Using clinopyroxene mineral chemistry to decipher magma composition changes over the 13 million year history of the Izu-Bonin volcanic arc

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Abstract

International Ocean Discovery Program Expedition 350 recovered 2000 meters of volcanic rock core in spring, 2014 at the Izu-Bonin-Mariana Rear Arc. The core has been divided into seven lithostratigraphic units, from age 0 at the top to at least 13 million years at the bottom. The major and trace element geochemistry of representative mineral grains in volcaniclastic rocks throughout the core from top to bottom were analyzed and used as a proxy for interpreting magma compositional changes through time. The clinopyroxene from all units and the glass from Unit I were analyzed for major elements (by SEM and electron microprobe) and trace elements (by Laser Ablation Inductively Coupled Plasma Mass Spectrometer, LA-ICP-MS). Six samples from Unit I and two samples each from Units IV, VI, and VII were analyzed. The trace elements were used to calculate host magma trace element compositions through use of trace element partitioning relationships. The mineral chemistry can thus be used as a proxy for understanding magma differentiation trends occurring through time in the rear arc setting. Changes were observed in the mineral chemistry from top the top of the core to the bottom that could reveal more about continental crust growth from island arcs.

Introduction/Rationale

The genesis of continental crust is a fundamental question of geology, as no other planet in the solar system has a similar type crust. Much existing continental crust seems to have been formed before the Archean period, but continents continue to grow (Reymer and Schubert, 1984). The basaltic magmatism that forms new crust at rift zones and divergent boundaries cannot produce continental crust, which is known to be andesitic in bulk composition (Rudnick, 1995). Trace element geochemistry also differs between continental and oceanic crust. This suggests that there must be some other method of continental crust growth.

The prevailing hypothesis is that the nucleus of continental crust forms above subduction zones, at island arcs where magma differentiation produces andesitic compositions. Accretion of these island arcs through time is thought to build the continental crust. However, the mechanisms for this magma differentiation have not been fully characterized.

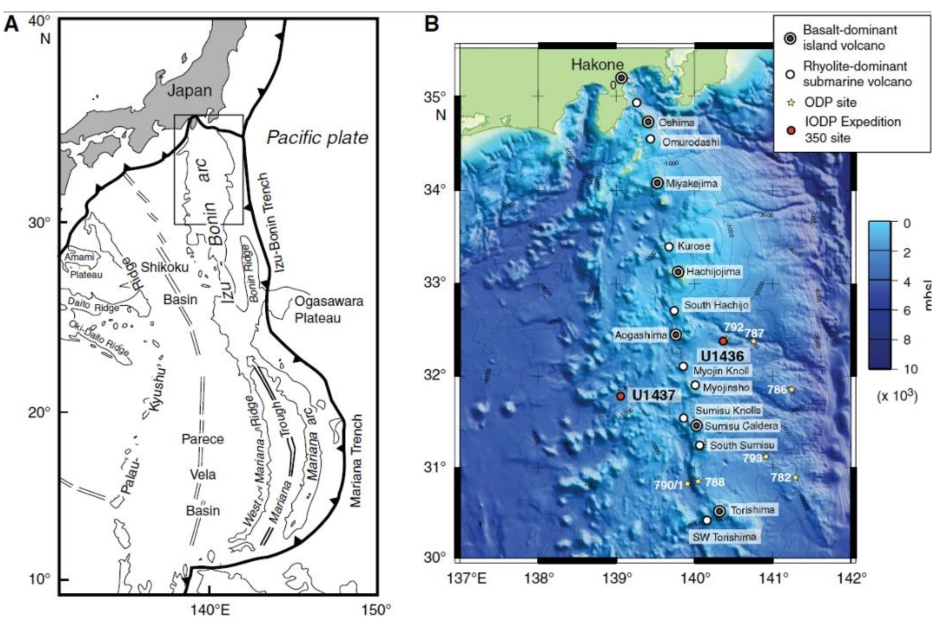


Figure 1: Map of Izu-Bonin-Mariana arc, with outset map showing the location of U1437, the core drilled in the rear arc. Figure Tamura et al, 2015

Taylor (1967) first suggested that island arcs, being andesitic in composition and closest to the bulk composition of continental crust, might be the source of continental crust. His research has been improved upon since by geophysical studies, which allow researchers to infer bulk composition. The Izu-Bonin-Mariana Arc (Figure 1) is a major area of investigation into the growth of continental crust (e.g., Suyehiro et al, 1996).

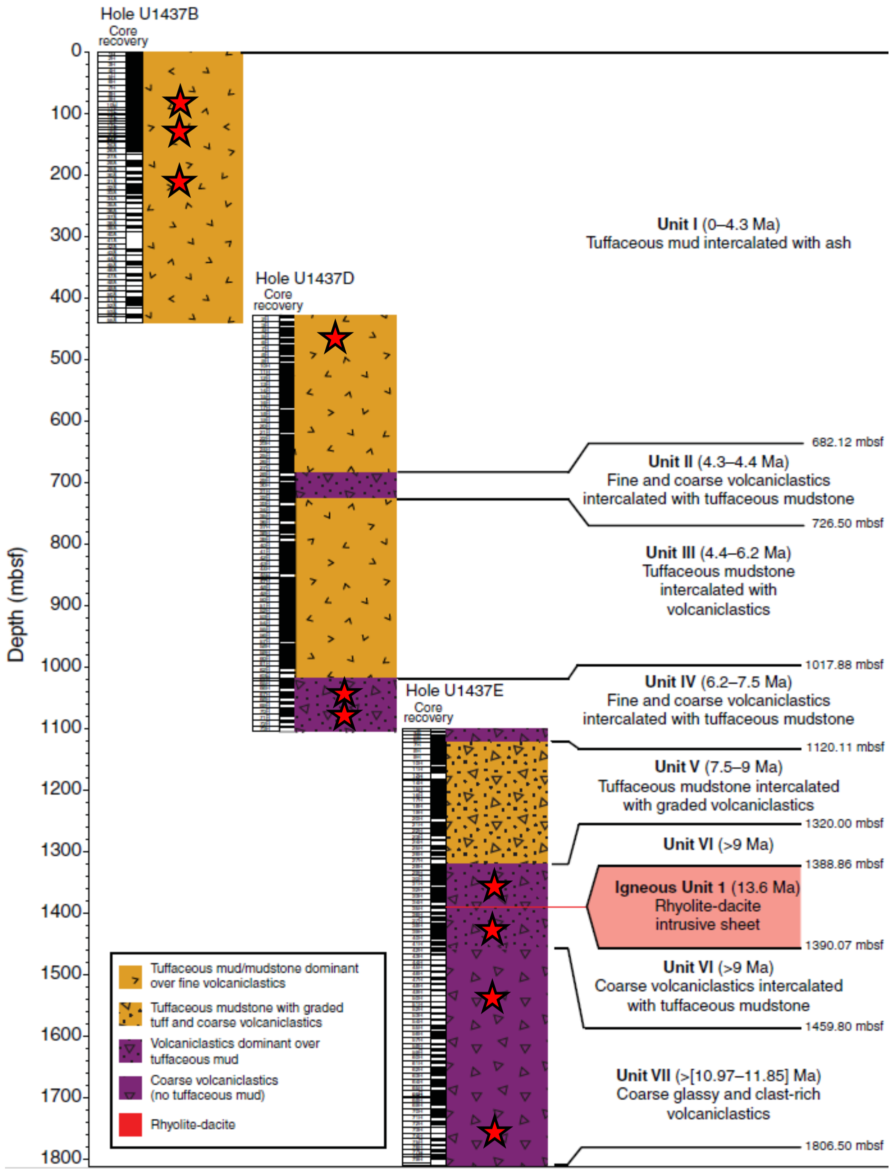


Figure 2: Depiction of core, showing the three separate drill holes. Stars indicate the location of segments analyzed.

Geologic Setting

Subduction at the Izu-Bonin-Mariana Arc (IBM) began around 50 Ma. Rifting at 25 Ma paused arc magmatism, but it resumed in the arc-front around 15 Ma and has remained stationary into the present. More recently in the arc front, rifting has developed (about 3 Ma) and continues to present. The rear arc includes all Neogene rocks behind the arc front (Tamura et al 2015). There are two primary types of rear-arc rocks: 17-3 Ma basaltic-rhyolitic seamount chains and younger than 3 Ma rocks from rifting.

Kodaira et al (2007) utilized geophysical investigations to constrain the composition and structure of the Izu-Bonin arc. Bulk composition was inferred to be felsic to intermediate beneath the arc, but still more mafic than typical continental crust. More precise estimates required drilling by the International Ocean Discover Program (IODP). Previous IODP expeditions had drilled the volcanic front of the Izu-Bonin-Mariana Arc (Taylor et al, 1992), and the geochemical composition is now known. Superficially, in major element chemistry, the volcanic front is more similar to continental crust than typical oceanic crust. However, trace element geochemistry was distinct. In contrast, in the rear arc, dredges of seamounts showed both major and trace element chemistry that had striking similarities to continental crust (Tollstrup et al., 2010). IODP Expedition 350 drilled in the rear arc in 2014, recovering 2000 meters of core.

The 2000 meters of core recovered from site U1437 ranges from age zero at the top to at least 13 Ma near the bottom. The site should be in a location that has been shielded from arc-front material due to topography, although some arc-front ash may be present (Tamura et al 2015).

Methods

The core was drilled in three parts: Holes B, D, and E, each recovering core from progressively deeper (Holes A and C recovered no core). The 2000 meters of recovered core were ultimately divided into seven lithostratigraphic units based on composition and appearance. Ten total segments of this core were analyzed in this report (Figure 2). Four of these segments came from Unit I, the mostly unconsolidated mixed volcaniclastic unit. Six segments were from deeper in the core: two each from units IV, VI, and VII. Table 1 summarizes the segment data.

Sample	Unit	Depth (m)
B17F2W 108/109	I	118
B21F2 5/7	I	135
B32X1 83/84	I	214
D8R1 68/69	I	486
D70R5 50/53	IV	1066
D71R1 7/9	IV	1076
E41R2 6/8	VI	1447
E41R2 21/24	VI	1450
E59R1 62/64	VII	1628
E72R5 0/4	VII	1738

Table 1: Unit and depth data for analyzed samples

In Unit I, volcanic glass and clinopyroxene coexisted in samples. Volcanic glass can be used to determine the exact composition of the magma chamber at the time that it crystallizes. In deeper units, however, all glass has been altered to clay and cannot be used to decipher original compositions. By analyzing the geochemistry of the coexisting glass and clinopyroxene in Unit I, partition coefficients could be developed that would allow the clinopyroxene in deeper units to be used to calculate original liquid compositions.

Unit I samples were used to make grain mounts, which were analyzed in SEM (using a Vega TS 5136MM with EDAX) at Western Washington University to determine grain locations and then using a JEOL 733 Superprobe (EMP) at the University of Washington. Deeper units were made into thin sections at XXXXX and were analyzed by petrographic microscope to determine mineral locations and then using a JEOL 8500F field emission electron microprobe at Washington State University. Then, all segments were analyzed at Western Washington University using the Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS), a New Wave UP-213 nm solid state Nd:YAG laser coupled to an Agilent 7500ce ICP-MS. This was done using a 40 um spot size, 10 Hz repetition, and a fluence of between 85% and 95%.

LA-ICP-MS data was reduced using Glitter. N610 was used as the standard, with Si compositions determined via microprobe used as the internal standard for each mineral. BHVO was also measured as an external standard. Relatively flat portions of signals were selected: if the signal sloped up, down, or had an abrupt spike for an element, that portion of the signal was not used. Data was then checked for consistency against the major element concentrations determined via microprobe. Measured BHVO values were then compared to the values cited in literature (GeoReM) to test for consistency of trace element values.

Data

In Unit I, major element data from the microprobe was used to create Harker diagrams (Figure 3). The potassium graph shows that some of these samples are low-K (B32X1 83/83 and B17F2W 108/109), while B21F2 5/7 is medium-K. D8R1W 68/69 is a mixed unit, with both medium-K and low-K glass. Major and trace element concentrations can be found in Appendix A.

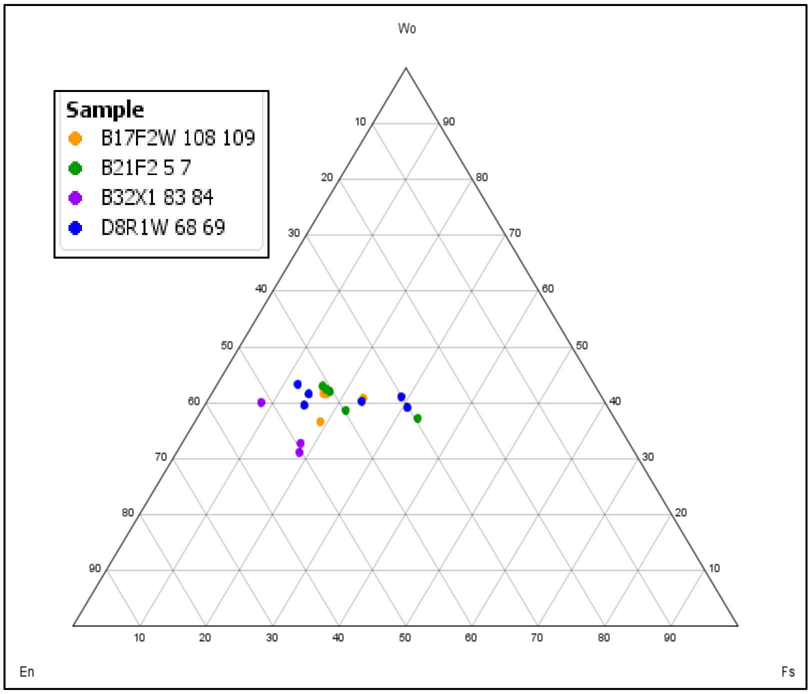
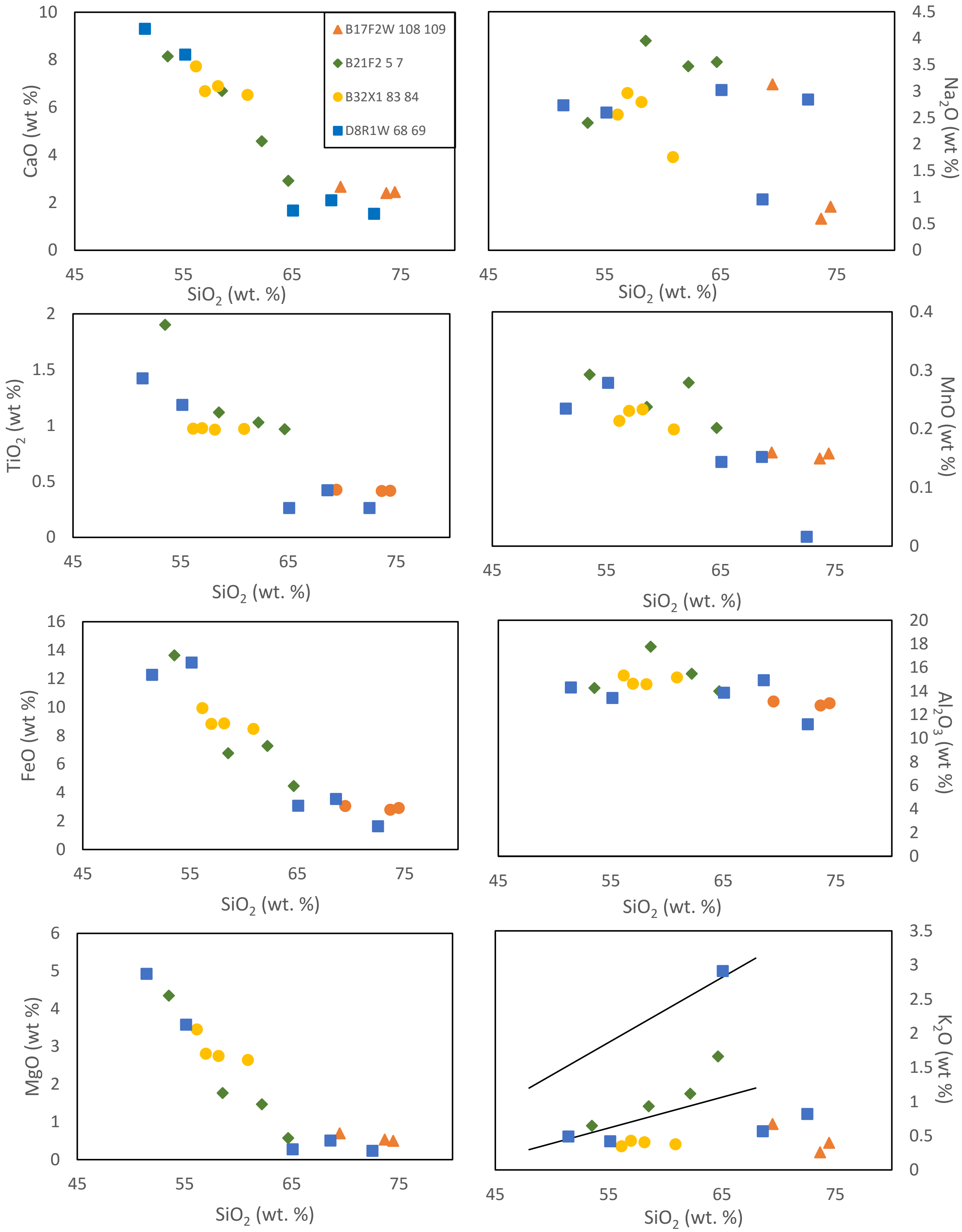


Figure 4: Clinopyroxene from Unit I plotted on the pyroxene ternary diagram

Plotting the clinopyroxene from Unit I (Figure 4), it is clear that the majority of cpx analyzed is closer in composition to diopside, although some crystals are closer to augite. There is a compositional range of cpx both within and between samples.

Rare earth element plots of clinopyroxene compositions show that Sm/La ratio can be an indicator of potassium value of the glass. Sm/La ratios of less than five are found in clinopyroxene in association with medium-K glass, while Sm/La ratios of greater than five are found in association with low-K glass in Unit I. Sm/La ratios are recorded in Appendix B.

Figure 3: Harker diagrams of glass based on major element microprobe data.



B17F2W 108/109

In this segment, a total of five clinopyroxene crystals and three glass pieces were analyzed (Figure 4). Major element data shows that this is a low-K unit. Trace element geochemistry (presented in the form of chondrite-normalized rare earth element diagrams, Figure 5) shows a relatively flat REE pattern for glass. The clinopyroxene REEs show a steep increase in concentration between La and Sm.

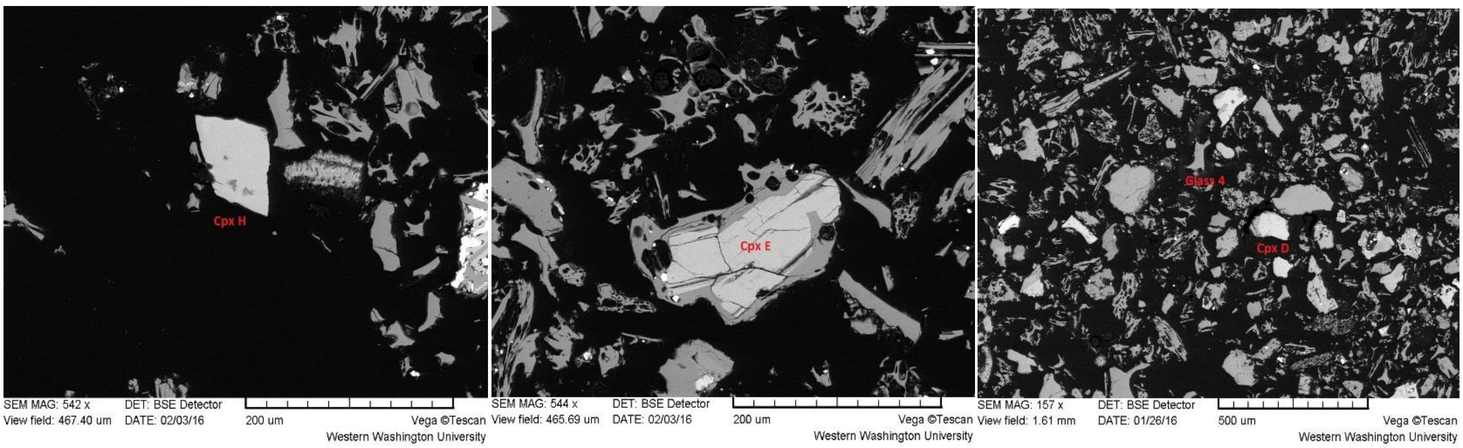


Figure 5: Representative cpx (all images) and glass (rightmost image) from segment B17F2W 108/109. Images taken via SEM.

