CLCS/TB/2

United Nations Convention on the Law of the Sea

Commission on the Limits of the Continental Shelf

Technical Bulletin #2

GEOCHEMISTRY

4 November 2026

1. PREAMBLE

1.1 The Scientific and Technical Guidelines[1] (the Guidelines) of the Commission on the Limits of the Continental Shelf (the Commission) were adopted on the 13 May 1999.[2] In view of the significant scientific and technical advances that have been achieved since that adoption, as well as the development of practice in the examination of submissions over the past decades, the Commission perceives a need for a series of scientific and technical bulletins that may assist coastal States towards delineating the outer limits of their continental shelf.

1.2 These bulletins are meant to complement the Guidelines in implementation of article 76 of the United Nations Convention on the Law of the Sea (the Convention) and the Statement of Understanding concerning a specific method to be used in establishing the outer edge of the continental margin (SOU). In cases of contradiction between the Guidelines and the bulletins, paramountcy is given to the Guidelines.

2. FORMULATION OF THE PROBLEM

2.1 This Technical bulletin concerns the application of the principles of geochemistry in the process of establishing the outer limits of the continental shelf of a coastal State beyond 200 M. Specifically, it discusses the use of geochemical data and information in providing supporting evidence in the following instances:

a) Characterization of the nature of the basement in determining the continent-ocean transitional zone (COT) along continental margins;
b) Identification of the base and foot of the continental slope (BOS and FOS respectively);
c) Identification of the extent of anomalous areas such as those associated with hotspot-ridge interactions, which can be part of a continental margin; and
d) Classification of a seafloor high in one of the legal categories established by article 76:

i) Oceanic ridges of the deep ocean floor (article 76, para 3);
ii) Submarine ridges (article 76, para 6); and
iii) Submarine elevations (article 76, para 6).

2.2 Considering the objectives listed in the previous paragraph, this Technical Bulletin is limited in its scope and contents to igneous geochemistry in general and specifically to

[1] CLCS/11. See also CLCS/11/Corr.1, CLCS/11/Corr.2, CLCS/11/Add.1 and CLCS/11/Add.1/Corr.1.
[2] See CLCS/12, para. 14.

the major and trace element concentrations/ratios as well as radiogenic isotopic characteristics of basalts in the following tectonic settings:

a) Divergent plate boundaries marked by mid-ocean ridge systems (Figure 1);



Figure 1: Divergent plate boundaries (red lines), world's major hotspots (orange circles) and convergent plate boundaries (green lines). As can be seen, many of the hotspots are co-located with, or are proximal to the global mid-ocean ridge systems (Source: Dyment et al. (2007), figure 1, https://doi.org/10.5670/oceanog.2007.84 open access article made available under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

b) Divergent plate boundaries marked by interaction with hotspots (Figure 1);

c) Convergent plate boundaries marked by volcanic "intra-oceanic arcs" (e.g. Tonga-Kermadec, Vanuatu, Solomon, Mariana, Izu-Bonin, Aleutian, and Lesser Antilles) or "continental arcs" (e.g. Andean Volcanic Belt, Kamchatka, and Cascade Volcanic Arc), depending on whether oceanic lithosphere is subducted beneath an oceanic lithosphere or beneath a continental lithosphere;

d) Continental margin island arcs, separated from continent by a marine basin (e.g. Kuril, and Japanese-Rykyu arcs);

e) Back-arc basins formed behind subduction zones in extensional basin settings (e.g. Japan Sea, Lau Basin, Manus Basin, North and South Fiji Basins, Parece Vela Basin, and Shikoku Basin);

f) Oceanic Large Igneous Provinces, which include rifted volcanic continental margins, oceanic plateaus, submarine ridges/submarine elevations, seamounts and ocean basin flood basalts (Figure 2).

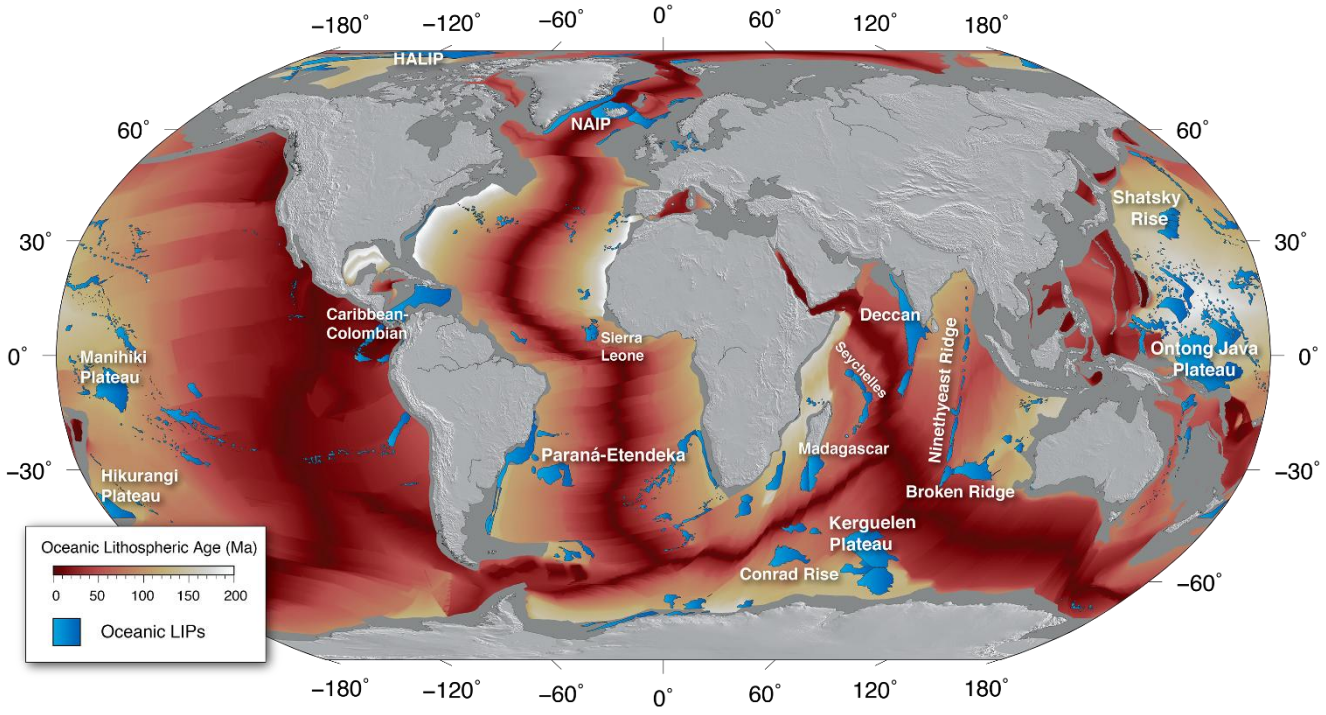


Figure 2: Locations of Oceanic Large Igneous Provinces (LIPs) in light blue, superimposed on a map of the age of the oceanic lithosphere. **NAIP:** North Atlantic Igneous Province, **HALIP:** High Arctic Large Igneous Province. This Graphic (version 03.09.2021) by Eivind O. Straume from Straume et al. (2019) is available via the open-access s-Ink repository. https://s-ink.org/oceanic-large-igneous-provinces.License: Attribution-ShareAlike 4.0 International (CC BY-SA). Related reference: Straume et al. (2019). https://doi.org/10.1029/2018GC008115.

2.3 The geochemistry of continental flood basalts is outside the scope of this bulletin.

3. RELEVANT PROVISIONS OF THE GUIDELINES

3.1 Considerations of geochemistry of rocks have been referred to in the Guidelines, in the context of identification of the BOS. Geochemical and radiometric data have been suggested as possible sources of information (Guidelines paras. 5.2.6 to 5.2.8). More specifically geochemical-isotope analysis has been cited as one of the approaches in determining the COT along rifted non-volcanic and sheared continental margins (Guidelines para. 6.3.10). Whenever evidence to the contrary is invoked, geochemical-isotope analysis could be considered by coastal States (Guidelines para. 9.3.17).

3.2 Characterization of the nature of the basement in determining the COT along continental margins:

3.2.1 Characterization of the nature of the basement is an important element in determining the outer edge of the continental margin in cases where evidence to the contrary to the general rule is invoked by a coastal State for locating the position of the FOS;

3.2.2 The Guidelines do not prescribe the application of a specific scientific methodology to define the location of the FOS when evidence to the contrary to the general rule is invoked. Rather, the Commission interprets this provision as an opportunity for coastal States to use the best geological and geophysical evidence available to them to locate the foot of the continental slope at its base when the geomorphological evidence given by the maximum change in the gradient as a general rule does not or cannot locate reliably the foot of the continental slope (Guidelines para. 6.1.10);

3.2.3 Acknowledging the difficulties in generalising the geological and geophysical evidence that a coastal State may introduce to establish the foot of the continental slope at its base by means of evidence to the contrary, the Guidelines state that, where the FOS is very difficult to define on the basis of bathymetric data, the Commission might consider the continental-oceanic transitional (COT) zone (figs. 6.1D to 6.1F, reproduced as Figure 3 in this bulletin) as the place to determine the outer edge of the continental margin. The landward limit of the transitional zone would then be considered as an equivalent of the foot of the continental slope in the context of paragraph 4, “provided that the submitted geophysical and geological data conclusively demonstrate that the submerged land mass of the coastal State extends to this point” (Guidelines para. 6.3.10);

