

CHEMISTRY OF THOLEIITIC BASALTS FROM ICELAND AND THEIR RELATION TO THE KVERKFJÖLL HOT SPOT

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1. INTRODUCTION

Ever since the universal occurrence and unique composition of "oceanic tholeiites" was defined by Engel et al. [1,2], the "differentiated" or "undepleted" nature of Icelandic basalts has become increasingly apparent [3-6]. This, in conjunction with the high elevation of Iceland relative to the Mid-Atlantic Ridge, and its anomalous volcanic productivity throughout 70 m.y. (as witnessed by the aseismic Wyville-Thompson ridge) has clearly defined Iceland the hot spot of the North Atlantic [7-9]. Adjacent to the hot spot a gradient has been established along the mid-ocean ridges next to Iceland, both in the elevation of the sea floor [several authors in this volume] and in the chemical and isotopic composition of the volcanics [10,11].

Morgan [8] suggested, contrary to Wilson [7], that the hot spots form an integral part of the mechanism driving the crustal plates. He visualized mantle material ascending along deep pipes to spread radially into the asthenosphere, a model subsequently used by Vogt [19] to explain the V-shaped ridges south of Iceland. In such a system partial melting would ensue at some stage as a result of the adiabatic decompression. Depending on the path travelled in vertical and horizontal direction by each volume of rock undergoing partial melting within the plume and its overflow, a geographical distribution of various types of basalt, representing various degrees and depths of partial melting, should obtain at the surface. Such geographic distribution was demonstrated by Schilling [10] and Hart, Schilling and Powell [11] for the Reykjanes Ridge. However, these authors elected to explain the chemical and isotopic evidence in terms of a model involving a number of

