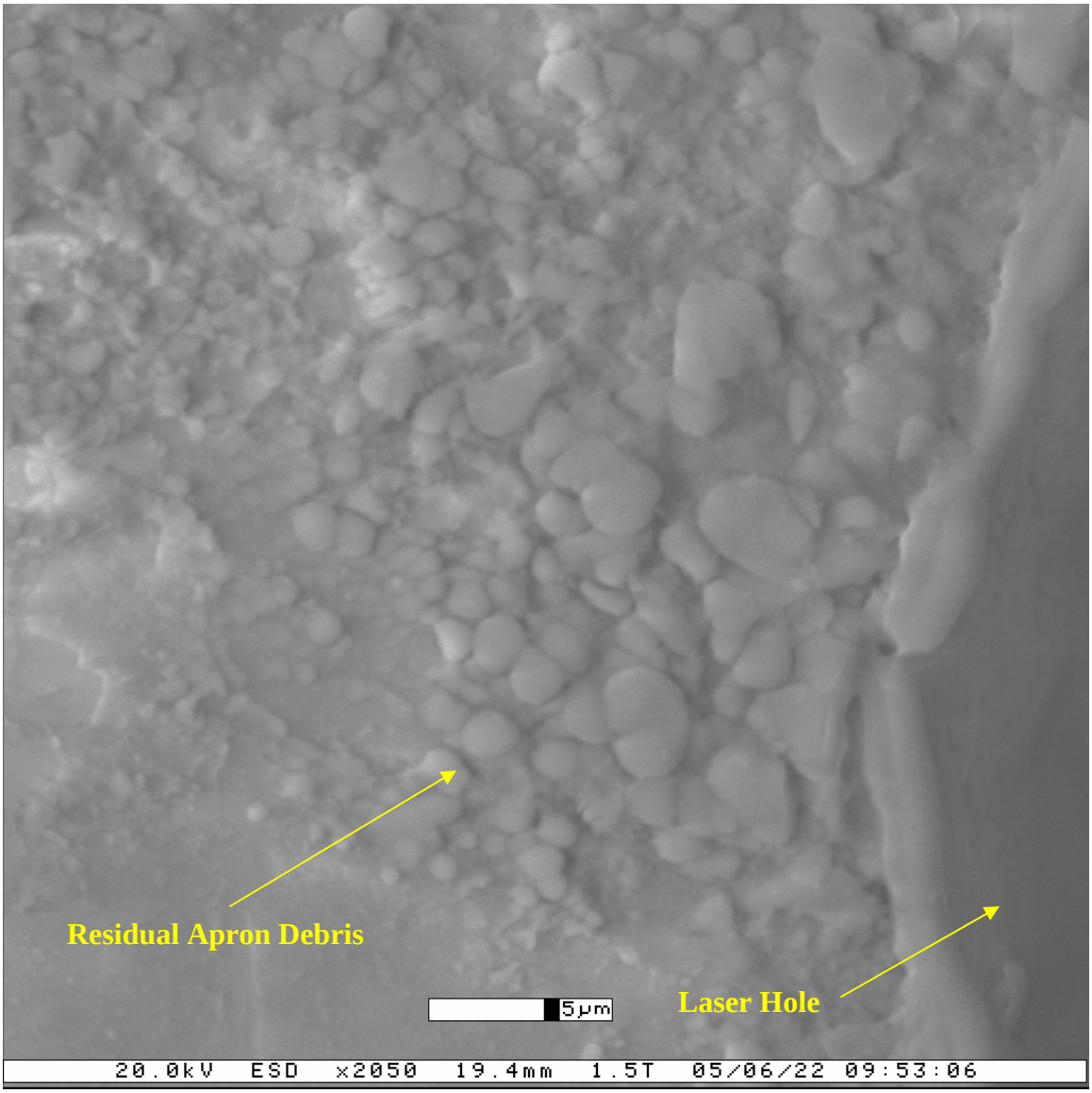
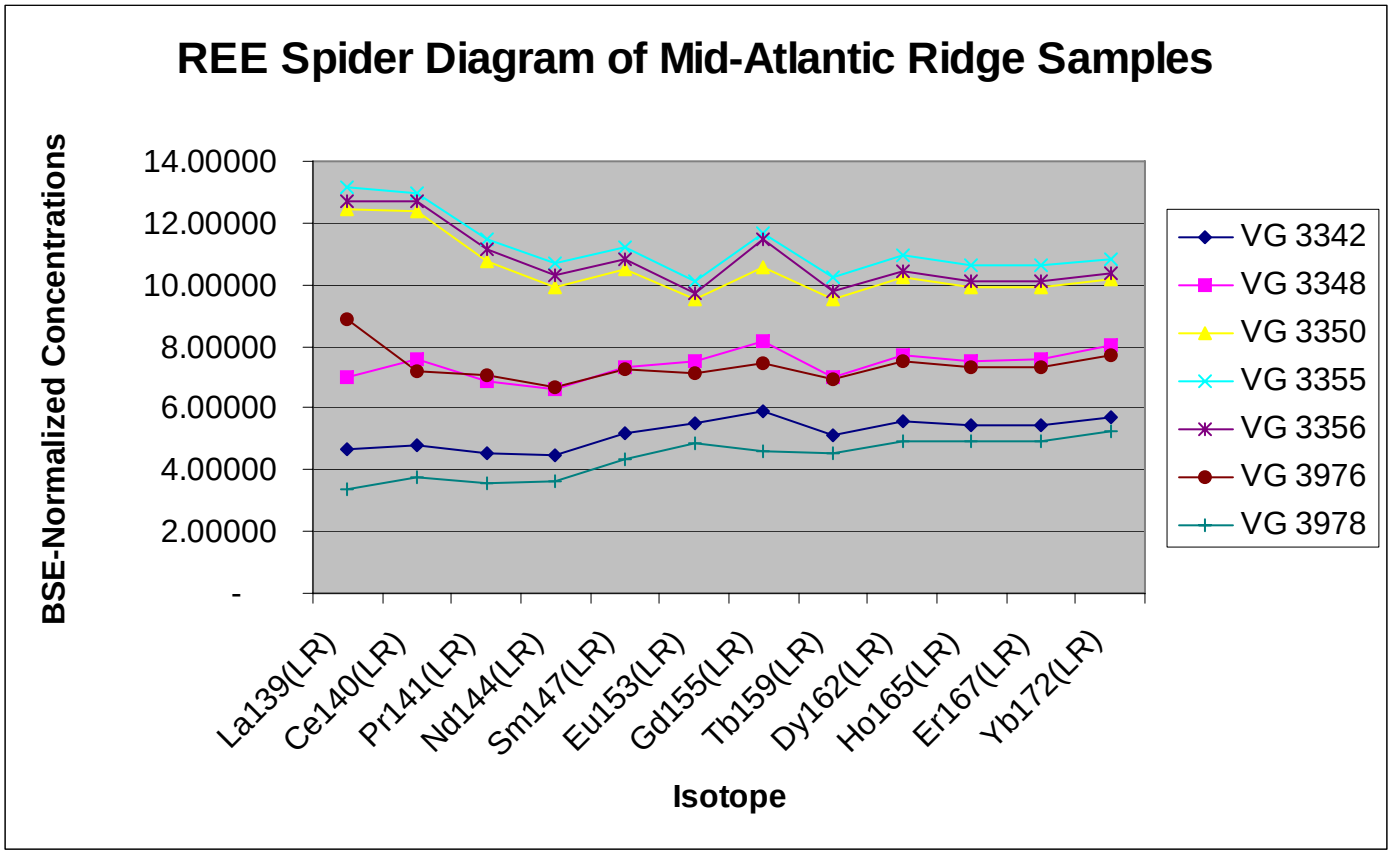
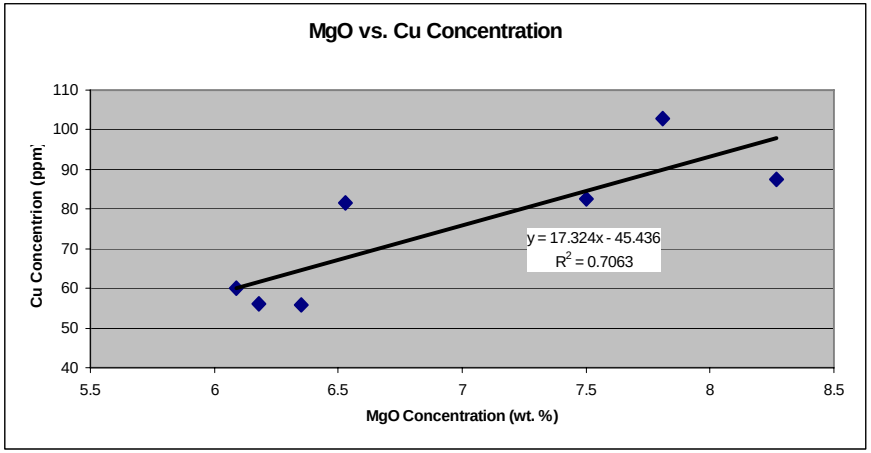


