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Biased chemical Range of Icelandic and oceanic Basalt Analyses: The Result of different sampling Methods and compositionally selective kinematic Evolution within Rift Zones

PÁLL IMSLAND
Nordic Volcanological Institute, University of Iceland, 101 Reykjavík

ABSTRACT

Over 50% of the rocks produced in the rift zones of Iceland are of the primitive MORB-type tholeiites. The remaining 50% consist of more evolved tholeiites, some FETI-enriched tholeiitic basalts and a small amount of intermediate and silicic rocks. The more evolved part of this suite is produced in central volcanoes, while the primitive part is the product of the fissure swarms in early stages of evolution. In the non-rifting volcanic zones, no primitive tholeiites are produced, but the bulk of the production is of the FETI-basalt type and enriched in alkalies. The relative share of intermediate and silicic rocks in these zones is much greater than in the rift zones, but the total rock production is much lower. Compared to the ocean floor, the Icelandic rift zones produce identical rock types but in greater relative volume. There is a close resemblance between the non-rifting zone production and the poorly defined off-ridge rocks of the oceans. The Tertiary rocks of Iceland which show low abundance of the most primitive tholeiites are the flank products of the main rift zones. This same low abundance characterizes the ridge flanks and older parts of the sea floor. This harmonizes with the kinematic evolution of the spreading centers and its compositionally selective nature. The idea behind the "Iceland geochemical anomaly" results from: 1) different data-banks and totally different information on samples of the different data-banks, which result from the different sampling methods in use on the ocean floor and in Iceland, and 2) compositionally selective nature of the kinematic evolution of the rift zones.

INTRODUCTION

In the literature on the petrochemistry of the oceanic rocks, one frequently meets with the idea of an "Iceland geochemical anomaly". This phrase is poorly defined but highly suggestive regarding the petrochemical difference between Iceland and the ocean floor. In the article, this idea will be examined. The data used is of three types: 1) general knowledge of the volcanology of Iceland and the evolution taking place on and within its volcanic zones (largely summarized by *Saemundsson* 1979), 2) available data on the chemistry of the Icelandic rocks and their distribution in relation to composition (summarized by *Imsland* 1978 and in press), and 3) for comparison, data from articles summarizing the petrochemistry of the ocean floor rocks (e.g. *Cann* 1971 and *Hart* 1976).

VOLCANO-TECTONICS AND PETROCHEMISTRY VERSUS SAMPLING METHODS

The methods used in collecting the rock samples from the ocean floor and from Iceland lead to fundamentally different background information on the samples.

In Iceland the samples are hand-picked after being selected on basis of general geological and volcanological information. The data-bank on Icelandic rock chemistry thus allows the correlation of the petrochemistry to a diversity of volcanic phenomena and other relevant features.

Both the dredge sampling- and drilling methods used in the case of the ocean floor sampling give samples without precise geological and volcanological information. The chemistry of the ocean floor rock samples can thus not be correlated to volcanotectonic origin in any detail. Only gross correlations or hypothetical deductions can be made.

On the basis of information gained in this way the present general ideas on the evolution of the rifting

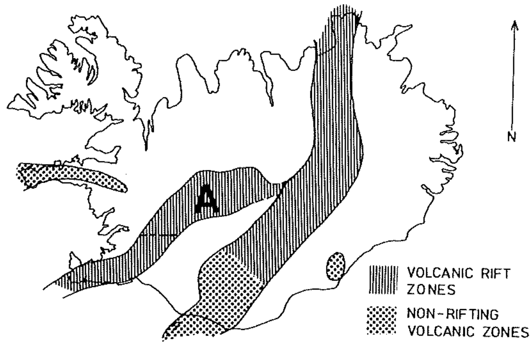

Fig. 1. The volcanic zones in Iceland as they are disinguished as rift zones and non-rifting zones. A part of the zone in Central Iceland (marked A) has, however, apparently been fading out as a rift zone during the late glacial and postglacial times. Simplified from *Imsland* (in press).

