CARLETON UNIVERSITY

Rock Project Assignment

Suite 1: 08-LT-21

ERTH2104A
Igneous Systems, Geochemistry and Processes
Presented to Professor Brian Cousens

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Abstract

A petrographic description and geochemical analysis was done on 3 suites comprised of 33 igneous rock samples. Suite 1 was concluded to be from a Volcanic Island Arc tectonic setting. Suite 2 is from either an Ocean Island Basalt or Continental Margin Arc. Suite 3 is from a Continental Crust tectonic setting. A Total-Alkalis-Silica diagram (TAS) and Alkalis-FeO-Mg (AFM) diagram were created to help determine which suites were more basaltic or felsic, and which ones where calc-alkaline, alkaline, etc. Trace elements such as Rare Earth Elements were also analysed to determine which tectonic settings were more likely. The main sample that is described in this paper is 08-LT-21. This specimen's rock name is Olivine-bearing Basaltic Andesite. That said, this sample's chemical composition and petrographic description is a "median" of Suite 1. Finally, Suite 3 was determined to be the eldest suite with the most varying composition. In contrast, Suite 2 was the one with the least divergent petrographic descriptions and chemical compositions. Only a handful of major petrographic differences were found such as flow banding in 11-BV-53 and lithic fragments in 13-UH-04.

Results

Petrographic description

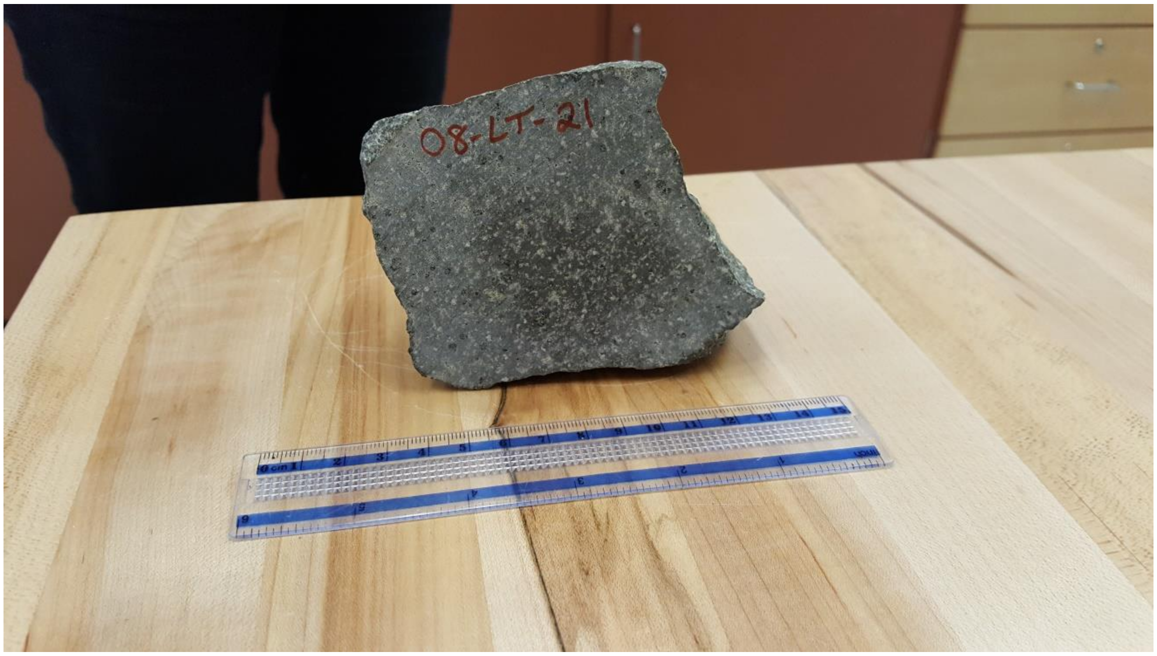

Figure 1: Hand-specimen #08-LT-21 with a ruler for scale.

Hand-specimen: The sample examined is 08-LT-21 from Suite 1. Using the orientation seen in Figure 1, the approximate dimensions are 8cm (width) x 11cm (height) x 6cm (thickness). It is porphyritic and non-vesicular. The general shade of grey seems to indicate it is from an intermediate igneous setting. Small phenocrysts were observed in a fine-grained medium grey aphanitic matrix. From this, a basic name could be "Andesitic porphyry". The matrix is too fine to be visually identified even with x10 magnification (hand lens). This implies it is from an extrusive/volcanic rock: frozen before are all crystals could completely form. The phenocrysts however were easily identified: it mainly consists of olivine, orthopyroxene (OPX) and plagioclase.

Olivine was identified through its cracked appearance, conchoidal-like fracture, its distinctive olive-green colour, vitreous lustre, transparent diaphaneity and its granular crystal habit. These grains were no greater than a few millimetres in diameter and are present throughout the sample. Orthopyroxene was identified by its dark green to black colour and mostly anhedral crystals. Cleavage could not be observed, but is visible in thin-section (discussed later). Plagioclase could be identified because of the white colour, its association with olivine and its hardness of about 6 on the Mohs scale (not scratched by pen knife).

The mineral percentage is approximately 15% olivine, 10% orthopyroxene, 25% plagioclase and 50% fine-grained matrix. The normalized values (without the matrix) indicated approximately 30% olivine, 20% orthopyroxene and 50% plagioclase. Based on this, a possible rock name is Olivine-bearing Basaltic Andesite.

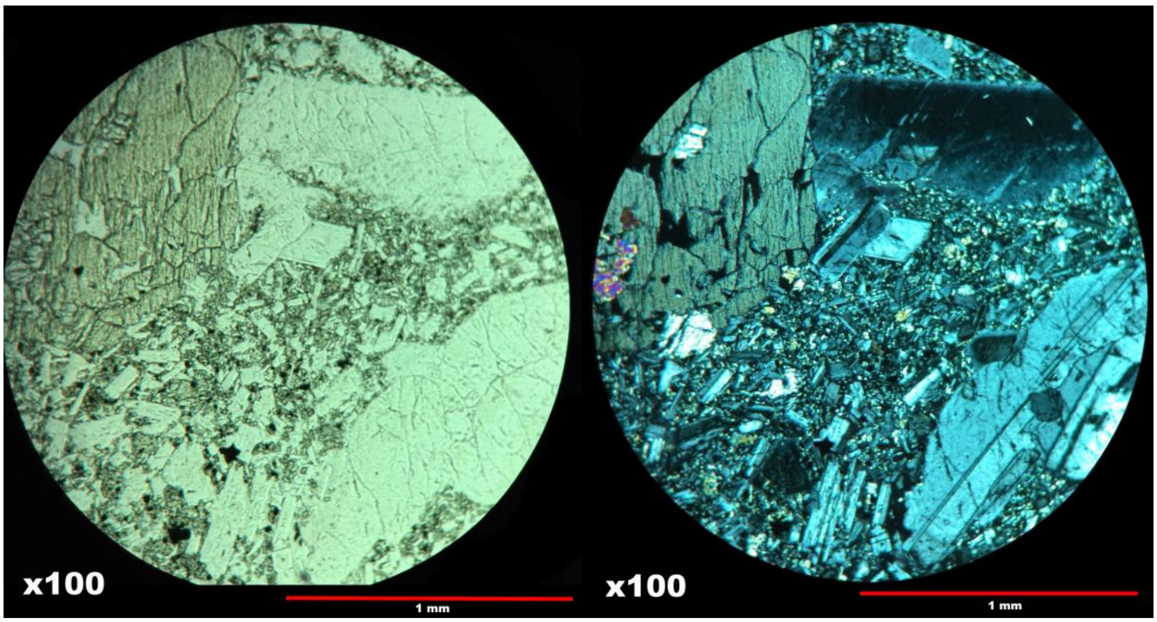

Figure 2: Thin-section of #08-LT-21 in PPL on the left and in XPL on the right with a Field of View (FOV) of approximately 2mm and magnification of 100x.