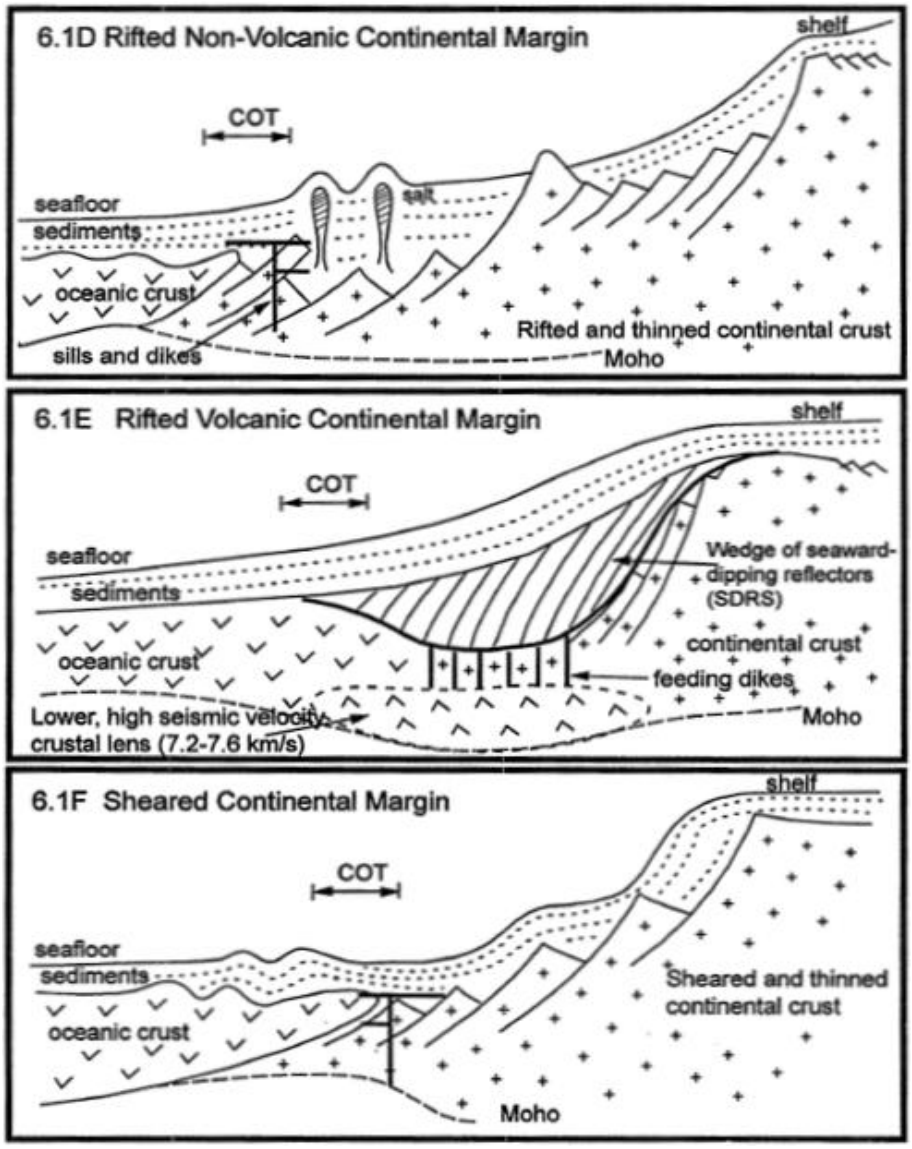


Figure 3: Schematic illustrations of different continental margin types, showing the locations of the COT from a geological perspective (Figure 6.1 from the Guidelines).

3.2.4 Among the geological data available for a coastal State, the Commission recognizes that geochemistry can also be used to provide support in instances where evidence to the contrary is invoked by a coastal State (Guidelines paras. 6.3.10 and 9.3.17);

> (Para. 6.3.10) “Apart from drilling, sampling and coring of crustal outcrops, including seamounts in the transitional area between continental and oceanic crust, can provide evidence of rock type or lithology and supply material for a variety of studies, for example,

radiometric age dating, paleontological age correlation, geochemical-isotope chemical analyses and palaeomagnetic studies. These results can be of use in determining the ocean-continent boundary along rifted non-volcanic and sheared continental margins…"

(Para. 9.3.17) "In the case of evidence to the contrary, it is recommended, in addition to the information described in the checklist in section 9.5, to include the following data obtained from sampling and coring of crustal subcrops at the continental margin with information about the source of the data:

- Lithology;
- Radiometric/palaeontological/palaeomagnetic age dating;
- Geochemical-isotope geochemical results".

3.3 Identification of the extent of anomalous areas such as those associated with hotspot-ridge interactions that can be part of a continental margin, and classification of seafloor highs:

3.3.1 The Guidelines (paras. 7.2.1 to 7.2.8) discuss the ridges/seafloor highs resulting from a variety of geological processes, including ridge-hotspot interaction and oceanic Large Igneous Provinces (LIPs). These seafloor highs constitute positive bathymetric features which, at least in a few cases to date, have been demonstrated to be submarine elevations that are natural components of the continental margin, in the sense of paragraph 6 of article 76. One of the supporting pieces of evidence submitted in such cases by coastal States has been the results of geochemical studies carried out on the basaltic rocks dredged or cored from the area (Annex I).

3.3.2 In the context of describing submarine elevations that can be regarded as natural components of the continental margin, the Guidelines state that Commission will base its views mainly on two considerations;

(Para. 7.3.1(a)) "In the active margins, a natural process by which a continent grows is the accretion of sediments and crustal material of oceanic, island arc or continental origin onto the continental margin. Therefore, any crustal fragment or sedimentary wedge that is accreted to the continental margin should be regarded as a natural component of that continental margin"

(Para. 7.3.1 (b)) "In the passive margins, the natural process by which a continent breaks up prior to the separation by seafloor spreading involves

thinning, extension and rifting of the continental crust and extensive intrusion of magma into and extensive extrusion of magma through that crust. This process adds to the growth of the continents. Therefore, seafloor highs that are formed by this breakup process should be regarded as natural components of the continental margin where such highs constitute an integral part of the prolongation of the landmass".

3.3.3 The above paragraphs open an avenue to coastal States to demonstrate, where possible, that seafloor highs which are submerged prolongations of their landmass may constitute a natural component of that margin in the context of paragraph 6 of article 76. Geochemical studies of crustal rocks provide evidence that may demonstrate that these seafloor highs share geological characteristics, origin and geological evolutionary history with that part of the land mass to which it is attached.

4. CLCS PRACTICE

4.1 Annex I lists recommendations related to submissions in which geochemical data and information have been provided by a coastal State in support of/to validate its arguments relating to the delineation of the outer limits of its continental shelf.

5. SUMMARY AND CONCLUSIONS

5.1 Characterising the nature of the basement as continental or oceanic, or establishing the extent of anomalous areas of hotspot-ridge interaction or the geological continuity between a seafloor high and the land mass of a coastal State to which it is attached, calls for a suite of geophysical data (e.g. seismic reflection/refraction, gravity, magnetic). The derived geophysical information can be constrained by petrological/geochemical studies of rock samples from the area. However, considering the wide range of compositions of basement/crustal rocks of different margins and transformations that a rock assemblage may undergo during its evolutionary history, it may not be practical to develop a general geochemical methodology that is applicable for all margins. Furthermore, and perhaps more important are the difficulties in obtaining basement samples from depths and the costs involved in collecting these samples.

5.2 The following Annexes may also assist coastal States:

Annex II – Geological and geochemical databases.
Annex III – Geochemical variations in basalts from different tectonic environments.
Annex IV - Glossary.

ANNEX I – CHRONOLOGICAL LIST OF RELEVANT RECOMMENDATIONS* – AS AT 31 JULY 2026

Submission	Date of Recommendations	Paragraphs	Figures	Application†
Australia (2004)	9 April 2008	Recommendations: 81, 82, 85 (Kerguelen Plateau Region); 107 (Lord Howe Region); 147 (Naturaliste Plateau Region); 169 (South Tasman Rise Region)	N/A	III
Joint submission by the Republic of Mauritius and the Republic of Seychelles - in the region of the Mascarene Plateau (2008)	30 March 2011	Recommendations: 71	N/A	II
Japan (2008)	19 April 2012	Summary of Recommendations: 140 (Southern Oki-Daito Ridge Region)	N/A	I
France - in respect of the areas of the French Antilles and the Kerguelen Islands (2009)	19 April 2012	Summary of Recommendations: 86, and 87	N/A	II and III
Joint submission by the Federated States of Micronesia, Papua New Guinea and Solomon Islands - concerning the Ontong Java Plateau (2009)	17 March 2017	Summary of Recommendations: 37, and 45	3 and 4	I and III
Norway - in respect of Bouvetøya and Dronning Maud Land (2009)	8 February 2019	Summary of Recommendations: 62 to 68 Corrigendum to the Summary of Recommendations: 1	15, 16, and 17	II and III

* Recommendations and Summaries of Recommendations are available at https://www.un.org/Depts/los/clcs_new/commission_submissions.htm

† This column lists the application of the principles of geochemistry in the process of establishing the outer limits of the continental shelf of a coastal State beyond 200 M. Specifically, it details the use of geochemical data and information in providing supporting evidence in the following instances:

I. Identification of the BOS and FOS
II. Identification of the extent of anomalous areas such as those associated with hotspot-ridge interactions; and
III. Classification of a seafloor high in one of the legal categories established by article 76.

Submission	Date of Recommendations	Paragraphs	Figures	Application†
France - in respect of La Réunion Island and Saint-Paul and Amsterdam Islands (2009)	4 March 2020	Summary of Recommendations: 66 (Saint-Paul and Amsterdam Islands)	18	II
Joint submission by France and South Africa - in the area of the Crozet Archipelago and the Prince Edward Islands	7 March 2023	Summary of Recommendations: 45	N/A	II
Russian Federation - partial revised Submission in respect of the Arctic Ocean (2015)	6 February 2023	Summary of Recommendations: 90	N/A	III
Iceland - revised Submission in respect of the western, southern and south-eastern parts of the Reykjanes Ridge (2021)	12 March 2025	Summary of Recommendations: 64 to 73, and 99	14, 15, 16, 17, 18, 19, 20, 24, 25, 26, and 27	II and III
Cook Islands - revised concerning the Manihiki Plateau (2021)	1 August 2025	Summary of Recommendations: 36 to 38, and 92 to 98	8, and 23	III

ANNEX II – GEOLOGICAL AND GEOCHEMICAL DATABASES – AS AT 31 JULY 2026

The list provided below is a non-exhaustive compilation of constantly updated geological/geochemical data and information which could assist coastal States during the preparation of submissions in respect of the outer limits of their continental shelf beyond 200 M.

1 The Deep Ocean Drilling Programs (see Figure II:1) under the Deep-Sea Drilling Project (DSDP 1966-1983); the Ocean Drilling Program (ODP 1983-2003), the Integrated Ocean Drilling Program (IODP 2003-2013) and the International Ocean Discovery Program (IODP 2013-2024) (https://iodp.tamu.edu/scienceops/maps.html). Many of the sites drilled have sampled basement rocks. The GeoMapApp map-based application (https://www.geomapapp.org) also has a compilation of geochemical data and information describing the site results from various drilling programs.

2 GEOROC (geochemistry of rocks from the oceans and continents) database at https://georoc.eu/georoc/new-start.asp (a comprehensive collection of published analyses of igneous and metamorphic rocks and minerals, including major and trace element concentrations, radiogenic and non-radiogenic isotope ratios, analytical ages for whole rocks, glasses, minerals and inclusions, metadata, analytical details and references).

3 RidgePetDB http://petdb.ldeo.columbia.edu/petdb (petrologic database of the ocean floor).

4 EarthChem portal https://www.earthchem.org, an integrated data synthesis facilitating access to chemical, isotopic, and mineralogical data from peer-reviewed literature, which provides access to multiple geochemical data systems including RidgePetDB.

5 The Marine Geology archive at the National Centers for Environmental Information of NOAA (https://www.ngdc.noaa.gov/mgg/geology/geology.html) which contains descriptions, images, and analyses of sediment and rock samples collected from the ocean floor and lakebeds, and also archived data collected during all the ocean drilling programs to date (https://www.nsf.gov/pubs/2017/nsf17037/nsf17037.jsp).

6 The Smithsonian Institution basalt glass data file (www.hrw.com/science/si-science/physical/geology/mineralsci/research/glass/).