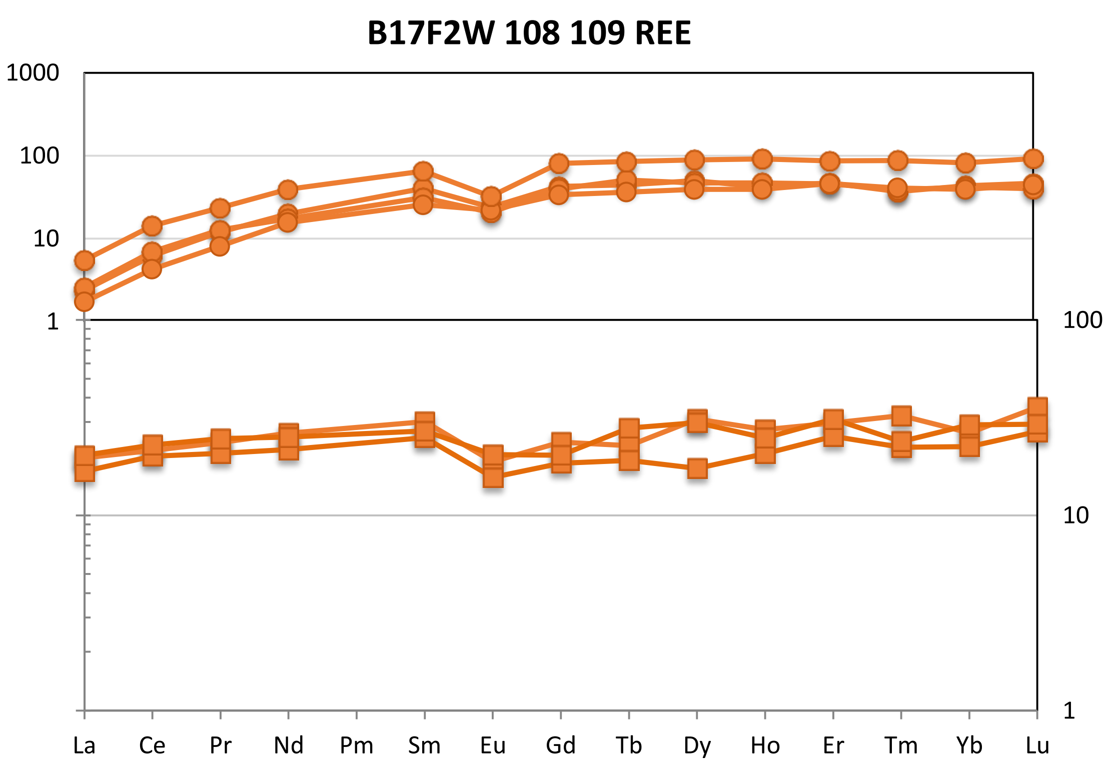


Figure 6: Chondrite-normalized rare earth element plot of laser data for segment B17F2W 108/109. Upper plot is cpx; lower is glass

B21F2 5/7

In this segment, five clinopyroxene and three glass were analyzed (Figure 6). Clinopyroxene A and Glass 1 were clearly associated. Major element geochemistry from this sample showed that it was a medium-K sample. Chondrite-normalized REE data (Figure 7) shows a steep, negatively sloping REE pattern for the glass. The clinopyroxene shows a slight increase in light rare earth elements.

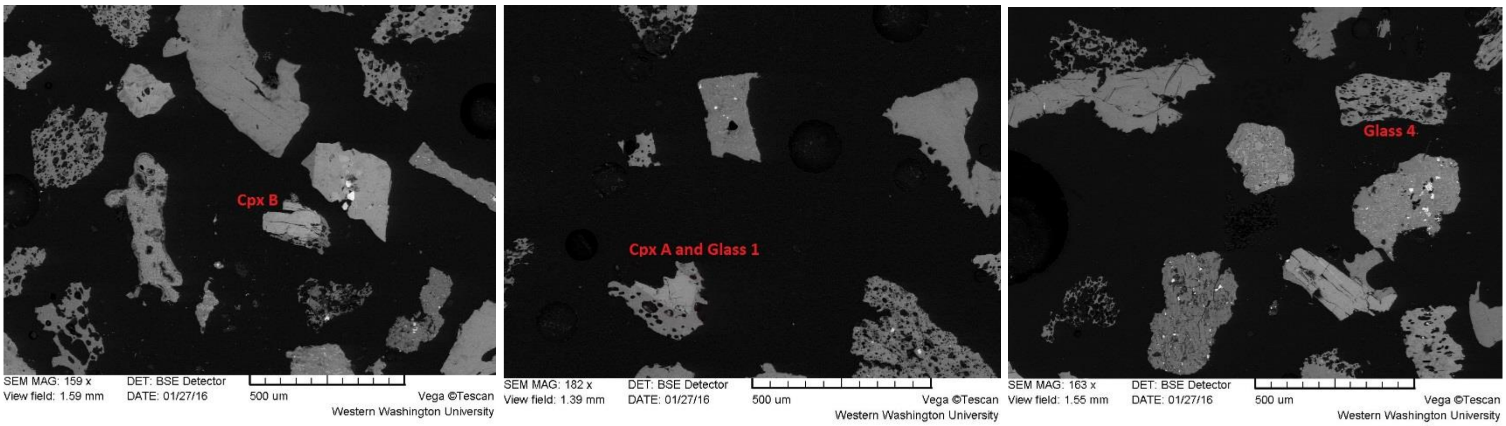


Figure 7: Representative glass and cpx from segment B21F2 5/7. Middle: clearly associated glass and cpx

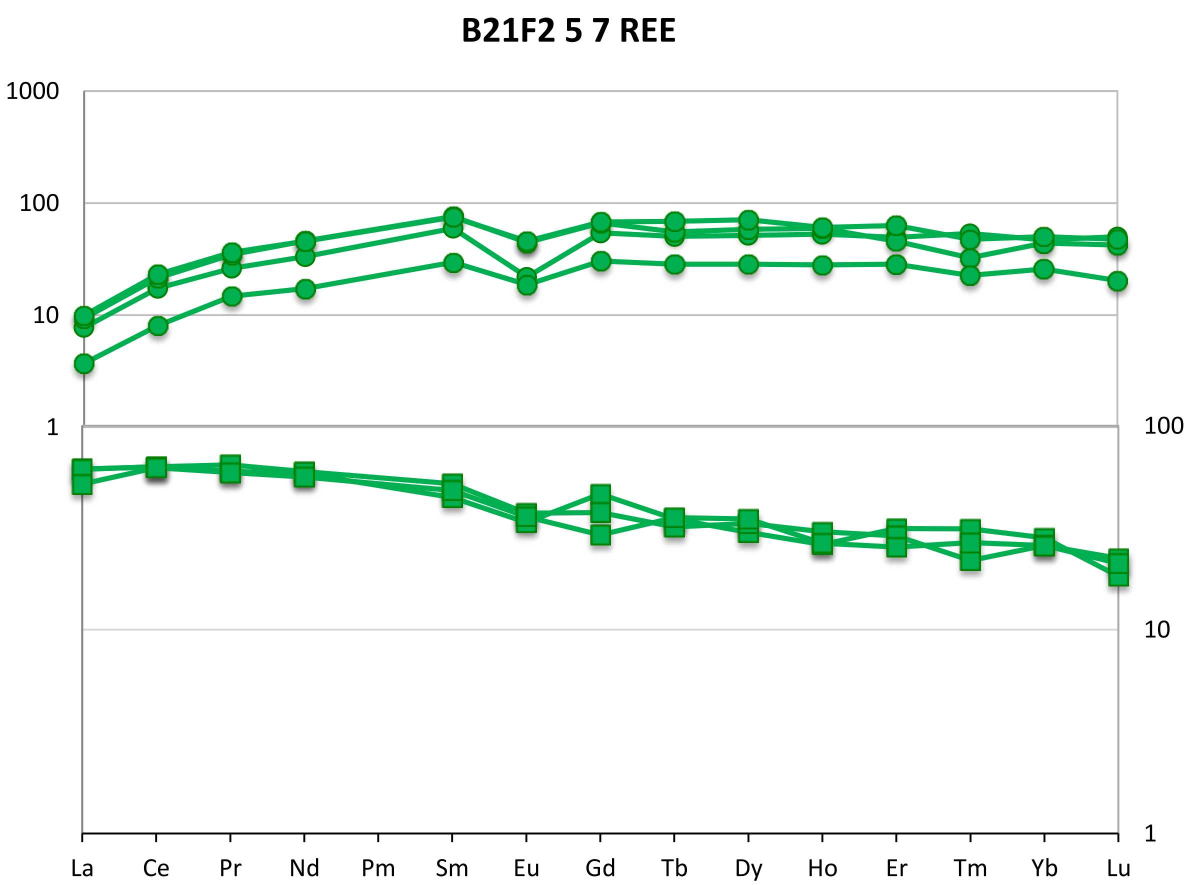


Figure 8: Chondrite-normalized REE plot of laser data for segment B21F2 5/7. Upper plot is cpx; lower is glass.

B32X1 83/84

In this segment, three clinopyroxene grains and four glass shards were analyzed (Figure 8). Major element geochemistry indicated the sample was low-K. Chondrite-normalized REE data (Figure 9) shows a flat REE pattern for glass and a steep increase in light rare earth element concentrations between La and Sm.

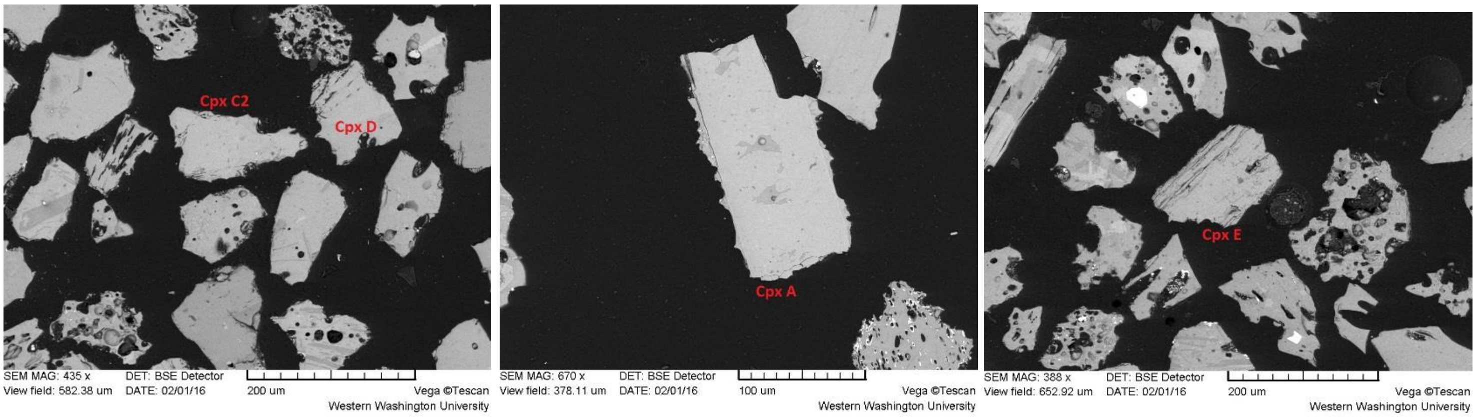


Figure 9: Representative SEM images from segment B32X1 83/84

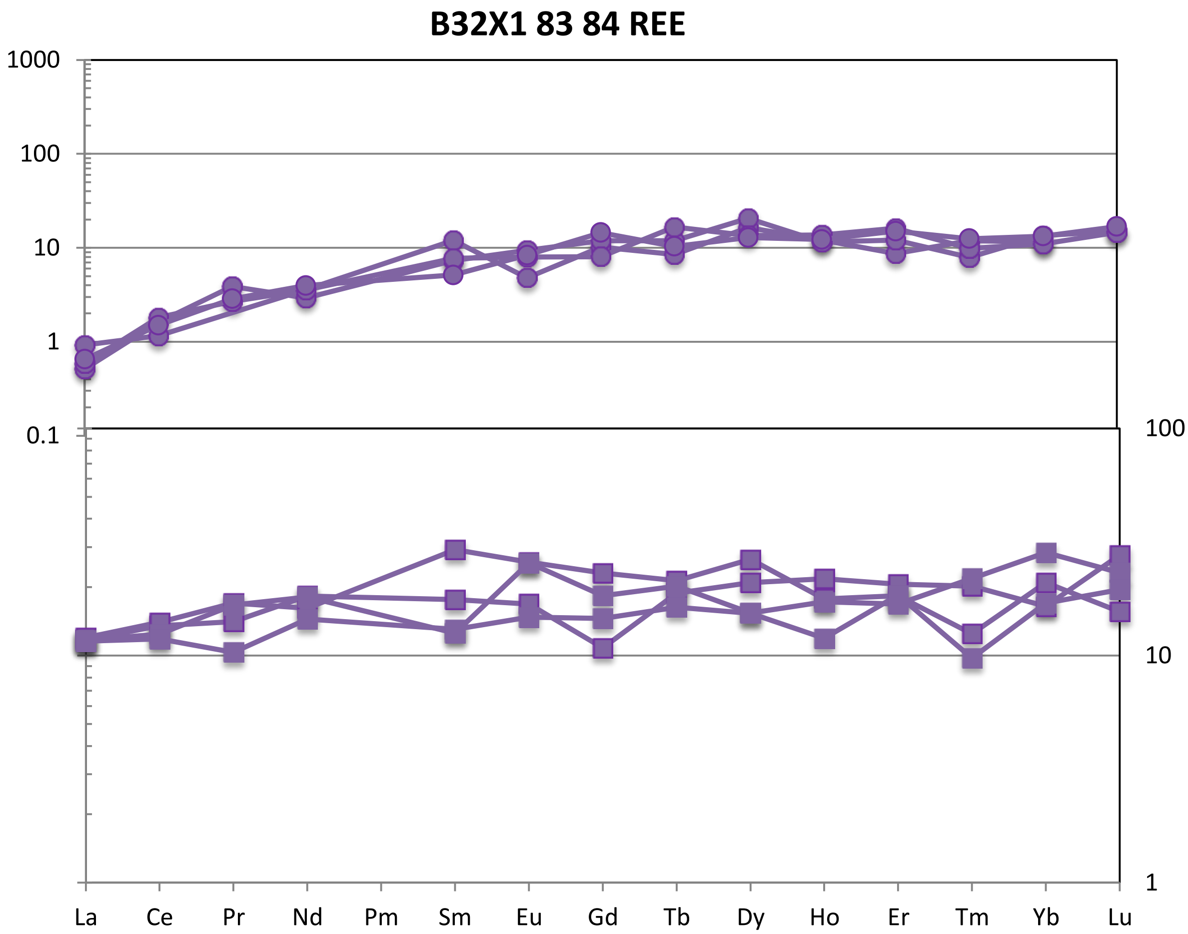


Figure 10: Chondrite-normalized REE plot of laser data for segment B32X1 83/84. Upper plot is cpx data; lower is glass

D8R1W 68/69

This segment had six analyzed clinopyroxene and two analyzed glass shards (Figure 10). Initial microprobe data indicated the segment contained both low-K and medium-K glass. However, all low-K glass was too small to analyze. As a result, all analyzed glass was low-K. Chondrite-normalized REE diagrams showed flat REE patterns. Coexisting clinopyroxene REE patterns had a shallow increase in light rare earth element concentrations between La and Sm (Figure 11).

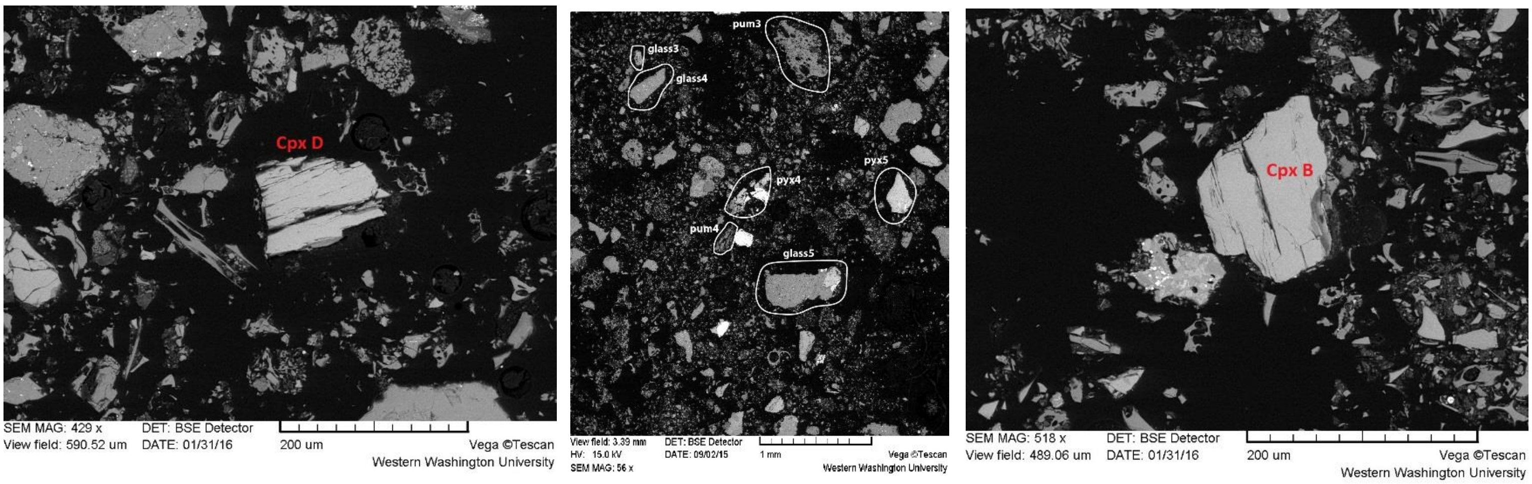


Figure 11: Representative SEM images of glass and cpx from segment D8R1W 68/69. Center image by Ricardo Escobar.

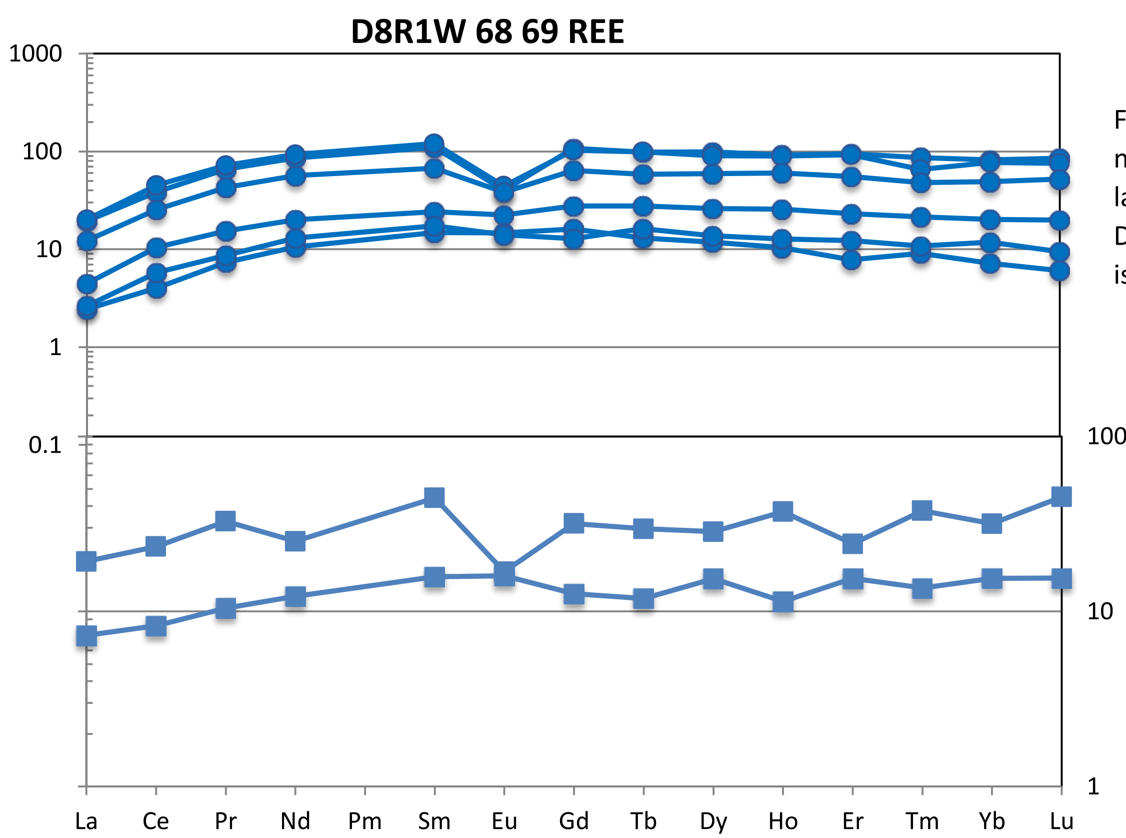


Figure 12: Chondrite-normalized REE plot of laser data for segment D8R1W 68/69. Upper plot is cpx data; lower is glass.