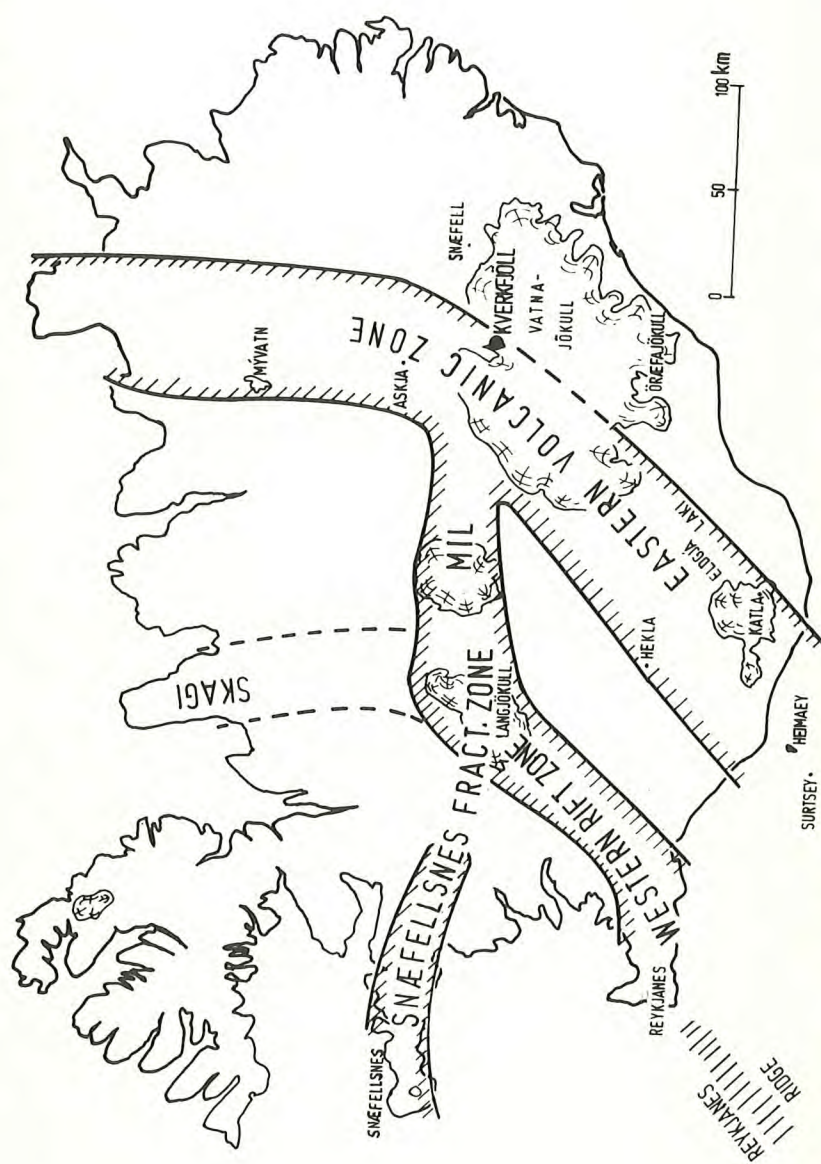


Fig. 1. An index map of Iceland, showing the neovolcanic zones and place names used in the article.

discrete mantle sources with some magma mixing at the source boundaries. We propose to show that the same variation continues across Iceland, and that it can be explained by a one-source model compatible with the mantle plume hypothesis.

2. EXTENT OF THE PETROCHEMICAL SURVEY

Active volcanism in Iceland is restricted to well-defined zones, termed the neovolcanic zones. They exhibit distinct petrological characteristics compatible with their respective tectonic natures. Thus, the volcanics in the western and north-eastern zones, which form the subaereal continuation of the Reykjanes and Kolbeinsey Ridges, respectively, are tholeiitic in composition whereas the volcanics of the Snaefellsnes and south-eastern zones are predominantly alkalic [12].

In the process of the present petrochemical survey over 500 samples from all the zones have been collected and analyzed. This suite is considered to cover volcanic activity in Iceland during the Brunhes palaeomagnetic period (700,000 years). The sampling was carried out so as to represent (a) the areal extent, (b) chronological formations, (c) morphological formations, and (d) petrochemical types. The morphological formations are subglacial pillow lavas and móberg (palagonite breccia), interglacial lavas, and postglacial volcanics. The latter may be divided according to volcano types into fissure and minor eruptions on the one hand, and shield eruptions on the other. The shield volcanoes are the postglacial counterparts of the subglacial stapis (table mountains). The volumes of the two types vary greatly: the shield volcanoes and stapis range from one to 15 km³ whereas the others, with a few very notable exceptions, are generally less than 1 km³.

3. CHEMICAL VARIATION IN THE THOLEIITES

The chemical variation observed in the North Atlantic centers on the Kverkfjöll area in Iceland (Fig. 1). The maximum values for K₂O, P₂O₅, and TiO₂ decrease continuously with distance from Kverkfjöll in both directions along the tholeiitic zones to the southwest and north (Fig. 2). Conversely the minimum values stay about the same throughout the zones. As seen from Fig. 3, K₂O and TiO₂ vary sympathetically. Fig. 4 shows a plot of Al₂O₃ versus TiO₂. Titanium is sensitive to pressure [13], whereas Al₂O₃ has been claimed to be a function of degree of melting [14]. Thus, taking Figs. 3 and 4 at face value it is indicated that the undepleted (low Al, high K) basalts formed at relatively high pressures whereas the depleted ones (low K, high Al) formed at shallower depths.