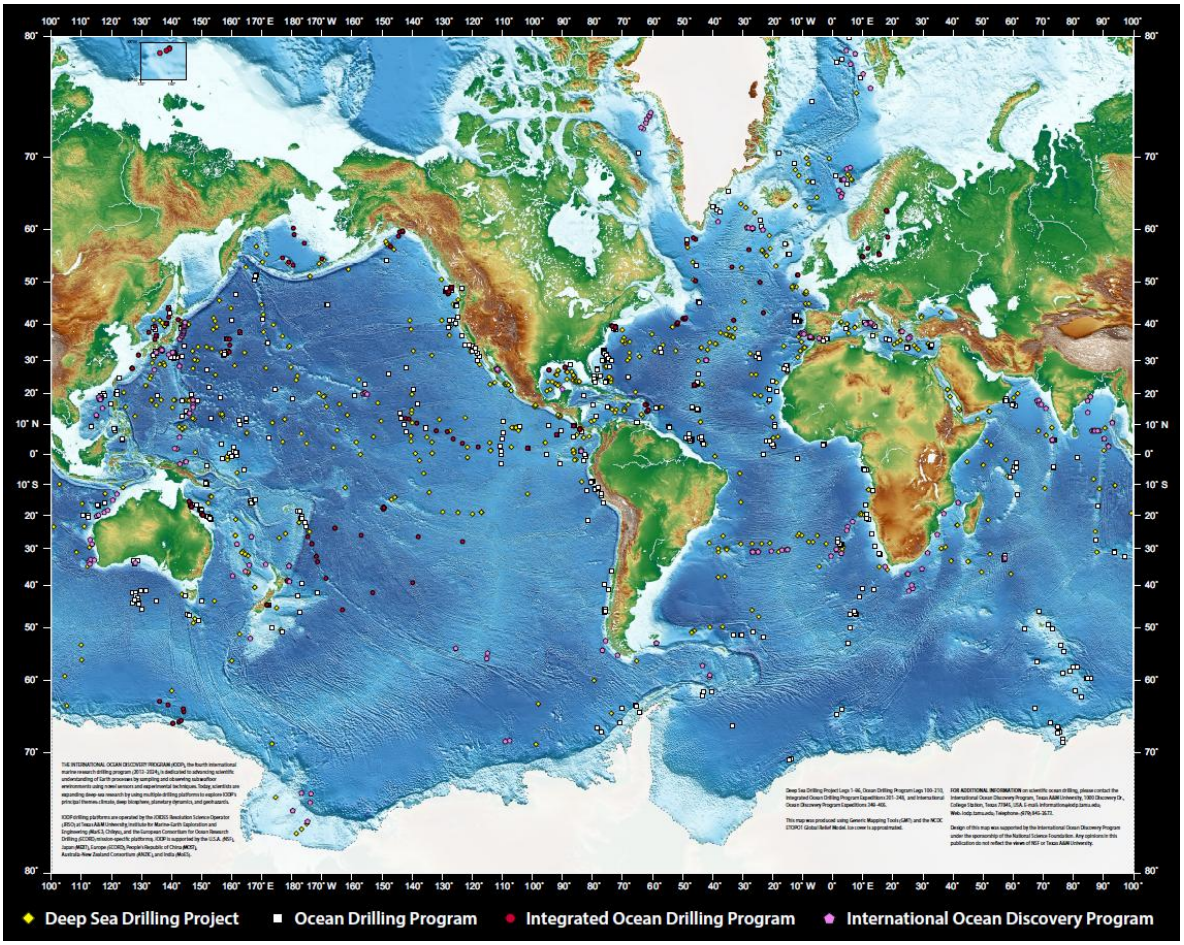


Figure II:1: Map showing the locations of the successive deep-sea drilling programs, under the Deep-Sea Drilling Project (DSDP 1966-1983); the Ocean Drilling Program (ODP 1983-2003), the Integrated Ocean Drilling Program (IODP 2003-2013) and the International Ocean Discovery Program (IODP 2013-2024). Source: https://iodp.tamu.edu/scienceops/maps/poster/combined.html, licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license (https://creativecommons.org/licenses/by/4.0/).

ANNEX III – GEOCHEMICAL VARIATIONS IN BASALTS FROM DIFFERENT TECTONIC ENVIRONMENTS

1. MAJOR ELEMENT VARIATIONS

1.1 Compositionally, oceanic basalts from all tectonic environments are in general, mafic dominant (<56 wt.% SiO_2). Basalts from divergent margins away from the influence of hotspots ("Normal" mid-ocean ridge basalts, "N-MORB", discussed further below) have a restricted compositional range compared to those from other tectonic settings. They are dominantly subalkaline tholeiites with 2.5%-3.5% by weight of total alkalis (Na_2O+K_2O; weight% K_2O ranges between 0.14 and 0.16% (Figure III:1A).

1.2 In intraplate settings, the composition of the rocks becomes more diverse, spanning both tholeiitic and alkali basalt compositions. For example, oceanic plateaus such as Ontong Java, Kerguelen and Manihiki, while predominantly basaltic in composition, also straddle the sub-alkaline-alkaline boundary. Whereas the Manihiki and the Ontong Java lavas are largely alkaline, the basaltic rocks of Kerguelen Plateau encompass a wider range, extending from trachy-basalt to trachy-andesite and trachyte, reflective of possible crustal contamination (Figure III:1B).

1.3 Concentration of Titanium (Ti) has commonly been used to categorise tholeiitic basalts into high-Ti (TiO_2 concentrations >2.0 weight %; mostly associated with ocean island basalts, OIB) and low-Ti (<2 wt% TiO_2; often characteristic of N-MORB) magma types. The low-Ti nature of basalts has been interpreted to reflect crustal contamination, or differences in mantle melting or crystallisation processes (high degree of melting or low-pressure crystallisation process). In contrast, formation of the relatively uncontaminated high-Ti varieties has been attributed to melting of mantle plume containing recycled oceanic crust or to high pressure crystallization process.

1.4 Convergent plate boundary rocks show the greatest compositional diversity and range, from basalt through andesite and dacite and rhyolite. The dominant rock is andesite. Three principal types of arc basalts can be distinguished: low-K tholeiitic basalt, high-K calc-alkaline basalt and shoshonite (a potassium-rich variety of basaltic trachyandesite).

1.5 Basalts in the intra-oceanic island arc settings are mainly tholeiitic, with minor calc-alkaline basalts and shoshonites (e.g., Izu-Bonin-Marianas). Some island arc chains (e.g. Japan) show two different series of rocks (tholeiitic and calc-alkali series). Basalts from back-arc settings tend to be more sub-alkaline with a compositional range between basalt and andesite (Figure III:1, C and D).

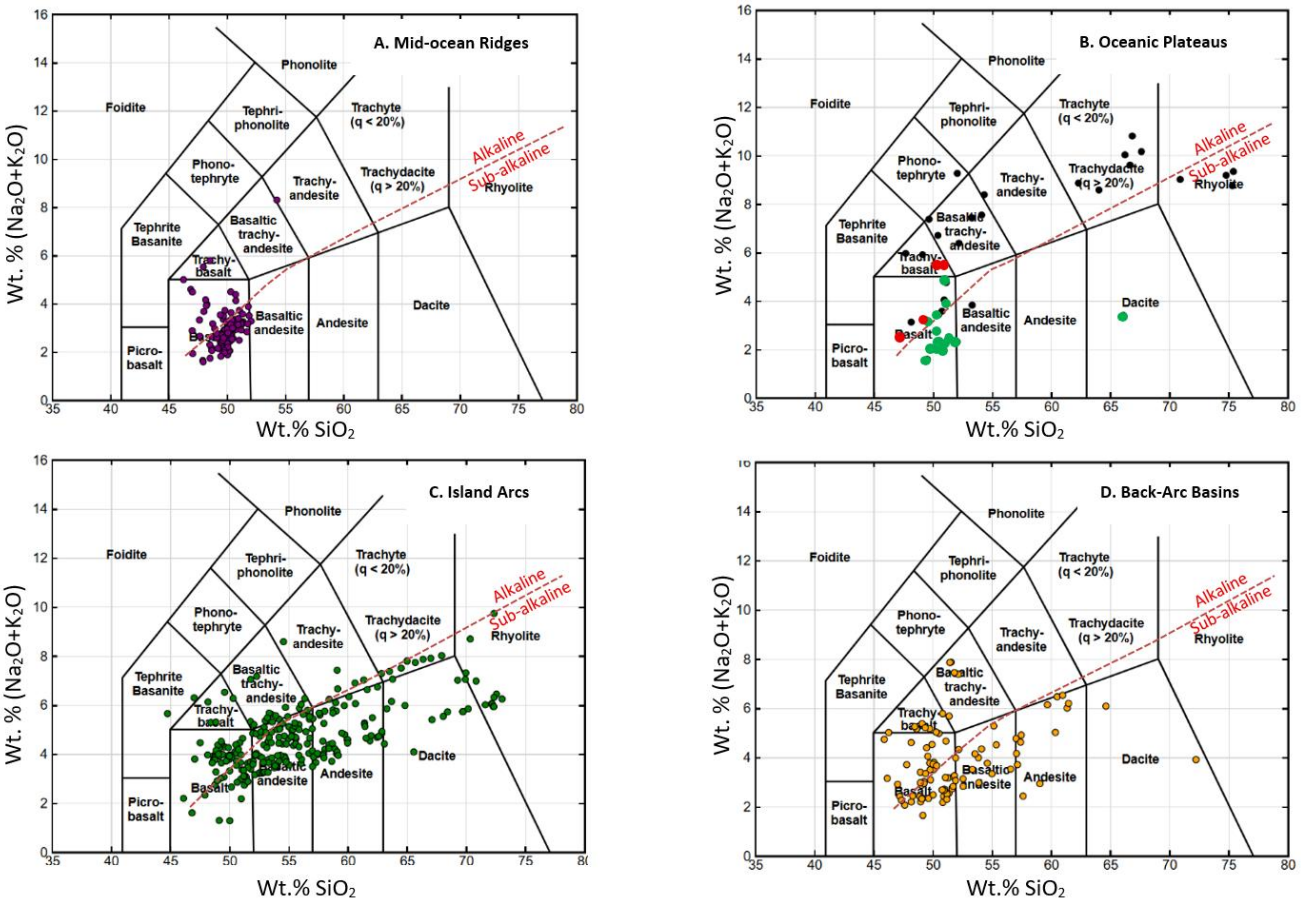


Figure III:1: Total Alkalis vs. Silica (TAS) Variation Diagram for volcanic rocks from four different tectonic settings: (A) "Normal" mid-ocean ridges; (B) Oceanic Plateaus (Green closed circles: samples from Manihiki Plateau; those in Red, samples from Ontong Java Plateau, and Black closed circles, samples from Kerguelen Plateaus); (C) Island Arcs; and (D) Back-arc basins. Data compiled from the global geochemical databases PetDB (http://www.earthchem.org/petdb) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/) by Ueki et al. (2018). The nomenclature for the different rocks using whole rock chemical data is as adopted by the International Union of Geological Sciences (IUGS).