In the deeper units, all glass had been altered to clay. Clinopyroxene remained unaltered and was analyzed in the same manner as clinopyroxene in Unit I. Major and trace element geochemistry for the deeper units can be found in Appendix C. The pyroxene compositions (Figure 13) were more clustered in deeper units than they had been in Unit I. Clinopyroxene from deeper in the core tends to be more iron-poor than cpx from Unit I. Compositionally, it is diopside or fairly Ca-rich augite.

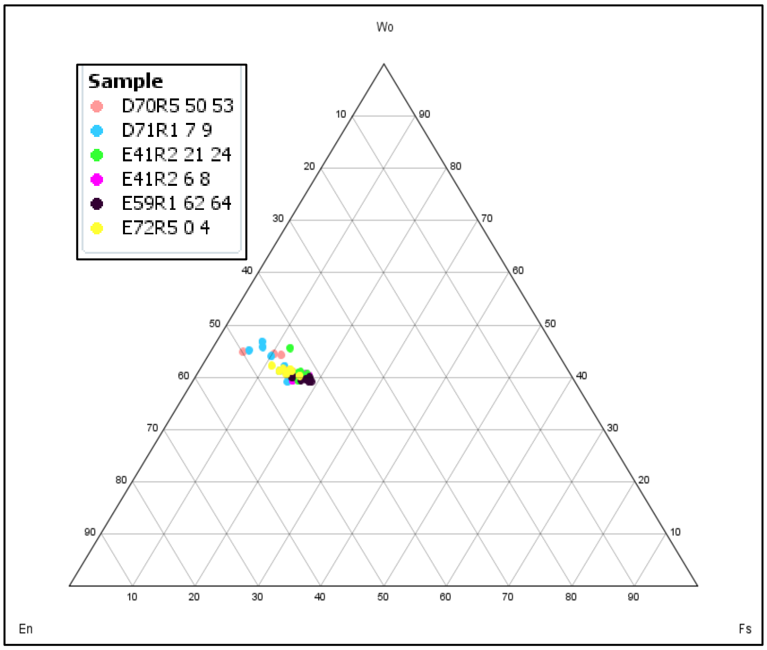


Figure 13: Clinopyroxene compositions from deeper in the core plotted on a ternary diagram

Two segments were analyzed from Units IV, VI, and VII respectively. From each unit, eight clinopyroxene grains were selected for further analysis. Each clinopyroxene was analyzed three times at different locations by microprobe and laser. The data that was most consistent between microprobe and laser in major element concentrations was chosen as the representative composition for that clinopyroxene.

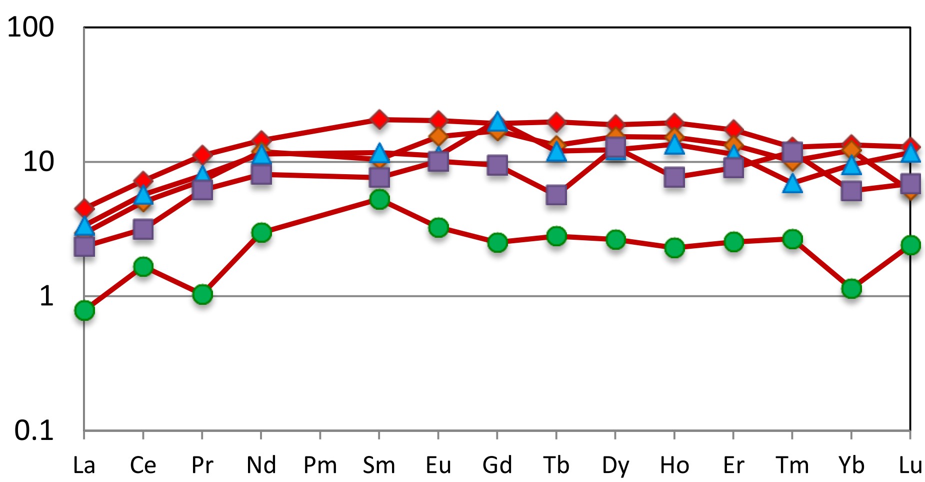


Figure 14: Chondrite-normalized REE graph of clinopyroxene compositions from D70R5 50/53

<u>D70R5 50/53</u>

A rare earth element graph of this Unit IV segment shows a shallow increase in rare earth element concentrations between La and Sm (Figure 14). The average Sm/La ratio is 2.7. Of the eight clinopyroxene that were analyzed in this sample, only five had data of high enough quality to include (Figure 15). This sample comes from a depth of 1066 meters.

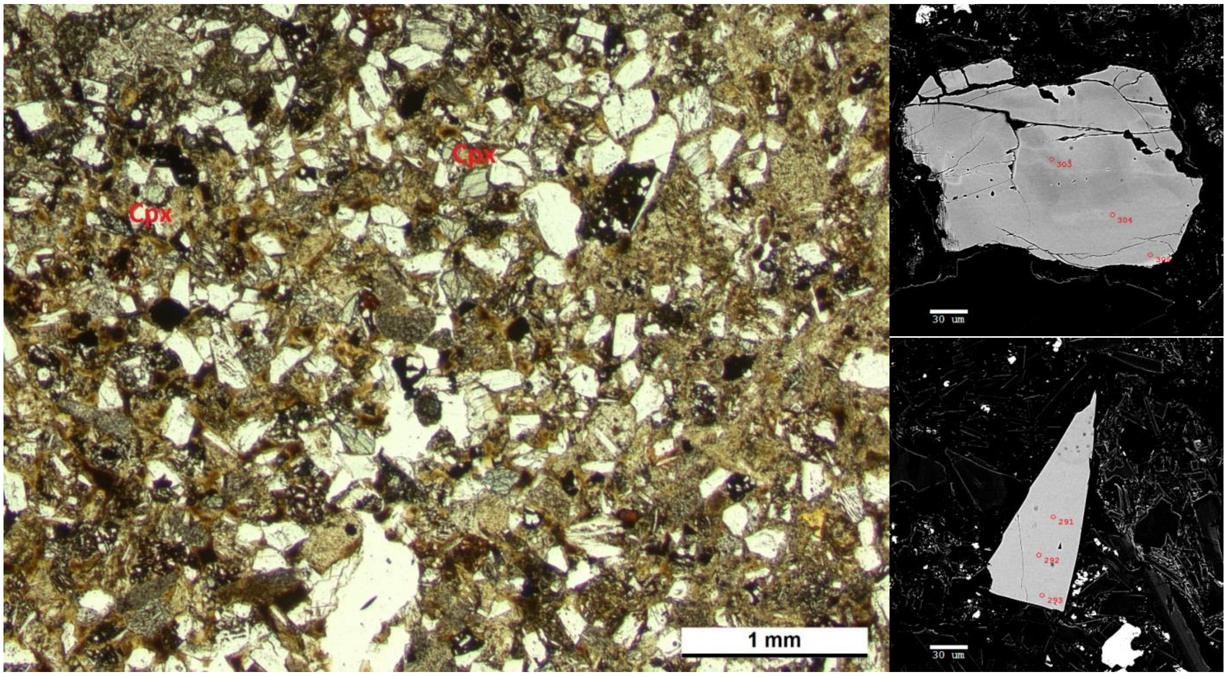


Figure 15: SEM and plain polarized light photographs of representative clinopyroxene from segment D70R5 50/53

D71R1 7/9

This sample, also from Unit IV, comes from an approximate depth of 1076 meters. Clinopyroxene from this sample is very similar compositionally to segment D70R5 50/53. This clinopyroxene also exhibits a less dramatic compositionally increase in rare earth element concentrations between La and Sm (Figure 16). The Sm/La ratio of this sample is less than five, with an average value of 2.72. Representative clinopyroxene grains are shown in Figure 17.

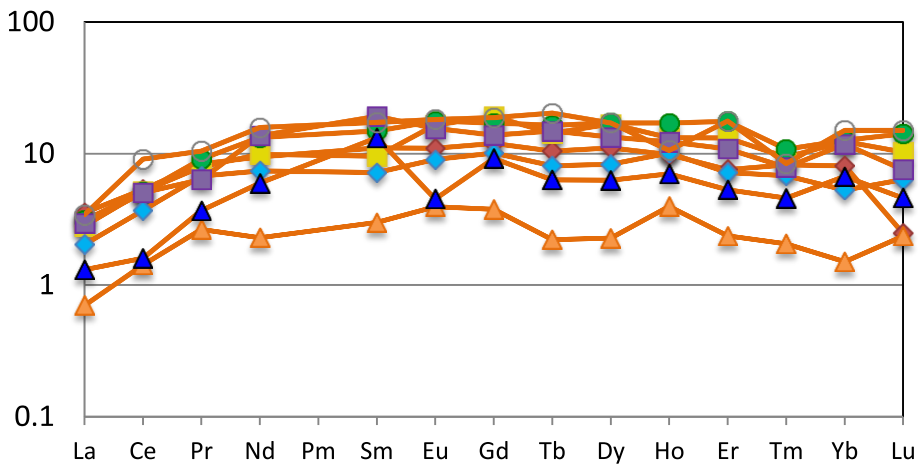


Figure 16: Chondrite-normalized REE plot from segment D71R1 7/9.

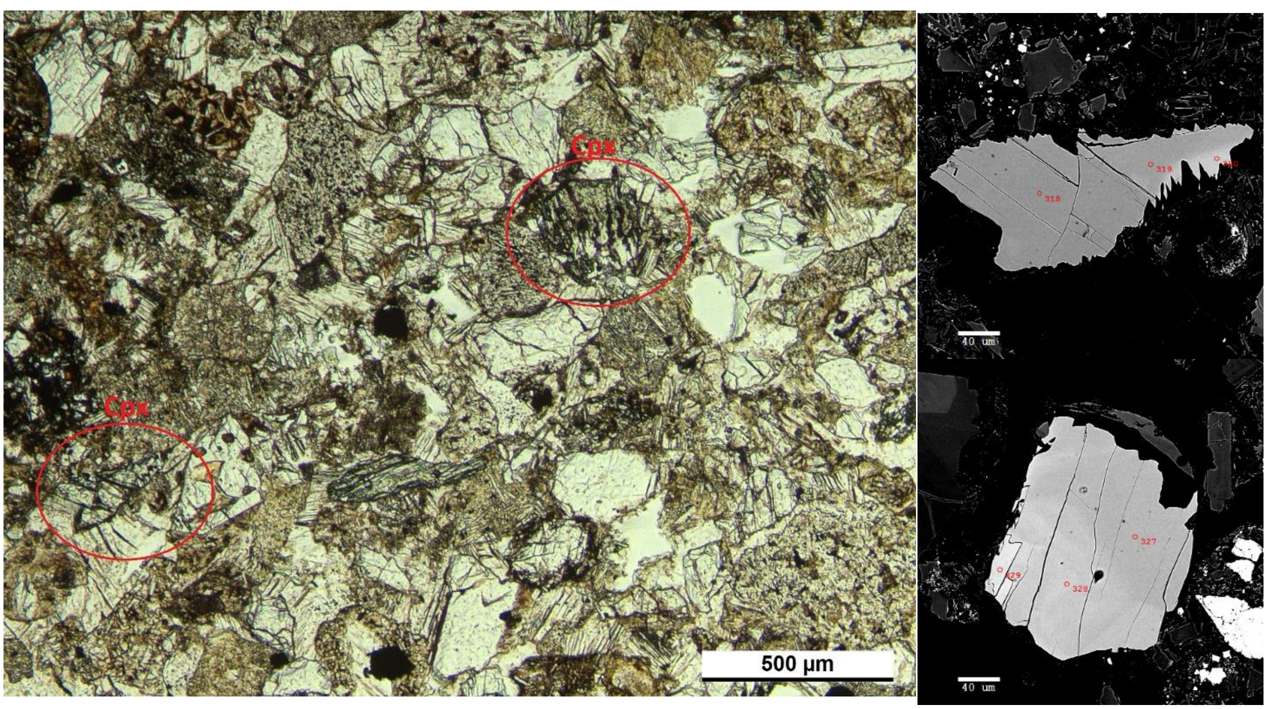


Figure 17: SEM and plain polar microscopy photos of D71R1 7/9 showing representative cpx mineral grains

E41R2 6/8

Segment E41R2 6/8 (Unit VI) comes from an approximate depth of 1447 meters. Clinopyroxene from this sample includes both steep and shallow increases in rare earth element compositions from La to Sm (Figure 18), which means both low and high Sm/La cpx is present in this segment. The average ratios are 4.5 and 6.3 respectively. Representative mineral grains are shown in Figure 19.

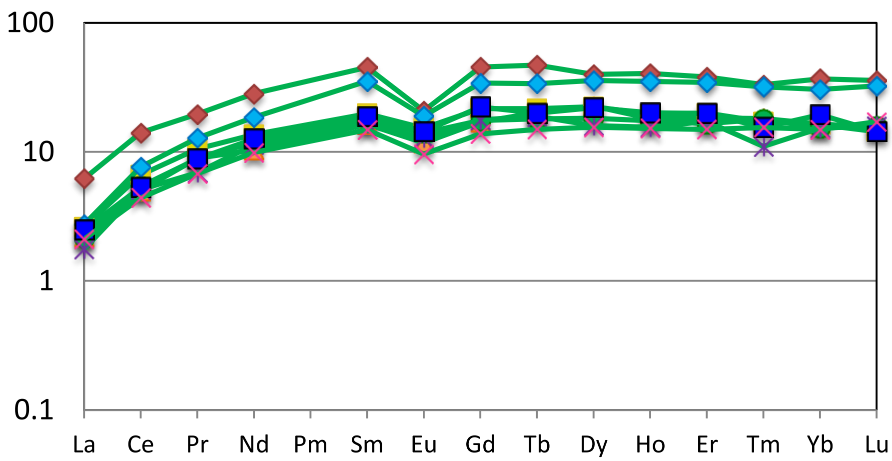


Figure 18: Chondrite-normalized REE plot of E41R2 6/8.

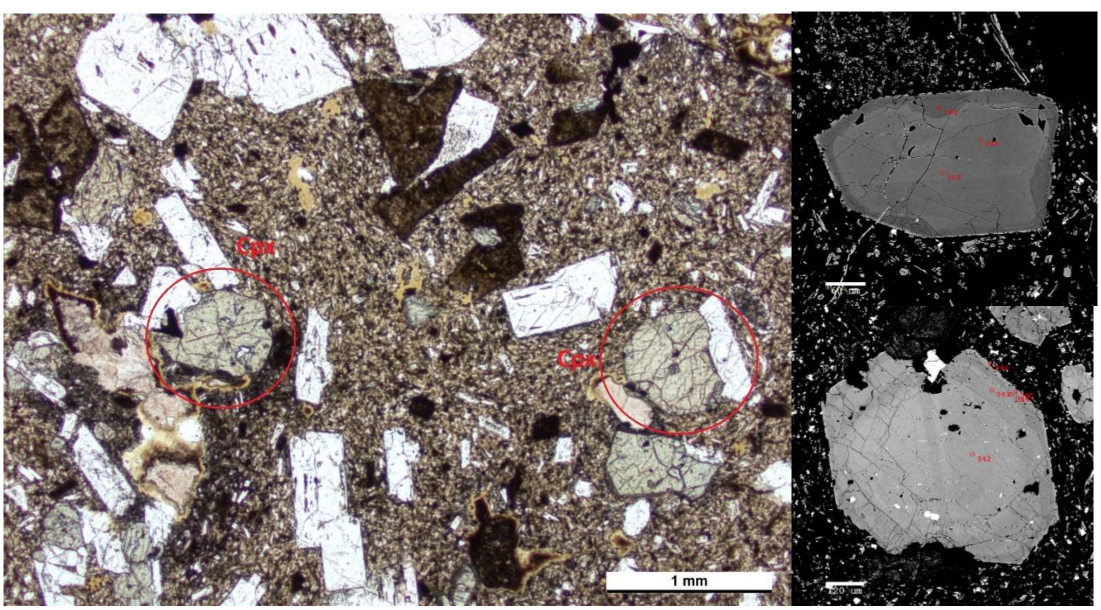


Figure 19: SEM and thin section microscopy (plain polar) photographs of representative mineral grains from E41R2 6/8

E41R2 21/24

Segment E41R2 21/24 (Unit VI) is from the same core segment as E41R2 6/8, but comes from slightly deeper in the segment, an approximate depth of 1450 meters. Clinopyroxene from this sample primarily includes steep light rare earth element patterns, where concentrations increase steeply from La to Sm (Figure 20). The average Sm/La ratio for this sample is 5.64, with the exception of one cpx grain. Representative minerals from this segment are shown in Figure 21.

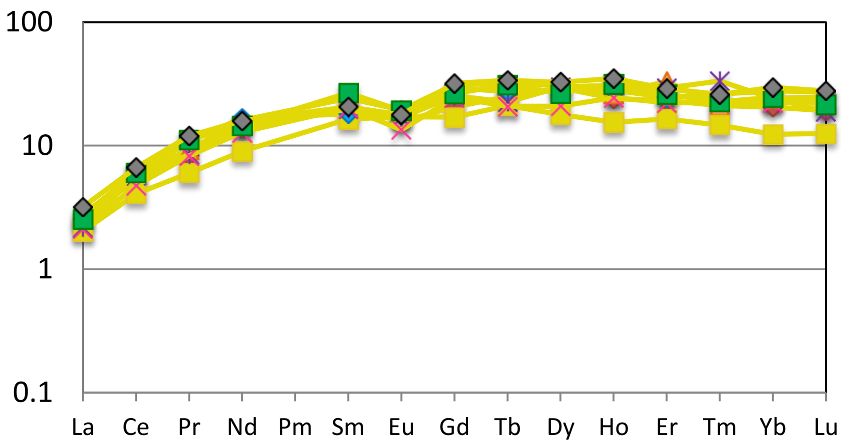


Figure 20: Chondrite-normalized REE plot from segment E41R2 21/24

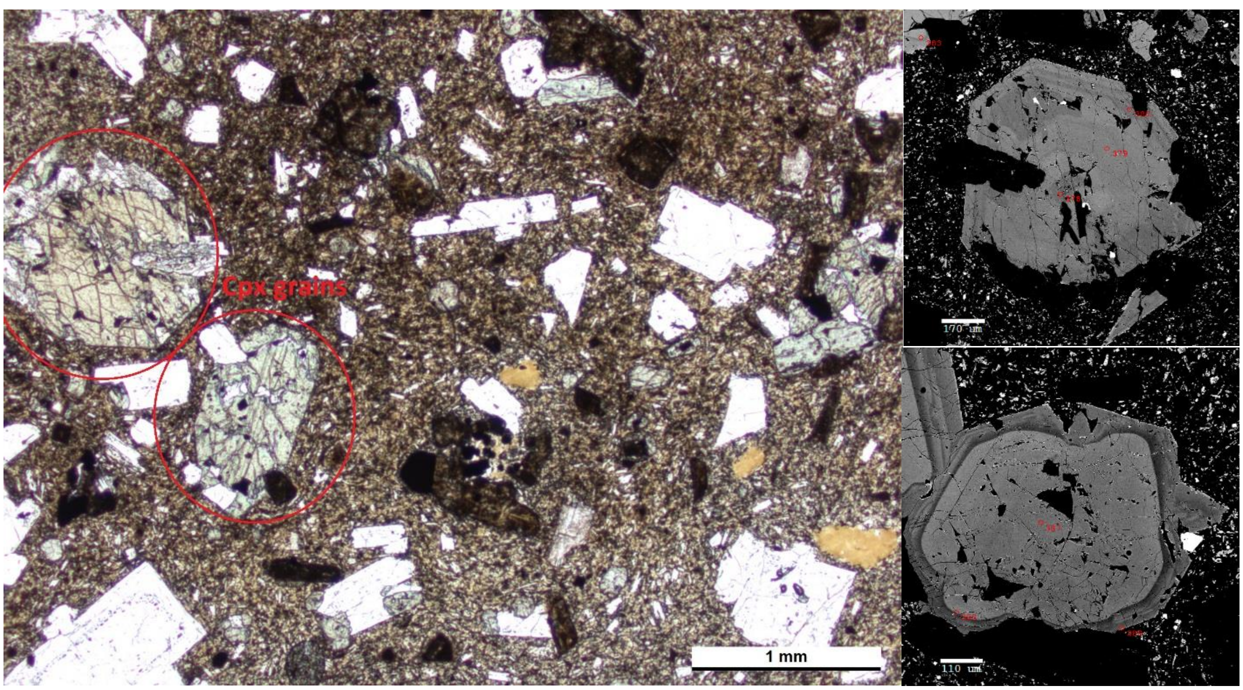


Figure 21: Representative mineral grains from E41R2 21/24. Photographs taken with SEM and plain polar microscopy

E59R1 62/64

This Unit VII segment comes from a depth of approximately 1628 meters. The rare earth element pattern, shown in Figure 22, contains a steep increase in concentrations from La to Sm: an average Sm/La ratio of 5.97. Representative mineral grains are shown in Figure 23.