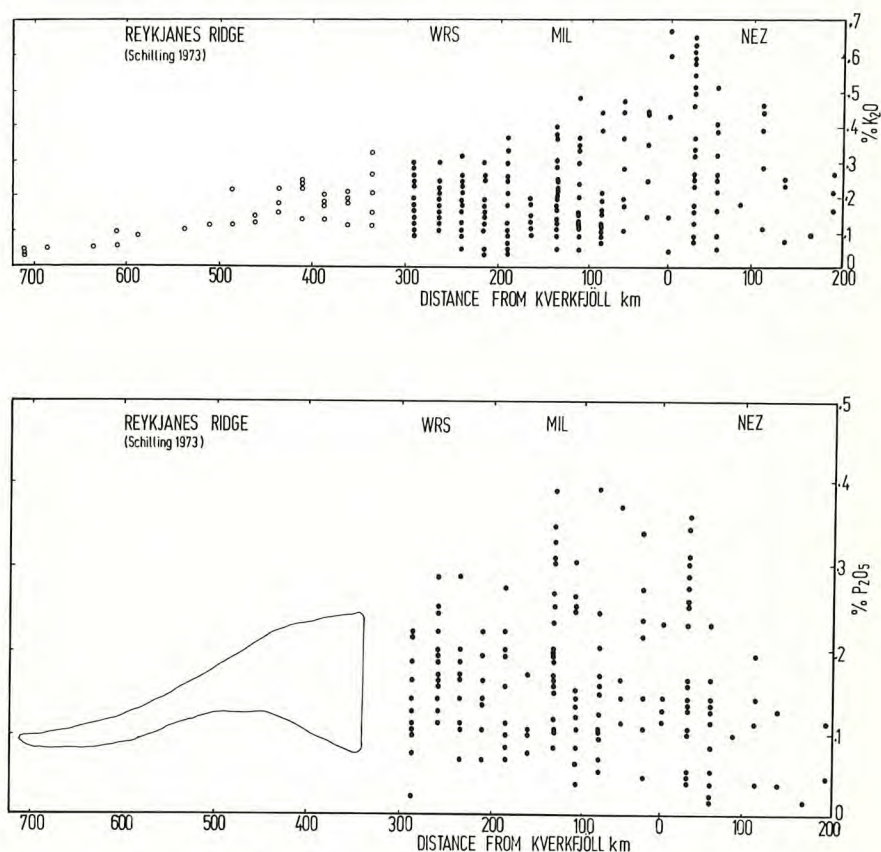


Fig. 2. Plot of K_2O and P_2O_5 versus distance from the Kverkfjöll hot spot. WRZ - Western Rift Zone; MIL - Middle Iceland; NEZ - Northeastern Iceland.

Many other chemical parameters show a positive correlation with K_2O , such as total iron, Zr, and Sr. Furthermore, similar lateral variation has been demonstrated on the Reykjanes Ridge for water and sulfur [15], rare earths [10], and Sr^{87}/Sr^{86} isotope ratios [11] and for Cl along the volcanic zones in Iceland [Sigvaldason et al., in preparation]. The iron enrichment of the Icelandic tholeiites relative to samples from the ocean floor was previously noted by Sigvaldason [4]. Samples from the Juan de Fuca Ridge resemble the Icelandic ones in this respect, in accordance with the fact that that area is reputed to be the site of a mantle plume as well [25].