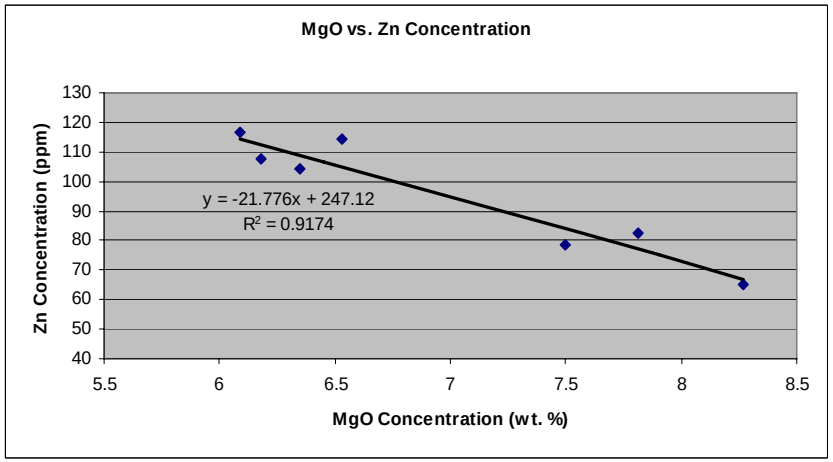
Figure 5: REE Spider Diagram for Mid-Atlantic Ridge Glass Samples