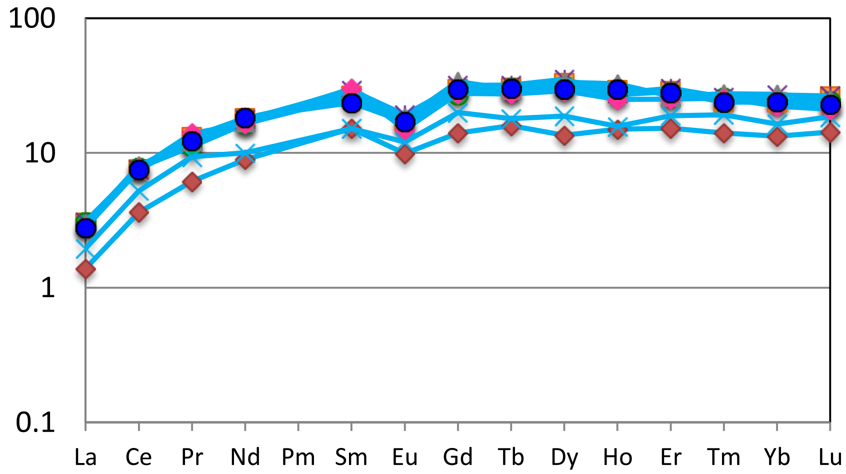


Figure 22: Chondrite-normalized REE graph from segment E59R1 62/64

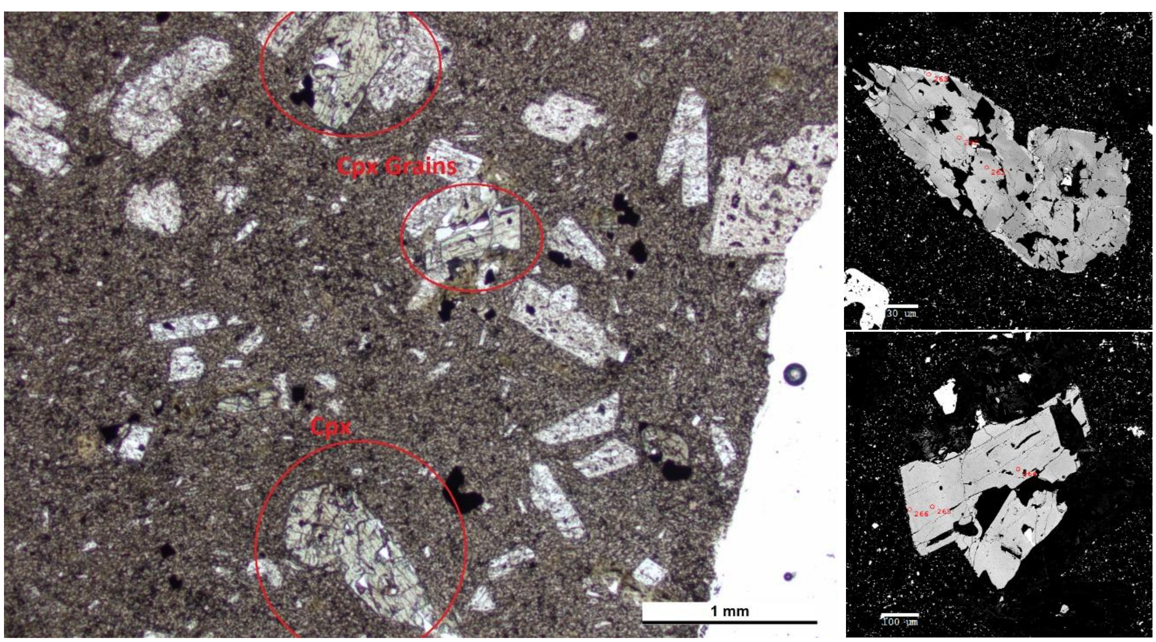


Figure 23: Representative minerals grains from E59R1 62/64. Photographs take on SEM and microscope.

E72R5 0/4

This Unit VII segment originated from a depth of approximately 1738 meters. The average Sm/La ratio was 4.25, indicating a more gradual increase in REE concentrations between the two elements (Figure 24). Representative mineral grains from this segment are shown in Figure 25. This segment showed grain alignment, and fewer cpx grains were present than in other samples. This may be related to it being the deepest sample.

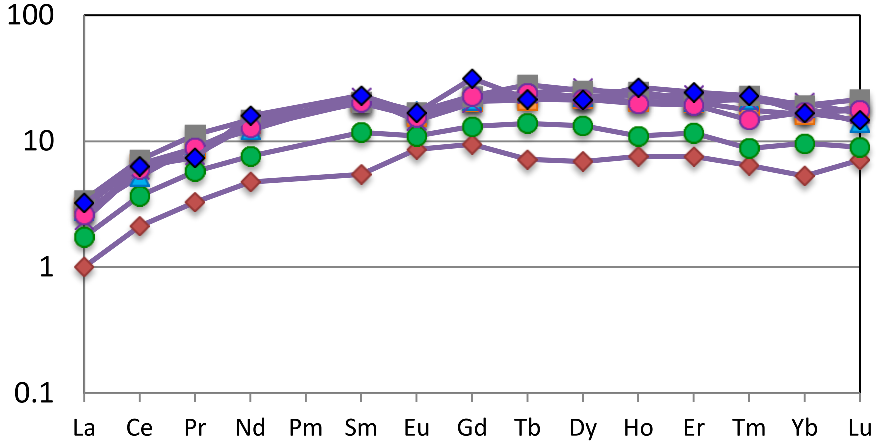


Figure 24: Chondrite-normalized REE graph from segment E72R5 0/4

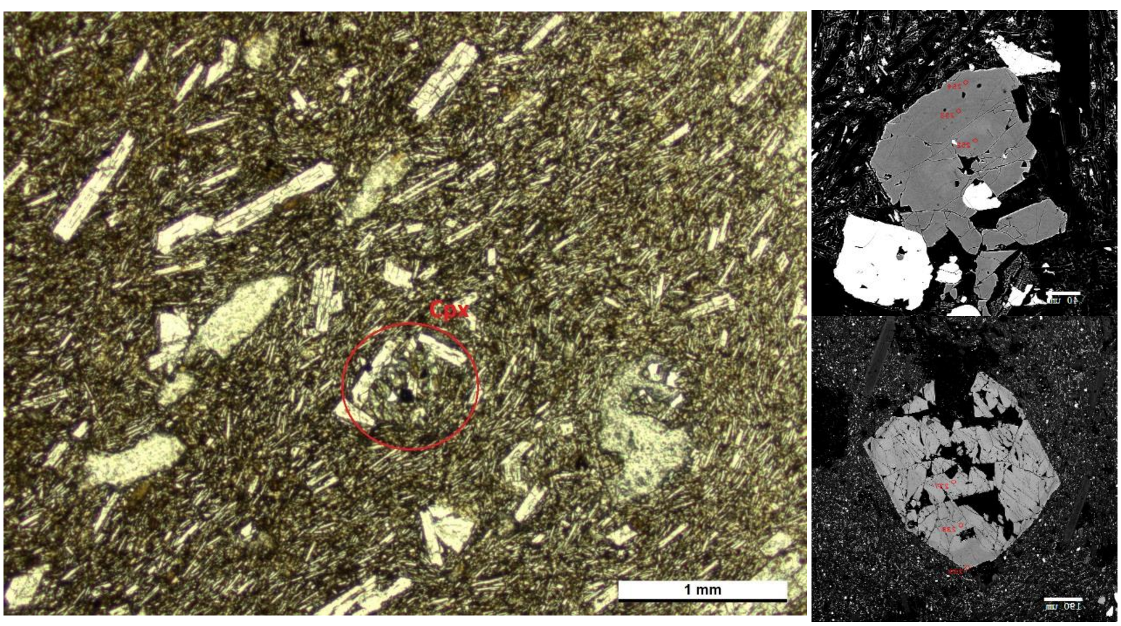


Figure 25: Representative mineral grains from E72R5 0/4. Microscope photograph shows the grain alignment observed in this sample.

Calculation of Partition Coefficients

As a magma chamber develops, minerals begin to crystallize based on the composition of the magma and Bowen's reaction series. Trace element concentrations, especially of rare earth elements, are not high enough to form their own minerals. Trace elements are instead incorporated into the structure of other minerals. Small quantities of trace elements can replace small quantities of major elements. Trace elements behave according to Henry's Law. Therefore, the ratio between the trace element concentration in a mineral grain (in this case clinopyroxene) compared to the trace element concentration in the magma can be defined numerically, as a partition coefficient. Glass can be used as a proxy for liquid because glass is magma that has cooled so rapidly that crystals have no time to form, and is therefore a mirror of the magma chamber concentration at the time of glass formation. Glass associated with clinopyroxene minerals represents liquid in equilibrium with clinopyroxene at the time of formation, and can be used to calculate a partition coefficient. In the equation $K_d = i_{cpx}/i_{glass}$ where i is the concentration of a particular element, K_d is the partition coefficient between the liquid (glass) and solid (clinopyroxene).

Partition coefficients were calculated for each segment of Unit I. For each segment, glass was paired with clinopyroxene based on composition. The primary elements used to pair the two were magnesium (Figure 26) and potassium. Magnesium was used to determine how felsic the liquid would have been. It was especially useful for pairing glass and clinopyroxene in segment B17F2W 108/109. In this segment, glass was typically about .6 weight percent MgO. Most of the clinopyroxene was relatively high in MgO, except for clinopyroxene I, which had only 11 weight percent MgO. For this reason, the most enriched in REE and most depleted in REE glass were used in partnership with only clinopyroxene I to calculate the partition coefficient for this segment. Throughout Unit I, high-Mg cpx was paired with high Mg-glass, and low-Mg cpx was paired with low-Mg glass when calculating partition coefficients.

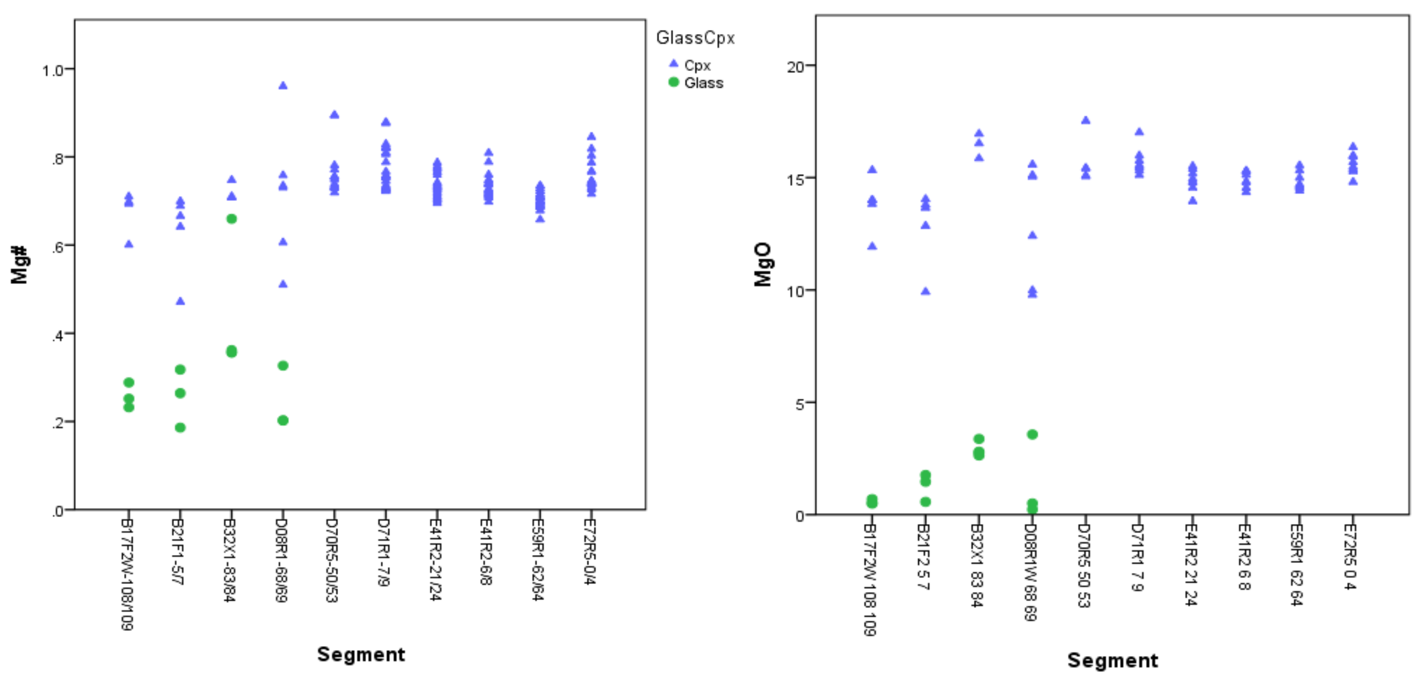


Figure 26: Graphs showing range of Mg content in all segments for both glass and cpx. Left: Mg #. Right: MgO wt %.

Potassium was utilized in a similar fashion. Harker diagrams (Figure 3) allowed us to determine which glass was low-K and which was medium-K. Sm/La ratios provided the same information for clinopyroxene. We were able to determine the usefulness of this ratio in segments B17F2W 108/109 (glass: low-K; Sm/La>5), B21F2 5/7 (glass: med-K; Sm/La <5), and B32X1 83/84 (glass: low-K; Sm/La>5). D8R1W 68/69 was initially determined to be a mixed low-K and medium-K segment from initial microprobe glass analysis. However, no medium-K glass could be analyzed. All analyzed clinopyroxene had Sm/La<5, which was the ratio that correlated to medium K. Therefore, this sample was excluded from partition coefficient development because the analyzed clinopyroxene and glass would not have existed in equilibrium with one another.

In segment B21F2 5/7, Glass 1 and Clinopyroxene A had been found grown together, which indicated they were associated. A partition coefficient was calculated between these two grains directly. For all other clinopyroxene, there were multiple glass fragments that could have been associated with them. For these cpx, a partition coefficient was calculated based on the most REE-enriched and REE-depleted glass shard. Figure 27 provides a graphical representation of the range of calculated coefficients while Appendix D provides the numerical values.

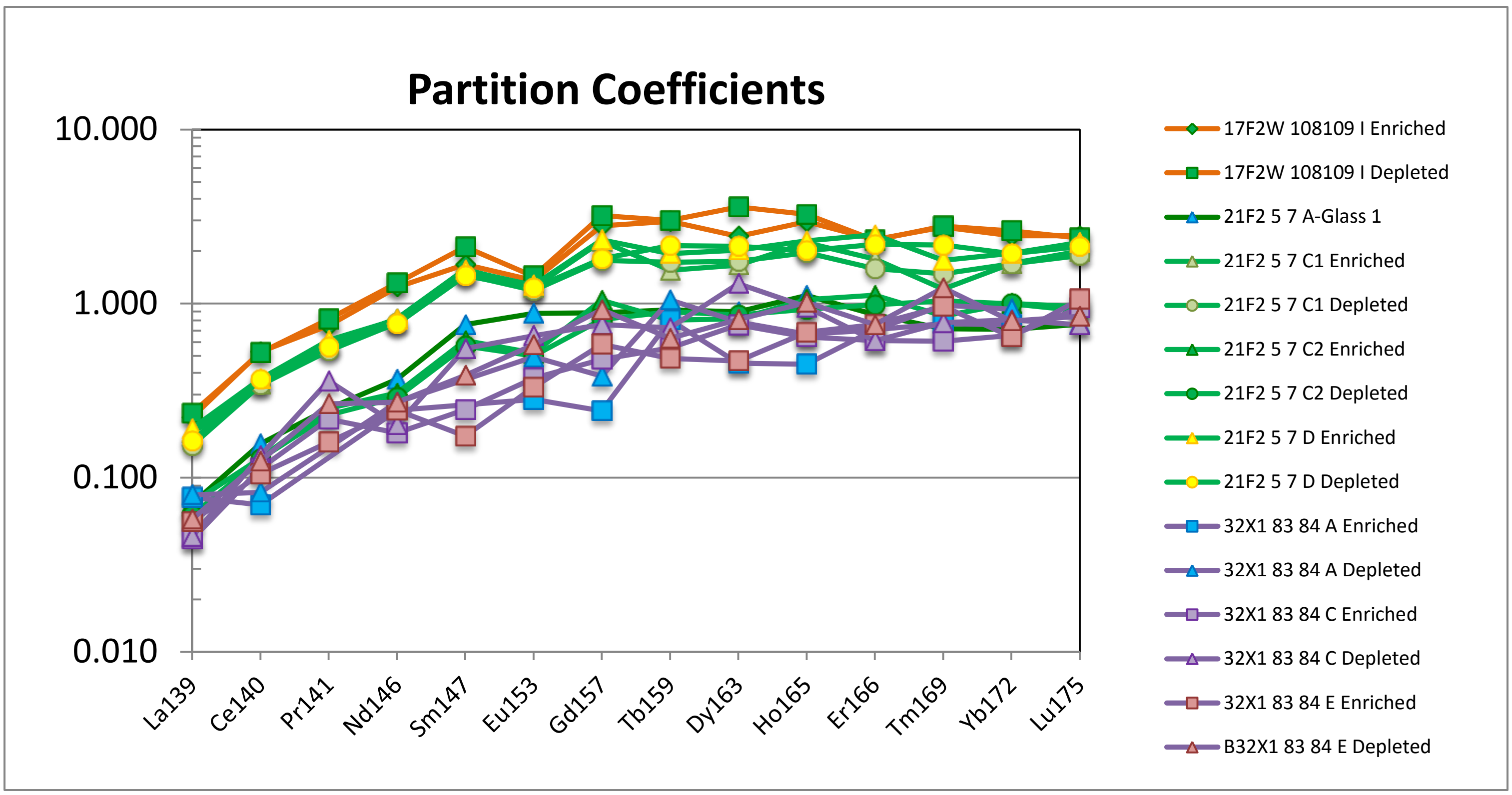


Figure 27: Graphical representation of the range of partition coefficients calculated

Calculation of Liquid Composition in Deep Units

Once calculated, partition coefficients were used to calculate original liquid composition based on existing unaltered clinopyroxene. When calculating liquid compositions, constraints were applied to determining which partition coefficient to use. First, Mg content of the deep unit clinopyroxene was analyzed (Figure 26). No deep unit segments had the low Mg content observed in the clinopyroxene and glass analyzed in Unit I segment B17F2W 108/109. For that reason, this group of partition coefficients were not used in calculation of original liquids. This left two groups of partition coefficients: A range calculated from the medium-K segment B21F2 5/7, and a range calculated from low-K segment B32X1 83/84.

Appendix E shows all calculated liquid compositions. Liquid compositions were calculated using the high and low partition coefficient. The high value is the highest value from B21F2 5/7 and the low value is from B32X 1 83/84. For each deep unit cpx, a liquid composition was calculated from both the high and low value. Sm/La ratios were used when determining which partition coefficient to apply to a clinopyroxene grain. For those deep-unit grains that had Sm/La>5, the low-K segment partition coefficients from B32X1 were used. For deep-unit grains that had Sm/La<5, the medium-K segment partition coefficients from B21F2 5/7 were used. Only the calculated liquids where Sm/La ratios matched between deep-unit cpx and calculated partition coefficients were graphed.

In D70R5 50/53 (Unit IV), all clinopyroxene had Sm/La<5. The calculated liquid compositions (Figure 28) showed a negatively slopping REE pattern that indicates the liquid was enriched in light Rare Earth Elements (LREEs).

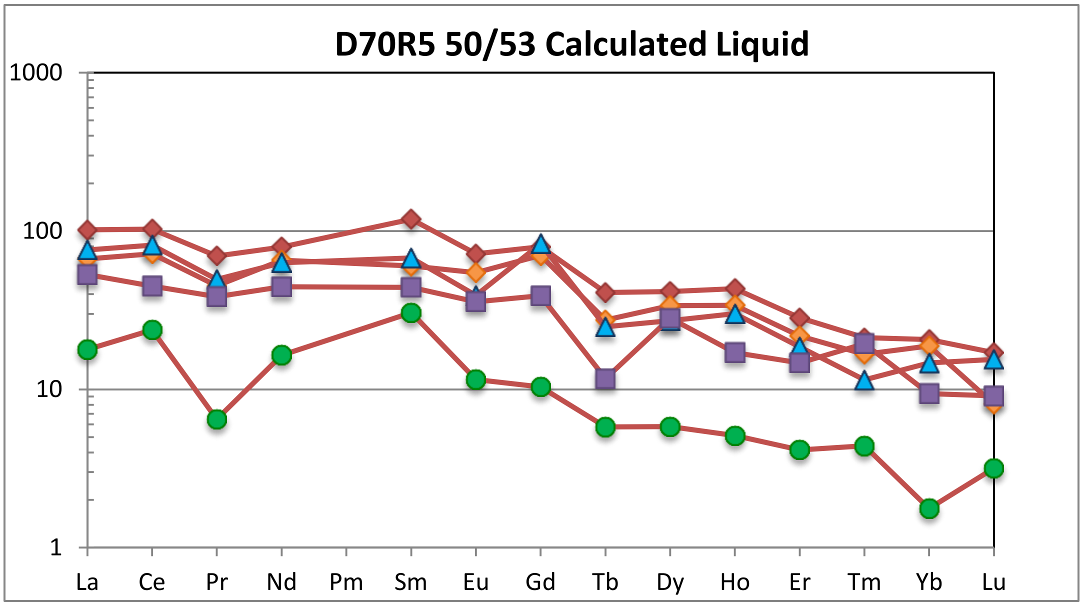


Figure 28: Calculated liquid compositions for D70R5 50/53

D71R1 7/9 calculated liquid showed a similar trend (Figure 29). One cpx grain from this segment had a higher Sm/La ratio, which generated the calculated liquid with the flattest trend. All other liquid calculated in this segment showed a negatively sloping REE pattern that indicates enrichment in LREE.