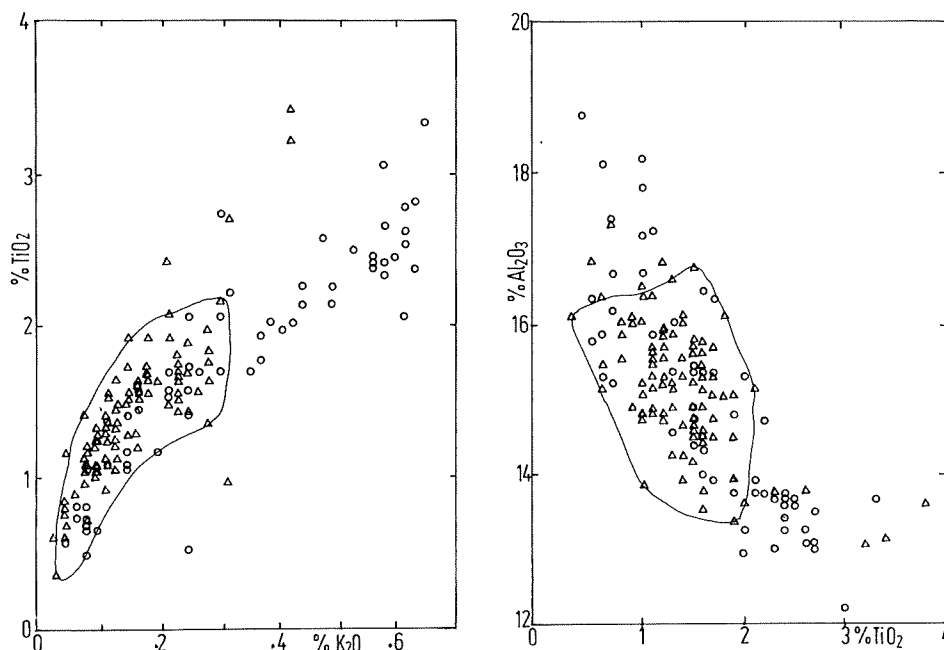


Fig. 3 (left). A plot of TiO_2 versus K_2O .

Fig. 4 (right). A plot of Al_2O_3 versus TiO_2 .

Circles: samples from Kverkfjöll and the north-eastern zone.

Triangles: samples from Middle Iceland and the Reykjanes peninsula, the latter enclosed by the solid line.

A pronounced correlation exists between the chemistry and volume of the tholeiites under consideration (Fig. 5, from [16]). This is especially notable in Central Iceland, where the composition range is large. The shield eruptions tend to be voluminous; chemically they are the most depleted rocks in Iceland and thus resemble the oceanic tholeiites most. They belong to the specific volcano-tectonic environment realized during the isostatic rebound of the country during the waning stages of the pleistocene glaciation. The upper mantle was suddenly disturbed toward lower pressure resulting in the melting of large batches of mantle material. Thus, a local decompression can produce a chemical variation in one area that is similar to the horizontal variation otherwise observed.

As previously noted, Schilling and his associates have demonstrated a gradient in $\text{Sr}^{87}/\text{Sr}^{86}$ isotopic ratios and REE patterns away from Iceland along the Reykjanes Ridge. Unfortunately, at this writing no such systematic analysis of these parameters has been undertaken on the Icelandic tholeiite suite. However, the data of Shimokawa and Masuda [6] and O'Nions and Grönvold [17] indicates that lavas of shield volcanoes have low La/Sm ratios (i.e. are relatively depleted in the light REE), olivine tholeiites, such as predominate in the Reykjanes peninsula, have higher La/Sm ratios, whereas tholeiites, such as the 1961 Askja lava, are the least depleted in light REE. Therefore, this chemical parameter seems to follow the others in Iceland as well as on the Reykjanes Ridge. Likewise the available Sr-isotope evidence [11,17] might be construed to indicate that the $\text{Sr}^{87}/\text{Sr}^{86}$ -ratios in the Icelandic rocks are chemistry-bound as well, for basalts from the alkaline Snaefellsnes peninsula possess slightly higher Sr-isotopic ratios than the tholeiites. This will be tested by further work.

To summarize the chemical evidence enumerated above, a continuous petrochemical gradation exists in the North Atlantic along the mid-ocean ridge that centers on the Kverkfjöll area in Iceland. The variation includes major, minor and rare earth elements, as well as Sr-isotopic ratios. Geochemical arguments, the geographic variation, and the circumstantial evidence of the shield volcanoes suggest that the compositional gradient results from the combination of changing P-T environment in an upwelling and laterally spreading mantle plume system, and a progressive depletion in the low-temperature melting fraction at the source.

4. A SINGLE SOURCE MODEL FOR THE NORTH ATLANTIC

The chemical evidence at hand for the North Atlantic has been explained both in terms of two or more primary magma sources [10,11] and in terms of one source [18]. According to the two-source model, which receives its chief support from the conventional doctrine of the "immutability of Sr-isotopes", magmas derived from the Icelandic plume source possess $\text{Sr}^{87}/\text{Sr}^{86}$ -ratios of the order of 0.7032, show undepleted REE-patterns, have high Fe/Mg-ratios and are relatively rich in K, Ti, P, and volatiles. Magmas from the oceanic source, on the other hand, have much more depleted chemistry and $\text{Sr}^{87}/\text{Sr}^{86}$ -ratios about 0.7026. The compositional gradient along the Reykjanes Ridge results, according to this theory, from the mixing of the two magmas.

