Establishing the mantle sources of post glacial Icelandic basalts using trace element analysis

Student Dissertation

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Establishing the mantle sources of post glacial Icelandic basalts using trace element analysis

A Report submitted as the examined component of the Project Module SXG390

Practical Project
Abstract

Extensive vulcanism makes the mid-Atlantic ridge rise above water and form Iceland. Its basalt lavas are distinct and show compositional variation compared to normal ridge basalts. Understanding how they formed is of interest and can inform studies of similar areas. Establishing sources of the basalts is difficult because mixing of different magmas and other processes causes alteration so they have different compositions from their sources. This leads to debate. Depleted mantle, the main source of mid-ocean ridges and a deep mantle plume are widely accepted as prominent sources although some studies reject one or the other. A number of other potential sources are discussed. Ongoing studies are required to provide evidence so a consensus can be reached.

Here, geochemical data from twelve locations across Iceland is extracted from existing datasets. Trace element concentrations are compared to reference compositions with the aim of finding evidence in favour of both depleted mantle and mantle plume sources. Additional sources are also looked for. Results are corroborated with element and isotope ratio information.

Depleted mantle is found at most locations and deep plume melting in flank and southern rift zones. A third source, depleted in trace elements, is found most prominent in the northeast, but it contributes at all locations. Several SW/NE patterns suggest no other sources feed the rift areas, but an additional enriched source is found at Snæfellssnes, a flank. It may be part of the plume but there is contradicting evidence, so it remains unresolved. Trace element methods provide an indication of sources but require corroboration from several other analyses to enable confident conclusions. This will also be obtained if this study is repeated with significantly more data as part of a wider suite of geochemical, petrological, and seismic analysis.

(289 words)

List of Abbreviations

Central Rift Zone Eastern Rift Zone (ERZ) Northern Rift Zone (NRZ) Western Rift Zone (WRZ).
Öræfajökull Volcanic Zone (OVZ)  Snaefell Volcanic Zone (SVZ)  Snaefellsnes Volcanic Zone (SNVZ)  South Iceland Volcanic Zone (SIVZ).

Depleted Mantle (DM)  Enriched Mantle (EM)  High U/Pb mantle (HIMU)  Primitive Mantle (PrM)  Plume Mantle (PM)

Depleted MORB (D - MORB)  Enriched MORB (E-MORB).  Mid-ocean ridge basalt (MORB)  Normal (MORB N- MORB)

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1. Introduction

1.1 Current understanding, debates and uncertainties

Iceland is a sub-ariel segment of the mid-Atlantic ridge (Dick and Zhou, 2015). It is widely accepted it also lies on top of an active mantle plume (e.g., Rasmussen et al., 2020), and that plume/ridge interaction causes extensive vulcanism which continues to form the island. This unique geological setting is of much interest in its own right but studying the formation of Iceland can also further understanding about the opening of the Atlantic, of mid-ocean ridges and ocean islands. There is access to vast numbers of sites above ground unlike other locations which are largely or completely under water. For findings to be effectively applied elsewhere Icelandic research needs to be fully contextualised. This requires a comprehensive understanding of sources, settings and processes involved.

The source of an igneous rock is part of the Earth's mantle or crust that melts to make the magma that eventually forms it. Each has a distinct composition. All parts of the mantle for example can currently be described as, or as a combination of, four endmembers: HIMU is enriched in U. Depleted mantle (DM) is depleted in trace elements and EM1and EM2 are enriched (Guo et al., 2021). Trace elements can substitute for the main elements that form rock in miniscule amounts. The extent each element does differs and varies and in different conditions.
Trace element concentrations of a basalt can provide information about its source and the setting it melted in. However, each volcanic process alters these values (Figure 1.1) as conditions are changed. Mixing between melts from different sources prior to eruption (Neave et al., 2013) also alters the proportions of each element.

Understanding how concentrations are affected at each process and mix is required to accurately work back and find the source and melting setting. This is complex and the reason why there is much debate on the matter.