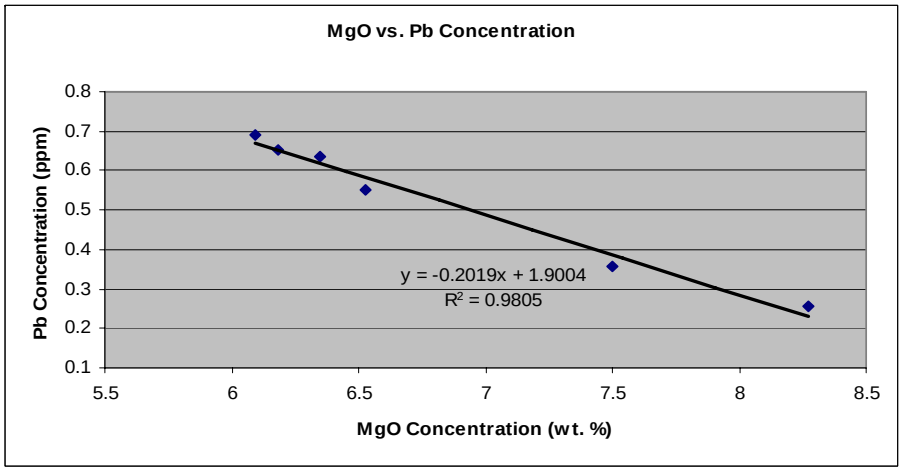


This figure shows that the concentrations of the REEs in the mid-Atlantic ridge samples varies and that the samples with the highest MgO concentrations have the lowest concentrations of REEs. This data shows that the samples do, indeed, represent a suite of samples related through crystal fractionation.