Thin-section: The observations made differ slightly from the previous description. The fine-grained grey matrix that could not be identified by the naked eye seems to be mainly plagioclase because it was the primary component of the fine-grained background mineral assemblage (with a few occasional large grains). The optical properties observed were very diagnostic: clear in Plain-Polarized Light (PPL) and showing polysynthetic twinning in Cross-Polarized Light (XPL). Orthopyroxene was identified since it exhibited parallel extinction, some exposed two cleavage planes at 90 degrees, thin wavy irregular exsolution lines and low birefringence. The Olivine grains were irregularly shaped (anhedral), display cracks and are transparent yet slightly green in PPL to light green in XPL. The remainder of the fine background grains were too small to identify using any diagnostic features. However, it was opaque in both PPL and XPL. Thus, it was concluded to be most probably titanium or iron oxides (confirmed by geochemistry). These characteristics can be seen in Figure 2. The observed mineral percentages are approximately 5% olivine, 15% orthopyroxene and 80% plagioclase with trace amounts of volcanic glass. Based on these observations in addition to the ones from the hand-specimen, the possible petrological name remains unchanged: an Olivine-bearing Basaltic Andesite.

Suite 1 Summary

All rocks within this suite showed an aphanitic matrix indicating they are of extrusive origin. Most, if not all, had a porphyritic texture with phenocrysts of plagioclase. Only a few of the samples of this suite had olivine phenocrysts (includes 08-LT-21). Based on the shade of grey of the samples, they clearly appear to be of a mafic to intermediate origin rather than felsic: somewhat evenly distributed within the basaltic to andesitic spectrum. However, there was a unique case of a rhyolite specimen. This shows that there is a significant level of chemical variability within this suite. That being said, all samples were plagioclase dominant. Out of the 15 samples in Suite 1, only 08-LT-12 had very many vesicles of about 0.5mm or less in diameter. In comparison, 08-LT-05 had fewer vesicles but they were, however, much larger: 3 to 5 mm in diameter. This sample also was much darker in colour: almost black in contrast to medium grey. Another unique case was 08-LT-19. This sample contains a large amount of volcanic glass: about 30 to 40%. Although, most of the samples did not have as much volcanic glass, all of them display a noticeable amount in thin-section. Specimen 08-LT-42 contains both clinopyroxene and orthopyroxene. By contrast, most had only orthopyroxene rather than both. Some opaque minerals such as titanium oxides, were, also observed. All in all, the entire suite was dominated by mafic associated minerals such as plagioclase, olivine and pyroxene (OPX and CPX).

Suite 2 Summary

The samples observed were mostly aphanitic with a porphyritic texture: therefor extrusive. All of them mainly have a mafic composition (observed by darker colour) with a few intermediate samples. Many of the samples have significant amounts of anhedral olivine phenocrysts. This is a rather diagnostic indicator that Suite 2 has a more mafic than intermediate composition *i.e.* more basaltic than andesitic. The plagioclase, observed under the microscope, was elongated. A unique case was 13-UH-04: it had lapilli-size lithic fragments with an average diameter of 5 to 6 mm. One of the elongated phenocrysts measured up to 1.6 mm. The rock name given is a lapilli tuff. The primary minerals observed were plagioclase, olivine and pyroxene.

Suite 3 Summary

The samples are aphanitic and porphyritic in texture. Plagioclase is the dominant mineral within Suite 3. A significant amount of the samples have olivine and most display vesicles. Of all suites, Suite 3 had the widest range of colours going from mafic to felsic. Sample 11-BV-53 displayed a unique trait of flow banding. Another unique case was 13-BV-04. In comparison to all the other rocks, this is the only sample with phenocrysts of about 4 mm in diameter spanning almost half of the rock's entire surface area. That being said, it is the only case that was observed to have significant amounts of visible biotite crystals. In thin-section, most of the minerals consisted of plagioclase, hornblende, biotite and even quartz. However, no pyroxene was found.

Comparison of all suites

In terms of the mafic to felsic spectrum, Suite 2, being exclusively mafic, was the least varying suite of all three. Suite 1 ranged from mafic to intermediate with the exception of a rhyolite. Suite 3 was by far the most extensive suite ranging from mafic all the way to felsic. In comparison to Suite 3, there are very few samples with vesicles in Suite 1. Suite 3 was the only one where biotite was observed. It was also the only one that showed unique case of flow banding. In contrast, Suite 2 seems to be the only one with the unique case of lithic lapilli size fragments. In summary, the plagioclase was the overall dominant component of all the studied samples. Suite 1 consists of mainly basalt to andesite. Suite 2 consists of mainly trachybasalt to basaltic trachyandesite. And finally, Suite 3 has samples of all kinds such as those from Suite 1 and Suite 2.