**Figure 1.1 Main processes that alter geochemical compositions. Not to scale. Author’s own.**

Two of the various settings that can force mantle to become sources and melt are focussed on here. Hot plumes originating near the Earth's core produce deep low volume magmas to rise. These interact the mantle types they encounter on ascent and form ocean island basalts (OIB). DM typically undergoes shallow high-volume decompression melting as the tectonic plates above move apart at mid-ocean ridges (MOR) and normal mid-ocean ridge basalt (N-MORB) is formed. Icelandic lavas form compositionally varied basalts different to the submarine N-MORB found to the north and south (Viccaro, Nicotra, and Urso, 2015) They are formed from at least one depleted and one enriched source. Some studies find two sources mixed in various proportions are enough to explain the variation (Koornneef et al., 2012). Others require at least three (Sigmarsson and Steinþórsson, 2007) or at least two enriched and two depleted (Thirlwall et al., 2004). Proposed sources additional to DM and plume material include slabs of subducted lithosphere contained in the upper mantle or in the deep mantle which get entrained in the ascending plume (Marshall et al., 2022). These can make both enriched and depleted mantle zones. Also, lower crust at the base of Iceland or material that has been altered when exposed to fluids (Eiler, Grönvold and Kitchen, 2000). Some studies find four plume source components explain the range and that DM doesn't contribute (Kokefelt et al., 2006). Others reject the existence of a plume based on seismic tomography studies and propose the enriched source is ancient, recycled crust, (Koornneef et al., 2012) or newer continental material (Foulger et al., 2020) which mixed in different proportions with DM. Seismic evidence of a weaker plume than is generally
accepted is presented (Yuan et al., 2020) as further evidence of continental material being a source.

1.2 Scope, justification and relevance of hypothesis

Given the debate and uncertainties, it is important to continue to study this subject. Often new research, (e.g., Geist et al., 2021), revisit areas previously studied because updated technology/techniques give more accurate values and make it possible to establish tighter constraints. Comparing existing and new data against developing interpretations as well as established knowledge advances understanding and provides evidence for or against viewpoints hopefully settling aspects of the debate.

The aim of this project is to investigate what the sources of Icelandic basalts are using trace element concentrations from existing data sets. Icelandic rift zones, (Figure 2.1) are associated with the mid-Atlantic ridge (Karson, 2017) so it is likely DM is a prominent depleting source. The existence of a plume with head beneath the centre of Iceland has been extensively evidenced (e.g., Metelkin et al, 2021). Plume melts are enriched with trace elements, so it is likely to be a prominent enriched source. Much mixing of sources or components of sources occur in different proportions prior to eruption, Winpenny and MacLennan, (2011) so it is unlikely other sources are required and work suggesting, for example, a continental, source have still to evidence its existence (Yuan, 2021). The hypothesis tested in this project therefore is:

Trace element analysis of postglacial Icelandic basalts indicate they are entirely formed from a combination of mantle plume material and depleted mantle from a mid-oceanic ridge setting.

Data for basalts less than 13000 years old from across the island is extracted. Vulcanism during this time occurs in rift zones and some off-rift (flank) areas (Figure 2.1). Both are included so a sample representative of the whole range of basalts is examined. Trace element concentrations are compared to widely accepted reference compositions of N-MORB and OIB to establish if both DM and plume material are present. Evidence of the existence or absence of other sources is inferred from differences between sample basalts and standard reference sets/interpretations.

2. Methods and Materials

2.1 Data set selection

Papers with accessible geochemical data sets are obtained through The Open University Library and Earth Chem database to create a sample without the systematic bias of any individual study. Data sets produced after 2000 are selected as they are assumed more accurate compared to older due to improved technology. Bulk rock analysis, pulverised basalt fragments analysed a mass spectrometer, are
selected as opposed to analyses of individual crystals or inclusions. This data is readily available and the type of data for each location is consistent.

To reduce complexities outlined in Figure 1.1 and facilitate comparisons, data for post-glacial, sub-ariel basaltic lavas is selected. Basalts are closer in composition to their source(s) than other lavas (Geist, 2021), and post eruption modification in underwater or glacial situations are not a factor. It is unlikely any significant change in source composition or melting regime has occurred during the short time period this study focuses on. Weathering and radioactive decay are also minimised as these are young rocks.

\%MgO (weight) in a sample is used a proxy for the degree of fractional crystallisation (Rollinson and Pease, 2021), a process which removes Mg rich minerals from magma prior to eruption and enriches it in trace elements. Data sets are restricted to those including entries with over 8% MgO to ensure the basalts have experienced relatively less fractional crystallisation. It also reduces the likelihood of including basalts with that have experienced significant crustal contamination during transport.

Locations of data sets selected are shown in Figure 2.2. Details of analysis techniques and associated errors can be accessed through Appendix 1.

![Figure 2.1](image.png)

**Figure 2.1. Location of sample data sets on Iceland map. Rift flank from various including Marshall (2021). Authors own/blank map (d-maps.com).**

2.2 Obtaining the sample

For each data set: paper with analysis details sample details, age, major and trace element abundance, isotope data, location, eruption type are extracted.
% SiO₂, K₂O and Na₂O by weight is checked against a Total Alkali Silica, (TAS), diagram (Le Maitre et al., 2004 on mindat.org) to confirm each lava is a basalt.

Trace elements Cs, Rb, Ba, Th, Nb, Ta, La, Ce, Pb, Pr, Sr, Nd, Zr, Hf, Sm, Eu, Gd, Tb, Dy, Ho, Y, Er, Tm, Yb, Lu are ordered for data processing as here in increasing compatibility. All trace elements are incompatible but relatively Cs prefers to exist in a melt and Lu in a solid crystal.