1.6 Segments of mid-oceanic ridges proximal to hotspots are characterised by diagnostic variations in major element geochemistry along and across the ridges, as for instance, the Reykjanes Ridge off Iceland, or the Galápagos in the central east Pacific. The Reykjanes Ridge basalts show a persistent along-axis variation in major elements, testifying to the decreasing influence of Iceland hotspot along the ridge. To the North of ~61°N, towards the hotspot, the basalts are enriched in TiO_2, K_2O and P_2O_5. Concurrently, both MgO and Mg# [expressed as $100Mg^{2+}/(Mg^{2+} + Fe^{2+})$] show a gradual decrease northwards, which is indicative of increasing olivine removal by fractional crystallisation (Murton et al., 2002). Southwards on the Reykjanes Ridge, beyond the Bight Fracture Zone at ~56.7°N, the basaltic composition assumes N-MORB values. The Galápagos hotspot and adjacent spreading Centre (GSC) constitute yet another

classic location of hotspot–ridge interaction. The Galápagos basalt geochemistry is marked by systematic variations along the spreading centre from west towards the hotspot. For example, average Mg # decreases progressively from west towards the most plume influenced portion of the ridge. Concurrently, the concentrations of K_2O, TiO_2, and H_2O show an increase along the GSC towards the hotspot (Detrick et al., 2002).

2. TRACE ELEMENT ABUNDANCE AND RATIOS

2.1 Trace element concentrations and their ratios offer yet another method to distinguish basement rocks of continental margins in terms of their geological environment (continental, oceanic or transitional). Some of the trace element concentrations that are commonly considered in studies of basaltic rocks are Niobium (Nb), Tantalum (Ta), Lead (Pb), and to a lesser extent, Strontium (Sr), Barium (Ba), Uranium (U) and Potassium (K). It may be noted, however, that trace elements abundance in basalts depend on several factors, including source composition, degree of melting and subsequent degree of fractional crystallisation and possible contamination of the magma. It is therefore prudent not to consider the trace element abundance variations in isolation, but to relate them to the tectonic environment.

2.2 Figure III:2 shows the general trace elements distribution pattern of average "normal" mid-ocean ridge basalts (N-MORB, those occurring along the ridge >500 km from hotspots; *sensu*, Gale et al., 2013), enriched mid-ocean ridge basalts (E-MORB, those occurring within 200 km of hotspots; see also Gale et al., 2013, for a chemical definition of E-MORB in terms of La/Sm_n; discussed further in Annex-IV, Glossary), ocean island basalts (OIB; Sun and McDonough, 1989) and average continental crust (Rudnick and Fountain, 1995). The concentrations are normalized to those of the primitive mantle and plotted in the order of increasing compatibility. As can be seen, N-MORB are in general, strongly depleted in the highly incompatible large-ion lithophile elements (LILE) such as K, Rb, Cs, Sr, Ba and Pb when compared to E-MORB and OIB. High field strength elements (HFSE) such as Nb and Ta are generally more depleted than light rare earth elements (LREE) like La and Ce, but less depleted than LILE. However, the depletion in Nb and Ta observed in N-MORB do not produce the sharp Nb-Ta anomaly typical of island arc basalts (discussed below). The behaviour of Pb is conspicuously anomalous, showing a sharp depletion relative to neighbouring elements across all oceanic basalts (N-MORB, E-MORB and OIB). Increasing (primitive mantle-normalised) concentrations of the more compatible elements in oceanic basalts also coincide with the corresponding decreases in their abundances in the continental crust (Figure III:2).

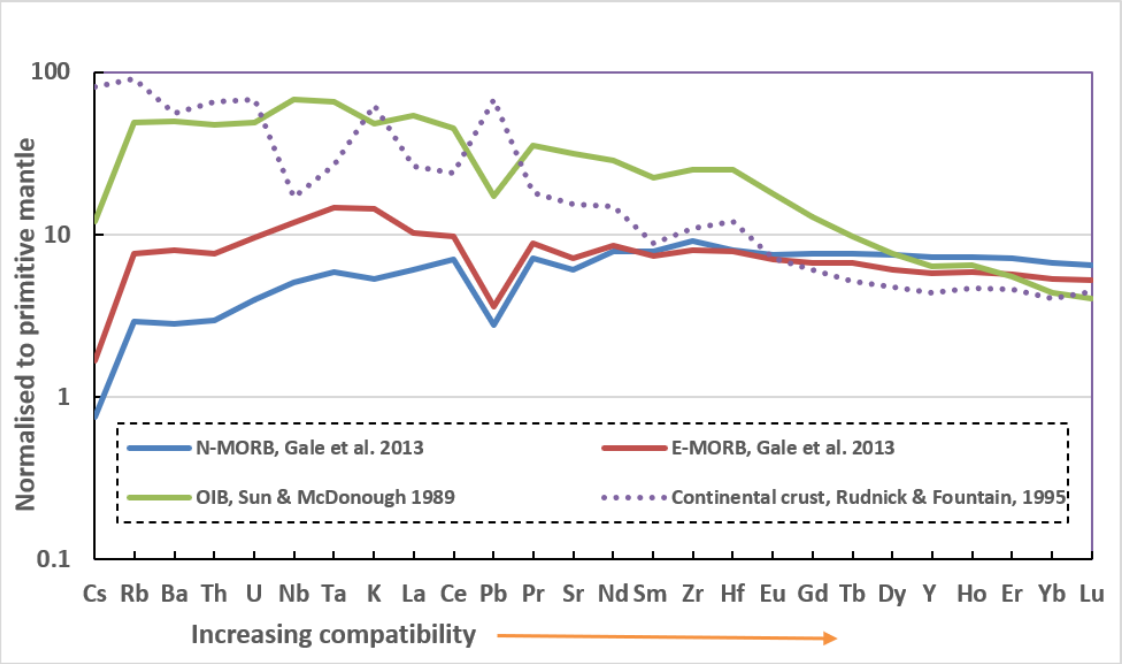


Figure III:2: Primitive mantle-normalised (Sun and McDonough, 1989) trace element patterns of ocean basalt compositions from different geological environments. N-MORB comprises all basalts occurring in oceanic spreading ridge segments >500 km from a hotspot and excluding back-arcs, while E-MORB refers to ocean ridge basalts occurring <200 km from a hotspot (see Gale et al. 2013). Data sources: Sun and McDonough, 1989 (primitive mantle and OIB); Rudnick and Fountain, 1995 (continental crust); and Gale et al., 2013 (N-MORB and E-MORB).

2.3 In contrast to MORB, island arc basalts (IAB) typifying subduction zone settings, are characterized by enrichment in LILE and LREE relative to primitive mantle. They are however, depleted in such HFSE as Nb, Ta, and Ti relative to neighbouring elements, producing distinctive negative anomalies on trace element diagrams (Figure III:3), OIB, like IAB, are also marked by elevated abundances of LILE; however, unlike IAB, OIB are not only enriched in Nb and Ta relative to neighboring elements but also show a progressive enrichment in the more incompatible elements.

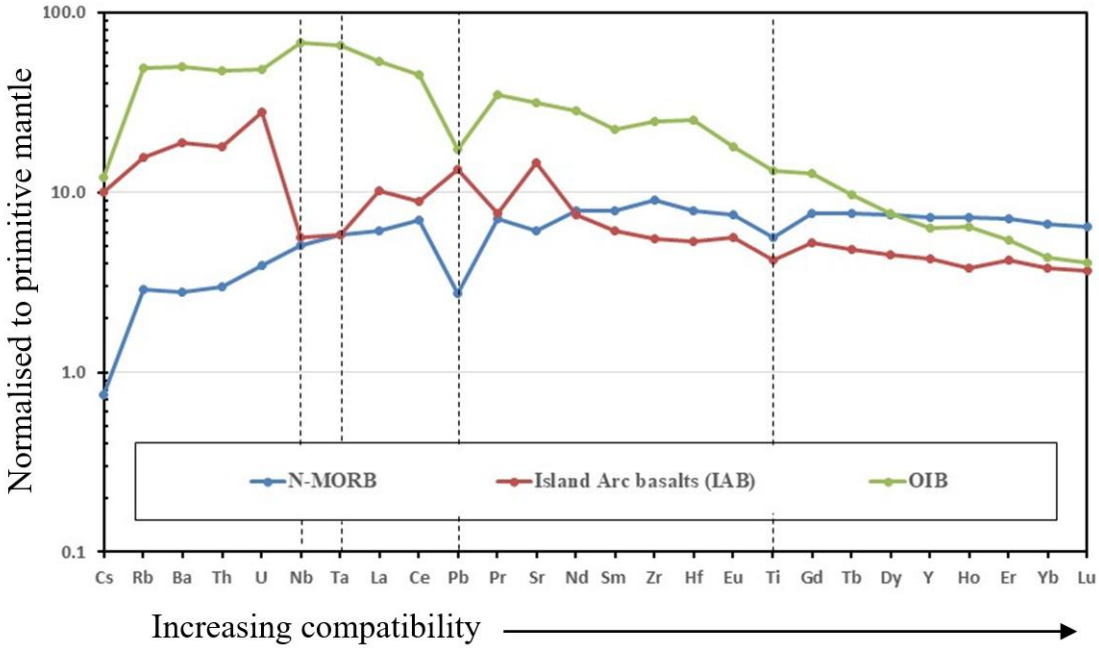


Figure III:3: Primitive mantle-normalised (Sun and McDonough, 1989) trace element distribution of the average compositions of island arc basalts (IAB), mid-ocean ridge basalts (N-MORB) and ocean island basalts (OIB). Data from Gale et al., 2013 (N-MORB), Kelemen et al., 2014 (IAB) and Sun and McDonough, 1989 (primitive mantle and OIB).

2.4 Ratios of trace element concentrations of incompatible pairs, such as Th/U, Nb/U, Nb/La, Ba/Th, Sr/Nd, Pb/Nd, Ce/Yb or La/Sm have been suggested to be useful in identifying mantle sources of oceanic basalts (MORB and OIB). Similarly, La/Sm ratios, normalised to primitive mantle ($(La/Sm)_n$) have been used to classify MORBs as "Normal" [N-MORB; $(La/Sm)_n$ <1.00, Arevalo and McDonough, (2010)], Depleted [D-MORB; $(La/Sm)_n$ ~0.6, Langmuir, 2017; <0.8, Gale et al., 2013], or Enriched [E-MORB; $(La/Sm)_n$ ≥1.00, Arevalo and McDonough, 2010; >1.50, Gale et al., 2013, Langmuir, 2017].

2.5 *Basalt discrimination diagrams* based on comparison of trace element concentrations have been widely in use for determining the tectonic settings (e.g. Pearce and Cann, 1973; Pearce, 2008; Nakamura, 2023). Some of the popular diagrams have been binary plots of trace elements and elemental ratios such as Ti-V, Zr–Zr/Y, Th/Yb vs. Nb/Yb, TiO_2/Yb vs. Nb/Yb, and ternary diagrams such as Zr-Ti-Y, Li-Y-Nb, and Th–Hf/3–Ta (See Pearce and Cann, 1973; Pearce and Norry, 1979; Li et al., 2015; Ueki et al., 2018; Shervais, 2022). (Figure III: 4 a, b, c and d).