Major element composition

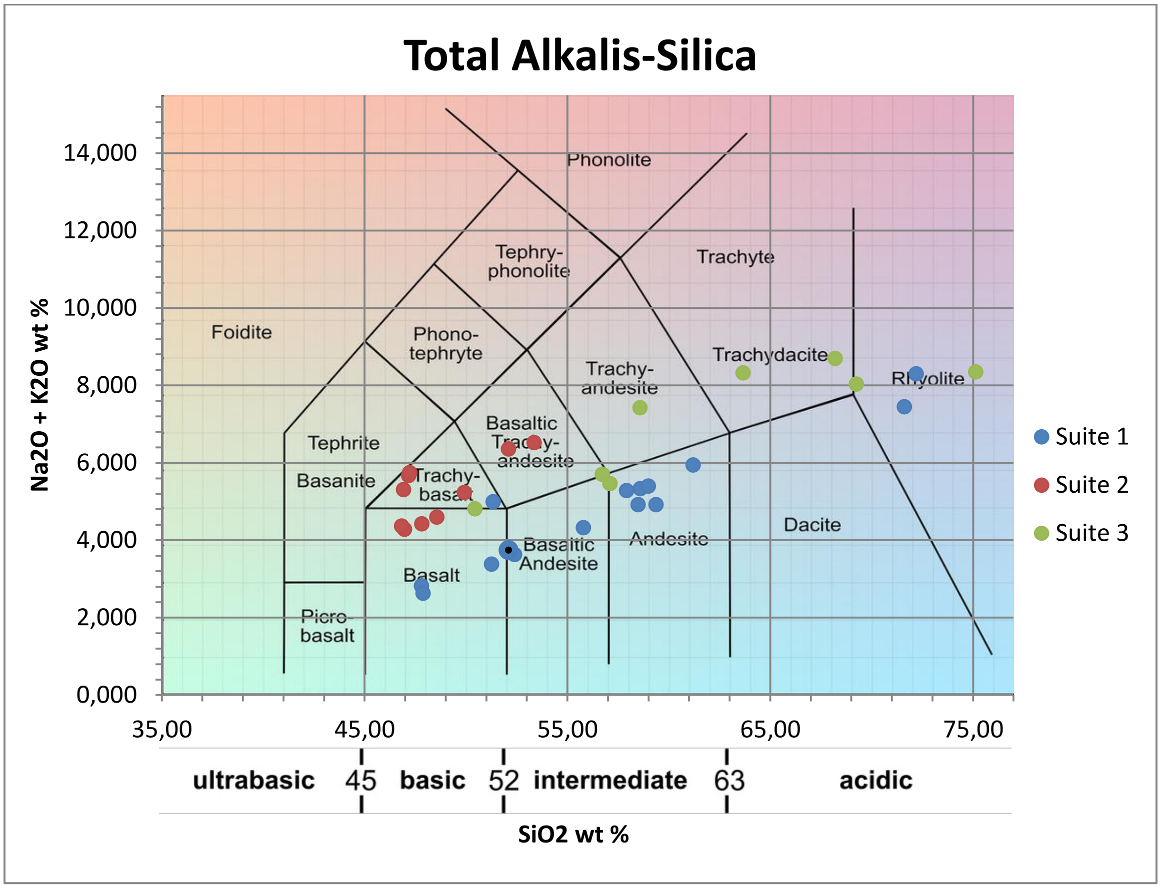

Figure 3: The International Union of Geological Sciences' (IUGS) Total Alkalis-Silica (TAS) chemical classification of volcanic rocks with plotted data from all suites. The black dot marks the sample 08-LT-21.

When looking at the Total Alkalis-Silica chemical classification diagram, many important observations can be made. The line that delimits Trachy-rocks from the basalt to dacite range, roughly conforms to the line between alkaline rocks and subalkaline rocks. Knowing this, we can confidently state that Suite 1 is subalkaline (with the exception of one or two samples). As well, Suite 2 is clearly alkaline. This can be observed in Figure 3. We also observe that sample 08-LT-21 is right on the border between basic (mafic) and intermediate (basaltic andesite to andesite) fields. In fact, sample 08-LT-21 has SiO_2 weight percent of 52.09% (not 52.00%) meaning it is a borderline Basaltic Andesite. This essentially confirms the petrographic observations: it is more or less intermediate. Thus, it is concluded that **08-LT-21 is Olivine-bearing**

Basaltic Andesite. Suite 1 seems to show a wide evolution from Basalt to Rhyolite. Similarly, Suite 3 also displays a wide range. However, it is spread out around the alkaline-subalkaline delimitation. In contrast, Suite 2 displays a narrower distribution ranging from Trachybasalt to Basaltic Trachyandesite.

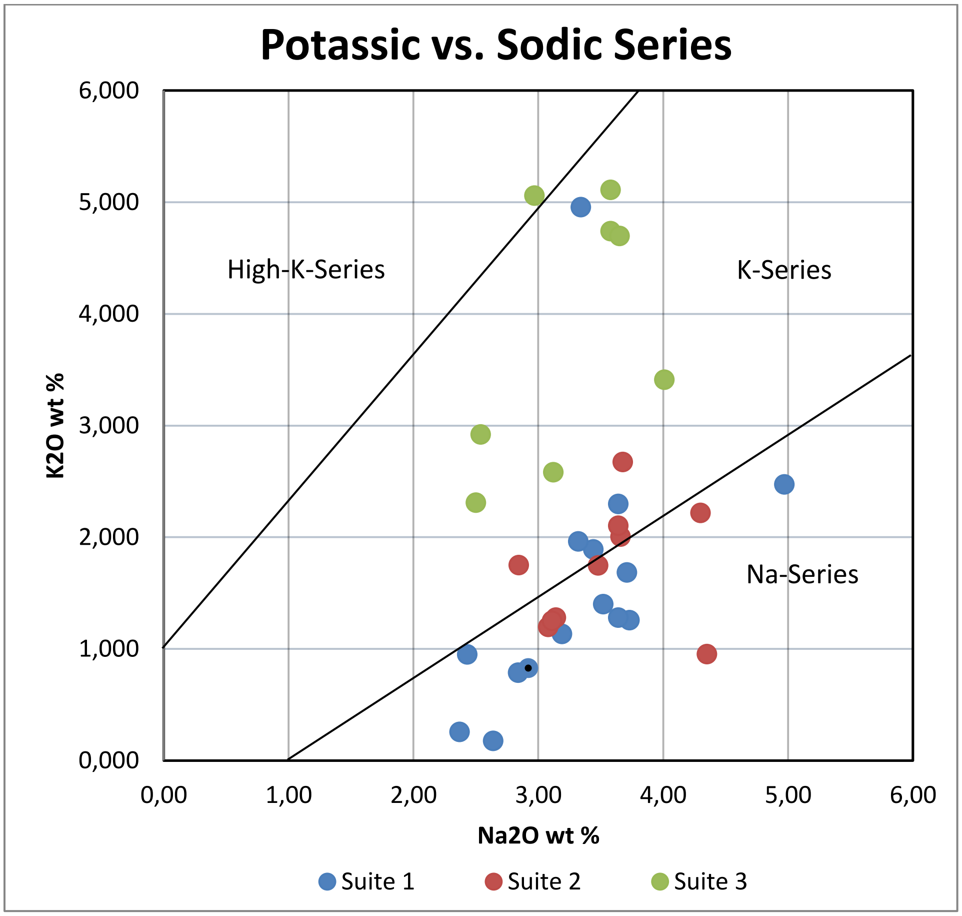

Figure 4: Potassic versus Sodic Series showing which alkalis are dominant in each suite. Black dot indicates sample 08-LT-21.

In Figure 4, one can observe that Suite 1 is primarily a Na-series dominated series with a few minor exceptions. The largest exception is 08-LT-32 which plots as a near High-K-Series. This sample, a Rhyolite, has a high silica content of about 72 wt.%. As with all the other near High-K-Series specimens, have high silica content. The range is from 68% to 75%. None of the mafic samples plot anywhere near the High-K-Series. On a separate not, Suite 2 seems to be tangential to the separation between the Na-series and K-series with a few exceptions. Last but not least, Suite 3 samples plot mainly as a K-series. That being said, sample 08-LT-21 plots in the Na-Series.