Concentrations for each element (ppm) are extracted and normalised to accepted reference concentrations for N-MORB (White and Klein, 2014)* and OIB (Sun and McDonough, 1989) by dividing element concentrations by the corresponding reference value to give by what factor the basalt samples are enriched or depleted in comparison.

Normalised values are plotted on spider diagrams e.g., Figure 3.1.

Element concentrations are also normalised to primitive mantle (PrM) (Palme and O’Neill*, 2014), and global mean MORB (GM-MORB) (White and Klein, 2014*) to enable further comparison.

* Accessed via Rollinson and Pease (2021) as originals inaccessible.

All reference sets are chosen as basalt values are relatively similar making comparisons more straightforward. They are the most up to date accepted references so assumed most reliable.

Spider diagrams of normalised results are plotted. Parallel lines suggest a suite of basalts from same source that are increasingly enriched due to fractional crystallisation in the magma chamber (higher lines) over time. The basalt with the lowest parallel line and highest %MgO is selected for the sample as it is the most primitive (source like) and also representative of the area.
2.3 Sample analysis

The twelve basalts selected are referred to as B1 to B12, their number referring to their location in Figure 2.1. The TAS diagram was used to note what type of basalt each is. All details in Appendix 1.

Spider diagrams for the sample to each normalisation are collated then divided groups if possible, according to their values and the shape of their lines. The existence of separate groups is confirmed statistically by comparing concentrations of elements that particularly define the groups. The Mann-Whitney U-Test at 5% significance is used as it tests how distinct two sets of numbers are and is used in geochemistry research (e.g., Shorttle et al., 2013).

For each group PM normalised spider diagrams of each group superimposed with N-MORB and OIB reference data are examined for comparisons in shape and values. Anomalies/points of interest are compared with relevant interpretations from other studies.

La/Yb values are calculated as they give an indication of depth of melting which differentiates possible sources. Values are super imposed on a coordinate grid of locations.

Elements with similar compatibilities, and element isotopes with identical compatibilities enter and exit melts in similar proportions. Their ratio to each other in a basalt is similar to that of its source(s). The following scatter graphs are therefore using created to back up other findings:

- Nb/Yb to Th/Yb
- N-MORM normalised Nb to Th
- $^{206}\text{Pb}/^{204}\text{Pb}$ to $^{87}\text{Sr}/^{86}\text{Sr}$
- $^{206}\text{Pb}/^{204}\text{Pb}$ to $^{207}\text{Pb}/^{204}\text{Pb}$
- $^{206}\text{Pb}/^{204}\text{Pb}$ to $^{208}\text{Pb}/^{204}\text{Pb}$

Results are compared to accepted reference discrimination diagrams which provide interpretations.

Icelandic basalts are mixed. Spider diagrams of 10%/90%, 25%/75% 50%/50% 75%/25% mix of OIB/N-MORB and OIB/B4 are created for further comparison although only relevant lines are presented.
3. Results

Each suite of basalts selected shows parallel lines (Appendix 1) suggesting they have a similar source. In all examples the least enriched lava of a suite of parallel lines also had the highest %MgO and was selected as the most primitive basalt closest in composition to the source.

3.1 Establishing groups

Collated results:

Figure 3.1. Spider diagrams to normalised to four reference compositions. Colours consistent for each basalt.

Figure 3.1 indicates there are at least two distinct groups of basalt compositions. Group 1 is more enriched and has a different gradient shape to Group 2, particularly in relation to the most incompatible elements on the left. Lines within each group are broadly parallel. Compatible elements at the right are closest to each reference set (value of 1) except in 3.1c. Broadly Group 1 is closest to PM and OIB and Group 2 to N-MORB.
Elements Nb, Ta, La, Ce, Pr, Nd, Hf, Sm are identified from Figure 3.1 as having concentrations which define the difference between the potential groups.

Mann-Whitney U-Tests at 5% significance shows concentration differences (Appendix 1) between Group 1 and 2 are too large to be random. This is additional evidence there are two distinct groups.

3.2 Group results
Figure 3.2. Spider diagrams: OIB, N-MORB and a) Group 1 b) Group 2 normalised to PM

Figure 3.3a shows Group 1 are the same shape but depleted compared to OIB. B6, B2, B11 are most enriched and have steeper negative slopes Pr to Lu and most closely resembles OIB. Figure 3.3b shows Group 2 are depleted compared to N-MORB although broadly parallel to it. They are parallel to each other.
Figure 3.3 shows Group 1 have the higher values. B2 and B6 have significantly higher values than the others but only half that of OIB. Group 2 values are similar to N-MORB. Broadly values get lower towards the NE in the rift areas.