Figure 6: Representative Graphs of Siderophile and Chalcophile Element Concentrations Plotted Against MgO Concentration

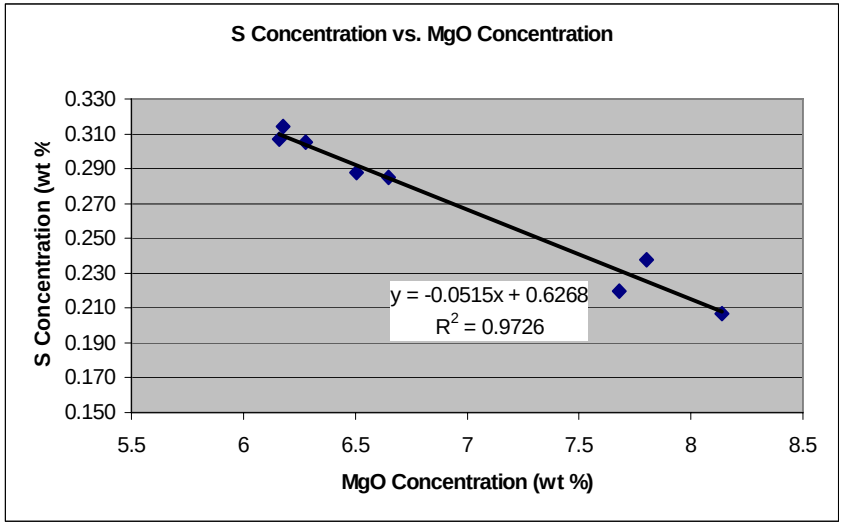


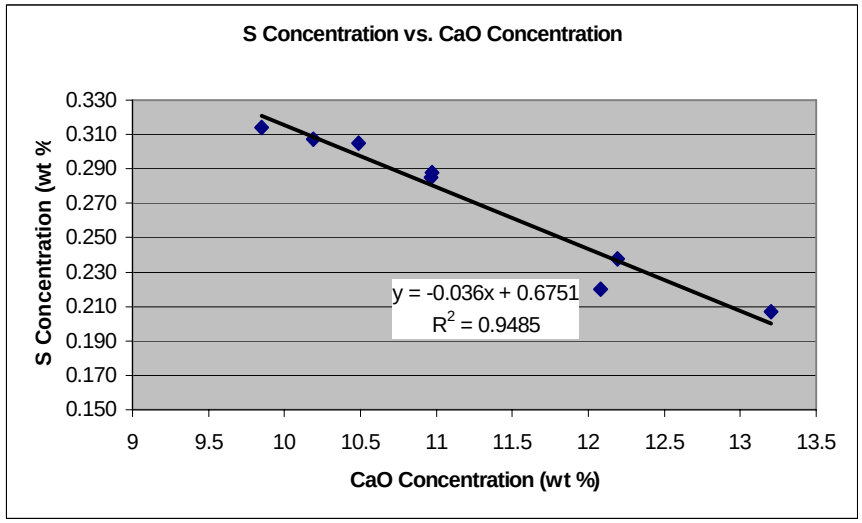




These three graphs show that chalcophile Cu displays compatible behavior while chalcophile Zn and Pb display incompatible behavior in this suite of mid-Atlantic ridge samples.

Figure 7: S Concentrations in Mid-Atlantic Ridge Glass Samples





These two graphs show that S concentration displays incompatible behavior when graphed against the major elements MgO and CaO.