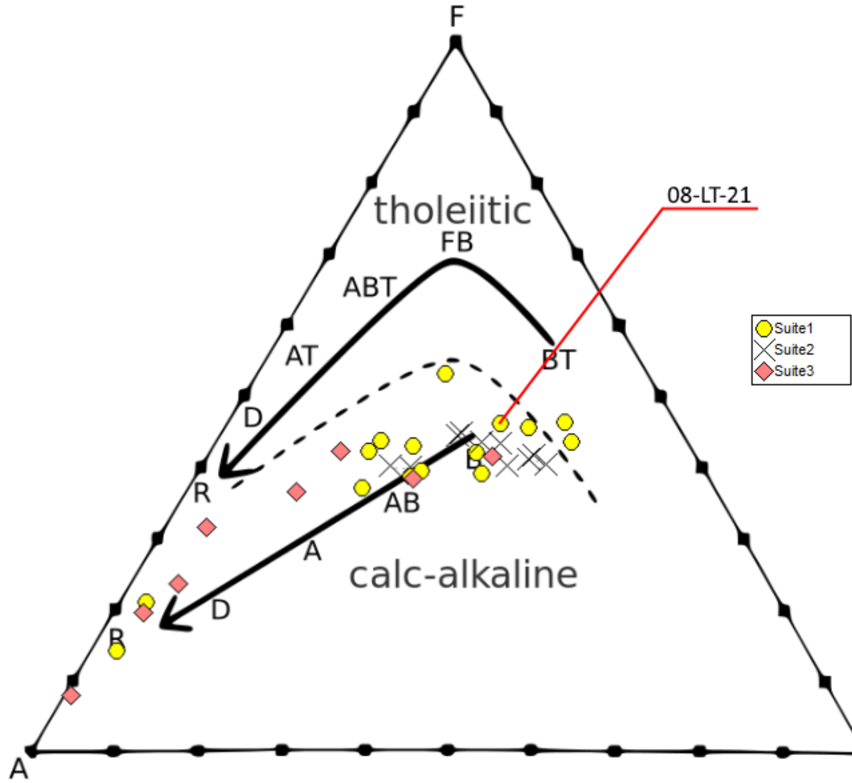

Figure 5: The Alkalis-Fe-Mg (AFM) diagram which plots rocks by K_2O+Na_2O (Alkalis), FeO and MgO. It shows the subalkaline trends: tholeiitic and calc-alkaline. (Template obtained from B. Cousens, 2017)

The Alkali-FeO-MgO diagram helps to subdivide the subalkaline series into tholeiitic and calc-alkaline magma series. It also shows the evolution from Basalt (termed as B) all the way to Rhyolite (termed as R). On this diagram all of the suites plot near the middle, with some progressively moving to a felsic composition. However, they all still plot in the calc-alkaline magma series with two exceptions. These two exceptions are plotted as more tholeiitic. Specimen 08-LT-21 is labelled in Figure 5 and is located near “B” (basalt) close to the centre. This means it is a calc-alkaline Medium-K magma series.

Harker diagrams

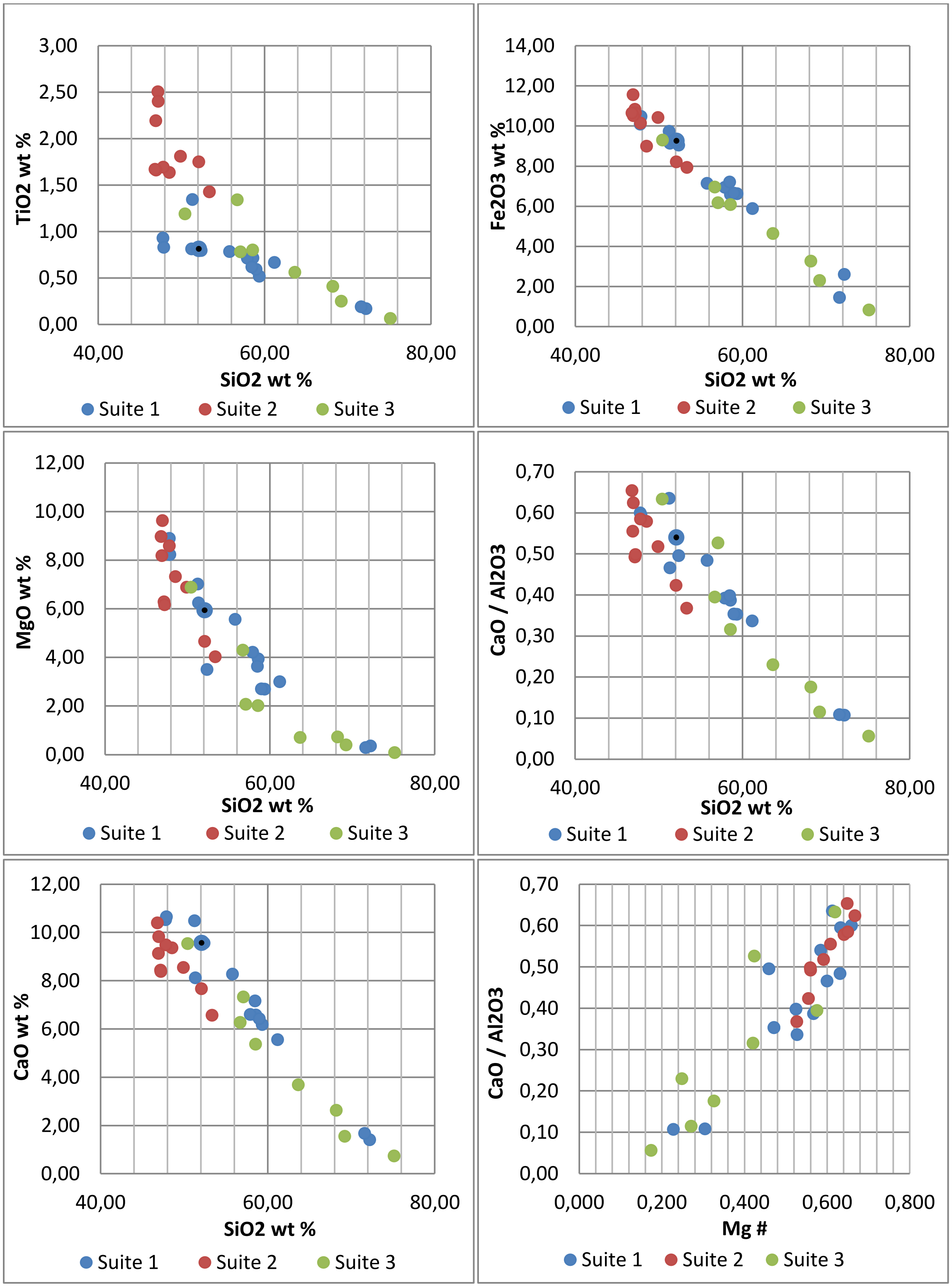

Figure 6: Several Harker diagrams showing clear trends of fractionation as the magma differentiates.