O'Nions and Pankhurst [19] and Sigvaldason et al. [18] have suggested that Sr-isotopic disequilibrium may exist in the mantle between mineral phases. Assuming this, the analytical evidence from Iceland [17] and the Reykjanes Ridge [11] becomes intelligible in terms of a single-source model: The plume is richer in volatiles

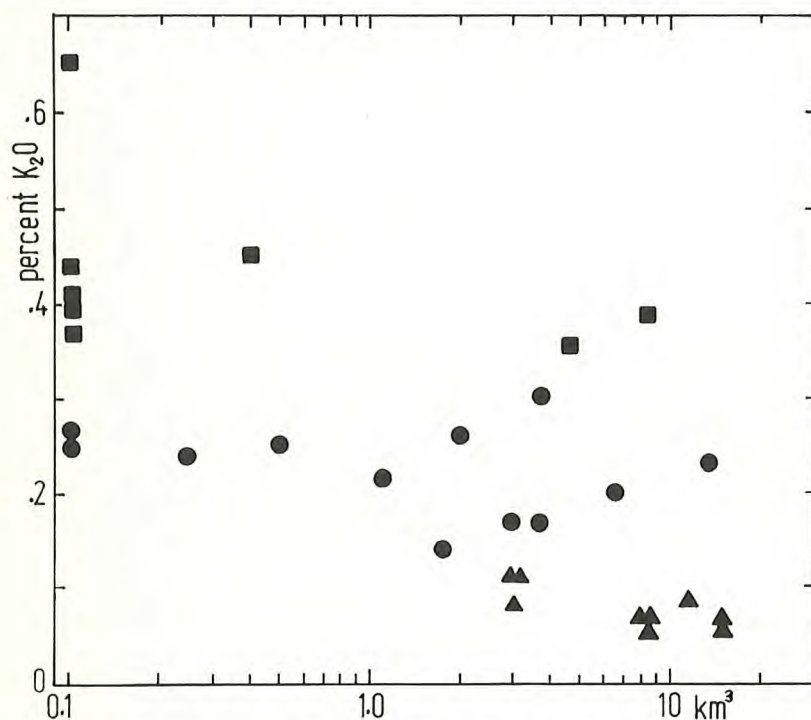


Fig. 5. A plot of lava volume vs. K_2O for the north-eastern volcanic zone (from [16]).

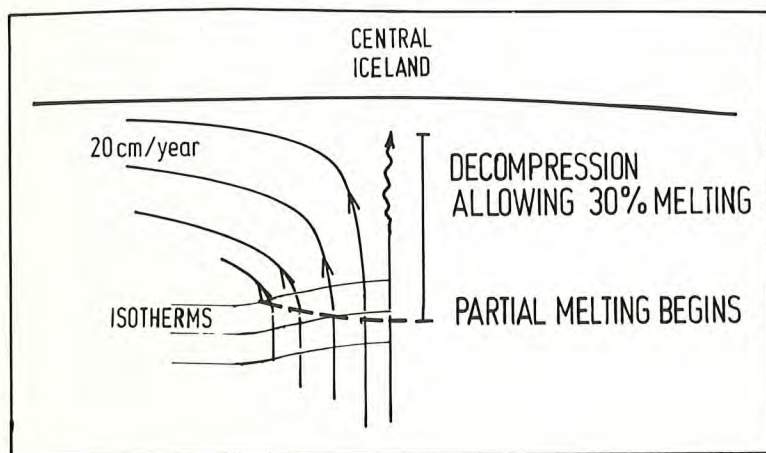


Fig. 6. A schematic section showing hypothetical flow lines within a mantle plume system.

and radioactivities than the surrounding mantle. As a result it is hotter and lighter and ascends diapirically through the mantle, providing the required buoyancy beneath the high-rising hot spots. The plume material appears to spread out laterally along preferred channels [9] as evidenced by the seismic work of Palmason [20]. Sigvaldason [16] predicted a temperature regime in and around the plume comparable to that of a hydrothermal system. Within the plume the thermal gradient is positive throughout, providing a thermal environment suitable for partial melting over an extended depth range. Conversely, in the plume overflows a temperature maximum occurs at the depth of partial fusion.