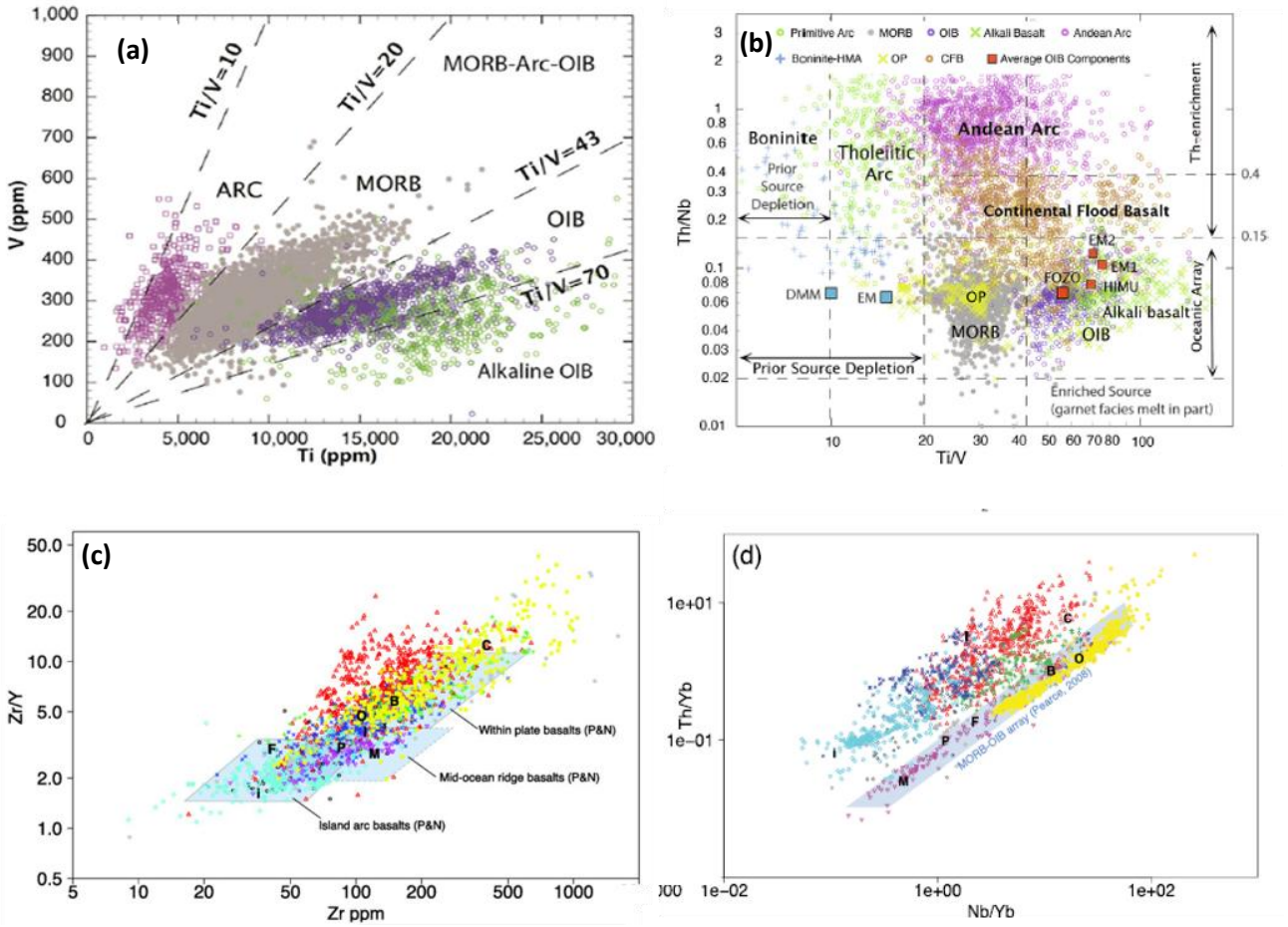


Figure III: 4: Illustrative examples of discrimination diagrams showing the range of basalts in different tectonic settings. (a) Ti-V linear plot, (b) Ti/V vs. Th/Nb ‘‘two-proxy” plot, (c) Zr vs. Zr/Y plot and (d) Nb/Yb vs. Th/Yb log–log plot. Abbreviations in (c) and (d): B, back-arc basin; C, continental arc: F, continental flood; I, island arc; i, intra-oceanic arc; M, midocean ridge; O, oceanic islands; P, oceanic plateau. Discrimination fields of Pearce and Norry, 1979 (P&N) and MORB-OIB array of Pearce, 2008 are also shown in (c) and (d). Panels (a) and (b) from Shervais, W. (2022), figures 1(A) and 9. https://doi.org/10.1016/j.gsf.2021.101319. Open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/). Reproduced with the kind permission of the journal. Panels (c) and (d) from Ueki et al. (2018), figures 4(c) and (d). https://doi.org/10.1029/2017GC007401. Open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License. Reproduced with the kind permission of publisher (Wiley)

2.6 With the availability of better constrained data sets, the recognition that mantle sources themselves are highly heterogeneous and that trace element abundances in basalts depend on several inter-connected factors, the effectiveness of discrimination diagrams is however, increasingly being cautioned against (e.g. Li et al., 2015; Nakamura, 2023). Nonetheless, these diagrams still remain a powerful tool in discriminating between volcanism in different tectonic settings, especially when used in conjunction with many different elements and isotopic ratios as well as petrographic data. Thus, for instance,

Ueki et al., (2018) have demonstrated that machine learning (ML) methods using global geochemical datasets for 24 elements and five isotopic ratios have allowed the discrimination between igneous rocks formed in eight different tectonic settings with a discriminant ratio better than 83% for all settings excluding oceanic plateaus and back-arc basins. The results of such studies indicate the potential of discriminant diagrams to provide a good handle for evaluating the tectonic settings of basalt magmatism.

3. RADIOGENIC ISOTOPIC COMPOSITION

3.1 Radiogenic isotope systems are invaluable proxy tracers of volcanic processes. The utility of isotopes in this regard is primarily because, in contrast to trace element abundance ratios, isotopes of an element generally undergo little fractionation during the igneous processes.

3.2 Among the different radiogenic isotopes present in ocean basalts, the isotopes of Sr, Nd, Pb, Hf, W and He have been found to be particularly useful in understanding mantle source heterogeneity and crustal recycling. Of these, the most extensively used isotope systems are those of Sr($^{87}Sr/^{86}Sr$), Nd($^{143}Nd/^{144}Nd$), Pb ($^{206}Pb/^{204}Pb$), Hf ($^{176}Hf/^{177}Hf$) and He ($^{3}He/^{4}He$ discussed separately in Section 4 below). In general, compared to the large variations observed in the isotopic ratios of Sr and Nd in OIB, the corresponding variations are however, much smaller in respect of MORB (Figure III: 5). The higher $^{87}Sr/^{86}Sr$ (and $^{206}Pb/^{204}Pb$, discussed further, below) and lower $^{143}Nd/^{144}Nd$ (and $^{176}Hf/^{177}Hf$ ratios) of OIB indicate inputs from possible mantle plumes enriched by recycling of old crustal material.

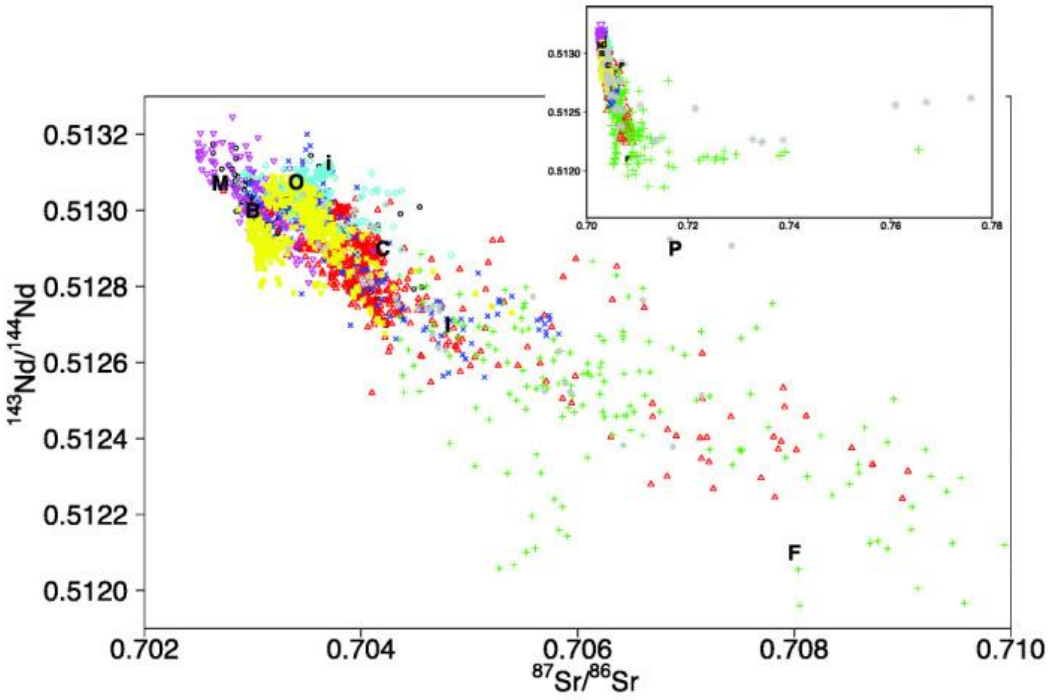


Figure III: 5: Sr–Nd isotope variation Diagram for representative compositions of basalts from different tectonic settings (B, back-arc basin; C, continental arc: F, continental flood; I, island arc; i, intra-oceanic arc; M, midocean ridge; O, oceanic islands; and P, oceanic plateau). The full compositional range of dataset is shown in the inset. Adapted from Ueki et al., (2018), figures 4 (e) and (f). https://doi.org/10.1029/2017GC007401. Open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License. Reproduced with the kind permission of publisher (Wiley).

3.3 In general, $^{143}Nd/^{144}Nd$ correlates negatively with $^{87}Sr/^{86}Sr$ (and positively with $^{176}Hf/^{177}Hf$). This linear correlation, termed 'Mantle Array' (DePaulo and Wasserburg, 1979) stems from the relative incompatibilities of trace elements, namely Rb > Sr, Nd > Sm, and Hf > Lu (Hofmann, 1997). Thus, mantle regions depleted in incompatible elements (Rb, Nd, Hf) would be characterised respectively by: low Rb/Sr and consequently low $^{87}Sr/^{86}Sr$ ratios; high Sm/Nd, and therefore high $^{143}Nd/^{144}Nd$ ratios; high Lu/Hf, and consequently high $^{176}Hf/^{177}Hf$. On the other hand, continental crust shows the opposite trend. Such linear relationship can be considered as representing a simple mixing trend between the two end-member compositions, a depleted mantle source (Depleted MORB mantle) and an enriched source (OIB). Divergence from this linear trend can be due a heterogeneous mantle source, mantle metasomatism or contamination of plume-derived magmas.