The Harker diagrams seen in Figure 6 show clear trends of minerals crystallizing as the magma evolves or differentiates. Most of them have been plotted by major elements as a function of the SiO_2. These relationships or correlations can help infer which specific minerals are crystallizing as the magma differentiates or in this case as the silica weight-percent increases. Harker diagrams assume that all rocks within a suite are related by fractional crystallization showing a clear trend, that each rock represents a liquid composition and that the parent magma is basalt from which other magmas will be derived. Since the diagrams in Figure 6 show very clear, distinct trends, based on these axioms, we believe that the sample is related by the fractionation of minerals. For example (Figure 6): as the silica weight-percent increases, the magnesium content decreases quite dramatically. This is mostly due to the crystallization of olivine. All three suites seem to follow a similar trend but differ in starting points and slope; this can be justified by the original melt compositions or by bulk composition. Moreover, what can be said, as the three suites evolved, is that the silica content increases *i.e.* becoming more "acidic" or "rhyolitic" (in other words, felsic). The downward trend of CaO/Al_2O_3 versus SiO_2 is most likely due to the fractionation of CPX or Hornblende.

Sample 08-LT-21: This specific sample contains (weight percentages) 52.09% SiO_2, 17.71% Al_2O_3, 9.57% CaO, 9.26% Fe_2O_3t* (*total), 5.94% MgO, 3.75% Alkalis (2.92% Na_2O + 0.838% K_2O) and 0.813% TiO_2 totalling a sum of about 99.1%.

Suite 1 (average): Although this suite had a relatively large range, the average composition was 57.14% SiO2, 17.08% Al_2O_3, 7.25% CaO, 7.26% Fe2O3t, 4.41% MgO, 4.87% Alkalis (3.31% Na_2O + 1.56% K_2O) and 0.699% TiO_2 totalling a sum of about 98.7%.

Suite 2 (average): As this suite did not cover such a large range, all its samples are relatively close to average composition of 48.69% SiO2, 16.70% Al_2O_3, 8.78% CaO, 9.99% Fe2O3t, 7.07% MgO, 5.25% Alkalis (3.53% Na_2O + 1.72% K_2O) and 1.87% TiO_2 totalling a sum of about 98.3%.

Suite 3 (average): This suite was the most varying: silica content ranged from a low 50.45% to a high 75.14%. Therefore, the average does not give very representative values, but in any case it does offer a midpoint which is helpful to infer a general setting. The average composition is 62.39% SiO2, 14.95% Al_2O_3, 4.64% CaO, 4.94% Fe2O3t, 2.14% MgO, 7.09% Alkalis (3.24% Na_2O + 3.85% K_2O) and 0.67% TiO_2 totalling a sum of about 96.8%.

Trace element composition

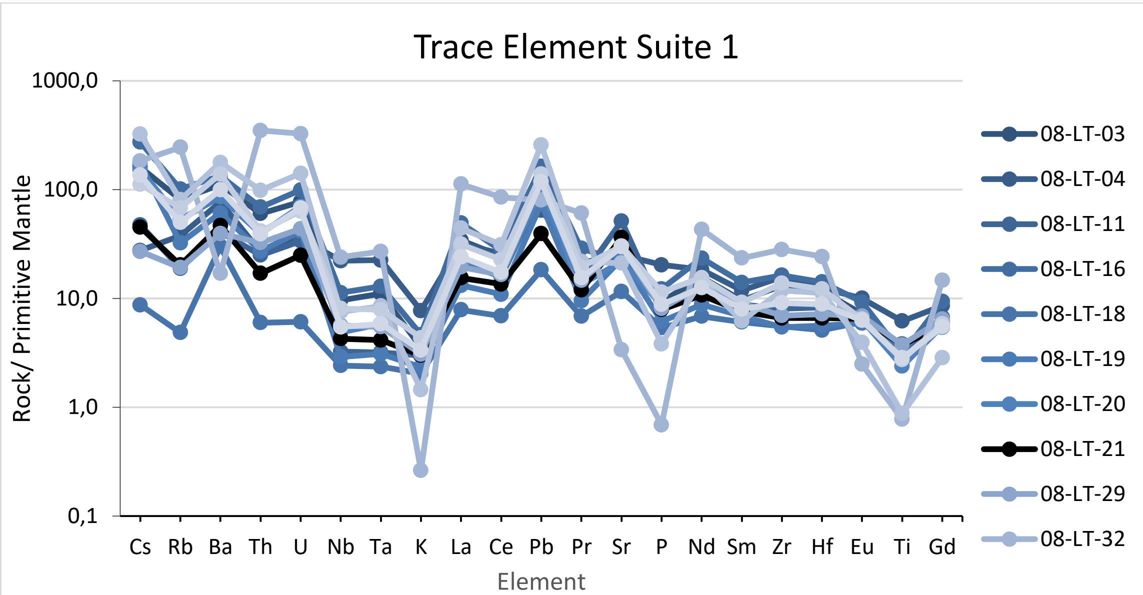

Figure 7: A Primitive Mantle (PRIMA)-normalized REE diagram for Suite 1. Sample 08-LT-21 is outlined in black.

The Primitive Mantle (PRIMA)-normalized diagrams are quite useful in characterising a tectonic setting. By assuming the parent magma is an evolved form of the primary magma that has undergone differentiation, we can observe the compatibility of the Rare-Earth-Elements (REE) and how they are depleted or incorporated. Looking at Figure 7, we can observe that there is a slight downwards slope towards the Heavy REEs (HREE). This is typical, as HREE are generally less compatible than are Light REEs (LREE). This can be better observed in Figure 8. Sample 08-LT-21 follows the general trend and does not appear to be an outlier. Additionally, we can observe a large drop in Niobium and Tantalum. This is typical for Continental Crust and Arc Basalt. This behaviour or trend can viewed more clearly with the comparison made in Figure 9.

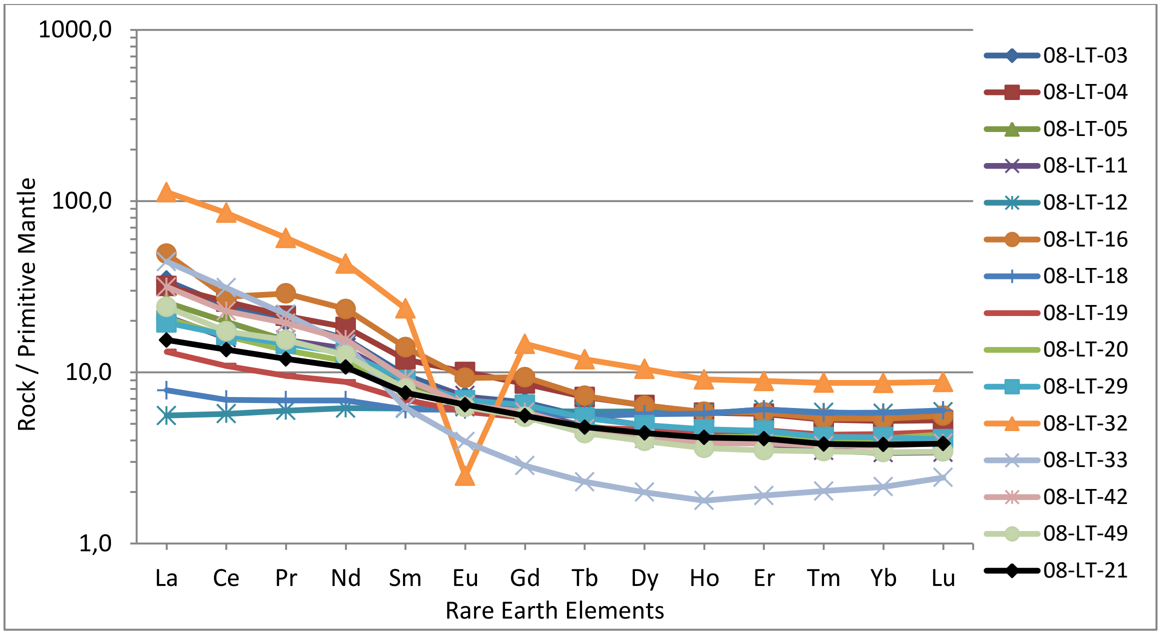

Figure 8: A PRIMA-normalized REE-only diagram of Suite 1.