Figure 3.4a&b define Group 1 as P-MORB, MORB enriched by a plume source and E-MORB, MORB that has also been enriched. Group 2 is defined as N-MORB. B10 is the basalt that doesn’t plot in a defined area.

Seven basalts had accessible isotope data. Figure 3.5 plots were compared to discrimination diagrams for melt source (Hoffmann, (2014) in Rollinson and Pease, 2021). In each scatter graph all basalts plot as having a DM source except B6 which plots as EM2. B5 plots on the boundary of DM and DM/EM1 overlap in 3.5a.

Figure 3.6 shows OIB/B4 mixes are similar to flank basalts and OIB/N-MORB mixes are similar to Group 1 rift.

b. normalised to N-MORB with Sacanni (2015) interpretations.

Figure 3.4. Th/Nb scatter graphs.
3.3 Mixing diagrams

![Mixing diagrams](image)

Figure 3.6. Mixes of a. N-MORB/OIB  b. B4/OIB

4. Discussion

4.1 Interpretation, contextualisation and limitations of study.

Figure 3.2 spider diagrams show the basalts can be split into least two groups. Figure 3.2c classifies Group 1 as transitional/alkali basalts and Group 2 as tholeiites (Kokfelt et al., 2006). Many studies (e.g., Peat et al., 2010) have reported similar results. Larger negative Th anomalies are seen compared to Kokfelt's. This study has used a newer set of reference values assumed more accurate. The discrepancy highlights that all reference values are formed through studies with assumptions, limitations and errors. New information refines the established iteratively but the magnitude of error of any value is never exactly known. This affects the confidence of findings in studies like this and one reason why other analyses are required to corroborate.
The Mann-Whitney U-test is used to provide statistical evidence of two distinct groups which is necessary because the sample is so small. Figure 3.1 indicates they split into two groups, but a larger sample possibly could have shown a continuous set of lines. Each pattern found in results here has to be checked against other work.

Group 1 B2 and B11 are located in flank areas to the east and west of the rift zones and are alkali basalts. The most enriched Group 1 transitional basalt is B7 in the southern flank area at the tip of the southward propagating ERZ. The others are found in ERZ and WRZ in contrast to other studies that find transitional basalts restricted to flank areas (Jakobsson, Jónasson and Sigurdsson, 2008). Group 1 transitional basalt compositions plot as tholeiite on the TAS diagram and so results here fit with the other studies in that tholeiites are found in rift zones and alkali basalts in flank. This includes B7 if the southern flank is accepted as in the process of converting to becoming a rift zone, (Karson, 2017). B6, the most enriched in Group 1 is an exception. It is located in a flank area to the west and is a tholeiite.

Hawaii is an ocean island not associated with a MOR (Hoffman and Jochum, 1996). Its alkali basalts and tholeiites are comparable with B2, B6 and B11, which is evidence of a plume presence in Iceland. Its tholeiites are depleted compared to its alkali basalts but they have the same steep negative slope from Pr to Lu on spider diagrams. This indicates they originated from a deep melt as minerals there hold onto compatible elements making them depleted in the melt. Group 1 tholeiites are similar but have shallower slopes (Figure 4.1), and Group 2 have a different shape altogether.

![Figure 4.1. Comparison of Group 1 (authors own) with Hawaii basalts (Hoffman and Jochum, 1996). Element order differs.](image)

This indicates at least one additional process or source distinct from plume activity is involved in forming rift basalts.

Three discrete groups are found which correlates exactly to Figure 3.4a. Th/Nb scatter diagrams plot the alkali basalts as P-MORB and Group 1 tholeiites as E-MORB. Interpretations are based on reference data from a different setting so using additional discrimination diagrams would provide greater confidence here. La/Yb show flank areas to have the highest values indicating a larger influence of deep melts. This is further evidence of a plume, although values are smaller than OIB.
Rift basalts have lower values but high enough to indicate some deep melt contribution. Pb/Sr isotope results show DM as a prominent source for all Group 1 except B6 which plots as EM2. Evidence both plume and DM source has been found.

Group 2 lines and La/Yb values are similar to N-MORB (Figures 3.2b and 3.3). They plot as N-MORB with a predominantly DM source (Figures 3.4 and 3.5). Their lines are however depleted from N-MORB by a factor of two to nine and not fully parallel. N-MORB has strong and weak negative anomalies for Sr and Eu respectively. Group 2 have the reverse, strong and weak positive Sr and Eu anomalies. Sr and Eu concentrations are particularly high in the lower crust due to accumulation due to fractional crystallisation of the mineral plagioclase which favours these elements (Tang, McDonough and Ash, 2017). Lower oceanic crust is generally depleted in other trace elements which explains the depletion of Group 2. Mantle magmas on route to the surface could entrain this material. Ba mobilises quickly in fluids and would be preferentially added to the magma which would explain the positive Ba anomalies. The Ba signal does not come from OIB or N-MORB, but it is also seen in Group 1. It is unlikely this level of contamination is happening in all locations.