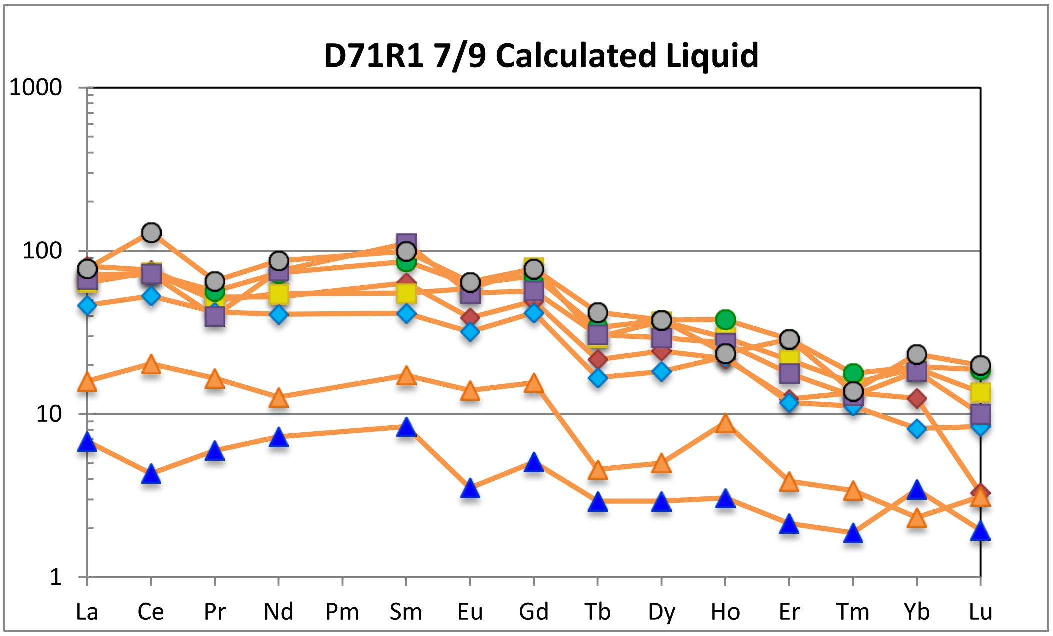


Figure 29: Calculated liquid compositions for D71 R5 7/9

Segment E41R2 6/8 contained both low and high Sm/La cpx. As a result, some calculated liquid (Figure 30) showed the negatively sloping REE pattern that indicates enrichment in LREE, while some calculated liquid has a flat pattern that is relatively depleted in LREEs compared to the low Sm/La cpx but enriched in LREEs compared to the typical REE pattern of oceanic crust.

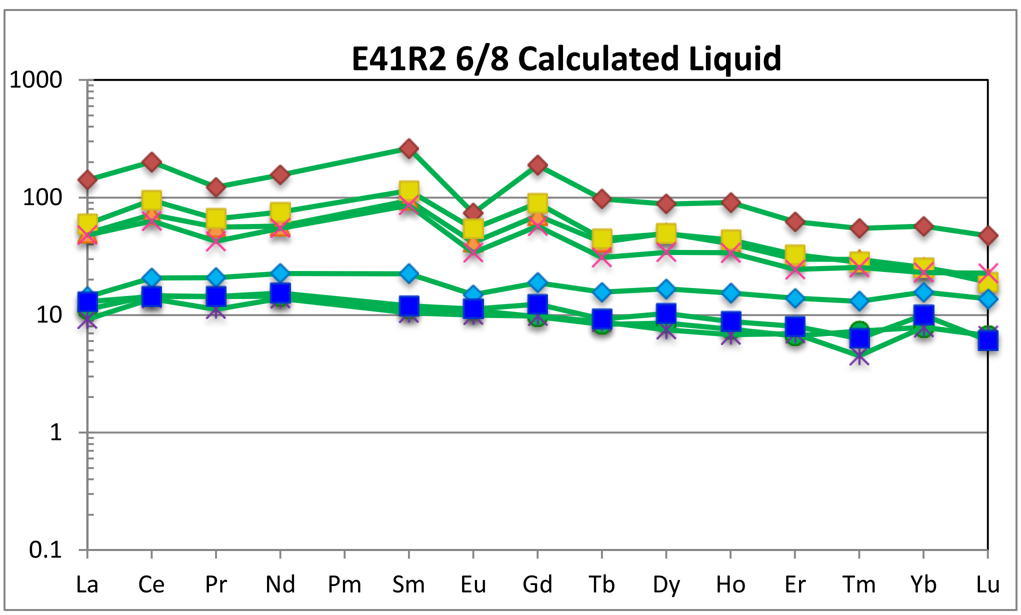


Figure 30: Calculated liquid compositions for E41R2 6/8. Liquids with higher concentrations of REEs correlate to cpx with low Sm/La ratios.

E41R2 21/24 contained primarily high Sm/La cpx. The calculated liquid composition (Figure 31) showed the flat REE trend that indicates neither enrichment nor depletion of LREEs. Two calculated liquid composition from this sample shows REE enrichment; these liquid compositions was calculated based from a low Sm/La cpx grains.

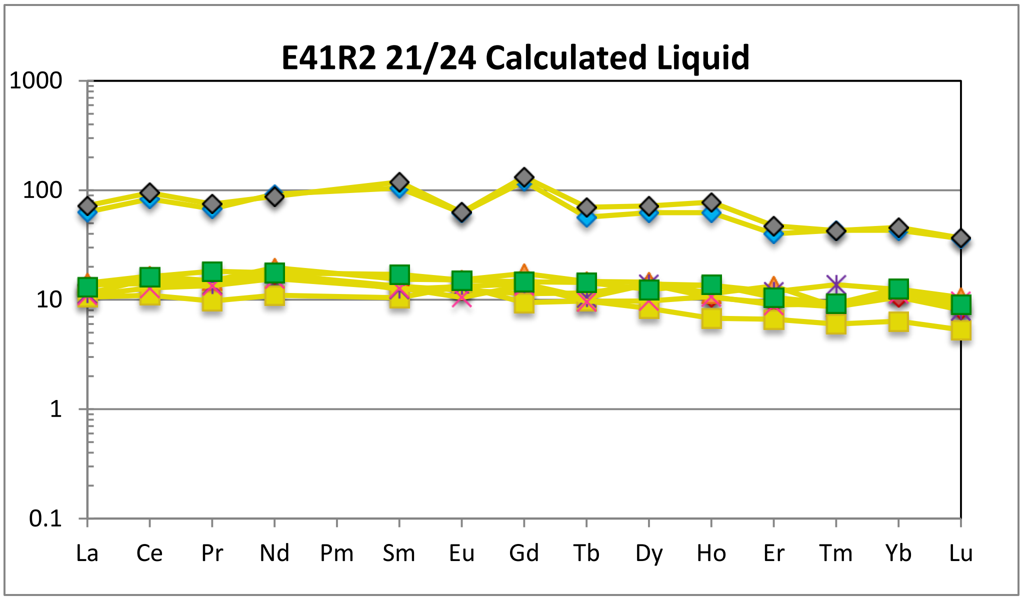


Figure 31: Calculated liquid compositions for E41R2 21/24.

E59R1 62/64 cpx had Sm/La>5 (high Sm/La cpx). The calculated liquid (Figure 32) had a flat REE pattern (with the exception of one calculated liquid composition from one odd cpx) that indicates neither enrichment nor depletion of LREEs.

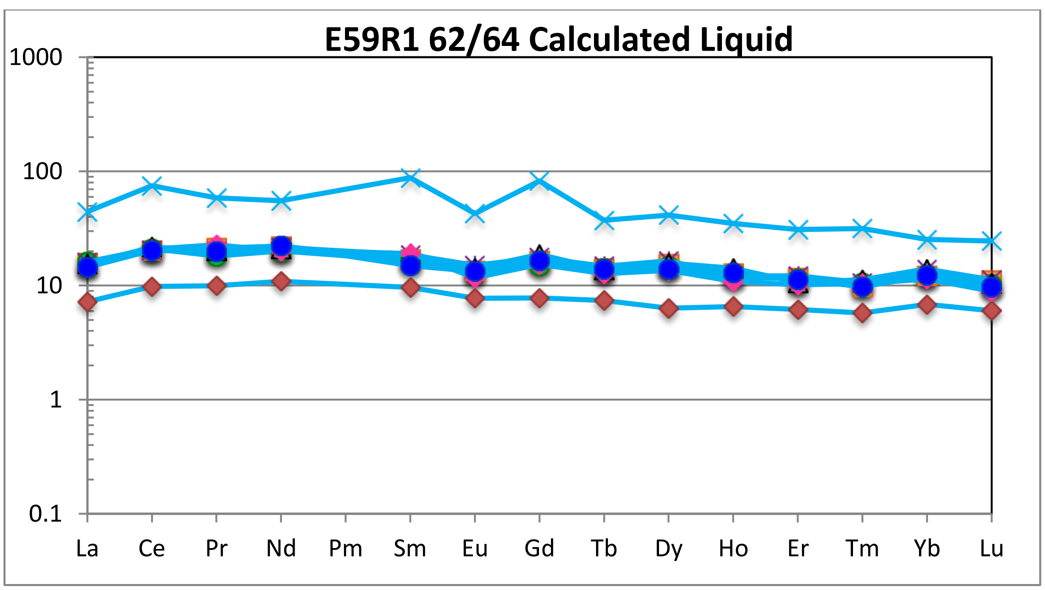


Figure 32: Calculated liquid compositions for E59R1 62/64.

The deepest segment, E72R5 0/4, typically had a low Sm/La ratio, although several cpx grains were slightly above the cut-off value of five. Calculated liquid compositions (Figure 33) are typically fairly negatively sloped, indicating enrichment in LREEs. Some of the liquid composition patterns are fairly flat.

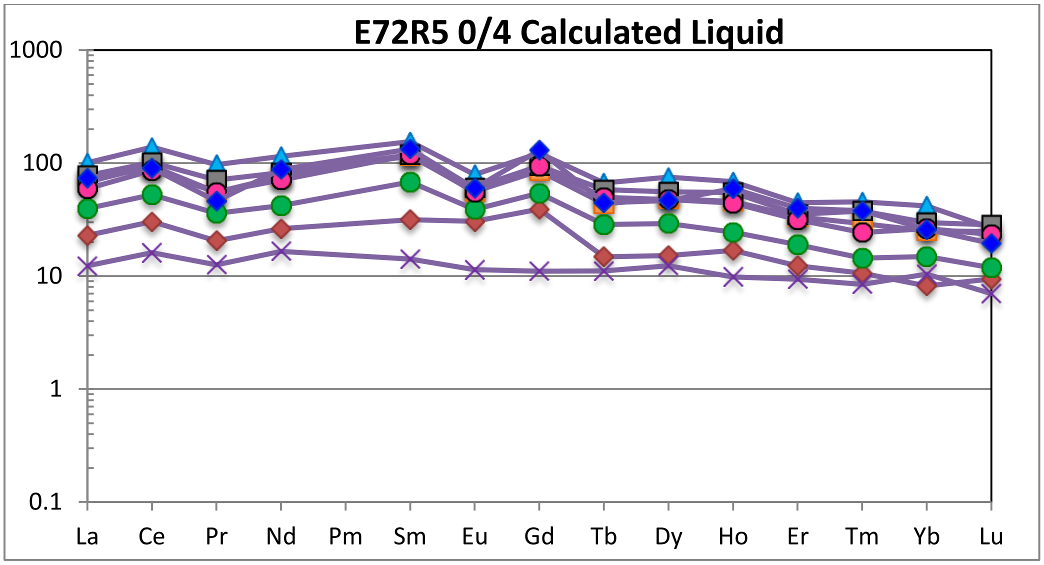


Figure 33: Calculated liquid compositions for 72R5 0/4.

Conclusions

Based on Unit I samples, it was clear that Sm/La ratios could be used to determine the K content of the magma a clinopyroxene grain had existed in equilibrium with. Sm/La of less than five was associated with medium-K glass, while Sm/La of greater than five was associated with low-K glass. La/Sm ratios of clinopyroxene in deeper units can therefore be used as a proxy for K-content of their parental magmas. Using this standard, we found that segments D70R5 50/53 and D71R1 7/9 would have had medium-K parental magmas. Medium-K magma is typically associated with continental crust. In contrast, E41R2 6/8, E41R2 21/24, and E59R1 62/64 would have had low-K parental magmas, which tends to be associated with oceanic crust. Those cpx with medium-K parental magmas are found closer to the top of the core, in Unit IV, while those cpx with low-K parental magmas were found more commonly in units VI and VII.

When observing trace element trends, the Unit IV segments show negatively sloping LREE patterns: this indicates relative enrichment in trace elements compared to deeper units. The REE patterns observed in the Unit IV segments are similar to REE trends observed in continental crust. In contrast, segments E41R2 6/8, E41R2 21/24, and E59R1 62/64 show primarily flat REE patterns. These REE patterns are not positively sloping, as is typically observed in oceanic crust, but are comparatively depleted in REEs compared to the Unit IV segments.

In addition, a negative Eu anomaly appears in the clinopyroxene from several units. The Eu anomaly is associated with cpx with Sm/La>5, which are those cpx with low-K parental magmas. Negative Eu anomalies are associated with the crystallization of plagioclase, because Eu^{2+} replaces some Ca^{2+} as plagioclase forms (Eu is compatible in plagioclase). This anomaly would be expected in clinopyroxene that crystallizes after plagioclase has formed, because there would be less Eu^{2+} present in the magma for clinopyroxene to accept. This crystallization order is typical of low-H_2O magmas. In contrast, medium-K magmas typically have higher H_2O contents, which leads to the suppression of plagioclase crystallization. For this reason, the two segments associated with medium-K parental magmas lack this Eu anomaly.

Taken together, these trends suggest that the deeper units, VI and VII, may have been compositionally similar to oceanic crust, and may have melted from an oceanic source. By the time Unit IV samples were deposited, the composition of the magmas had shifted and acquired a more continental signature, with medium-K magma that was relatively enriched in trace elements.

Unit VII segment E72R5 0/4 is an exception the trends observed in the other five samples. The clinopyroxene in this sample has Sm/La that indicates a medium-K parental magma. In addition, it is relatively more enriched in LREEs compared to E41R2 6/8, E41R2 21/24, and E59R1 62/64, the low-K samples. However, it exhibits a minor Eu^{2+} anomaly that would not be expected in a medium-K parental magma clinopyroxene. We hypothesize that this segment may somehow be transitional between the Unit IV and VII samples and something deeper, but further investigation is required. This might prove difficult as E72R5 0/4 is one of the deepest segments recovered.

The Izu-Bonin back arc seems to contain evidence of a shift to continental crust growth from subduction at an island arc. The process by which this might occur is still unclear: more investigation is required to pinpoint where and why this shift from an oceanic to a continental trace element signature is occurring.

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Appendix A: Major and trace element chemistry: Unit I

A1: Major element concentrations, clinopyroxene

Label	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O
B17F2W 108109 D	52.55	0.3772	1.6656	10.98	0.6927	14.22	19.87	0.2356
B17F2W 108109 E	51.19	0.4943	2.252	10.57	0.5859	13.83	19.99	0.2175
B17F2W 108109 H	51.65	0.4142	1.697	10.9	0.7229	13.88	19.59	0.2364
B17F2W 108109 I	51.17	0.2945	1.3475	14.14	1.2395	11.92	18.8	0.247
B17F2W 108109 J	52.01	0.304	1.9924	12.07	0.3853	15.33	17.53	0.1533
B21F2 5 7 A	47.23	1.5061	6.26	11.5	0.3785	12.85	18.74	0.3383
B21F2 5 7 B	51.66	0.2372	0.8404	19.84	1.0798	9.91	17.34	0.1896
B21F2 5 7 C1	52.76	0.3664	1.4088	10.77	0.6653	14.04	20.36	0.2722
B21F2 5 7 C2	52.22	0.4596	1.3641	13.6	0.6226	13.65	18.46	0.1997
B21F2 5 7 D2	52.16	0.457	1.6722	11.12	0.7105	13.79	19.94	0.2572
B32X1 83 84 A	50.35	0.5012	3.3	12	0.3553	16.52	15.23	0.1538
B32X1 83 84 C	50.66	0.4927	3.27	12.48	0.3915	16.95	14.55	0.1469
B32X1 83 84 E	49.12	0.5341	3.17	9.54	0.2876	15.86	16.04	0.1791
D8R1W 68 69 pyx5	50.18	0.3002	0.9118	18.85	1.3119	9.78	17.69	0.2332
D8R1W 68 69 B	52.38	0.4248	2.1385	9.7	0.4922	15.05	19.88	0.2679
D8R1W 68 69 C	51.26	0.2398	0.8775	17.09	1.1722	9.98	18.94	0.258
D8R1W 68 69 E	51.29	0.677	3.21	8.59	0.3368	15.11	20.42	0.2471
D8R1W 68 69 F	51.91	0.4876	2.2679	10.25	0.3419	15.58	18.89	0.2239
D8R1W 68 69 H	52.2	0.257	0.9834	14.38	1.0661	12.4	19.03	0.2159

A2: Trace Element Compositions, clinopyroxene

Label	P31	S34	K39	Sc45	V51	Cr52	Co59	Ni60	Cu65	Zn66	Rb85	Sr88	Y89	Zr90	Nb93	Cs133	Ba137
B17F2W 108109 D	44.59	<93.85	8.24	208.61	120.36	1.99	27.56	1.31	0.52	138.98	<0.047	10.29	57.49	17.23	<0.0128	0.034	<0.099
B17F2W 108109 E	29.98	125.63	6.2	184.69	142.57	0.99	27.26	0.85	0.57	128.49	0.069	10.11	51.32	17.81	0.0138	<0.0109	0.23
B17F2W 108109 H	46.43	276.82	<2.16	188.43	87.66	1.14	19.08	0.63	0.76	110.21	<0.034	7.71	39.64	11.61	0.034	<0.0071	<0.00
B17F2W 108109 I	23.41	<88.20	<2.65	526.77	43.07	2.79	15.83	4.48	0.98	348.65	<0.045	10.43	112.7	25.56	0.024	0.025	<0.078
B17F2W 108109 J	22.04	135.97	4.75	139.88	525.79	300.98	59.15	52.6	6.97	70.58	<0.031	6.1	9.14	3.16	<0.0131	<0.0097	0.24
B21F2 5 7 A	87.25	197.45	3.69	145.7	428.5	10.8	37.2	8.24	1.14	65.85	<0.041	19.2	38.99	36.6	0.0173	<0.0107	0.116
B21F2 5 7 B	210.97	148.13	44.19	322.12	3.96	1.82	20.4	<0.140	1.22	222.32	0.033	12.35	67.89	25.38	0.039	0.0061	0.32
B21F2 5 7 C1	26.79	83.92	<2.78	234	119.89	1.53	30.31	0.75	<0.17	120.11	<0.042	21.45	69.31	34.09	0.064	<0.017	<0.055
B21F2 5 7 C2	32.46	107.11	24.57	178.57	102.44	0.55	38.18	0.45	0.93	123.29	<0.039	13.13	35.19	15.88	<0.0184	<0.019	0.132
B21F2 5 7 D2	43.24	126.84	<3.27	248.42	130.99	0.67	28.21	1.19	0.72	115.79	<0.041	17.99	77.7	43.72	<0.0141	<0.0076	<0.00
B32X1 83 84 A	34.28	<318.37	59.06	165.73	409.19	142.43	66.46	53.32	<2.32	86.58	<0.37	9.33	18.97	8.86	<0.137	<0.21	2.05
B32X1 83 84 C	18.79	<195.04	<12.19	192.89	497.18	170.42	61.55	51.71	3.97	64.84	0.35	7.73	19.69	9.95	<0.115	<0.175	<0.92
B32X1 83 84 E	42.05	<145.23	91.74	161.31	374.05	75.74	57.12	33.98	4.13	79.85	<0.29	11.88	19.78	10.2	<0.094	<0.177	3.2
D8R1W 68 69 pyx5	<9.50	149.11	<6.63	385.03	2.62	<0.66	15.95	0.62	<1.00	237.47	<0.092	16.62	115.84	32.4	<0.0188	0.0137	<0.11
D8R1W 68 69 B	20.53	75.1	<7.53	121.79	218.81	2.72	41.86	11.05	<1.19	75.32	<0.110	23.48	29.25	16.61	0.027	<0.021	<0.152
D8R1W 68 69 C	<11.54	271.05	<7.83	385.29	4.42	<0.80	19.48	<0.33	<1.23	210.39	<0.114	22.65	106.15	43.45	<0.032	<0.0236	0.154
D8R1W 68 69 E	<20.77	<136.24	<13.90	125.08	233.45	<1.45	30.72	<0.55	<2.11	47.69	<0.210	32.08	13.74	7.49	<0.056	<0.035	<0.30
D8R1W 68 69 F	16.15	<101.26	<9.81	108.2	423.19	161.47	49.36	61.15	3.97	57.35	<0.136	21.82	16.47	8.49	<0.054	<0.031	<0.166
D8R1W 68 69 H	<10.58	209.61	7.63	287.97	4.93	1.07	19.42	0.44	<1.10	176.49	<0.103	26.39	70.81	24.07	0.02	<0.0214	0.85

A3: Trace Element Compositions, clinopyroxene cont.