The downwards slope leads to an almost flat plateau: this is typical of garnet crystallizing since it has high compatibility with HREEs. Another aspect to be noticed is the unique large Europium drop in sample 08-LT-32.

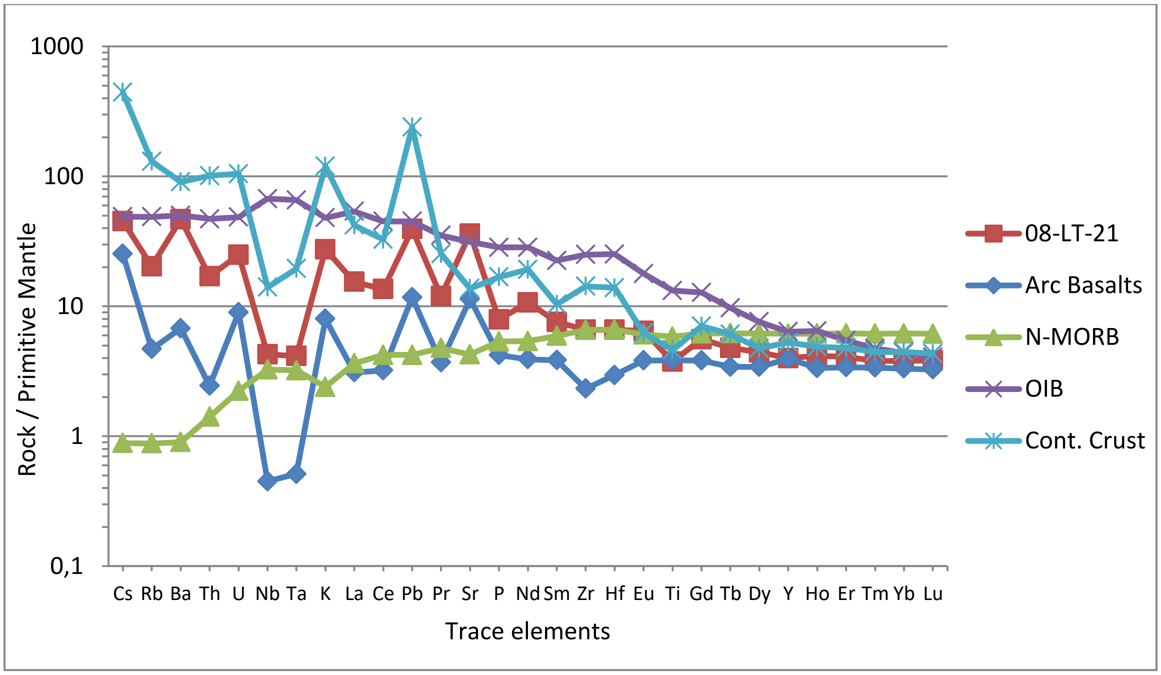

Figure 9: a PRIMA-normalized diagram showing a comparison of different settings.

In Figure 9, sample 08-LT-21 seems to be following the general trend described earlier. Consequently, 08-LT-21 is either from a Continental Crust or Arc Basalt setting.

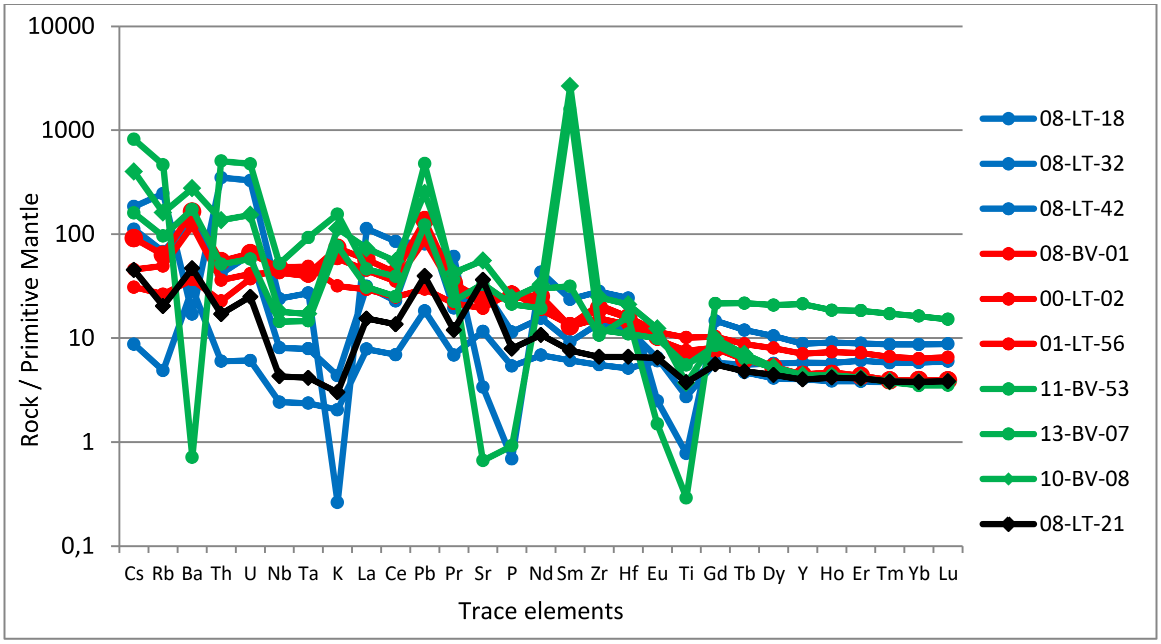

Figure 10: a PRIMA-normalized diagram displaying the general trends of all suites. Blue is Suite 1, Red is Suite 2, Green is Suite 3 and Black is sample 08-LT-21

As mentioned before, Suite 2 is the least varying of the three suites. This is exposed quite distinctively in the comparison to other suites shown in Figure 10. Suite 1 varies significantly but nowhere as much or as extensively as Suite 3. This large variance is most likely due to more extensive magma differentiation than in Suite 2.