Instead, lower crust material could be a part of a subducted slab contained in the upper mantle. If it interacts with fluids, then Ba concentration as well as Sr and Eu would be high. Being an actual source would help explain the Ba signal influencing more volcanic systems. Depleted recycled lower oceanic crust is found in central/north Iceland (Hartley, De Hoog and Shorttle, 2021) as inferred here. Marshall et al., (2022) also finds a depleted source but one that has experienced deep melting. Here the depleted source, (D2), is seen to undergo shallow decompression melting instead and not a plume component. More detailed studies to reconcile both findings are required however it appears D2 is additional source to that expected by the hypothesis.

Group 1 tholeiites have broadly parallel lines (Figure 3.2a) and get progressively depleted towards NE along WRZ and ERZ. Group 2 are parallel and also become depleted towards NE along the NRZ. La/Yb values have broadly a similar pattern (Figure 3.3) decreasing towards NE indicating depth of melting is shallower, and percentage of the source that melts is higher moving across the entire rift system. This may be related to the size of the rift which is certainly weaker where ERZ is extending to the south and WRZ which is becoming less active (Karson, 2017). Many more results are required to check this by, for example, plotting distance along rift axis segments against La/Yb and using R² to give a measure of confidence that there is a connection. Alternatively, the pattern may be perpendicular to the ridge axis; more enriched to its sides, but this is impossible to tell until additional results can be correlated against a detailed map of the rifts. Pb isotopes also become increasingly less radiogenic through the rift towards the NE (Shorttle et al., 2013) which correlate with the long axis pattern above. Given the multiple straight trends it makes it likely there are no other sources affecting the rift zones. More would
make an undulating pattern. Three sources are agreed by (Shorttle et al., 2013) who suggests the compositional variation seen in each volcanic system is related to transportation time, fractional crystallisation and melting during outflow.

To ensure three sources can provide the full range of basalts mixing models are explored. There appears to be a boundary south of the CRZ with Group 1 to the south and Group 2 to the north (Figure 4.2 and 4.3). The northern boundary of where deep plume related melting occurs is parallel but 100km north (Harðardóttir, Halldórsson and Hilton, 2018), (Figure 4.3) and is likely to be connected. The enriched source for ERZ is not found in NRZ (Peate et al., 2010) which suggests no plume influence north. This is consistent with findings and the plume does favour outflow to the south but given its proximity to NRZ seems unlikely there isn't some influence. Pb isotope ratios can distinguish between different Icelandic volcanic systems. Mixing occurs at each, but at any one system only two end members are found (Peate et al., 2010). End members can be a direct source, or a blend of sources mixed earlier in the mantle called a pseudo-end member. Group 1 has been shown to originate from plume material and DM. Group 2, a mix of DM and D2. All basalts have a positive Ba anomaly (Figure 3.2) unlike the reference concentrations. If this comes from D2 it means D2 is also a source of Group 1 but given the endmember rule, possibly a D2/DM blend may be mixing with the plume material in the south. Figure 3.6a shows a 75% - 90% N-MORB mixed with OIB give similar values and slope to Group 1 tholeiites. Mixing lines are enriched slightly in Zr and Hf and now don't have the Ba anomaly. This suggests a small amount of D2 is blended with DM here. For the flank basalts a better fit is 50% - 75% B4, (the most depleted DM/D2 blend), mixed with OIB. Although extremely crude and with many factors not considered these lines shows mixing of the three sources can feasibly describe the compositional range seen. This also shows high percentages of N-MORB and DM don't affect the plume shape on the spider diagram meaning it is unlikely there is a plume influence in the north. A few element concentrations may need to be explained by a refinement of percentages or by processes particularly at the flanks where magma has to travel through thicker crust before eruption.

Spider diagrams are a tool which can suggest likely sources by comparisons but here they do not show the DM source which is instead found through isotope and element ratios diagrams, constructed originally to corroborate. The shallow N-MORB lines means they don't overly affect the shape of other sources even when they are a high proportion of the mix. The EM2 source found at SNVZ requires isotope scatter graphs to find it. Over printing because of new mixes or processes can also hide many signals. A strong understanding of context and other geochemical work is required, and this project would have benefited from have used more of it, particularly Pb isotope analysis in the planning stage. Spider diagrams are useful for modeling with different mixes however work with Pb isotope plots and gradients can provide more detailed information and mathematical mixing models can include process factors. Incorporating petrographic studies not included here would again vastly improve understanding and inferences made.
Plume, DM and an additional depleted source has been found plus an enriched one at SNVZ. No crustal sources have been found. Given the limitations of this study results are compared with a recent different type of study.