	La139	Ce140	Pr141	Nd146	Sm147	Eu153	Gd157	Tb159	Dy163	Ho165	Er166	Tm169	Yb172	Lu175	Hf178	Ta181	Pb208	Th232	U238
W 108109 D	0.57	3.91	1.14	9.5	6.33	1.46	9.21	1.75	13.52	2.54	8.24	0.98	7.53	1.21	1.27	0.0123	4.55	<0.0171	<0.0102
W 108109 E	0.49	3.46	0.99	7.67	5.77	1.55	7.83	1.51	10.92	2.3	7.77	1.07	6.21	1.03	1.29	<0.0177	0.065	<0.0160	<0.0135
W 108109 H	0.42	2.66	0.77	7.33	3.91	1.3	7.05	1.38	10.2	2.26	7.77	1.06	6.57	1.13	0.89	<0.0162	0.191	<0.0129	0.019
W 108109 I	1.33	8.92	2.23	18.54	10.14	1.94	17.2	3.3	23.64	5.37	14.91	2.31	14.05	2.38	1.72	0.0132	0.121	<0.0163	0.0088
W 108109 J	0.128	0.67	0.137	0.94	0.74	0.35	1.11	0.203	2.24	0.39	1.36	0.206	1.24	0.204	0.174	<0.0078	<0.040	<0.0195	0.0107
5 7 A	1.17	6.95	1.66	11.27	5.19	1.82	7.34	1.07	8.25	1.75	5.02	0.56	4.03	0.571	1.22	0.032	0.47	0.027	<0.0116
5 7 B	1.84	10.62	2.43	15.22	8.82	1.23	10.78	1.82	12.65	2.88	7.93	1.32	7.55	1.23	1.42	<0.0128	0.113	<0.0126	<0.013
5 7 C1	2.22	13.16	3.21	21.07	11.24	2.5	13.25	1.99	14.29	3.24	7.33	0.8	7.06	1.04	1.79	<0.0109	<0.023	<0.0087	0.024
5 7 C2	0.88	4.95	1.37	7.87	4.38	1.05	6.06	1.03	7.02	1.53	4.55	0.56	4.16	0.5	0.64	<0.0119	<0.043	<0.0134	<0.0171
5 7 D2	2.35	14.15	3.37	20.84	11.1	2.58	13.52	2.48	17.45	3.32	10.1	1.17	8.09	1.17	2.05	<0.0191	<0.041	0.033	<0.0139
83 84 A	0.212	0.61	<0.115	1.81	<0.87	0.4	1.2	0.62	3.06	0.44	2.24	0.246	2.5	<0.159	1.39	<0.183	<0.67	<0.28	<0.35
83 84 C	0.122	0.99	0.36	1.34	1.08	0.53	2.37	0.428	5.08	0.63	1.94	0.195	2.17	0.37	<0.48	<0.159	<0.57	<0.27	<0.29
83 84 E	0.154	0.92	0.266	1.81	0.76	0.47	2.89	0.373	3.16	0.67	2.4	0.309	2.14	0.414	0.74	<0.153	<0.52	0.25	<0.30
/ 68 69 pyx5	4.59	23.7	6.1	39.3	16.26	2.26	21.31	3.55	24.29	5.01	15.17	2.14	13.17	2.09	1.88	<0.0125	0.098	<0.0144	0.0222
/ 68 69 B	1.06	6.42	1.43	9.18	3.57	1.26	5.5	1	6.41	1.4	3.69	0.529	3.25	0.489	0.826	0.044	0.609	<0.0164	0.0126
/ 68 69 C	4.77	27.69	6.67	42.43	17.77	2.49	20.46	3.58	22.23	4.9	14.8	1.62	12.45	1.86	2.09	0.028	0.145	<0.021	0.0211
/ 68 69 E	0.581	2.47	0.683	4.83	2.19	0.83	3.21	0.469	2.91	0.566	1.25	0.225	1.16	0.149	0.291	<0.0220	<0.083	<0.051	<0.0263
/ 68 69 F	0.626	3.53	0.805	5.95	2.56	0.79	2.55	0.585	3.37	0.698	1.96	0.266	1.9	0.232	0.431	<0.0188	<0.056	<0.0255	<0.0195
/ 68 69 H	2.9	15.59	3.98	25.88	10	2.16	12.73	2.11	14.56	3.29	8.85	1.19	7.88	1.28	1.43	<0.0125	0.343	<0.0157	0.0127

A4: Major Element Compositions, glass

Label	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O
B17F2W 108109 Glass 2	69.48	0.4229	13.1	3.05	0.1597	0.693	2.6577	3.13
B17F2W 108109 Glass 3	73.68	0.4137	12.77	2.7907	0.1492	0.5267	2.392	0.5935
B17F2W 108109 Glass 4	74.48	0.4152	12.95	2.9112	0.1578	0.4933	2.4353	0.8188
B21F2 5 7 Glass 1	64.67	0.9667	13.97	4.45	0.2014	0.5705	2.9095	3.55
B21F2 5 7 Glass 4	62.22	1.0258	15.46	7.27	0.279	1.4636	4.57	3.47
B21F2 5 7 Glass 3	58.56	1.1154	17.75	6.75	0.2375	1.7628	6.69	3.95
B32X1 83 84 Glass 1	60.91	0.9679	15.13	8.47	0.199	2.6358	6.52	1.7559
B32X1 83 84 Glass 3	58.18	0.9618	14.57	8.85	0.2331	2.7461	6.89	2.7955
B32X1 83 84 Glass 4	56.99	0.9757	14.6	8.81	0.2305	2.8015	6.68	2.9653
B32X1 83 84 Glass 5	53.67	0.9691	14.47	3.1	0	3.37	7.8	2.4098
D8R1W 68 69 glass3	55.16	1.1821	13.41	13.12	0.2783	3.57	8.21	2.5958
D8R1W 68 69 pum2b	68.63	0.4192	14.9	3.54	0.1521	0.5034	2.0919	0.9571
D8R1W 68 69 shard2	72.55	0.2613	11.18	1.6296	0.0156	0.2321	1.5273	2.8391

A5: Trace element compositions; glass.

	P31	S34	K39	Sc45	V51	Cr52	Co59	Ni60	Cu65	Zn66	Rb85	Sr88	Y89	Zr90	Nb93	Cs133	Ba137	La139	Ce140
08109 Glass 2	423.87	10671.19	7129.3	16.12	13.38	0.97	5.61	16.64	5.99	80.57	11.4	128.5	45.36	131.69	1.85	0.66	149.7	5.98	16.86
08109 Glass 3	388.46	278.55	6889.81	13.21	9.81	0.81	2.28	1.36	5.97	306.12	10.33	106.09	36.71	119.61	2.24	0.67	164.17	5.67	17.04
08109 Glass 4	354.97	<131.87	6537.79	15.2	9.36	<0.65	1.57	1.13	5.28	71.25	9.25	109.45	37.15	133.97	2.16	0.86	148.74	5.84	15.65
Glass 1	1496.4	<146.00	12571.17	17.06	56.89	4.96	5.89	0.92	14.08	81.96	27.67	182.64	46.3	230.83	5.25	0.633	128.98	16.51	44.42
Glass 4	2352.48	<121.07	9226.31	20.7	21.38	1.32	7.92	0.25	3.07	147.44	15.82	220.57	43.06	154.04	5.05	0.513	109.08	12.27	38.22
Glass 3	1877.55	446.11	9821.51	31.38	221.73	3.56	19.4	3.1	34.15	94.57	22.89	271.59	43.64	184.36	5.45	0.477	117.22	14.5	38.56
4 Glass 1	528.79	636.81	3482.79	38.39	255.8	2.78	19.82	2.74	36.08	139.17	4.57	174.12	31.27	64.17	0.52	0.26	95.58	2.69	8.46
4 Glass 3	533.87	549.65	3344.23	34.15	270.2	3.12	21.11	4.59	44.85	136.62	4.25	182.95	31.26	62.45	0.57	0.46	111.26	2.75	8.74
4 Glass 4	491	597.65	3188.78	34.14	261.8	<1.15	20.71	1.89	36.89	137.07	4.35	176	29.95	62.78	0.66	0.45	103.83	2.69	7.78
4 Glass 5	401.92	575.94	2921.76	36.34	352.27	1.71	30.84	2.74	74.23	111.73	4.05	166.51	24.39	48.71	0.387	0.62	79.45	2.66	7.39
69 glass3	372.6	285.82	2959.8	50.82	442.37	8.69	39.57	14.71	178.79	136.18	4.05	147.1	20.89	34.68	0.434	0.436	63.36	1.73	5.07
69 pum2b	989.31	96.2	2808.65	9.31	36.86	1.98	1.017	1.04	2.49	31.67	5.8	218.63	17.21	105.13	1.27	0.186	40.64	8.64	20.26
69 shard2	237.34	400.1	7931.84	11.37	8.18	7.95	1.59	5.45	15.09	62.73	8.01	53.61	37.72	127.27	1.01	0.79	177.26	4.57	14.4

A6: Trace element compositions; glass

Label	Pr141	Nd146	Sm147	Eu153	Gd157	Tb159	Dy163	Ho165	Er166	Tm169	Yb172	Lu175	Hf178	Ta181	Pb208	Th232	U238
B17F2W 108109 Glass 2	2.98	14.89	6.05	1.43	6.15	1.11	9.7	1.82	6.38	0.84	5.73	0.97	5.37	0.065	7.58	0.69	0.38
B17F2W 108109 Glass 3	2.74	14.1	4.8	1.35	5.38	1.1	6.59	1.65	6.45	0.83	5.37	1	4.57	0.203	7.12	1.06	0.45
B17F2W 108109 Glass 4	2.82	13.33	6.15	1.62	5.85	1.42	9.31	2.19	7.26	0.75	6.94	0.79	4.04	0.24	4.86	0.93	0.52
B21F2 5 7 Glass 1	6.66	30.65	6.85	2.07	8.29	1.16	9.2	1.57	5.8	0.78	5.66	0.75	5.37	0.288	5.43	1.53	0.562
B21F2 5 7 Glass 4	5.47	25.66	7.14	2.02	5.81	1.28	8.59	1.45	4.07	0.66	4.16	0.52	3.88	0.209	3.53	0.89	0.54
B21F2 5 7 Glass 3	5.98	27.22	7.68	2.1	7.48	1.15	8.16	1.65	4.62	0.54	4.17	0.55	4.75	0.51	3.11	1.03	0.337
B32X1 83 84 Glass 1	1.38	8.4	2.64	0.93	2.31	0.68	5.32	1.2	3.55	0.53	2.6	0.69	1.64	<0.153	3.79	0.26	0.32
B32X1 83 84 Glass 3	1.66	7.42	4.39	1.42	4.95	0.77	6.74	0.98	3.16	0.321	3.31	0.391	1.3	<0.183	2.73	<0.33	<0.37
B32X1 83 84 Glass 4	1.63	8.33	1.88	1.41	3.93	0.73	3.92	0.95	2.9	0.56	4.49	0.58	3.87	<0.185	2.02	<0.29	0.33
B32X1 83 84 Glass 5	1	6.66	1.96	0.81	3.13	0.59	3.9	0.66	3.17	0.251	2.69	0.49	1.42	<0.147	2.14	0.33	<0.32
D8R1W 68 69 glass3	0.97	5.57	2.34	0.9	2.51	0.428	3.79	0.622	2.47	0.336	2.49	0.381	1.25	0.089	2.49	0.072	0.052
D8R1W 68 69 pum2b	2.5	11.61	2.65	0.79	2.39	0.399	2.72	0.495	1.97	0.306	2.22	0.387	2.23	0.158	4.03	1.387	0.46
D8R1W 68 69 shard2	3.04	11.49	6.59	0.95	6.32	1.07	7.02	2.03	3.89	0.93	5.11	1.11	3.17	2.62	15.09	0.73	0.285

Appendix B: Sm/La ratios for all units

Label	Sm/La Type	La	Sm	Sm/La
B17F2W 108 109 D	Low	0.56	5.98	10.679
B17F2W 108 109 E	Low	0.61	4.61	7.557
B17F2W 108 109 H	Low	0.41	3.78	9.220
B17F2W 108 109 I	Low	1.3	9.68	7.446
B21F2 5 7 A	Med	1.17	5.19	4.436
B21F2 5 7 B	Med	1.84	8.82	4.793
B21F2 5 7 C1	Low	2.22	11.24	5.063
B21F2 5 7 C2	Med	0.88	4.38	4.977
B21F2 5 7 D	Med	2.35	11.1	4.723
B32X1 83 84 A	Low	0.218	1.77	8.119
B32X1 83 84 C	Low	0.122	1.08	8.852
B32X1 83 84 D	Low	0.138	1.14	8.261
B32X1 83 84 E1	Med	0.154	0.76	4.935
D08R1W 68 69 B	Med	1.06	3.57	3.368
D08R1W 68 69 C	Med	4.77	17.77	3.725
D08R1W 68 69 E	Med	0.581	2.19	3.769
D08R1W 68 69 F	Med	0.626	2.56	4.089
D08R1W 68 69 H	Med	2.9	10	3.448
D08R1W 68 69 pyx5	Med	4.59	16.26	3.542
D70R5 50 53 1M	Med	1.061	3.05	2.875
D70R5 50 53 4M	Med	0.696	1.54	2.213
D70R5 50 53 5C	Med	0.794	1.73	2.179
D70R5 50 53 7M	Med	0.186	0.78	4.194
D70R5 50 53 8C	Med	0.555	1.13	2.036
D71R1 7 9 1C	Med	0.84	1.63	1.940
D71R1 7 9 2C	Med	0.166	0.443	2.669
D71R1 7 9 3C	Med	0.667	1.41	2.114
D71R1 7 9 4M	Med	0.739	2.2	2.977
D71R1 7 9 5C	Med	0.483	1.06	2.195
D71R1 7 9 6M	Med	0.7	2.84	4.057
D71R1 7 9 7R	Low	0.31	1.95	6.290
D71R1 7 9 8M	Med	0.812	2.55	3.140
E41R2 21 24 1R	Low	0.62	3.1	5.000
E41R2 21 24 2M	Low	0.647	3.58	5.533
E41R2 21 24 3M	Low	0.482	2.43	5.041
E41R2 21 24 4M	Med	0.658	2.68	4.073
E41R2 21 24 5C	Low	0.516	2.92	5.659
E41R2 21 24 6C	Low	0.5	2.99	5.980
E41R2 21 24 7M	Low	0.6	3.96	6.600
E41R2 21 24 8M	Med	0.754	3.05	4.045
E41R2 6 8 1C	Med	1.47	6.69	4.551

E41R2 6 8 2C	Med	0.52	2.42	4.654
E41R2 6 8 3C	Med	0.62	2.93	4.726
E41R2 6 8 4C	Low	0.51	2.63	5.157
E41R2 6 8 5M	Low	0.65	5.23	8.046
E41R2 6 8 6C	Low	0.419	2.43	5.800
E41R2 6 8 7M	Low	0.66	4.09	6.197
E41R2 6 8 8C	Med	0.5	2.2	4.400
E59R1 62 64 1C	Low	0.328	2.25	6.860
E59R1 62 64 2M	Low	0.722	3.94	5.457
E59R1 62 64 3R	Low	0.733	3.86	5.266
E59R1 62 64 4M	Med	0.463	2.25	4.860
E59R1 62 64 5M	Low	0.729	4.33	5.940
E59R1 62 64 6M	Low	0.704	4.43	6.293
E59R1 62 64 7M	Low	0.662	4.44	6.707
E59R1 62 64 8M	Low	0.66	3.49	5.288
E72R5 0 4 1M	Med	0.239	0.81	3.389
E72R5 0 4 2M	Med	0.712	2.98	4.185
E72R5 0 4 3C	Med	0.413	1.74	4.213
E72R5 0 4 4M	Med	0.668	3.29	4.925
E72R5 0 4 5R	Low	0.56	3.3	5.893
E72R5 0 4 6M	Med	0.81	3.04	3.753
E72R5 0 4 7M	Med	0.621	3.03	4.879
E72R5 0 4 8M	Med	0.771	3.42	4.436

Appendix C: Major and trace element geochemistry for Units IV, VI, and VII

C1: Major element chemistry

Label	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O
D70R5 50 53 1M	52.0746	0.558256	2.16886	9.9275	0.411285	15.093	19.5793	0.243447
D70R5 50 53 4M	51.5977	0.614785	3.31151	8.95498	0.240624	15.4224	19.562	0.282443
D70R5 50 53 5C	51.5334	0.626293	3.31392	7.96188	0.239636	15.0561	21.0184	0.243516
D70R5 50 53 7M	52.8907	0.217257	3.25209	3.66809	0.084872	17.5233	21.858	0.181615
D70R5 50 53 8C	51.5774	0.588562	3.36457	7.70033	0.228558	15.4112	21.1194	0.243421
D71R1 7 9 1C	51.2926	0.644851	3.94489	6.17217	0.194198	15.7526	21.6329	0.249063
D71R1 7 9 2C	52.3711	0.263984	4.08175	4.17818	0.088251	17.0078	21.8464	0.154475
D71R1 7 9 3C	51.2585	0.667385	3.35378	10.0669	0.327361	15.1121	18.7427	0.339714
D71R1 7 9 4M	51.2856	0.636588	2.73639	10.3147	0.390407	15.4332	18.3614	0.292633
D71R1 7 9 5C	52.5506	0.503421	2.86998	6.68531	0.183325	15.9803	21.3608	0.21132
D71R1 7 9 6M	51.8188	0.576936	3.18324	8.71508	0.295229	15.3115	20.0778	0.245766
D71R1 7 9 7R	50.734	0.525126	4.9916	5.9441	0.13031	15.5028	21.964	0.183444
D71R1 7 9 8M	51.4045	0.565019	2.34465	9.46785	0.353332	15.5519	19.3949	0.28258
E41R2 6 8 1C	52.6271	0.425762	1.37341	11.0667	0.5304	14.3533	19.3099	0.276486
E41R2 6 8 2C	52.412	0.412348	1.54351	10.2185	0.398153	15.3014	19.2159	0.2368
E41R2 6 8 3C	52.4612	0.47021	1.81103	10.3249	0.426747	14.8192	19.3308	0.260287
E41R2 6 8 4C	51.9347	0.521642	2.03407	10.7677	0.417781	14.7934	19.0001	0.266049
E41R2 6 8 5M	52.6616	0.417304	1.32489	10.1575	0.439624	15.1217	19.321	0.277579
E41R2 6 8 6C	51.7078	0.610696	2.64383	10.5263	0.389973	15.2801	18.6362	0.265899
E41R2 6 8 7M	52.7338	0.458877	1.63063	10.7111	0.471367	14.5456	19.5951	0.266577
E41R2 6 8 8C	51.8969	0.550113	2.328	9.56723	0.321843	15.2818	19.5971	0.263857
E41R2 21 24 1R	52.4571	0.456518	1.72067	9.81866	0.414965	15.3851	19.3029	0.239721
E41R2 21 24 2M	52.2566	0.534789	1.8572	10.7461	0.396328	14.828	19.194	0.279132
E41R2 21 24 3M	49.961	0.825335	5.08886	8.71133	0.235868	13.9455	21.0105	0.257906
E41R2 21 24 4M	52.5775	0.488321	1.77877	10.3613	0.44501	14.7718	19.7258	0.258787
E41R2 21 24 5C	52.5144	0.534363	2.03736	10.3099	0.376002	15.1841	18.9508	0.246007