Tables:

Table 1: Indian Mid-Ocean Ridge Glass Samples

MD 57 D9-12
JC 217 D1 (1) A
JC 217 D1 (1) B
MD 23 Site 2 (1)
MD 23 Site 2 (2) A
MD 23 Site 2 (2) B
MD 23 Site 2 (2) C
MD 23 Site 3 CIR
MD 23 Site 4 (4)
MD 3707 04 D1 (2) A
MD 3707 04 D1 (2) B
MD 3707 04 D7 (2)

Table 2: North Atlantic Mid-Oceanic Ridge Glass Samples—Suite 1

Smithsonian ID	PETDB Database ID	SiO_2	TiO_2	Al_2O_3	FeOT	MgO	CaO	Na_2O	K_2O	P_2O_5	Latitude	Longitude	Elevation (ft)	Expedition
VG 3356	AII0077-2-016-067	51.26	1.91	14.3	12.26	6.09	10.54	2.51	0.2	0.19	36.44	-33.64	-2518	AII077
VG 3355	AII0077-2-016-066	51.76	1.89	14.39	12.3	6.18	10.54	2.56	0.21	0.18	36.44	-33.64	-2518	AII077
VG 3350	AII0077-2-016-057	51	1.81	14.4	11.94	6.35	10.74	2.67	0.2	0.2	36.44	-33.64	-2518	AII077
VG 3348	AII0077-2-016-012	52.15	1.3	14.24	10.89	6.53	11.57	2.23	0.14	0.14	36.44	-33.64	-2518	AII077
VG 3349	AII0077-2-016-001	52.75	1.36	14.24	10.78	6.66	11.6	2.23	0.17	0.13	36.44	-33.64	-2518	AII077
VG 3933	GIL0103-027-048	52.14	1.33	14.74	10.33	6.9	11.68	2.43	0.16	0.14	36.452	-33.682	-2484	GS103
VG 3802	GIL0103-037-001	51.78	1.18	14.72	10.31	7.04	11.87	2.1	0.19	0.14	36.453	-33.643	-2579	GS103
VG 3910	GIL0103-009-025	51.96	1.1	14.9	9.67	7.33	12.17	2.22	0.16	0.13	36.463	-33.63	-2590	GS103
VG 3342	AII0077-2-015-003	51.69	0.97	14.74	9.16	7.5	12.56	1.87	0.14	0.1	36.44	-33.68	-2437	AII077
VG 3976	ALV0828-006	51.2	1.01	15.12	9.52	7.81	12.52	2.13	0.13	0.13	36.45	-32.7	-2542	ALVIN 0828
VG 3954	GIL0103-046-004	51.46	1.15	15.14	9.47	7.93	12.48	1.98	0.16	0.13	36.442	-33.685	-2484	GS103
VG 3901	GIL0103-004-011	51.23	0.92	15.04	8.89	8.02	13.09	1.88	0.12	0.11	36.443	-33.6267	-2616	GS103
VG 3978	ALV0828-009	51.11	0.84	15.46	N/A	8.27	13.32	2.1	0.07	0.08	36.45	-32.7	-2542	ALVIN 0828
VG 3788	GIL0103-004-009	51.54	0.89	15.15	8.51	8.55	13.42	2.19	0.13	0.1	36.443	-33.6267	-2616	GS103
VG 3863	ALV0826-002	49.69	0.71	16.48	8.26	8.98	13.79	1.88	0.05	0.1	36.48	-33.69	-2536	ALVIN 0826

Note: Major element data is in weight percent (wt %)