4.2 Comparison with a different type of study

Bulk analysis data is an average of element concentrations from all crystals and glasses in a basalt sample. It gives a good overview, but individual crystals or inclusions within early formed crystals can be examined as they reflect melt compositions before any alteration takes place. Figure 4.2 shows results here mapped against the four sources identified by Rasmussen et al (2020) from element and $^3\text{He}/^4\text{He}$ ratios in early formed olivine crystals and its inclusions. Rasmussen descriptions are in *italics*.

![Figure 4.2 Location of samples and where Rasmussen (2020) sources are most prominent. Authors own/blank map (d-maps.com).](image)

C1 heterogenous, high $^3\text{He}/^4\text{He}$. Peridotite and pyroxenitic material indicating both shallow and deep mantle melt. The pyroxenitic, (deep) component is found most dominant at SIVZ. Consistent with plume/DM found here in this area and reinforces that enriched B7 at the southern flank is connected to the rift.

C2 is similar to MORB and more depleted to the north. Consistent with DM/D2 mix for Group 2. This study suggests C2 prominence extends to B8 in CRZ.

C3 Peridotite (MORB-like), possibly slightly re-fertilised but shows no signs of plume influence or being enriched through recycled crust interaction. This is contradictory to findings here as evidence indicates a strong plume influence. However, low $^3\text{He}$
values (Harðardóttir, Halldórsson and Hilton, 2018) suggest shallow melting and shallow options for an EM2 source such as melt fluid interactions do exist.

*C4 MORB and EM1. Very similar to NRZ with either recycled sediments or continental material that has melted only found at ÓVZ. Not represented in this study.*

B2 area is not discussed.

Rift zone results and mixing suggestions correlate with Rasmussen. The plume head is located at the east of the CVZ and outputs most material to the SW and there is a depleted shallow source, (D2) at the N/E. This fits with La/Yb and Pb isotope trends.

4.3 Potential model, implications and priorities for future research

Figure 4.3. Possible spatial trends of Icelandic basalts and their sources. Authors own/blank map (d-maps.com).
Limitations of model

The locations of actual sources underground will be different compared to Figure 4.2 due to lateral transport of magma prior to eruption which can be up to 100km (Peate et al., 2010) so detailed studies of underground storage and transport systems are required to then place the sources.

This model describes the possible current pattern. Repeating the study with basalts from different times prior would enable understanding of changes over time furthering understanding and enable this model to be refined.

Expanding the study to include RRZ, OVZ and adjacent Reykjanes and Kolbeinsey ridges will allow the whole of Iceland to be mapped and enable understanding on how Iceland sources are connected to typical mid-Atlantic ridge.

This study is confined to basalts. Rhyolites and other lavas also form from the same volcanic systems (Geist et al., 2021). Studying them again may lead to further information about transport systems and storage as these are more evolved than basalts.

Figure 4.3 shows the overall broad tends seen through this island wide study. The two expected sources are found with one depleted in the north and potentially an enriched source in the east. The compositional variety is likely formed by the positions of rift and plume geography in relation to the other sources and mixes facilitated by transport and storage structures which in turn affects the degree of fractional crystallisation and assimilation associated with any eruptive event. Patterns are continuous across the island, but a discreet change can be seen between volcanic systems (Shorttle et al., 2013). Similar, but detailed studies with larger samples of adjacent volcanic systems are required to unpack the detail. Results may find other source components and would certainly pick up minor heterogeneities in the mantle sources.

Flank basalts show a higher proportion of OIB as they are not as flooded by DM. The EM2 source at SNVZ is located where plume input is expected to be seen however conflicting results and comparisons show this might not be the case. Further investigation is required here particularly because one of the options of how EM2 forms involves continental material. This has been proposed as a source relatively recently and so findings of a study in this area could possibly help alter general understanding of how Iceland formed.

5. Conclusions

- Alkali basalts are found in flank areas, tholeiites in rift zones broadly in agreement with literature.
• Plume material, DM, and a second depleted source is found to form most basalts across Iceland. EM2 is a source restricted to SNVZ. It is unclear if it is part of the plume or originated elsewhere.

• From SW to NE basalts become less enriched and Pb becomes less radiogenic. This pattern correlates with maximum plume outflow in the south and the depleted source in the north making it unlikely there are other sources involved in rift zones.

• Flank basalts to the east and west are more enriched and resemble typical OIB. The southern flank contains the most enriched transitional tholeiites and fits in with rift patterns.

• This study suggests trends of sources across Iceland and that other more detailed studies involving trace elements and isotope information with higher levels of confidence are conducted in all volcanic systems to explore the detail of what has been found here, particularly the additional sources.