The plume is a closed thermal system -- partial melting only occurs as a result of decompression (Fig. 6). In the center of the plume the entire decompression projects on a small area at the surface, the center of the hot spot, where up to 30% partial melting can take place in a vertical column. Towards the margin of the plume the vertical component of the movement is more restricted, and the various products of the partial melting are spread horizontally, as evidenced by the chemical variation at hand.

The upper mantle, where magma segregation is supposed to take place, probably consists of olivine, two pyroxenes, plagioclase, and minor phases, including amphibole and phlogopite [14,21,22]. When such an assemblage melts, the phlogopite would tend to melt completely before the other more refractory phases started breaking down [23]. The K- and Rb-enriched composition of the basalts in Central Iceland result from the important contribution of phlogopite to the early partial melts of the plume. Recent experimental evidence by Mysen [26] indicates that some such "extraneous" source is necessary to obtain all K-values other than the low ones observed in oceanic tholeiites. Phlogopite contains of the order of 7% K, 250 ppm Rb, and 18 ppm Sr [23]. The other components in the upper mantle contain between 1 and 0.1 ppm Rb. The high Rb content of the phlogopite results in an increased $\text{Sr}^{87}/\text{Sr}^{86}$ ratio relative to the rest of the mantle. Using the above cited values for Rb and Sr in phlogopite the $\text{Sr}^{87}/\text{Sr}^{86}$ -ratio would increase by 7×10^{-5} every million years. Conversely, the highest Rb/Sr ratios observed in Icelandic tholeiites yield an increase of 2×10^{-6} every million years, whereas the Sr-isotopic ratio of the depleted ocean tholeiites has very little capacity for change with time, and probably reflects that of the bulk of the upper mantle [18]. Considering that phlogopite crystals must form but a small fraction of the upper mantle (Griffin and Murthy [23] use 0.5 wt. %) they must be relatively few and far between. Thus it is difficult, barring complete melting or recrystallization, to visualize but partial isotope equilibration. Even so only the immediate vicinity of each phlogopite crystal should be affected - which probably will eventually be the first to melt subsequent to the phlogopite as a result of the fluxing effect of the water released.

The chief virtue of the two-source theory is its conceptual simplicity and its adherence to well-worn notions about a pervasive equilibration of Sr-isotopes at elevated temperatures. However, the growing body of evidence on Sr-isotopes in Iceland threatens to call for an ever-increasing number of primary sources -- the Snaefellsnes province is already being suggested as a third one.

The chemical gradient observed on the Reykjanes Ridge does not terminate at Iceland, but continues uninterrupted to center at Kverkfjöll. Were this to be explained by the mixing of two homogeneous magmas the plume would have to be very thin indeed.

Finally, Schilling et al. [24] have analyzed a sequence of samples collected on a line perpendicular to the Mid-Atlantic Ridge, in which no chemical variation was found. Such uniformity through time can only be accomplished by constantly replenishing the source of partial fusion. This could be done in three ways, (a) by a convective system below the ridges, (b) by asthenospheric flow from Iceland, and (c) by drifting the plate system relative to the upper mantle to constantly tap fresh portions of the low-velocity zone.

The universal symmetry of magnetic anomaly patterns about the mid-ocean ridges shows that the plate systems cannot be rooted to subcrustal convection cells - on the contrary they must drift passively about the surface of the Earth relative to the mantle plumes. The last alternative (above) seems a doubtful one as a general process, whereas an asthenosphere flow along the ridges away from the plumes, as described above, would account for all the facts.

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