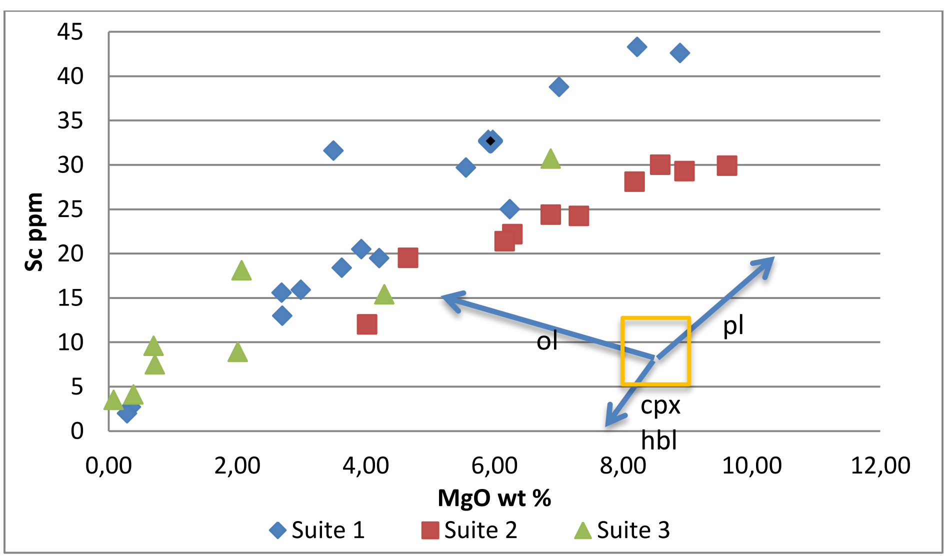

Figure 11: A Harker diagram of trace element Scandium ppm vs Mg# (Mg number). Black dot marks sample 08-LT-21.

Both the Harker diagram in Figure 11 and the CaO/Al_2O_3 vs. Mg# in Figure 6 have similar crystalizing trend going towards the left is probably olivine crystallizing, towards the top-right is plagioclase and towards the bottom-left is CPX or Hornblende. This is mainly as the magma mature (*i.e.* as Mg decreases), Calcium is used up by plagioclase and CPX. As the trace element Scandium partitions into CPX, we observe that CPX seems to be crystalizing in all three suites.

Isotope data

Suite 1 and Suite 2 mainly plot in the Ocean Island Basalt (OIB) field whereas Suite 3 plots near the Continental Crust field. This can be observed in Figure 12. In general, Suite 3 seems to be the one with the most evolved isotopic composition: highest $^{87}Sr/^{86}Sr$ ratio with the lowest $^{143}Nd/^{144}Nd$. This means Suite 3 has a greater age, followed by Suite 2 and finally Suite 1.

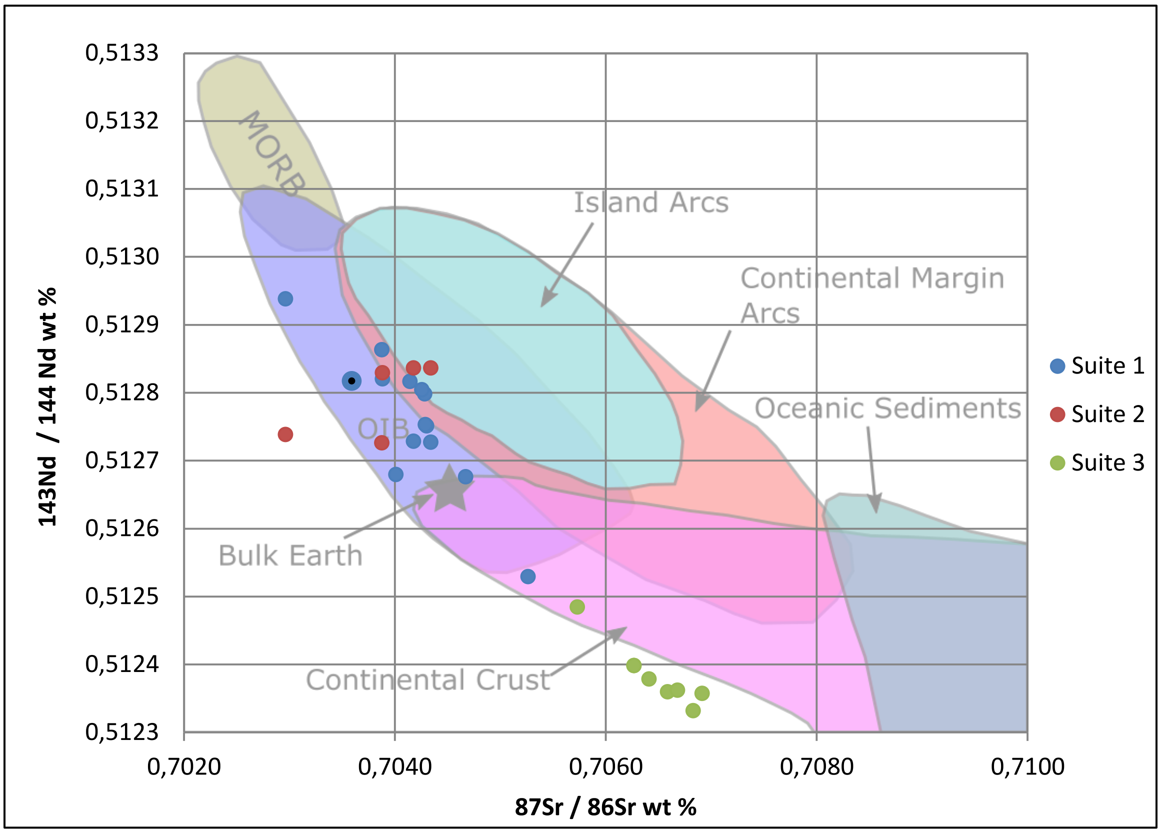

Figure 12: A Nd-Sr Isotope Plot for Mafic Volcanic Rocks with common settings. (Modified, based on original from S. A. Nelson, 2011)

If there is wall rock or crustal contamination, it is possible that the values in the graph are shifted towards the right: especially Suite 3 being completely outside of the fields. A test diagram with the values shifted to the left results in a near perfect fit for all suites.

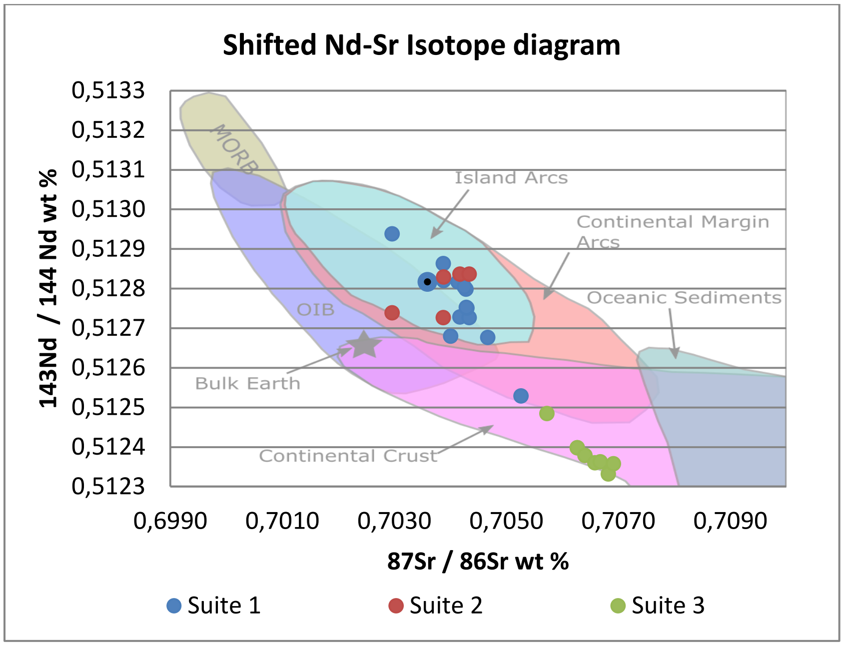

Figure 12B: the shifted version of Figure 12.