(4899 words)

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<tr>
<th>Word</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali basalt</td>
<td>A basalt rich in Na$_2$O and K$_2$O and less silica.</td>
</tr>
<tr>
<td>Basalt</td>
<td>Igneous rock that has erupted from magma rich in Mg and Fe with 43% - 65% silica.</td>
</tr>
<tr>
<td>Compatibility (of elements)</td>
<td>A measure of how readily an element substitutes for major elements in a crystal or remains in a melt.</td>
</tr>
<tr>
<td>Crustal contamination</td>
<td>When a magma entrains the rock, it is traveling through. It mixes in.</td>
</tr>
<tr>
<td>Discrimination diagram</td>
<td>Diagrams from experimental studies on rock from understood settings that provide interpretations.</td>
</tr>
<tr>
<td>Endmembers</td>
<td>Discreet compositions by which all parts (of the mantle) can be described as a blend of.</td>
</tr>
<tr>
<td>Flank</td>
<td>An area of relatively thick lithosphere.</td>
</tr>
<tr>
<td>Fractional crystallisation</td>
<td>When magma cools specific crystals form first and may sink and be removed from the melt that erupts.</td>
</tr>
<tr>
<td>Geochemical</td>
<td>Chemical data which can be used to learn about geological processes.</td>
</tr>
<tr>
<td>Lithosphere</td>
<td>The crust and upmost lay of the mantle which together form tectonic plates.</td>
</tr>
<tr>
<td>Mantle plume</td>
<td>Hot material originating for near the Earth’s core that ascends and forms ocean islands.</td>
</tr>
<tr>
<td>Mid-oceanic ridge</td>
<td>Underwater mountain range formed from the basalt created when tectonic plates move apart.</td>
</tr>
<tr>
<td>Peridotite</td>
<td>A rock found in the upper mantle</td>
</tr>
<tr>
<td>Picrite</td>
<td>A basalt with less than 43% silica.</td>
</tr>
<tr>
<td>Postglacial</td>
<td>The last 13000 years.</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>A rock that can be formed by deep material from a plume melting and interacting with peridotite.</td>
</tr>
<tr>
<td>Radiogenic</td>
<td>An isotopes of an element that formed from radioactive decay of a different element.</td>
</tr>
<tr>
<td>Recycled (material)</td>
<td>Subducted lithosphere that returned to the mantle at a subduction zone.</td>
</tr>
</tbody>
</table>
Rift zone
Boundary where tectonic plates are moving apart on land.

Subduction
When the lithosphere returns to the mantle when it is far from the rift zone and is cold and dense.

Tholeiite
A basalt with relatively less Na$_2$O and K$_2$O and more silica.

Trace element
Occurs in a rock in minute amounts and can substitute in for major elements.

Transitional basalt
A tholeiite with relatively more Na$_2$O and K$_2$O.

Appendix 1

Table 1. General Sample Information

<table>
<thead>
<tr>
<th>Basalt</th>
<th>Paper</th>
<th>Sample Name</th>
<th>Eruption details</th>
<th>Rift/Flank</th>
<th>Group</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Geist (2021)</td>
<td>HS5-7</td>
<td>Less than 1.5kyr</td>
<td>ERZ</td>
<td>1</td>
<td>19°34'W 63°59'N</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>Peate et al (2010)</td>
<td>408738</td>
<td>Snæfellsjökull</td>
<td>Flank east of ERZ</td>
<td>1</td>
<td>15°34'W 64°48'N</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>Stracke et al (2003)</td>
<td>9313</td>
<td>10.5 and 7 kyr</td>
<td>NRZ</td>
<td>2</td>
<td>16°48'W 65°52'N</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>Stracke et al (2003)</td>
<td>9356</td>
<td>Langavatn, 10kkyr</td>
<td>NRZ</td>
<td>2</td>
<td>16°48'W 65°52'N</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>Shortle 2013</td>
<td>KOT09-1</td>
<td>Kollertindjunga 1.15 - 12 kyr</td>
<td>NRZ</td>
<td>2</td>
<td>16°33'W 65°11'N</td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>KORFELD (2006)</td>
<td>H106</td>
<td>Berserkjahraun, E post glacial</td>
<td>SNP Flank</td>
<td>1</td>
<td>22°53'W 64°58'E</td>
<td></td>
</tr>
<tr>
<td>B8</td>
<td>KORFELD (2006)</td>
<td>Q6</td>
<td>Hofsjókull, NW post glacial</td>
<td>CRZ</td>
<td>2</td>
<td>18°52'W 65°01'N</td>
<td></td>
</tr>
<tr>
<td>B9</td>
<td>KORFELD (2006)</td>
<td>H127</td>
<td>Jeiðareykir, Borgarhraun, postglacial</td>
<td>NRZ</td>
<td>2</td>
<td>17°0'W 65°51'N</td>
<td></td>
</tr>
<tr>
<td>B10</td>
<td>Koornneef et al (2011)</td>
<td>WV18</td>
<td>Skjálf, post glacial</td>
<td>WRZ</td>
<td>1</td>
<td>20°55'W 64°26'N</td>
<td></td>
</tr>
<tr>
<td>B11</td>
<td>Koornneef et al (2011)</td>
<td>SP-28</td>
<td>Gásfjarðaráhraun, post glacial</td>
<td>SNP Flank</td>
<td>1</td>
<td>21°35'W 64°45'N</td>
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</tr>
<tr>
<td>B12</td>
<td>Koornneef et al (2011)</td>
<td>WV31</td>
<td>Hallmundarhraun AD 1050</td>
<td>WRZ</td>
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<td>20°50'W 64°45'N</td>
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Table 2. % Major element oxide and basalt type