E41R2 21 24 6C	53.106	0.479723	1.74481	9.95056	0.369748	15.5077	19.3365	0.242664
E41R2 21 24 7M	52.6276	0.450145	1.55689	10.4578	0.418555	14.9513	19.7196	0.2308
E41R2 21 24 8C	52.706	0.482842	1.52723	11.0314	0.492078	14.8351	19.2636	0.234965
E59R1 62 64 1C	52.8178	0.442946	1.84538	10.0208	0.327255	15.5401	19.3539	0.234941
E59R1 62 64 2M	52.7684	0.406744	1.17165	11.6906	0.486573	14.5454	18.9116	0.210088
E59R1 62 64 3R	52.3881	0.463347	1.5303	11.9	0.462394	14.6001	18.8507	0.236113
E59R1 62 64 4M	52.2983	0.430099	2.35956	9.8791	0.298771	15.3153	19.3933	0.240976
E59R1 62 64 5M	52.4047	0.438951	1.60207	11.211	0.46253	14.4174	19.1748	0.240736
E59R1 62 64 6M	52.4862	0.458609	1.58282	11.2638	0.437213	14.6977	19.0695	0.231645
E59R1 62 64 7M	52.3891	0.441399	1.4238	11.6197	0.442827	14.6487	18.9679	0.236823
E59R1 62 64 8M	52.5099	0.395993	1.53548	10.9958	0.412338	14.997	18.9356	0.255211
E72R5 0 4 1M	52.945	0.382432	2.90362	7.14692	0.199653	16.3552	20.5787	0.215223
E72R5 0 4 2M	52.498	0.535333	2.09326	9.51376	0.346049	15.2495	19.8234	0.253224
E72R5 0 4 3C	52.4767	0.487123	2.37639	8.63437	0.260558	15.977	19.8682	0.23246
E72R5 0 4 4M	51.8168	0.714773	2.68081	10.4638	0.353284	14.8004	19.1846	0.262352
E72R5 0 4 5R	51.9669	0.574956	2.31043	9.70934	0.334869	15.4795	19.8283	0.267899
E72R5 0 4 6M	52.4542	0.533376	2.12333	9.43112	0.318675	15.2806	19.9938	0.24969
E72R5 0 4 7M	52.5933	0.521847	1.98733	9.55975	0.347269	15.6891	19.6192	0.231272
E72R5 0 4 8M	52.6431	0.496347	1.89237	9.58956	0.341942	15.3862	19.965	0.248626

C2: Trace element chemistry

Label	P31	S34	K39	Sc45	V51	Cr52	Co59	Ni60	Cu65	Zn66	Rb85	Sr88	Y89	Zr90	Nb93	Cs133	Ba137	La139
D70R5 50 53 1M	<16.77	<234.17	<9.89	157.25	291.57	2.86	41.32	11.94	<1.33	69.34	<0.156	28.2	25.89	12.76	0.037	<0.022	<0.24	1.061
D70R5 50 53 4M	19.16	<277.99	<10.37	121.5	419.78	60.53	46.36	69.88	2.35	57.61	<0.144	26.59	15.43	14.27	0.031	<0.033	0.4	0.696
D70R5 50 53 5C	30.76	<281.75	<9.99	127.62	323.32	195.55	42.57	55.43	3.89	50.54	<0.142	23.2	16.71	13.42	0.06	<0.024	0.18	0.794
D70R5 50 53 7M	<23.67	<617.33	<18.50	79.46	219.59	5622.36	33.13	214.85	3.56	20.84	<0.23	23.51	4.24	2.82	<0.024	<0.044	<0.24	0.186
D70R5 50 53 8C	22.31	<577.14	<17.38	121.81	371.49	152.83	44.07	73.7	2.36	45.21	<0.22	21.45	13.16	10.72	<0.032	<0.037	0.33	0.555
D71R1 7 9 1C	47.31	<190.61	<9.19	115.51	301.1	1502.82	33.59	108.04	<1.13	33.31	<0.142	27.59	11.78	12.61	0.03	<0.038	<0.125	0.84
D71R1 7 9 2C	16.65	<166.27	<7.80	84.66	238.89	1743.52	29.21	168.51	1.41	12.06	<0.122	21.32	4.27	3.23	<0.0156	<0.029	<0.110	0.166
D71R1 7 9 3C	25.61	<202.10	<9.37	133.48	385.96	30.29	48.07	40.2	6.25	66.5	<0.144	21.95	19.99	12.36	0.0207	<0.019	0.5	0.667
D71R1 7 9 4M	44.34	<298.09	<12.74	161.06	410.89	115.44	44.17	34.4	3.46	59.09	<0.189	20.27	19.06	11.79	0.031	<0.031	<0.151	0.739
D71R1 7 9 5C	<22.80	<348.35	<14.31	121.51	313.9	384.31	38.45	89.39	1.69	27.39	<0.198	24.22	10.13	9.29	<0.038	<0.048	<0.127	0.483
D71R1 7 9 6M	22.59	<387.81	<15.13	131.23	347.6	37.07	41.44	43.25	<1.55	49.86	0.27	22.94	15.31	9.52	<0.035	0.074	0.45	0.7
D71R1 7 9 7R	53.49	<476.43	<18.18	135.29	407.99	1514.2	37.59	106.94	<1.69	27.29	<0.25	25.33	8.23	7.98	<0.032	<0.047	<0.295	0.31
D71R1 7 9 8M	28.99	454.54	15.08	132.46	294.86	5.55	47.74	21.09	2.24	73.15	<0.150	26.35	22.89	14.92	<0.026	<0.027	4.19	0.812
E41R2 6 8 1C	526.16	<59.42	<5.56	152.94	195.21	6.84	39.49	14.16	2.09	114.12	<0.080	12.48	53.79	17.72	<0.023	<0.0212	<0.134	1.47
E41R2 6 8 2C	13.48	76.02	29.27	108.54	220.26	11.4	44.39	39.41	4.1	84.52	<0.080	10.43	26.08	9.32	<0.019	<0.021	0.23	0.52
E41R2 6 8 3C	30.38	162.53	<5.41	119.36	259.51	13.68	43.95	30.96	2.78	97.57	<0.082	12.54	28.27	14.38	<0.027	<0.0182	0.37	0.62
E41R2 6 8 4C	11.7	<59.51	<5.45	108.42	324.25	39.53	44.91	50.75	<1.83	77.53	<0.078	12.67	24.53	11.09	<0.022	<0.022	<0.094	0.51
E41R2 6 8 5M	23.19	91.71	18.14	182.32	221.12	8.05	37.31	11.74	<1.72	108.87	0.19	11.74	49.15	26.48	<0.025	0.022	0.172	0.65
E41R2 6 8 6C	<9.38	106.03	104.12	109.1	344.84	10.43	48.71	31.89	2.96	75.09	0.43	11.03	22.99	12.08	0.025	<0.017	<0.141	0.419
E41R2 6 8 7M	22.78	71.58	<4.89	159.02	219.96	10.55	38.26	26.01	2.3	100.33	<0.082	13.55	40.66	15.8	0.019	<0.0155	<0.125	0.66
E41R2 6 8 8C	<9.48	<58.72	70.24	111.34	296.79	517.17	40.97	75.93	3.51	57.05	0.34	12.48	24.57	27.44	<0.022	<0.019	0.24	0.5
E41R2 21 24 1R	<22.09	598.88	<13.78	149.28	253.89	13.62	41.86	29.49	2.26	87.09	<0.183	13.29	32.35	15.93	<0.039	<0.043	<0.26	0.62
E41R2 21 24 2M	34.48	<475.45	<14.08	151.12	280.74	23.29	43.16	42.89	3.01	97.46	<0.217	13.49	34.55	14.78	<0.028	<0.041	<0.32	0.647
E41R2 21 24 3M	40.65	<324.19	<9.34	217.35	524.27	44.3	33.75	13.4	<1.25	38.22	<0.146	16.98	26.73	17.64	0.022	<0.030	0.3	0.482
E41R2 21 24 4M	30.47	482.66	<12.64	163.41	246.13	10.42	41.27	26.71	<1.80	92.94	<0.183	13.94	38.63	16.13	<0.032	<0.036	0.069	0.658
E41R2 21 24 5C	37.34	<444.99	<12.06	147.27	302.54	56.26	45.02	52.69	2.69	75.6	<0.20	12.59	31.36	14.8	<0.036	<0.029	<0.15	0.516
E41R2 21 24 6C	59.72	<453.67	<12.04	144.08	317.49	20.89	47.63	69.17	1.98	84.8	<0.182	14.55	31.77	13.84	0.0226	<0.033	0.3	0.5

E41R2 21 24 7M	35.75	<619.07	<15.68	166.72	223.14	9.35	40.41	23.6	<2.22	80.08	<0.213	13.05	36.98	12.89	<0.041	<0.055	0.082	0.6
E41R2 21 24 8C	65.31	<962.96	<23.58	176.5	277.12	7.04	45.65	27.75	<3.24	89.91	<0.38	13.49	47.6	20.14	<0.0280	0.112	0.25	0.831
E59R1 62 64 1C	29	121.35	<3.05	121.68	321.3	748.04	48.05	122.98	4.6	67.13	<0.046	10.73	20.13	9.34	0.0182	<0.0084	0.098	0.328
E59R1 62 64 2M	30.36	85	5.2	162.15	214.32	7.02	46.41	27.1	2.27	100.1	0.069	11.31	37.66	14.38	0.0265	<0.0112	<0.078	0.722
E59R1 62 64 3R	49.29	112	<3.34	160.51	237.01	7.12	52.04	28.6	3.9	111.22	<0.048	12.38	40.84	16.69	<0.0163	0.0158	0.171	0.733
E59R1 62 64 4M	29.25	59.12	<3.83	151.93	378.74	438.7	53.19	94.59	4.08	84.87	<0.057	14.11	27.33	13.58	0.045	<0.0156	0.49	0.463
E59R1 62 64 5M	19.76	<65.49	9.18	175.09	229.68	7.42	50.34	28.19	2	104.62	<0.068	12.29	43.45	16.55	<0.023	<0.0104	<0.137	0.729
E59R1 62 64 6M	38.23	134.79	<4.76	178.9	248.08	42.63	47.72	39.18	4.39	102.62	<0.065	12.01	43.3	17.09	<0.029	<0.0157	<0.113	0.704
E59R1 62 64 7M	57.82	74	6.48	180.23	401.66	15.48	45.29	31.13	3.28	110.37	0.044	10.71	33.52	20.48	<0.016	<0.0083	0.63	0.662
E59R1 62 64 8M	43.14	38.96	6.15	144.21	229.03	9.4	42.75	32.75	2.45	94.34	<0.050	11.11	34.64	15.62	<0.0120	<0.0091	0.33	0.66
E72R5 0 4 1M	<5.54	79.63	<3.50	114.27	392.34	1576.32	47.75	106.1	4.2	44.73	<0.054	16.11	10.74	5.14	<0.0178	<0.0108	0.281	0.239
E72R5 0 4 2M	33.78	156.57	179.22	147.77	319.38	0.62	47.52	14.7	4.86	81.28	0.285	19.92	25.97	12.98	0.07	0.0272	3.48	0.712
E72R5 0 4 3C	19.6	136.77	26.31	132.88	422.19	17.89	51.06	112.4	1.51	58.81	0.075	14.91	15.93	7.38	<0.0135	<0.0115	0.89	0.413
E72R5 0 4 4M	46.73	66.47	11.05	186.38	395.56	2.1	43.35	13.62	2.71	73.78	<0.059	15.94	40.79	20.96	<0.016	<0.0119	0.297	1.051
E72R5 0 4 5R	18.44	157.91	5.7	171.76	346.76	2.97	46.91	14.48	3.34	71.13	<0.062	13.93	29.56	14.07	0.023	<0.0136	0.107	0.56
E72R5 0 4 6M	30.49	115.44	<3.61	162.36	348.28	1.56	48.35	16.52	5.79	79.14	0.067	18.4	31.2	14.19	<0.020	<0.0099	0.53	0.81
E72R5 0 4 7M	37.18	89.62	15.92	162.05	346.88	1.12	50.07	16.84	6.23	69.79	0.072	17.07	27.5	13.24	<0.0183	<0.0080	0.86	0.621
E72R5 0 4 8M	43.86	<80.78	8.43	180.11	382.82	<0.62	51.35	15.65	6.02	84.69	<0.088	18.56	34.88	16.17	<0.025	0.041	0.7	0.771

C3: Trace element chemistry cont

Label	Ce140	Pr141	Nd146	Sm147	Eu153	Gd157	Tb159	Dy163	Ho165	Er166	Tm169	Yb172	Lu175	Hf178	Ta181	Pb208	Th232	U238
D70R5 50 53 1M	4.42	1.035	6.57	3.05	1.14	3.83	0.715	4.64	1.063	2.77	0.318	2.15	0.317	0.92	0.02	0.148	<0.038	<0.0200
D70R5 50 53 4M	3.09	0.67	5.43	1.54	0.869	3.38	0.479	3.78	0.833	2.13	0.25	1.96	0.15	0.55	0.043	<0.156	<0.026	0.029
D70R5 50 53 5C	3.5	0.736	5.23	1.73	0.623	4	0.434	3.03	0.737	1.82	0.172	1.53	0.288	0.425	<0.0188	<0.135	<0.018	<0.0252
D70R5 50 53 7M	1.021	0.096	1.36	0.78	0.183	0.5	0.101	0.65	0.125	0.406	0.066	0.184	0.059	<0.050	<0.0228	<0.22	0.058	<0.00
D70R5 50 53 8C	1.93	0.573	3.68	1.13	0.568	1.88	0.204	3.15	0.419	1.44	0.292	0.98	0.169	0.333	<0.026	0.37	<0.034	<0.0281
D71R1 7 9 1C	3.27	0.774	4.31	1.63	0.619	2.37	0.377	2.72	0.536	1.21	0.203	1.3	0.061	0.58	<0.0214	<0.174	0.028	<0.035
D71R1 7 9 2C	0.871	0.246	1.05	0.443	0.222	0.75	0.08	0.56	0.217	0.379	0.051	0.242	0.058	0.162	<0.0133	<0.146	<0.0176	<0.0206
D71R1 7 9 3C	3.17	0.736	4.51	1.41	0.932	3.81	0.516	4.13	0.722	2.1	0.232	1.99	0.253	0.565	<0.0109	<0.189	0.0229	<0.025
D71R1 7 9 4M	3.13	0.842	6.05	2.2	0.994	3.39	0.592	4.21	0.93	2.81	0.266	2.03	0.348	1	0.0198	<0.21	<0.029	<0.035
D71R1 7 9 5C	2.27	0.626	3.38	1.06	0.507	2.01	0.292	2.04	0.55	1.15	0.168	0.85	0.156	0.57	0.0167	0.4	0.033	0.034
D71R1 7 9 6M	3.1	0.59	6.23	2.84	0.874	2.74	0.535	3.28	0.669	1.74	0.194	1.9	0.186	0.349	0.027	5.74	<0.041	<0.037
D71R1 7 9 7R	0.981	0.342	2.72	1.95	0.254	1.83	0.228	1.54	0.383	0.85	0.113	1.08	0.113	0.66	0.0171	0.42	0.045	<0.034
D71R1 7 9 8M	5.55	0.969	7.2	2.55	1.023	3.73	0.733	4.21	0.577	2.82	0.207	2.42	0.369	0.77	<0.0144	<0.17	<0.023	<0.0138
E41R2 6 8 1C	8.62	1.82	12.9	6.69	1.17	9.06	1.7	9.83	2.22	6.1	0.82	5.94	0.88	0.781	<0.0102	0.079	<0.0122	<0.0084
E41R2 6 8 2C	3.07	0.83	4.73	2.42	0.66	3.39	0.73	5.56	0.99	2.93	0.447	2.65	0.38	0.631	<0.0127	0.071	<0.0115	<0.0079
E41R2 6 8 3C	4.06	0.98	6.21	2.93	0.86	4.31	0.78	5.5	1.07	3.19	0.422	2.62	0.353	0.67	<0.0168	0.158	0.0177	<0.0105
E41R2 6 8 4C	3.32	0.82	5.42	2.63	0.79	3.48	0.65	4.49	0.95	2.64	0.442	2.46	0.39	0.488	<0.0145	0.076	<0.0082	<0.0088
E41R2 6 8 5M	4.69	1.19	8.47	5.23	1.07	6.78	1.22	8.78	1.92	5.52	0.79	4.91	0.8	1.67	<0.0109	0.439	<0.0115	<0.0080
E41R2 6 8 6C	3.13	0.64	5.19	2.43	0.72	3.52	0.68	3.94	0.85	2.76	0.272	2.46	0.39	0.71	0.0042	0.076	<0.0150	<0.0097
E41R2 6 8 7M	4.22	1.05	8.13	4.09	1.04	4.93	0.96	7.25	1.49	4.21	0.59	4.04	0.67	0.73	<0.0104	0.074	<0.0091	<0.0065
E41R2 6 8 8C	2.7	0.63	4.52	2.2	0.54	2.75	0.54	3.82	0.83	2.39	0.382	2.4	0.421	0.76	<0.0094	0.123	0.0297	<0.0120
E41R2 21 24 1R	3.21	0.773	6.41	3.1	0.882	4.09	0.899	7.25	1.314	3.72	0.521	3.3	0.471	0.95	<0.0213	<0.23	<0.040	<0.028
E41R2 21 24 2M	3.73	0.854	7.34	3.58	1.092	6.24	1.142	7.64	1.42	5.31	0.518	3.91	0.611	0.709	0.0242	<0.23	0.032	<0.045
E41R2 21 24 3M	2.5	0.558	4.12	2.43	0.962	3.38	0.76	4.38	0.847	2.63	0.363	1.99	0.309	0.84	<0.0089	<0.173	0.023	<0.0201
E41R2 21 24 4M	3.59	1.007	7.62	2.68	0.988	5.82	0.991	6.98	1.535	3.93	0.645	4.48	0.672	0.687	0.0164	<0.209	<0.034	<0.0192
E41R2 21 24 5C	3.51	0.785	6.61	2.92	0.948	5.05	0.812	7.32	1.69	4.69	0.827	3.88	0.465	0.81	<0.0221	<0.20	<0.024	<0.029
E41R2 21 24 6C	2.91	0.768	5.87	2.99	0.756	4.86	0.752	5.13	1.338	3.56	0.55	3.55	0.565	0.697	0.0106	<0.20	<0.031	<0.0176

E41R2 21 24 7M	3.68	1.04	6.63	3.96	1.082	5.25	1.124	6.53	1.726	4.17	0.559	3.96	0.53	0.78	0.0286	0.46	<0.032	<0.032
E41R2 21 24 8C	5.14	1.173	10.63	5.11	1.46	6.48	1.36	10.42	2.27	5.98	0.691	4.69	0.884	0.9	<0.026	0.68	<0.069	<0.059
E59R1 62 64 1C	2.23	0.571	4.09	2.25	0.557	2.8	0.577	3.33	0.819	2.45	0.348	2.14	0.351	0.531	<0.0049	0.064	<0.0077	<0.0033
E59R1 62 64 2M	4.65	1.22	8.3	3.94	0.97	5.94	1.1	8.16	1.6	4.63	0.59	3.83	0.648	0.713	<0.0082	0.054	<0.0063	0.005
E59R1 62 64 3R	4.76	1.04	7.54	3.86	0.96	5.37	1.1	7.81	1.48	4.55	0.639	3.92	0.6	0.96	0.0082	0.197	<0.0068	0.0055
E59R1 62 64 4M	3.21	0.87	4.58	2.25	0.68	3.97	0.651	4.63	0.86	3.03	0.475	2.64	0.457	0.558	<0.0097	0.127	0.0102	<0.0046
E59R1 62 64 5M	4.62	1.14	8.09	4.33	1.08	6.32	1.15	8.69	1.52	4.83	0.64	4.35	0.654	1.07	<0.0064	0.086	<0.0099	<0.0077
E59R1 62 64 6M	4.94	1.15	7.82	4.43	1.02	6.74	1.07	8.26	1.78	4.21	0.68	4.38	0.609	0.9	<0.0140	0.079	<0.0115	0.0026
E59R1 62 64 7M	4.73	1.3	7.54	4.44	0.84	5.5	0.99	7.12	1.36	4.02	0.63	3.58	0.518	1.68	0.0126	0.078	0.0112	0.0029
E59R1 62 64 8M	4.61	1.14	8.37	3.49	0.96	5.94	1.09	7.33	1.63	4.49	0.59	3.86	0.565	0.72	0.0158	0.203	<0.0045	0.0063
E72R5 0 4 1M	1.3	0.305	2.17	0.81	0.484	1.88	0.259	1.7	0.414	1.212	0.159	0.854	0.175	0.31	<0.0070	0.131	<0.0053	<0.0055
E72R5 0 4 2M	4.04	0.82	6.3	2.98	0.888	4.13	0.764	5.41	1.125	3.28	0.438	2.62	0.46	0.739	<0.0097	0.175	0.0146	0.0157
E72R5 0 4 3C	2.26	0.535	3.48	1.74	0.619	2.61	0.5	3.27	0.6	1.86	0.217	1.55	0.221	0.423	<0.0113	0.121	<0.0094	0.013
E72R5 0 4 4M	5.95	1.44	9.48	3.96	1.26	5.9	1.167	8.38	1.68	4.38	0.68	4.34	0.496	1.19	0.0155	0.439	<0.0102	<0.0043
E72R5 0 4 5R	3.65	0.721	6.23	3.3	0.82	3.98	0.864	6.5	1.228	3.73	0.511	3.26	0.408	0.923	<0.0105	0.067	0.0165	<0.0025
E72R5 0 4 6M	4.36	1.049	6.79	3.04	0.96	4.55	1.016	6.21	1.343	3.45	0.566	3.11	0.528	0.843	0.0095	0.123	0.0133	0.0118
E72R5 0 4 7M	3.69	0.821	5.87	3.03	0.876	4.53	0.868	5.32	1.086	3.1	0.365	2.74	0.433	0.591	<0.01	0.225	0.0219	0.0102
E72R5 0 4 8M	3.88	0.686	7.28	3.42	0.95	6.27	0.777	5.23	1.46	3.92	0.568	2.7	0.362	0.86	<0.0130	0.269	<0.0059	<0.0078