Mynd 1. Íslensku gosbeltin og skipting þeirra í rekbelti og reklaus. Hluti gosbeltisins um Mið-Ísland (merkt A) virðist sýna minnkandi rek frá því á seinni hluta ísaldar. Kortið er einföldun á korti Imslands (í útgáfu).

system of the world oceans, regarding petrochemistry and its relation to volcano-tectonics, has been reached. Simplified, this general picture of the petrochemistry of the ocean floor depicts primarily MORB-type tholeiites, produced at the volcanically active central axis (rift zones) of the Mid-Ocean Ridges, and less active flanks and older ocean floor parts, containing a diversity of evolved tholeiites and non-MORB-type basalts (see e.g. *Bryan et al.* 1976). This diversity is occasionally simplified and summarized under the FETI-basalt heading.

In contrast, the general picture of the Icelandic petrochemistry shows us volcanically active areas, some of which are rift zones while others are non-rifting zones (see Fig. 1). The rift zone volcanism in Iceland produces primitive MORB-type tholeiites and tholeiites of weak alkaline enrichment, trending towards the FETI-basalts. The volcanism of the non-rifting zones produces primarily basalts of strong FETI-basalt characteristics with clear alkaline affinities, but generally little – and in most cases no – primitive tholeiitic rocks. In addition to this basalt production, both zones produce small volumes of silicic and intermediate rocks, which are extremely scarce, but occur among the ocean floor samples. In Iceland this production of silicic and intermediate rocks takes place in central volcanoes (for further information on this generalized and simplified picture of the Icelandic situation see *Saemundsson* (1979) and *Imsland* (in press).

THE CHEMICAL RANGE OF THE ICELANDIC ROCK SUITES AND A SAMPLING BIAS

In the rift zones of Iceland, faults, open fissures, and crater rows, the surface expressions of the rift tend to group into swarms, so-called fissure swarms. Centrally these may evolve into major volcanoes as time goes on *(Sigvaldason et al.* 1976), so-called central volcanoes. This evolution comprises changes in the entire volcanic features, but in this context the changes in petrochemistry are of greatest interest.

The fissure swarms, and the scarce but frequently voluminous volcanism in between fissure swarms, produce primarily MORB-type rocks i.e. primitive tholeiites having low incompatible element content, a high K/Rb, Na/K, and Mg/Mg+Fe ratios and so on. These are frequently called olivine tholeiites.

Imsland (in press) places the initiation of the central volcano stage at the first appearance of qz-normative rocks on the fissure swarm, as no gap or drastic change marks its initiation. After this stage is reached, the rift zone central volcanoes produce, in addition to the primitive MORB, evolved tholeiites and a small volume of silicic and intermediate rocks. These evolved tholeiites are qz-normative, enriched in the incompatible elements, and have lower K/Rb, Na/K, and Mg/Mg+Fe ratios and so on, than the primitive MORB-type tholeiites. Compositionally they approach or trend towards the extreme FETI-basalt characteristics.

Those recent rocks, which are atypical for the oceanic environment and are erupted in the rift zones of Iceland are thus produced solely in the central volcanoes, which only cover very small areas of the entire rift zones. The bulk of the rift zones is thus covered by the MORB-type rocks. The dredge sampling method used on the Icelandic rift system would accordingly give overwhelmingly MORB-type samples, as it does in the case of the oceanic spreading axis.

The rocks that form the basis for the concept of the "Iceland geochemical anomaly" are thus produced in the central volcanoes of the rift zones and primarily on the non-rifting zones. The causes of the non-rifting volcanism are discussed by *Oskarsson et* *al.* (1982) and will not be discussed here, but it is firmly stressed that the productivity of the non-rifting volcanism is much less than that of the rift zone volcanism.

In order to compare the petrology of the Icelandic rift zones and the ocean floors, all analysed tholeiites of the Icelandic rift zones (see *Imsland* in press), have been divided into two groups, containing more and less than 0.2 wt.% K_2O, respectively. The 0.2% value is an arbitrary choice, but a lower K_2O content is a clear indication of a low incompatible element content, a MORB restriction. In this selection the primitive picritic cumulates of the Icelandic rift zones (see *Jakobsson et al.* 1978) containing over ~ 10 wt.% MgO have been excluded, because of the strong effect of the picrites on the parameter of primitiveness used.

These low K_2O tholeiites are compared in Table 1, on basis of average compositions, to the average MORB compositions reported by *Cann* (1971) and *Hart* (1976) for the ocean floor. This selection of the Icelandic rift zone tholeiites depicts a slighly lower incompatible element content than the two ocean floor MORB averages they are compared to, but an identical primitiveness, as expressed through the Mg/Mg+Fe ratio.