3.4 Hotspot-proximal MORB are characterised by higher $^{87}Sr/^{86}Sr$ ratios and lower εNd and εHf values compared to MORB away from plume influence (εNd and εHf, refer respectively to the deviations in $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios of a sample with respect to CHUR, Chondritic Uniform Reservoir, normally expressed in parts per ten thousand). Interaction between the depleted upper mantle material and the enriched

plume component can produce identifiable geochemical gradients in Sr-Nd-Hf isotopic ratios along the mid-ocean ridge with the ratios shifting from "normal" MORB values towards “enriched” OIB signatures (e.g., Blichert-Toft et al., 2005; Nicolaysen et al., 2007). Crucially, unlike the generally coupled Sr-Nd system, various deep-Earth processes and mantle heterogeneities can also produce decoupled Hf-Nd isotopic signatures in oceanic basalts. These decoupled signatures are physically driven by mechanisms such as deep melting within the garnet stability field (which fractionates Lu/Hf more heavily than Sm/Nd), disequilibrium or fractional melting of ancient, depleted mantle residues, and the selective subduction-related introduction of recycled pelagic sediments or fluid-rock metasomatic agents into the magma source.

3.5 Compared to Sr, Nd and Hf, the isotope data for Pb are more complex. Lead has four naturally occurring isotopes: non-radiogenic ^{204}Pb (primordial), and the radiogenic ^{206}Pb, ^{207}Pb and ^{208}Pb which are the decay products of U and Th (see Annexure-IV, Glossary). Unlike Sr-Nd isotope ratios, the U/Pb ratio and initial Pb isotope composition of the primordial Earth cannot be obtained directly from meteorite composition, because the Bulk Silicate Earth is severely depleted in Pb compared to primitive meteorites (Hofmann, 1997). Nonetheless, lead isotope geochemistry of oceanic basalts (OIB, MORB and basalt variants related to hotspot-ridge interaction) has been demonstrated to be a powerful tool for understanding mantle evolution. For instance, MORB in general are characterised by low ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios compared to OIB, reflective of the former’s depleted mantle source (

3.6 Figure III: 6). In contrast, the higher and more variable Pb isotope ratios of OIB can be traced to a deeper mantle source or recycled crustal materials from deeper within the mantle. Basalts characterised by ridge-hotspot interaction show increasing Pb isotope ratios with increasing proximity to the hotspot.

3.7 Considering that, like Rb-Sr, the parent isotopes of Pb (Th and U) are more incompatible than Pb, a positive correlation between Pb and Sr isotopes (^{206}Pb/^{204}Pb vs. ^{87}Sr/^{86}Sr) is to be expected. However, the behavior of Pb is paradoxical. Although the isotope ratios in MORB from the Atlantic and Pacific oceans do show a positive correlation, same is not the case in regard to the MORB isotopic ratios from the Indian Ocean (Hofmann, 1997; 2003: also see Annex-IV, “DUPAL Anomaly”).

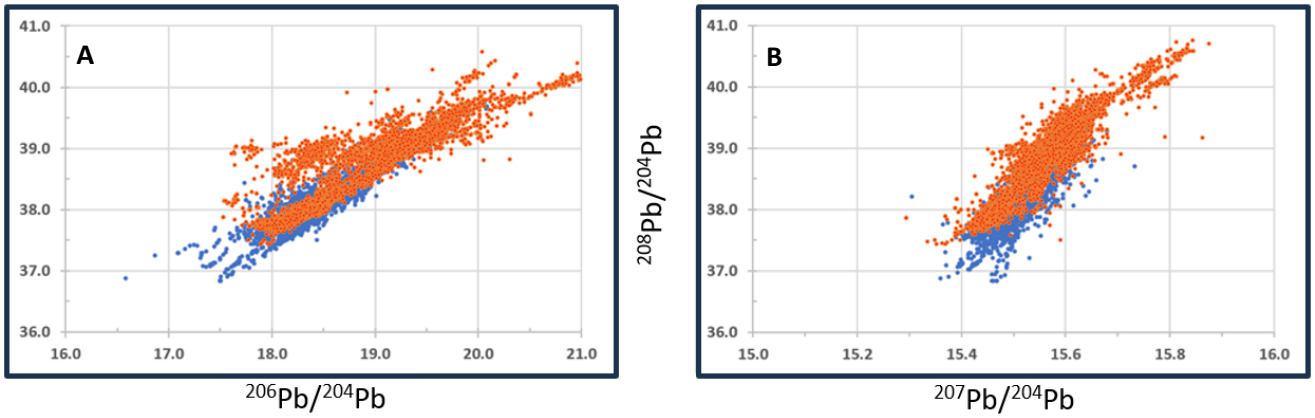


Figure III: 6: (A) $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ and (B) $^{207}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$ for MORB (blue filled circles) and OIB (red filled circles). The data used are from the PetDB (http://www.earthchem.org/petdb) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/) databases. Related references: Stracke et al. (2022a), https://doi.org/10.5880/digis.e.2024.008, licensed under Creative Commons Attribution 4.0 International; Stracke et al. (2022b).

3.7 The isotopic heterogeneity of OIB relative to MORB led to the introduction of the concept of endmember compositions (Zindler and Hart, 1986). Four endmember compositions have been suggested: HIMU (high μ = $^{238}U/^{204}Pb$), EM=1 (Enriched Mantle I), EM-2 (Enriched Mantle II), and DMM (depleted MORB mantle). The mixing arrays defined by these endmembers are usually represented in 3-D Sr-Nd-Pb(-Hf) isotopic space (e.g. Figure 3 of Weis et al., 2023). The focal area of convergence of these four endmembers has been variously termed as PREMA (PREvalent MAntle, Zindler and Hart, 1986), FOZO (Focus Zone, Hart et al., 1992), C (Common Component, Hanan and Graham, 1996), or PHEM (Primitive Helium Mantle, Farley et al., 1992).

3.8 As regards volcanic rocks from subduction zone settings, the Sr and Nd isotopic ratios are spread over a larger area compared to MORB and OIB and typically show an elevated Sr isotopic signature compared to N-MORB (Figure III: 7). This offset to higher values of $^{87}Sr/^{86}Sr$ could be due to the addition of volatiles to the source. Basalts from intra-oceanic arc (IOA) settings (e.g. Mariana, Izu-Bonin, Tonga-Kermadec) plot close to MORB, featuring low Sr and high Nd isotopic ratios. In contrast, continental arcs (CA) such as the Andes, the Cascades and the Central American volcanics are characterised by the most extreme Sr-Nd isotopic variations, marked by high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ values. Island arc (IA) basalts such as those of Kuril, Lesser Antilles, Sunda arc and the Aleutians represent a transitional state between IOA and CA, marked by moderate Sr and Nd isotopic ratios (Figure III: 7).

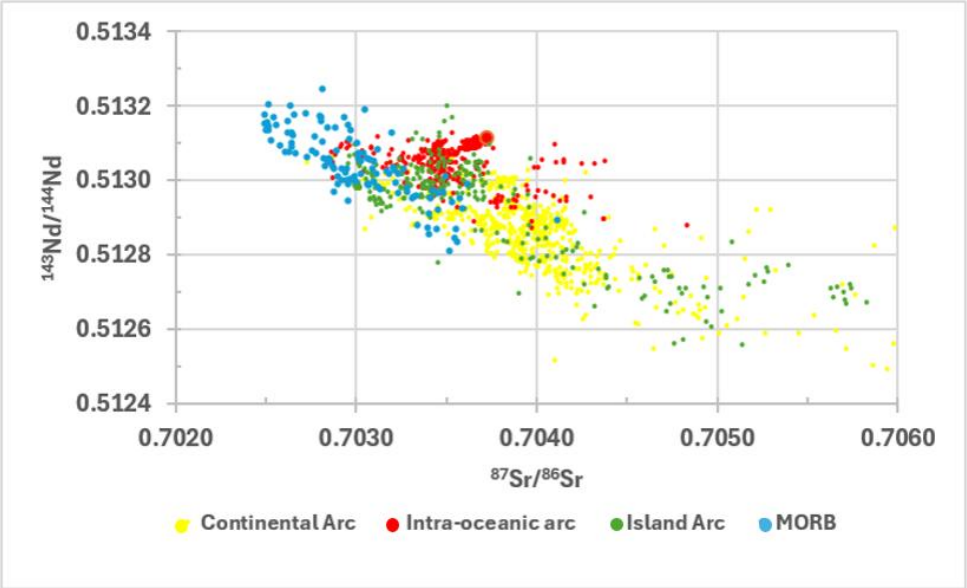


Figure III: 7: Nd-Sr isotopic compositions of arc volcanics from different convergent margins compared with those of MORB. The data used are from the PetDB (http://www.earthchem.org/petdb) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/) databases, compiled by Ueki et al. (2018). https://doi.org/10.1029/2017GC007401 An open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License.

4. VARIATIONS IN NOBLE GAS ISOTOPIC RATIOS

4.1 There are two naturally occurring isotopes of He- ^{3}He and ^{4}He. ^{4}He produced by the radioactive decay of U and Th is constantly lost from the Earth. In contrast, nearly all of ^{3}He is primordial. Variations in the ratio of ^{3}He to ^{4}He in basalts (normalised to the present-day atmospheric ratio of $1.384x10^{-6}$, expressed as R_A) can therefore provide critical information on the different mantle sources. MORB generally have ratios of $8.8\pm2.5R_A$, whereas OIB are characterised by higher ratios (of up to $43R_A$), suggestive of their derivation from a less degassed primordial deep mantle domain, compared to the mantle that gives rise to MORB.

4.2 The existence of high $^{3}He/^{4}He$ in basalts from Hawaii, Iceland, Galapagos and other known hotspot locations is consistent with the acceptance of their origin from a ^{3}He-rich plume-derived magma (Figure III: 8). In contrast, since MORB are products of a depleted and less enriched upper mantle, along mid-oceanic ridges away from hotspots, the $^{3}He/^{4}He$ ratios show lower values. Variations in He isotope values along ridges thus can be related to ridge-hotspot interactions, with the signals heavily influenced by plume strength, distance to the ridge, and along-axis transport.