Table 3: North Atlantic Mid-Oceanic Ridge Glass Samples—Suite 2

PETDB Database ID	Smithsonian ID	SiO_2	TiO_2	Al_2O_3	FeOT	MgO	CaO	Na_2O	K_2O	P_2O_5	Latitude	Longitude	Elevation (ft)	Expedition
VG R54	KNO0054-058-001	51.87	2.15	14.82	10.4	5.64	9.46	4.12	0.29	0.25	18.128	-81.732	-4965	AII077
VG R36	KNO0054-033-041	51.29	2.17	15.59	9.89	6.1	9.63	3.89	0.25	0.26	18.967	-81.71	-4874	AII077
VG R38	KNO0054-039-006B	51.33	2.14	16.1	9.29	6.36	10.02	3.66	0.31	0.32	18.817	-81.547	-5157	AII077
VG R24	KNO0054-026-020	51.1	2.15	14.91	10.43	6.41	9.32	3.9	0.28	0.3	18.11	-81.87	-4001	AII077
VG 10378	ABP0016-054-009	51.98	1.74	15.01	9.91	6.62	10.67	2.83	0.24	0.19	15.412	-46.682	-3700	AII077
VG R55	KNO0054-058-008	51.69	2.07	15.55	9.71	6.79	9.68	3.87	0.25	0.22	18.128	-81.732	-4965	GS103
VG 8720	ALV1685-001	50.1	2.02	15.23	10.39	6.8	10.61	3.26	0.15	0.15	23.22	-44.95	-3555	GS103
VG 252	AII0020-006-048	51.19	1.7	14.85	10.41	7.21	11.4	2.79	0.08	0.13	11.27	-43.65	-3095	GS103
VG 10354	NAUFARA-018-002A	51.5	1.34	15.92	9.08	7.68	11.54	2.64	0.18	0.15	15.514	-46.638	-4630	AII077
VG 8477	ABP0002-040-001	50.65	1.35	15.4	9.41	8.02	12	2.68	0.04	0.14	12.4	-44.1	-4550	ALVIN 0828
VG 8736	ALV1692-002	50.23	1.38	16.64	8.88	8.03	11.41	2.89	0.25	0.17	22.9	-44.97	-3174	GS103
VG 10576	NAUFARA-007-007G	50.01	1.19	15.7	8.97	8.44	11.62	2.33	0.35	0.2	15.028	-44.93	-3920	GS103
VG 10366	NAUFARA-019-003	50.04	1.23	16.28	9.31	8.56	11.25	2.71	0.16	0.14	15.568	-46.698	-3280	ALVIN 0828
VG 10322	ABP0016-069-015	50.31	1	15.42	8.9	8.9	11.94	2.1	0.19	0.17	14.7352	-45.122	-3225	ALVIN 0826

Note: Major element data is in weight percent (wt %)

Table 4: Representative LA-ICP-MS Blank Measurement

Isotope	Average Counts Per Second (cps)
^{7}Li	4014.4
^{34}S	88790.5
^{43}Ca	12035.7
^{45}Sc	50490.7
^{47}Ti	22252.4
^{51}V	3406
^{53}Cr	5941
^{55}Mn	11753.6
^{57}Fe	14683.2
^{59}Co	4524
^{60}Ni	14703
^{63}Cu	6948.7
^{66}Zn	854.2
^{69}Ga	827.1
^{73}Ge	569.6
^{75}As	3067.5
^{77}Se	544
^{85}Rb	7640
^{88}Sr	1296.1
^{89}Y	122.1
^{90}Zr	98.1
^{93}Nb	16
^{95}Mo	95
^{106}Pd	108
^{109}Ag	451.8
^{111}Cd	77
^{121}Sb	198
^{138}Ba	187.3
^{139}La	9
^{140}Ce	9
^{141}Pr	6
^{144}Nd	7
^{147}Sm	5
^{153}Eu	12
^{155}Gd	17
^{159}Tb	9
^{162}Dy	2
^{165}Ho	3
^{167}Er	5
^{172}Yb	12
^{180}Hf	4
^{182}W	1
^{185}Re	5
^{208}Pb	1688.8
^{232}Th	1
^{238}U	2

Table 5: Relative Compatibilites of Siderophile and Chalcophile Elements in this Study

Highly Incompatible: Mo, Pb, Pd, Zn Incompatible: Ga, Se, Cd, Co Compatible: Ni, Cu Insufficient Data: Ag, Re

By plotting the concentrations of these elements against MgO and comparing the slopes, the relative compatibilities of the elements in the mid-Atlantic ridge samples measured could be determined.

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