TABLE 1

	1	2	3
	IRZ	MORB	OFB
SiO_2	48.56	49.92	49.61
TiO_2	1.21	1.46	1.43
Al_2O_3	15.56	16.08	16.01
$FeO^{tot.}$	10.64	9.38	11.49
MnO	0.18	0.17	0.18
MgO	8.74	7.75	7.84
CaO	12.89	11.21	11.32
Na_2O	2.00	2.79	2.76
K_2O	0.12	0.17	0.22
P_2O_5	0.11	0.15	0.14
Fe_2O_3/FeO	0.32	0.19	
At. Mg/Mg+Fe	0.588	0.597	0.550
No. of samples in average	96	49	94

Average composition of Icelandic and Oceanic MORB. 1) IRZ = Icelandic rift zones (*Imsland* in press) 2) MORB = Mid ocean ridge basalts (*Hart* 1976) 3) OFB = Ocean floor basalts (*Cann* 1971).
Tafla 1. Meðaltalssamsetningar fyrir hiðfrumstæða basalt af rekbeltum Íslands og úthafshryggjanna. 1) IRZ = rekbelti Íslands (Imsland í útgáfu) 2) MORB = Miðhafshryggjabasalt (Hart 1976) 3) OFB = Úthafsbasalt (Cann 1971).

The average presented in the table comprises about half of the analysed basalt samples of the rift zones in Iceland which are sampled on basis of geological knowledge of the sample locations, and equally represent all geological formations, regardless of their volume relations. The volume relations are overwhelmingly in favour of the MORB-type. This average thus shows that in terms of volume the Icelandic rift zone products overwhelmingly are of the MORB-type composition.

The other half of the rift zone rocks are: 1) less primitive, more incompatible element enriched MORB-tholeiites, which dominate this rest, 2) the incompatible element enriched relatives of the MORB, the FETI-basalts and so on, and 3) a small portion of highly evolved rocks, tholeiitic icelandites, icelandites, dacites and rhyolites.

Various approaches and calculations have been used in the past to estimate the amount of intermediate and silicic rocks in Iceland. The estimates obtained range from 3 to 9% of the total volcanic production. *Sigurdsson* (1970) found 3% of the total postglacial production to be of intermediate and silicic composition and *Thorarinsson* (1967) found that only 4% of the intermediate and silicic products in Iceland formed during postglacial time were produced in the volcanic rift zones. The other 96% are products of non-rifting volcanism. It is thus clear that only 0.12% of the rift zone production is of intermediate and silicic compositions.

If the primitive MORB-type tholeiitic magma is the primary magma type of the oceanic volcanism and the parental magma to the tholeiitic rock suites, then the general increase in rock evolution, through the iron- and incompatible element enrichment of the evolved tholeiites and towards the intermediate and silicic rocks to rhyolites, apparently displays the entire evolution of the oceanic tholeiitic rock suits. The relations of the rock chemistry of individual samples to geological features, such as fissure swarms and volcano-tectonics in general, are practically unknown in the case of the ocean floor. In Iceland, on the other hand, it has been shown that the magma evolution in the rift zones takes place along with volcano-tectonic evolution *(Sigvaldason et* *al.* 1976, *Jakobsson et al.* 1978, *Imsland* in press). Fissure swarms evolve into central volcanoes at the same time as the rocks evolve from primitive tholeiites (MORB) alone towards increasing volumes of qz-normative and evolved tholeiites and further towards icelandites and dacites and finally rhyolites. Therefore it is concluded, since the Icelandic rift zone rock suites and the oceanic rock suites do not differ in types, that the Icelandic rock suites serve as a key to the classification of oceanic tholeiites in general, both regarding chemical evolution and tectonic setting – but not vice versa.

The non-rifting volcanism in Iceland has not been specifically dealt with here, but in a generalized manner it may be compared to the off-ridge and remote island volcanism in the oceanic environment.

It may be concluded that, as a whole, Iceland produces a relatively greater volume of evolved rocks than the submerged oceanic spreading ridges, but the Icelandic rift zones do so only to a very small degree. The evolved rocks of Iceland and the oceanic environment in general are of the same types. The difference between Icelandic and ocean floor rock production is in proportions, not in types. When refering to the presently active rift zones, the "Iceland geochemical anomaly" is the result of different sampling methods and lack of background information on samples from the ocean floor.