Appendix D: Partition Coefficients

Sample	La139	Ce140	Pr141	Nd146	Sm147	Eu153	Gd157	Tb159	Dy163	Ho165	Er166	Tm169	Yb172	Lu175
17F2W 108109 I Enriched	0.222	0.529	0.748	1.245	1.676	1.357	2.797	2.973	2.437	2.951	2.337	2.750	2.452	2.454
17F2W 108109 I Depleted	0.235	0.523	0.814	1.315	2.113	1.437	3.197	3.000	3.587	3.255	2.312	2.783	2.616	2.380
21F2 5 7 A-Glass 1	0.071	0.156	0.249	0.368	0.758	0.879	0.885	0.922	0.897	1.115	0.866	0.718	0.712	0.761
21F2 5 7 B Enriched	0.150	0.278	0.444	0.593	1.235	0.609	1.855	1.422	1.473	1.986	1.948	2.000	1.815	2.365
21F2 5 7 B Depleted	0.127	0.275	0.406	0.559	1.148	0.586	1.441	1.583	1.550	1.745	1.716	2.444	1.811	2.236
21F2 5 7 C1 Enriched	0.181	0.344	0.587	0.821	1.574	1.238	2.281	1.555	1.664	2.234	1.801	1.212	1.697	2.000
21F2 5 7 C1 Depleted	0.153	0.341	0.537	0.774	1.464	1.190	1.771	1.730	1.751	1.964	1.587	1.481	1.693	1.891
21F2 5 7 C2 Enriched	0.072	0.130	0.250	0.307	0.613	0.520	1.043	0.805	0.817	1.055	1.118	0.848	1.000	0.962
21F2 5 7 C2 Depleted	0.061	0.128	0.229	0.289	0.570	0.500	0.810	0.896	0.860	0.927	0.985	1.037	0.998	0.909
21F2 5 7 D Enriched	0.192	0.370	0.616	0.812	1.555	1.277	2.327	1.938	2.031	2.290	2.482	1.773	1.945	2.250
21F2 5 7 D Depleted	0.162	0.367	0.564	0.766	1.445	1.229	1.807	2.157	2.138	2.012	2.186	2.167	1.940	2.127
32X1 83 84 A Enriched	0.077	0.070		0.244		0.282	0.242	0.805	0.454	0.449	0.709	0.766	0.755	
32X1 83 84 A Depleted	0.080	0.083		0.272		0.494	0.383	1.051	0.785	0.667	0.707	0.980	0.929	
32X1 83 84 C Enriched	0.044	0.113	0.217	0.181	0.246	0.373	0.479	0.556	0.754	0.643	0.614	0.607	0.656	0.946
32X1 83 84 C Depleted	0.046	0.134	0.360	0.201	0.551	0.654	0.757	0.725	1.303	0.955	0.612	0.777	0.807	0.755
32X1 83 84 E Enriched	0.056	0.105	0.160	0.244	0.173	0.331	0.584	0.484	0.469	0.684	0.759	0.963	0.647	1.059
B32X1 83 84 E Depleted	0.058	0.124	0.266	0.272	0.388	0.580	0.923	0.632	0.810	1.015	0.757	1.231	0.796	0.845

Appendix E: Calculated Liquid Compositions for deeper units (REEs only). Highlighted rows indicate liquid calculations were Sm/La ratio of Unit I sample matched that of deeper unit sample.

Label	K Level	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
D70R5 50 53 1M Low	Medium K	101.75	103.01	69.71	79.43	119.12	71.80	79.53	40.92	41.55	43.36	28.29	21.21	20.64	17.07
D70R5 50 53 1M High	Medium K	23.32	19.48	18.10	17.51	13.09	15.85	10.65	9.18	8.82	8.50	6.98	5.27	6.87	5.45
D70R5 50 53 4M Low	Medium K	66.74	72.01	45.12	65.65	60.15	54.73	70.19	27.41	33.85	33.98	21.75	16.67	18.82	8.08
D70R5 50 53 4M High	Medium K	15.30	13.62	11.72	14.47	6.61	12.08	9.40	6.15	7.19	6.66	5.36	4.14	6.26	2.58
D70R5 50 53 5C Low	Medium K	76.14	81.57	49.57	63.23	67.57	39.24	83.06	24.84	27.13	30.06	18.59	11.47	14.69	15.51
D70R5 50 53 5C High	Medium K	17.45	15.42	12.87	13.94	7.43	8.66	11.12	5.57	5.76	5.90	4.58	2.85	4.89	4.95
D70R5 50 53 7M Low	Medium K	17.84	23.79	6.47	16.44	30.46	11.53	10.38	5.78	5.82	5.10	4.15	4.40	1.77	3.18
D70R5 50 53 7M High	Medium K	4.09	4.50	1.68	3.62	3.35	2.54	1.39	1.30	1.24	1.00	1.02	1.09	0.59	1.01
D70R5 50 53 8C Low	Medium K	53.22	44.98	38.59	44.49	44.13	35.78	39.04	11.68	28.20	17.09	14.71	19.48	9.41	9.10
D70R5 50 53 8C High	Medium K	12.20	8.50	10.02	9.81	4.85	7.90	5.23	2.62	5.99	3.35	3.63	4.84	3.13	2.90
D71R1 7 9 1C Low	Medium K	80.55	76.21	52.13	52.11	63.66	38.99	49.21	21.58	24.35	21.86	12.36	13.54	12.48	3.28
D71R1 7 9 1C High	Medium K	18.46	14.41	13.54	11.49	7.00	8.61	6.59	4.84	5.17	4.29	3.05	3.36	4.15	1.05
D71R1 7 9 2C Low	Medium K	15.92	20.30	16.57	12.69	17.30	13.98	15.57	4.58	5.01	8.85	3.87	3.40	2.32	3.12
D71R1 7 9 2C High	Medium K	3.65	3.84	4.30	2.80	1.90	3.09	2.09	1.03	1.06	1.74	0.95	0.84	0.77	1.00
D71R1 7 9 3C Low	Medium K	63.96	73.88	49.57	54.52	55.07	58.70	79.11	29.53	36.98	29.45	21.45	15.47	19.10	13.62
D71R1 7 9 3C High	Medium K	14.66	13.97	12.87	12.02	6.05	12.96	10.59	6.63	7.85	5.78	5.29	3.84	6.36	4.35
D71R1 7 9 4M Low	Medium K	70.87	72.94	56.71	73.14	85.92	62.61	70.39	33.88	37.70	37.94	28.70	17.74	19.49	18.74
D71R1 7 9 4M High	Medium K	16.24	13.79	14.73	16.12	9.44	13.82	9.42	7.60	8.00	7.44	7.08	4.41	6.48	5.98
D71R1 7 9 5C Low	Medium K	46.32	52.90	42.16	40.86	41.40	31.93	41.74	16.71	18.27	22.43	11.74	11.21	8.16	8.40
D71R1 7 9 5C High	Medium K	10.61	10.00	10.95	9.01	4.55	7.05	5.59	3.75	3.88	4.40	2.90	2.78	2.71	2.68
D71R1 7 9 6M Low	Medium K	67.13	72.24	39.74	75.32	110.92	55.05	56.90	30.62	29.37	27.29	17.77	12.94	18.24	10.01
D71R1 7 9 6M High	Medium K	15.38	13.66	10.32	16.60	12.19	12.15	7.62	6.87	6.23	5.35	4.38	3.21	6.07	3.20
D71R1 7 9 7R Low	Low K	29.73	22.86	23.03	32.88	76.16	16.00	38.00	13.05	13.79	15.62	8.68	7.54	10.37	6.08
D71R1 7 9 7R High	Low K	6.81	4.32	5.98	7.25	8.37	3.53	5.09	2.93	2.93	3.06	2.14	1.87	3.45	1.94
D71R1 7 9 8M Low	Medium K	77.87	129.34	65.26	87.04	99.59	64.43	77.45	41.95	37.70	23.54	28.80	13.81	23.23	19.87
D71R1 7 9 8M High	Medium K	17.84	24.45	16.95	19.19	10.94	14.23	10.37	9.42	8.00	4.62	7.10	3.43	7.73	6.34
E41R2 6 8 1C Low	Medium K	140.97	200.89	122.58	155.95	261.29	73.69	188.13	97.30	88.02	90.56	62.30	54.69	57.02	47.38

E41R2 6 8 1C High	Medium K	32.30	37.98	31.83	34.38	28.71	16.27	25.19	21.84	18.69	17.76	15.36	13.58	18.97	15.12
E41R2 6 8 2C Low	Medium K	49.87	71.55	55.90	57.18	94.52	41.57	70.39	41.78	49.78	40.38	29.92	29.81	25.44	20.46
E41R2 6 8 2C High	Medium K	11.43	13.53	14.52	12.60	10.39	9.18	9.42	9.38	10.57	7.92	7.38	7.40	8.46	6.53
E41R2 6 8 3C Low	Medium K	59.46	94.62	66.00	75.08	114.44	54.17	89.50	44.64	49.25	43.65	32.58	28.15	25.15	19.01
E41R2 6 8 3C High	Medium K	13.63	17.89	17.14	16.55	12.58	11.96	11.98	10.02	10.45	8.56	8.03	6.99	8.37	6.07
E41R2 6 8 4C Low	Low K	48.91	77.37	55.23	65.52	102.72	49.76	72.26	37.20	40.20	38.75	26.96	29.48	23.62	21.00
E41R2 6 8 4C High	Low K	11.21	14.63	14.34	14.44	11.29	10.99	9.68	8.35	8.54	7.60	6.65	7.32	7.86	6.70
E41R2 6 8 5M Low	Low K	62.33	109.30	80.15	102.40	204.26	67.39	140.79	69.82	78.61	78.32	56.37	52.69	47.14	43.07
E41R2 6 8 5M High	Low K	14.28	20.67	20.81	22.57	22.45	14.88	18.85	15.67	16.69	15.36	13.90	13.08	15.68	13.75
E41R2 6 8 6C Low	Low K	40.18	72.94	43.10	62.74	94.91	45.35	73.09	38.92	35.28	34.67	28.19	18.14	23.62	21.00
E41R2 6 8 6C High	Low K	9.21	13.79	11.19	13.83	10.43	10.01	9.79	8.73	7.49	6.80	6.95	4.50	7.86	6.70
E41R2 6 8 7C Low	Low K	56.58	75.97	55.23	69.64	108.97	51.02	92.20	41.21	48.53	44.87	32.48	25.48	30.05	19.06
E41R2 6 8 7C High	Low K	12.97	14.36	14.34	15.35	11.97	11.26	12.34	9.25	10.30	8.80	8.01	6.33	10.00	6.08
E41R2 6 8 8C Low	Medium K	47.95	62.92	42.43	54.64	85.92	34.01	57.10	30.91	34.20	33.86	24.41	25.48	23.04	22.67
E41R2 6 8 8C High	Medium K	10.99	11.90	11.02	12.05	9.44	7.51	7.65	6.94	7.26	6.64	6.02	6.33	7.67	7.24
E41R2 21 24 1R Low	Low K	59.46	74.81	52.06	77.49	121.07	55.55	84.93	51.45	64.92	53.60	37.99	34.75	31.68	25.36
E41R2 21 24 1R High	Low K	13.63	14.14	13.52	17.08	13.31	12.27	11.37	11.55	13.78	10.51	9.37	8.63	10.54	8.09
E41R2 21 24 2M Low	Low K	62.04	86.93	57.52	88.74	139.82	68.78	129.57	65.36	68.41	57.92	54.23	34.55	37.54	32.90
E41R2 21 24 2M High	Low K	14.22	16.44	14.94	19.56	15.37	15.19	17.35	14.67	14.52	11.36	13.37	8.58	12.49	10.50
E41R2 21 24 3M Low	Low K	46.22	58.26	37.58	49.81	94.91	60.59	70.19	43.50	39.22	34.55	26.86	24.21	19.10	16.64
E41R2 21 24 3M High	Low K	10.59	11.02	9.76	10.98	10.43	13.38	9.40	9.76	8.33	6.78	6.62	6.01	6.36	5.31
E41R2 21 24 4M Low	Medium K	63.10	83.66	67.82	92.12	104.67	62.23	120.85	56.72	62.50	62.61	40.13	43.02	43.01	36.18
E41R2 21 24 4M High	Medium K	14.46	15.82	17.61	20.31	11.50	13.74	16.18	12.73	13.27	12.28	9.90	10.68	14.31	11.55
E41R2 21 24 5C Low	Low K	49.48	81.80	52.87	79.91	114.04	59.71	104.86	46.47	65.54	68.94	47.90	55.16	37.25	25.04
E41R2 21 24 5C High	Low K	11.34	15.47	13.73	17.61	12.53	13.18	14.04	10.43	13.91	13.52	11.81	13.70	12.39	7.99
E41R2 21 24 6C Low	Low K	47.95	67.82	51.72	70.96	116.78	47.62	100.92	43.04	45.93	54.58	36.36	36.68	34.08	30.42
E41R2 21 24 6C High	Low K	10.99	12.82	13.43	15.64	12.83	10.51	13.51	9.66	9.75	10.70	8.97	9.11	11.34	9.71
E41R2 21 24 7M Low	Low K	57.54	85.76	70.04	80.15	154.66	68.15	109.02	64.33	58.47	70.40	42.59	37.28	38.02	28.54
E41R2 21 24 7M High	Low K	13.19	16.22	18.19	17.67	17.00	15.05	14.60	14.44	12.41	13.81	10.50	9.26	12.65	9.11
E41R2 21 24 8M Low	Medium K	72.31	95.08	75.03	87.89	119.12	62.99	132.27	69.82	71.90	77.91	47.39	42.75	45.70	36.77

E41R2 21 24 8M High	Medium K	16.57	17.98	19.48	19.37	13.09	13.91	17.71	15.67	15.26	15.28	11.69	10.62	15.20	11.74
E59R1 62 64 1C Low	Low K	31.45	51.97	38.46	49.45	87.88	35.08	58.14	33.02	29.82	33.41	25.02	23.21	20.54	18.90
E59R1 62 64 1C High	Low K	7.21	9.83	9.99	10.90	9.66	7.75	7.78	7.41	6.33	6.55	6.17	5.76	6.83	6.03
E59R1 62 64 2M Low	Low K	69.24	108.37	82.17	100.34	153.88	61.10	123.34	62.96	73.06	65.27	47.28	39.35	36.77	34.89
E59R1 62 64 2M High	Low K	15.87	20.49	21.34	22.12	16.91	13.49	16.51	14.13	15.51	12.80	11.66	9.77	12.23	11.14
E59R1 62 64 3R Low	Low K	70.29	110.93	70.04	91.15	150.76	60.47	111.51	62.96	69.93	60.37	46.47	42.62	37.63	32.30
E59R1 62 64 3R High	Low K	16.11	20.97	18.19	20.09	16.57	13.35	14.93	14.13	14.85	11.84	11.46	10.58	12.52	10.31
E59R1 62 64 4M Low	Medium K	44.40	74.81	58.59	55.37	87.88	42.83	82.44	37.26	41.46	35.08	30.94	31.68	25.34	24.61
E59R1 62 64 4M High	Medium K	10.17	14.14	15.22	12.21	9.66	9.46	11.04	8.36	8.80	6.88	7.63	7.87	8.43	7.85
E59R1 62 64 5M Low	Low K	69.91	107.67	76.78	97.80	169.11	68.02	131.23	65.82	77.81	62.00	49.33	42.69	41.76	35.21
E59R1 62 64 5M High	Low K	16.02	20.36	19.94	21.56	18.58	15.02	17.57	14.77	16.52	12.16	12.16	10.60	13.89	11.24
E59R1 62 64 6M Low	Low K	67.51	115.12	77.45	94.54	173.02	64.25	139.96	61.24	73.96	72.61	42.99	45.35	42.05	32.79
E59R1 62 64 6M High	Low K	15.47	21.77	20.11	20.84	19.01	14.18	18.74	13.74	15.70	14.24	10.60	11.26	13.99	10.47
E59R1 62 64 7M Low	Low K	63.48	110.23	87.55	91.15	173.41	52.91	114.21	56.66	63.75	55.48	41.05	42.02	34.37	27.89
E59R1 62 64 7M High	Low K	14.55	20.84	22.74	20.09	19.06	11.68	15.29	12.72	13.53	10.88	10.12	10.43	11.43	8.90
E59R1 62 64 8M Low	Low K	63.29	107.43	76.78	101.19	136.31	60.47	123.34	62.38	65.63	66.49	45.85	39.35	37.06	30.42
E59R1 62 64 8M High	Low K	14.50	20.31	19.94	22.30	14.98	13.35	16.51	14.00	13.93	13.04	11.31	9.77	12.33	9.71
E72R5 0 4 1M Low	Medium K	22.92	30.30	20.54	26.23	31.64	30.49	39.04	14.82	15.22	16.89	12.38	10.61	8.20	9.42
E72R5 0 4 1M High	Medium K	5.25	5.73	5.33	5.78	3.48	6.73	5.23	3.33	3.23	3.31	3.05	2.63	2.73	3.01
E72R5 0 4 2M Low	Medium K	68.28	94.15	55.23	76.16	116.39	55.93	85.76	43.73	48.44	45.89	33.50	29.21	25.15	24.77
E72R5 0 4 2M High	Medium K	15.65	17.80	14.34	16.79	12.79	12.35	11.48	9.81	10.28	9.00	8.26	7.25	8.37	7.91
E72R5 0 4 3C Low	Medium K	39.60	52.67	36.03	42.07	67.96	38.99	54.20	28.62	29.28	24.47	19.00	14.47	14.88	11.90
E72R5 0 4 3C High	Medium K	9.08	9.96	9.36	9.27	7.47	8.61	7.26	6.42	6.22	4.80	4.68	3.59	4.95	3.80
E72R5 0 4 4M Low	Medium K	100.79	138.66	96.98	114.61	154.66	79.36	122.51	66.79	75.03	68.53	44.73	45.35	41.66	26.71
E72R5 0 4 4M High	Medium K	23.10	26.22	25.19	25.26	17.00	17.52	16.40	14.99	15.93	13.44	11.03	11.26	13.86	8.52
E72R5 0 4 5R Low	Low K	53.70	85.06	48.56	75.32	128.89	51.65	82.64	49.45	58.20	50.09	38.09	34.08	31.30	21.97
E72R5 0 4 5R High	Low K	12.31	16.08	12.61	16.60	14.16	11.40	11.07	11.10	12.36	9.82	9.39	8.46	10.41	7.01
E72R5 0 4 6M Low	Medium K	77.68	101.61	70.65	82.09	118.73	60.47	94.48	58.15	55.60	54.78	35.23	37.75	29.86	28.43
E72R5 0 4 6M High	Medium K	17.80	19.21	18.35	18.09	13.05	13.35	12.65	13.05	11.80	10.74	8.69	9.37	9.93	9.07
E72R5 0 4 7M Low	Medium K	59.55	85.99	55.29	70.96	118.34	55.18	94.07	49.68	47.63	44.30	31.66	24.34	26.30	23.31

E72R5 0 4 7M High	Medium K	13.65	16.26	14.36	15.64	13.01	12.18	12.59	11.15	10.11	8.69	7.81	6.05	8.75	7.44
E72R5 0 4 8M Low	Medium K	73.94	90.42	46.20	88.01	133.57	59.84	130.20	44.47	46.83	59.55	40.03	37.88	25.92	19.49
E72R5 0 4 8M High	Medium K	16.94	17.10	12.00	19.40	14.68	13.21	17.43	9.98	9.94	11.68	9.87	9.41	8.62	6.22