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ca</th>
<th>MgO</th>
<th>Na2O</th>
<th>K2O</th>
<th>Basalt Type</th>
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<tbody>
<tr>
<td>B1</td>
<td>2.8</td>
<td>4.0</td>
<td>0.4</td>
<td>0.0</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>B2</td>
<td>0.17</td>
<td>0.15</td>
<td>0.05</td>
<td>0.5</td>
<td>Akaital basalt</td>
</tr>
<tr>
<td>B3</td>
<td>0.18</td>
<td>0.19</td>
<td>0.06</td>
<td>0.6</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>B4</td>
<td>0.19</td>
<td>0.21</td>
<td>0.07</td>
<td>0.7</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>B5</td>
<td>0.20</td>
<td>0.22</td>
<td>0.08</td>
<td>0.8</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>B6</td>
<td>0.21</td>
<td>0.23</td>
<td>0.09</td>
<td>0.9</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>B7</td>
<td>0.22</td>
<td>0.24</td>
<td>0.10</td>
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<td>Tholeiite</td>
</tr>
<tr>
<td>B8</td>
<td>0.23</td>
<td>0.25</td>
<td>0.11</td>
<td>1.1</td>
<td>Tholeiite</td>
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<tr>
<td>B9</td>
<td>0.24</td>
<td>0.25</td>
<td>0.12</td>
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<tr>
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Table 3 Concentrations of trace elements (ppm).

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<tr>
<th>Sample</th>
<th>Cs</th>
<th>Ba</th>
<th>Sr</th>
<th>Y</th>
<th>Eu</th>
<th>Tb</th>
<th>Dy</th>
<th>Ho</th>
<th>Er</th>
<th>Tm</th>
<th>Yb</th>
<th>Lu</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>2.8</td>
<td>33.0</td>
<td>4.0</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B2</td>
<td>0.17</td>
<td>0.15</td>
<td>0.05</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
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<tr>
<td>B3</td>
<td>0.18</td>
<td>0.19</td>
<td>0.06</td>
<td>0.6</td>
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<td>0.0</td>
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<td>0.0</td>
</tr>
<tr>
<td>B4</td>
<td>0.19</td>
<td>0.21</td>
<td>0.07</td>
<td>0.7</td>
<td>0.0</td>
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<td>0.0</td>
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<tr>
<td>B5</td>
<td>0.20</td>
<td>0.22</td>
<td>0.08</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>B6</td>
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<td>0.23</td>
<td>0.09</td>
<td>0.9</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B7</td>
<td>0.22</td>
<td>0.24</td>
<td>0.10</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B8</td>
<td>0.23</td>
<td>0.25</td>
<td>0.11</td>
<td>1.1</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
</tr>
<tr>
<td>B9</td>
<td>0.24</td>
<td>0.26</td>
<td>0.12</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B10</td>
<td>0.25</td>
<td>0.27</td>
<td>0.13</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B11</td>
<td>0.26</td>
<td>0.28</td>
<td>0.14</td>
<td>1.4</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>B12</td>
<td>0.27</td>
<td>0.29</td>
<td>0.15</td>
<td>1.5</td>
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<td>0.0</td>
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</tbody>
</table>
Figure 1 Illustrative diagram of a suite of basalts with different amounts of fractional crystallisation. (From Geist 2021).

<table>
<thead>
<tr>
<th>Group</th>
<th>Samples</th>
<th>Nb</th>
<th>Ta</th>
<th>La</th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Hf</th>
<th>Sm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B1,B2,B6,B7,B10,B11,B12</td>
<td>11.30</td>
<td>0.71</td>
<td>8.29</td>
<td>19.44</td>
<td>2.86</td>
<td>13.00</td>
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<td>2.17</td>
</tr>
<tr>
<td>2</td>
<td>B3,B4,B5,B8,B9</td>
<td>1.6</td>
<td>0.104</td>
<td>1.7</td>
<td>4.54</td>
<td>0.746</td>
<td>3.91</td>
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Table 4. Median-concentrations of incompatible elements (ppm).