THE CAUSES OF BIASED CHEMICAL RANGE IN RIFT ZONE PRODUCTS EXPOSED OFF-RIFT

In the discussion above, reference has been made to the pattern of volcano-tectonics as well as petrochemical evolution of the Quaternary volcanism of Iceland, where the entire chemical range of the products of the volcanic rift zones can be studied. *Wood* (1978) refers to the "Iceland geochemical anomaly", based on studies of the Tertiary rocks of Eastern Iceland. This lava pile is composed of the lateral products of the rift zones. The entire production of a rift zone cannot be represented by the lithospheric segment pushed out of the rift zone, according to the kinematic evolution of the rift zones. This is demonstrated by Fig. 2, which simplifies a mathematical model of the rift zone kinematics presented by *Palmason* (1973, 1980).

According to the kinematics, the lava pile of Eastern Iceland is all produced in relatively small lateral

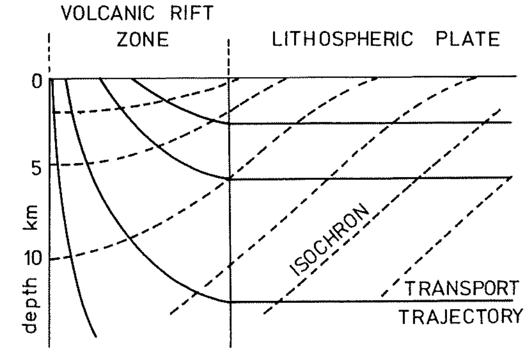

Fig. 2. A model diagram of the evolution of a lithospheric plate, generated in a rift zone. Isochrons and the trajectories of the right half of the rift zone products are shown. The figure is simplified from *Palmason* (1973) and serves to account, in a general way, for the formation of the oceanic plate, including Iceland. It shows how the products of the central parts of the rift zones subside and drift, such that they are never exposed on the surface. Only the lateral products of the rift zones drift out of the zone on the surface or without subsiding below levels reached by general later erosion. The erosion of the Tertiary lava piles of Iceland does not exceed 2 km and probably represents the deepest erosion levels of an undeformed oceanic bottom. The scales of the figure are dependent on the spreading rate, volcanic production and rift zone width.

Mynd 2. Líkan-mynd er sýnir þróun jarðskorpu, sem verður til í rekbelti. Jafnaldurslínur (isochrons) og færsluferlar efnisins (transport trajectories) eru sýnd fyrir hægri helming rekbeltisins og þeirrar skorpu, sem þar verður til. Myndin er einföldun á mynd Guðm. Pálmasonar (1973) og sýnir á almennan hátt, myndun úthafsjarðskorpu, þar með talið Ísland. Myndin sýnir hvernig efni, sem berst til yfirborðsins í miðhluta rekbeltisins sekkur og rekur burt án þess að eiga nokkurn tíma möguleika á að finnast aftur á yfirborðinu. Það sem berst til yfirborðsins hliðlægt í rekbeltunum rekur út úr beltunum á yfirborðinu eða svo grunnt að það getur fundist aftur eftir rof. Rofið í tertíera jarðlagastaflanum á Íslandi er undir 2 km og er það líklega hámarksrof á úthafsbotni fyrir utan fellingasvæði. Skalar myndarinnar eru háðir rekhraða, framleiðni eldvirkninnar og breidd rekbeltanna.

fissure swarms and central volcanoes which were driven out of the rift zone by more efficient and productive fissure swarms, positioned more centrally within the rift zone. These more efficient fissure swarms are the ones that are most productive in primitive rocks, and these rocks do generally not drift out of the rift zones on the surface; they subside within the rift zone to depths below general later exposure. In the Tertiary lava piles of Iceland, the most primitive tholeiites are thus underrepresented, when compared to the entire rift zones.

This causes a bias in the chemical spectrum of the Tertiary rocks, when they are compared to those of the present rift zones of both Iceland and the ocean floor. On the other hand, a similarity emerges between the Eastern Iceland lava pile and the off-ridge oceanic floor, as the primitive MORB-type basalts are practically confined to the spreading centers in case of the ocean floor, as stated by *Bryan et al.* (1976). This parallelism is in harmony with the kinematic evolution of the ocean floor in general, and is not surprising, when it is kept in mind that Iceland is a natural part of the ocean floor, regarding both materials and crustal structures, as well as processes of formation.