This modification confirms Suite 1 to be from an Island Arc setting, Suite 2 possibly an OIB or Island Arc and Suite 3 as Continental Crust (seen in Figure 12B). Otherwise, there would be a large contradiction with previous mentioned observations. However, it is possible there was contamination (such as wall rock) to cause all values to shift. If that is the case, it would still confirm Suite 1 as an Island Arc setting and make all suites conform reasonably well to the diagram.

Discussion

Firstly, 08-LT-21 (Figure 1) has been determined to be an Olivine-bearing Basaltic Andesite. This was confirmed with geochemical data (such as the TAS diagram in Figure 3) and petrographic observations. This sample fits within Suite 1 which generally ranges from basalt to andesite, with two exceptions of rhyolite. As for 08-LT-21, it can be considered as the median sample within this suite: as it does not exclude olivine and is a midpoint on a petrographic and geochemical level. As for Suite 2, it ranges from trachybasalt to basaltic trachyandesite. Suite 3 seems to have a little of everything: trachybasalt, andesite. trachydacite, and even rhyolite. Based on the major elements data, Suite 1 is subalkaline; more precisely calc-alkaline (cross-reference with the AFM diagram in Figure 5) with an average of 57%[1] silica content. Suite 2 is a somewhat alkaline series with an average of 49% silica content. Finally, Suite 3 is a on a tangent between subalkaline and alkaline. Its silica content averages 63%, but has a low value of 50.45% and a high value of 75.14%. With Harker diagrams we believe the magma evolves by fractionation from basalt. That said, as the magma differentiates it will increase in silica content. This behaviour can be observed in Figure 6. Thus, Suite 3 is the most evolved and Suite 2 the least. This can be observed in Figures 5 and 12. With respect to age, Suite 1 lies between Suite 2 and Suite 3. Additionally, the trends shown in Figure 6 confirm that the rocks are related by fractionation. The decreasing trends of TiO_2, MgO, Fe_2O_3t (t=total), CaO/Al_2O_3 or CaO, as SiO_2 increases, may be due to the fractionation of Ti-oxides, Olivine, Fe-Oxides (such as Magnetite or Hematite), and Plagioclase. The TAS diagram (Figure 3) is reflects to a certain extent a Harker diagram also. Bearing this in mind, alkali (Na_2O+K_2O) content seems to increase as SiO_2 content increases. Knowing these alkalis are not intergrated into the olivine, plagioclase or other oxides, it means that there is an increase in liquid. (B. Cousens, 2017). Therefore, the further the suite shifts towards the right ("acidic" as in 60%+ silica), the more the suite has undergone a greater degree of partial melting and evolution. The vesicles found are evidence of decompression melting where volatiles like gas escape from the magma.

[1] All percentages here are chemical weight percentages.

Characteristic Series	Plate Margin		Within Plate	
	Convergent	Divergent	Oceanic	Continental
Alkaline	Yes		Yes	Yes
Tholeiitic	Yes	Yes	Yes	Yes
Calc-alkaline	Yes			

Figure 13: A table showing the possible locations for characteristic series. (Obtained from B. Cousens, 2017).

Since Suite 1 is confirmed to be calc-alkaline. Therefore, it must be from a convergent plate margin setting. The LREEs in suite1 are not depleted like the HREEs are. Thus we have a classic fan shaped trend. As magma undergoes more partial melting, the magma will tend to be depleted in REEs: more of HREEs are depleted than LREEs since they are less compatible. Since there is a depletion slope (observed in Figure 8): suite 1 has clearly undergone partial melting.

Large-Ion Lithophile Elements (LILE) such as K, Rb, Cs, Ba are commonly accommodated by the main minerals of the mantle with the exception of K-Feldspar. High Field-Strength Elements (HFSE) such as Zr, Nb, Th, U do not substitute for the major element minerals (F. Albarède, 2003). For Suite 1, there are clear depletions of Nb, Ta, Ti and K: this is diagnostic of Island Arcs. Moreover, Nb, Ta, Ti are retained in the subducting slab mostly likely by minerals such as Rutile. (B. Cousens, 2017). This confirms that the suite is from a subduction zone such as an Island Arc. That being said, the other HFSE in 08-LT-21 are relatively in even amounts: no other anomalies to discuss. We know there was most probably water because LILEs are hydrophilic. Since there's only a large K depletion it could suggest a subduction zone within an ocean environment. As mentioned before, Suite 1 ranges from mafic to intermediate (Basalt to andesite). These should come from the deep mantle. Therefore it is more probable for an oceanic setting than a continental one: ruling out the Continental Crust setting. There was also a very significant Niobium and Tantalum depletion: this is typical for Continental Crust and Arc Basalt. Thus, suite is an Arc Basalt. The andesites found in Suite 1 had abundant plagioclase because water supresses the crystallization temperature. (B. Cousens, 2017).

On a separate note, the Nd-Sr isotope diagram in Figure 12 is one of clearest diagrams to distinctively tell the origin or type of the tectonic setting: other than the possible error of contamination discussed earlier. In Figure 12B, the shifted values plot Suite 1 as an Island Arc, Suite 2 as OIB (or Continental Margin Arc) and Suite as Continental Crust. It also clearly shows the most varying suite that is Suite 3 is in fact the eldest and the most modified. Suite 2 is in a general sense the youngest with Suite 1 being a little more modified or evolved. All the values seem to plot a little on the outside of all the fields: this is strong evidence that there could have been crustal contamination. Especially due to the outlier 08-LT-42 from Suite 1 which plots as a Continental Crust.

Conclusion

In conclusion, sample 08-LT-21 was identified as an Olivine-bearing Basaltic Andesite. It was plagioclase dominated under the form of the aphanitic texture and phenocrysts. There were also OPX and mainly Olivine phenocrysts. No vesicules were observed, however other samples in Suite 1 did have them. The general rock types found in Suite 1 was volcanic basalt to andesite. Knowing Suite 1 is calc-alkaline, is medium-K, has diagnostic Nb-Ta depletion, has evidence of a subduction within an ocean setting, we may conclude that 08-LT-21 is in fact from a Volcanic Island Arc. This is crossed-referenced and confirmed by the (shifted) Nd-Sr isotope diagram. Looking at all the suites, Suite 2 is OIB (or Continental Margin Arc) and does not vary in chemical composition as extensively as Suite 1or Suite 3 (which was found to be from a Continental Crust setting). Suite 2 had the most iron oxide content. Both Suite 2 and 3 had significantly more MgO than Suite 1: they are possibly from the deeper parts of the mantle.

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