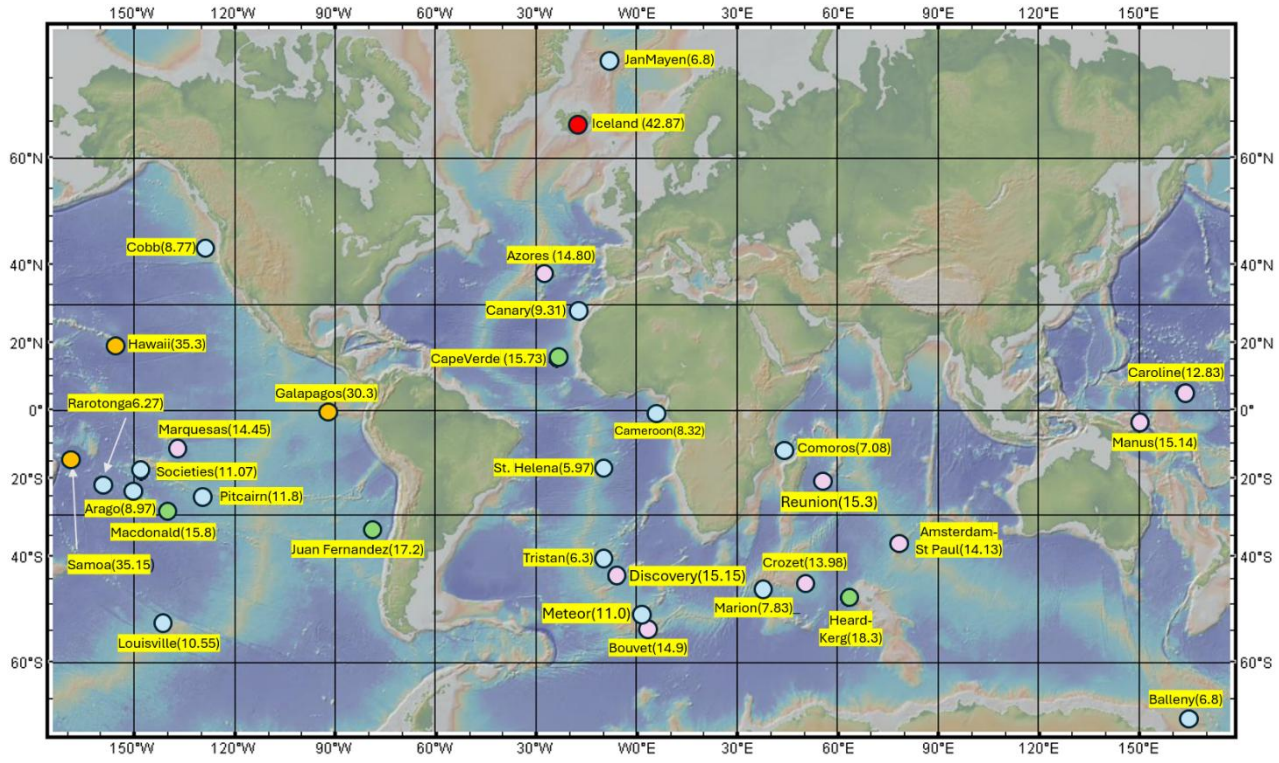


Figure III: 8: Oceanic hotspots with $^{3}He/^{4}He$ measurements, showing the maximum $^{3}He/^{4}He$ values at each location. Data downloaded from PetDB database (https://explore.earthchem.org/dataset/17543). Related reference: Harðardóttir,S. & Jackson, M.G (2025) High 3He/4He plumes are hotter and melt more: evidence from the petrology and geochemistry of ocean island basalts. *Earth and Planetary Science Letters* 666, 119490. doi:10.1016/j.epsl.2025.119490. Figure made with GeoMapApp (www.geomapapp.org)CC BY / CC BY (Ryan et al., 2009).

4.3 Isotopic ratios of other heavy noble gases such as Ne, Ar, Kr and Xe in mantle rocks are also sensitive tracers of the subducted material (Mukhopadhyay and Parai, 2019; Weis et al., 2023). These gases, which have distinctive isotopic compositions, are incorporated into the mantle through subduction. Syn- to post eruptive atmospheric contamination, however, makes it difficult to decipher the mantle record from the isotopic signatures of gases such as Xe and Kr. Nonetheless this data can also provide good constraints on the degree of atmospheric contamination.

In summary, some of the diagnostic geochemical characteristics of basaltic rocks from different tectonic settings as relevant to the continental margin delineation are provided in the Table 1 below:

Tectonic setting	Dominant rock type	Major element concentrations	Trace element abundance	Trace element and Isotope ratios	Remarks
Mid-Ocean Ridge (segments >500 km from hotspots and back-arc basins)	"NMORB"; Sub-alkaline tholeiitic basalt	SiO_2 49–51 wt. %; Al_2O_3 15–17% wt. %; MgO 6–8 wt. %; K_2O<0.25 wt %.	Strongly depleted in the most highly incompatible LILE and enriched in the middle to-heavy REE compared to EMORB and OIB. Nb and Ta are generally more depleted than LREE but less depleted than LILE.	La/Sm_n ratio<1.0; restricted range of variations in isotopic ratios; lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ compared to OIB; lower Pb isotope ratios relative to OIB; lower $^{3}He/^{4}He$ ratios compared to hotspot-proximal ridges	"N-MORB" of Gale et al. (2013). Discriminant diagrams such as Ti-V, Th/Yb-Nb/Yb, TiO_2/Yb-Nb/Yb and Th–Hf/3–Ta, TiO_2-MnO-P_2O_5 can be quite useful in identifying the tectonic setting, particularly if used in conjunction with other geochemical data
Hotspot-proximal ridges (segments <200 km from hotspots)	E-MORB; tholeiitic basalts and their derivatives, with small amounts of alkalic rocks in later sequences	Along-axis variations, with enrichment in TiO_2, K_2O towards plume source; in contrast, MgO and Mg# increase away from the plume source; low Na_2O relative to MORB and subduction zones	More enriched in highly incompatible LILE and LREE relative to N-MORB; depletion in LREE and enrichment in HFSE compared to neighbouring elements	High La/Sm values and high $^{3}He/^{4}He$ ratios compared to N-MORBs; higher $^{87}Sr/^{86}Sr$ ratios and lower εNd and εHf values compared to N-MORB; increase in Pb ratios with increasing proximity to plume source	Not all plume-influenced basalts show enrichment in incompatibles; La/Sm_n constraints hotspot proximity better than enrichment in incompatibles (Gale et al. 2013)
Oceanic Islands (intra-plate settings)	Spans both tholeiite and alkali basalt fields; dominantly alkaline	Tholeiitic Ocean Island Basalts (OIB) similar to MORB; MgO content more abundant than at MORs. Alkali olivine basalt abundant type in alkalic OIB suites	Overall and progressive enrichment in the more incompatibles relative to N-MORB and E-MORB; depletion in LREE and enrichment in HFSE compared to neighbouring elements	$^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$ defines the mantle array in respect of OIB; departure from array reflective of crustal contamination; distinct geochemical, isotopic signatures compared to MORB; more variable and higher Pb ratios relative to MORB.	End-member characterisation in terms of Sr-Nd-Pb(-Hf) a good proxy for the degree of mantle heterogeneity and/or crustal contamination

Tectonic setting	Dominant rock type	Major element concentrations	Trace element abundance	Trace element and Isotope ratios	Remarks
Oceanic plateaus	Sub-alkaline to alkaline tholeiitic basalts with <11 wt % MgO	Low Ti (crustal contamination/ differences in mantle melting/ crystallisation) High Ti (uncontaminated); mantle plumes?	Trace element pattern similar to MORBs in general, but slightly more enriched in incompatible elements. Relatively flat chondrite-normalized REE pattern diagnostic.	$^{87}Sr/^{86}Sr$ and ε_{Nd} values generally less depleted compared to N-MORBs. Elevated initial Sr ratios are reflective of hydrothermal alteration or crustal contamination	Kerguelen plateau basalts show geochemical characterises of both continental flood basalts (early plume-derived volcanism) and younger oceanic intraplate settings
Intra-oceanic arcs Island arc settings	Andesite-dacite, tholeiite (low-K) to high-K calc alkaline and shoshonite. Andesites most diagnostic.	High-Alumina basalts with relatively high Na_2O	Enrichment in LILE and LREE but depletion in Nb, Ta, Hf relative to neighbouring elements. HFSE depletion relative to LILE and LREE (Ni-Ta anomaly) is typical of subduction zone magmas. +ve spike for Pb	Low $^{87}Sr/^{86}Sr$ and high ε_{Nd} ratios. The ratios cover a large range, and overlaps with both MORB and OIB	The addition of volatiles imparts higher Sr isotope values at constant ε_{Nd}
Continental margin arcs	Calc-alkaline, with subordinate tholeiite and shoshonites.	Arc tholeiitic basalts show mild Fe-enrichment with SiO_2 enrichment	Higher concentrations of Rb, Cs, Ba, K, Th, and LREE compared to MORBs	Larger Sr-Nd isotope variations compared to intra-oceanic arcs	
Back arc basins	Sub-alkaline (basalt-andesite).	Low in alkalis compared to island arc basalts	Compared to MORBs, ~20% less concentrations of incompatibles, except for Cs, Rb, Ba, and Pb peaks. Shows both arc-like and MORB geochemical characteristics	Isotopic characteristics reflective of mixing of a MORB and island-arc basalt source	

Table 1: Geochemical characteristics of basaltic rocks from different tectonic settings

ANNEX IV – GLOSSARY

I. PRINCIPAL TYPES OF BASALTIC VOLCANISM

1 Introduction

1.1 The three principal types of basaltic volcanism are the mid-ocean ridge basalt (MORB) volcanism where magma is erupted at divergent plate boundaries (spreading centers), the subduction zone (or arc) volcanism, where lavas are formed at convergent plate boundaries, and the volcanism marking the **Large Igneous Provinces (LIPs)**. LIPs have been defined as "magmatic provinces with areal extents $>1\times10^5$ km^2, igneous volumes $>1\times10^5$ km^3 and maximum lifespans of ~50 Myr that have intraplate tectonic settings or geochemical affinities and are characterised by igneous pulse(s) of short duration (~1–5 Myr), during which a large proportion (>75%) of the total igneous volume has been emplaced. They are dominantly mafic, but also can have significant ultramafic and silicic components, and some are dominated by silicic magmatism."(Bryan and Ernst, 2008).

2 Occurrence of LIPs (Reference: Coffin and Eldholm, 2019)

2.1 LIPs occur both on continents and in the oceans and include continental flood basalt provinces (e.g. Deccan Traps, Siberian Traps and the Columbia flood basalt provinces), giant continental dyke swarms and mafic ultramafic intrusive provinces (e.g. Mackenzie, Bushveld), the Silicic LIPs (e.g. Whitsunday), volcanic continental margins (e.g. East African rift, the eastern and western margins of India, the northern and north-eastern Atlantic, south Atlantic, south-west African margin, the US Atlantic margin, the western Australian margin etc.), oceanic plateaus (e.g. Kerguelen, Mascarene, Ontong Java-Manihiki-Hikurangi, Rio Grande Rise, Shatsky Rise, Sierra-Leone) submarine ridges/submarine elevations (e.g. Agulhas, Alpha-Mendeleyev, Chagos-Laccadive, Ninety East, Walvis,), seamounts (e.g. Clipperton, Comores, Discovery, Guadelupe, Hawaiian-Emperor, Lord Howe Rise, Tasmantid, Tahiti) and ocean basin flood basalts (e.g. Nauru Basin, east Mariana).