The "Iceland geochemical anomaly", when it refers to the Tertiary lava piles of Iceland, is the result of compositionally selective kinematic processes at the spreading axis.

CONCLUSION

The "Iceland geochemical anomaly" is a miscoined phrase which does not stand for differences in rock types, magmatic evolutionary processes, or magma generating sources. As found in the literature, the idea stands for skewness in volume relations and increased total productivity. If used at all, the phrase should be the „Iceland productivity anomaly", which is the reason for the ocean floor above sea level, called Iceland. The idea of a chemical anomaly in Iceland originates through different sampling methods and compositionally selective kinematic evolution within the volcanic rift zones.

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FRÁVIKSTILHNEIGING Í EFNASAMSETNINGU BASALTS Á ÍSLANDI OG ÚTHAFSHRYGGJUNUM:

Afleiðing mismunandi söfnunaraðferða og áhrifa hreyfingaferla landreksins á dreifingu berggerða

Páll Imsland, Norrænu Eldfjallastöðinni

Í heimsbókmenntunum um bergfræði úthafsins sést oft þeirri skoðun haldið fram, að Ísland sé afbrigðilegt hvað varðar bergsamsetningu.

Á Íslandi eru sýnishorn af gosbergi valin á grundvelli ýmissa jarðfræðilegra upplýsinga. Gagnabanki um íslenska gosbergið leyfir þess vegna, að stillt sé saman samsetningarþáttum þess og fjöldanum öllum af öðrum jarð- og eldfjallafræðilegum þáttum. Sýnishorn af úthafsberginu eru hins vegar ekki valin. Þau eru skröpuð upp og er þá tilviljun, hvað kemur í vörpuna, eða þau eru boruð upp úr botninum og kemur þá eingöngu upp það, sem finnst í viðkomandi örmjóu sniði. Jarðfræði hafsbotnsins er mjög illa þekkt í smáatriðum, einkum ef borið er saman við Ísland. Sams konar samstillingu á samsetningarþáttum og jarðfræðilegum þáttum, hvað þá eldfjallafræðilegum, verður því ekki komið við í tilfelli úthafsbergsins.

Við samanburð kemur í ljós (tafla 1), að frumstæða bergið á íslensku rekbeltunum og á úthafshryggjunum er mjög líkt. Það íslenska berg, sem helst virðist vera frábrugðið úthafshryggjaberginu á rót sína að rekja til íslensku megineldstöðvanna. Þar sem þær eru mjög lítill hluti af heildarflatarmáli gosbeltanna, eru líkur til þess, að væri skröpunaraðferðinni beitt á íslensku rekbeltin við söfnun sýna, yrði ekki merkjanlegur munur á bergsamsetningu þessara tveggja staða. Því er hér haldið fram, að sú skoðun, að Ísland sé afbrigðilegt um bergsamsetningu sé röng og til komin vegna þess reginmunar sem er á söfnunaraðferðum bergs á íslensku rekbeltunum annars vegar og á úthafshryggjunum hins vegar.

Þegar litið er til tertíera hraunlagastaflans á Íslandi, virðist vera marktækur samsetningarmunur á bergi hans og ungu rekbeltanna. Megineinkenni þessa munar er, að frumstæðasta basaltið vantar í tertíera staflann. Sams konar munur kemur fram í úthafinu. Ef borið er saman basalt frá úthafshryggjunum og sjávarbotninum utan þeirra, vantar frumstæðasta bergið í safn hins síðarnefnda. Því er hér haldið fram, að þessi munur sé í báðum tilvikum raunverulegur og eigi rót sína að rekja til þess, hvernig jarðskorpan þróast og hreyfist áður en hana rekur út úr rekbeltunum bæði á Íslandi og í úthafinu. Við þessa þróun á sér stað bæði rek og sökk efnisagna. Sökkið gerist að langmestu leyti inni við miðju rekbeltanna, en þar er einnig mest framleiðsla á frumstæðasta basaltinu. Þetta basalt rekur því nær aldrei út úr rekbeltunum og finnst þar af leiðandi hvorki í tertíera hraunlagastaflanum á Íslandi né á gamla sjávarbotninum utan við rekhryggina. Örlög þessa basalts eru að sökkva í rekbeltunum niður á meira dýpi en svo, að rof sýni það á yfirborði síðar og því finnst það hvorki á eldra sjávarbotni né í tertíera hraunlagastaflanum, þrátt fyrir djúpt rof hans.