3 LIPs, Mantle plumes and hotspots

3.1 Most LIPs have been linked to the arrival at the base of the lithosphere of a **mantle plume**.

3.2 **A mantle plume** is a buoyant upwelling of abnormally hot material from deep within the Earth's mantle, probably at depths near the core−mantle boundary (~2,900 km). The surface manifestation of a plume is a **Hotspot.**

3.3 **Hotspot-Ridge interaction** (**References: Ito et al. 2003; Dyment et al. 2007; Bao et al., 2022**): Many of the hotspot regions are marked by bathymetric swells, and hotspot swells proximal to mid-ocean ridges are locations of **hotspot–ridge interaction** (e.g. Iceland, Galapagos, Kerguelen). Interaction between ridges and hotspots results in a thicker-than-normal oceanic crust, elevated topography, P-wave velocities greater than 7.1 km/s for the lower crust, and basaltic rocks with compositional affinities to OIB that point to the presence of/interaction with a "plume" component. The "plume" component is largely concentrated in magmas erupted near hotspot centres but becomes progressively weaker away from the hotspot (e.g., Reykjanes Ridge off Iceland).

3.4 A large number of hotspots, traceable to mantle plumes, lie near divergent plate boundaries, and quite a few are co-located with the ridge axes (e.g., Iceland, Azores, Afar, Jan Mayen, and Galapagos). Intraplate plume-related processes have also been documented (e.g. the South China Sea, the Sea of Japan, and the west Philippine Basin).

4 Arguments against mantle plume hypothesis (References: Anderson and Natland, 2005; Foulger, 2010; White, 2015; Jackson, 2018)

4.1 The conventional mantle plume hypothesis has also been subject of intense academic debate ever since it was proposed, because:

- Plumes not only limited to upwelling from the core-mantle boundary but also include secondary plumes and local melting anomalies of low eruptive volume, originating in the upper-lower mantle transition zone (~410-660 km);
- Many of the ocean island chains (the so-called "tails") do not seem to be linked to any of the known LIPs ("the heads");
- There are some oceanic plateaus (e.g., Ontong Java) that have no succeeding hotspot tracks, and isolated seamounts (e.g., Bermuda) that cannot be related to deep mantle plumes;
- There are regions of the mid-ocean ridge characterised by basalts with OIB-like geochemistry (e.g., the 45˚N area of the

Mid-Atlantic Ridge), but without any evidence of a mantle plume.

4.2 Despite these, the mantle plume hypothesis has come to be recognised as the most plausible mechanism that can explain many, if not most, of the observed geological, geophysical and geochemical characteristics and genesis of rifted volcanic continental margins, oceanic plateaus and oceanic island chains.

5 Major-, minor-, trace-, REEs, compatible and incompatible elements

5.1 Major elements are constituents of the minerals making up a rock, e.g. silicon, aluminium, chromium, magnesium, iron, calcium, sodium, and oxygen. These elements are essential constituents of the upper-mantle minerals-olivine, pyroxene, garnet, spinel, and plagioclase. In contrast, minor elements are those that typically comprise 0.1 to 1 weight % of a magma or rock.

5.2 **Trace elements** are those that are not structural components of major mantle minerals and which occur in very low concentrations in common rocks (in parts per million, {ppm} or parts per billion, {ppb}). Trace elements most commonly used for the interpretation of the petrogenesis of igneous rocks include Ni, Cr, Sc, V, Rb, Ba, Sr, Zr, Y, Nb and the rare earth elements [REE] (La to Lu) (Figure IV:1).

5.3 **Rare Earth Elements (REEs):** The *lanthanide elements*, also called the rare earth elements (REE), having atomic numbers 57 (La) to 71 (Lu), are very important trace elements with high field strength (Figure IV:1). Elements 57 through 64, La through Gd, are considered light REEs; 65-71, Tb through Lu, are heavy REEs. Y and Sc are sometimes grouped with the heavy REEs due to similar properties.

5.4 **Compatible and incompatible elements:** *Compatible* elements are those that substitute readily into common mantle minerals such as olivine, pyroxenes, spinel and garnet. *Incompatible* elements are those that do not readily substitute into these minerals. Being excluded from mantle minerals, these elements partition into magma when melting occurs and consequently have become concentrated in the crusts.

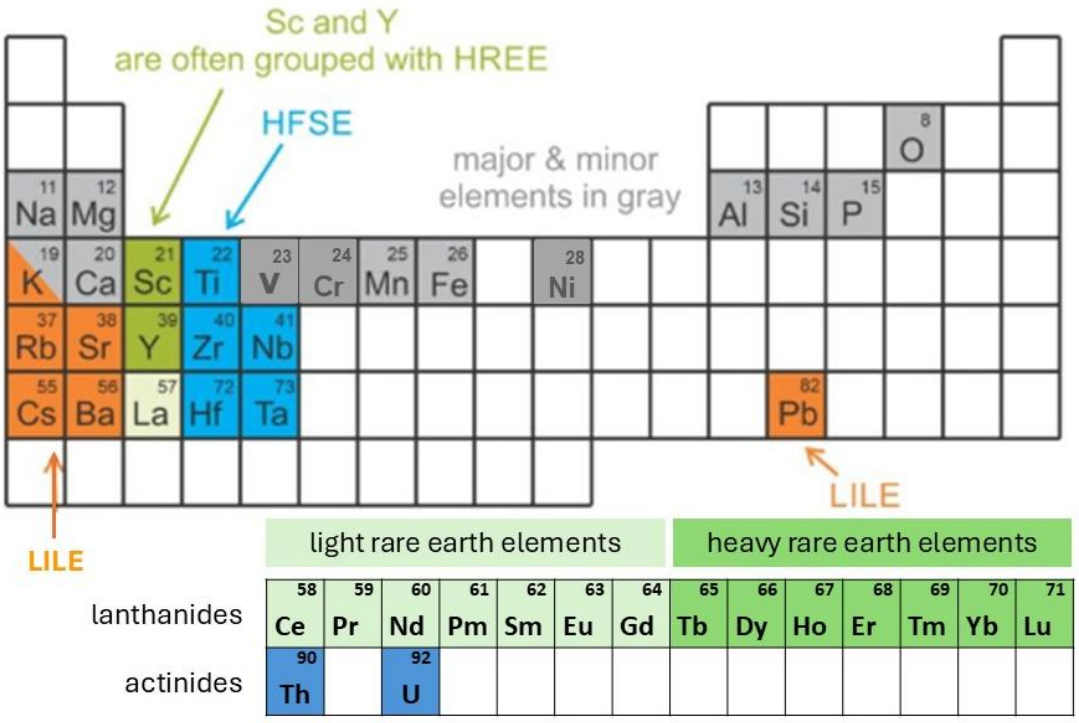


Figure IV:1: Geochemical Periodic Table showing some key elements in igneous rocks (https://opengeology.org/petrology/03-magma/).

6 N-MORB, E-MORB, D-MORB

6.1 Mid-ocean ridge basalts (MORB) are derived from partial melting through adiabatic decompression of the upper mantle material along mid-ocean ridges. Based on variations in incompatible trace element concentrations and their abundance ratios, isotopic compositions as well as the distance from the influence of hotspots, Gale et al., (2013) have sub-divided the MORBs into normal-, enriched-, and depleted- mid-ocean ridge basalts (N-MORB, E-MORB and D-MORB respectively) as described below:

6.1.1. **N-MORB:** Normal mid-ocean ridge basalts, found along segments of the global ridge system more than 500 km from hotspots and back-arc basins. Also defined as MORB characterized by $(La/Sm)_n$ <1.00, where the "n" refers to normalization to chondritic meteorites (Hofmann, 2003).

6.1.2. **E-MORB**: Incompatible trace-element enriched mid-ocean ridge basalts, occurring along segments of ridge system, within 200 km of hotspot locations, e.g., Jan Mayen, Iceland, Azores, Ascension, Juan

de Fuca/Cobb. E-MORB are marked by a higher concentration of incompatibles relative to N-MORB and have also a deeper mantle source compared to N-MORB. However, not all E-MORB segments are associated with mantle plumes or are proximal to a hotspot. Considering the lack of a clear correspondence between E-MORB segments and hotspot proximity, Gale et al., (2013) have proposed a chemical definition of E-MORB, as comprising segments of MORB with a $La/Sm_n>1.5$, rather than a spatial definition.

6.1.3. **D-MORB:** Depleted mid-ocean ridge basalts, the trace element-depleted end-member of the MORB population. D-MORB have a (La/Sm)n ~0.6 (Langmuir, 2017); <0.8, Gale et al., 2013).

7 Spider diagrams (References: Sun and McDonough, 1989; Wilson, 1989)

7.1 The customary practice for displaying trace element/REE abundances is to normalize them to chondritic abundances and then to plot these normalized abundances in order of atomic number, Z. The two most popular normalising materials are: (i) CI chondrites (**Ivuna-type carbonaceous chondrites**, whose overall chemical composition is considered as representative of the Early Earth chemical composition; and (ii) '**primitive**' or 'primordial' mantle composition, computed from the observed trends in the chemical makeup of upper mantle peridotites. In such a diagram, the order of trace-element incompatibility in oceanic basalts (both MORB and OIB) along the X axis is (from most incompatible to less incompatible): Cs ≈Rb (≈Tl) ≈ Ba (≈W) > Th > U ≈Nb ≈Ta ≈ K > La > Ce ≈ Pb > Pr (≈Mo) ≈Sr >P ≈Nd (> F) > Zr = Hf ≈ Sm > Eu ≈Sn (≈Sb) ≈Ti > Dy≈ (Li) > Ho ≈Y > Yb. This order is mainly based upon the depletion pattern of N-MORB.

8 Radiogenic isotopes

8.1 Isotopic ratios of certain radiogenic elements are sensitive tracers of the potential magmatic sources especially because they do not fractionate significantly during melting or crystallization (Hofmann, 2003; White, 2015). Table below lists the long-lived radiogenic isotope systems that are most commonly used in igneous petrogenesis studies.

Parent	Daughter	Measured Ratio
^{40}K	^{40}Ar	$^{40}Ar/^{36}Ar$
^{87}Rb	^{87}Sr	$^{87}Sr/^{86}Sr$
^{147}Sm	^{142}Nd	$^{143}Nd/^{144}Nd$
^{176}Lu	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	^{187}Os	$^{187}Os/^{188}Os$
^{232}Th	^{208}Pb, ^{4}He	$^{208}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{235}U	^{207}Pb, ^{4}He	$^{207}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{238}U	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

8.2 DUPAL ANOMALY (References: Dupré and Allègre, 1983; Hart, 1984; Meyzen et al., 2005; Tian et al. 2022, and references therein): Named after the French geochemists Dupré and Allègre, DUPAL anomaly is a large-scale feature in Earth's mantle that extends as a broad band across the Southern Ocean encompassing the Indian Ocean, the South Atlantic Ocean, and the southwestern Pacific Ocean. The oceanic basalts from this region are characterised by anomalously high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ isotope ratios for a given $^{206}Pb/^{204}Pb$, high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ when compared to the Northern Hemisphere. The exact causes of this anomaly are a topic of academic debate and have been variously attributed to processes by which ancient subcontinental crust or sediments were recycled into the asthenospheric mantle and subsequently incorporated into the upper mantle, or to deep-mantle upwellings from large low shear velocity provinces (LLSVPs).

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