Elemental and Sr Isotope Variations in Basic Lavas From Iceland and the Surrounding Ocean Floor

The Nature of Mantle Source Inhomogeneities

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Abstract. Major and trace element data are used to establish the nature and extent of spatial and temporal chemical variations in basalts erupted in the Iceland region of the North Atlantic Ocean. The ocean floor samples are those recovered by legs 38 and 49 of the Deep Sea Drilling Project. Within each of the active zones on Iceland there are small scale variations in the light rare earth elements and ratios such as K/Y: several central complexes and their associated fissure swarms erupt basalts with values of K/Y distinct from those erupted at adjacent centres; also basalts showing a wide range of immobile trace element ratios occur together within single vertical sections and ocean floor drill holes. Although such variations can be explained in terms of the magmatic processes operating on Iceland they make extrapolations from single basalt samples to mantle sources underlying the outcrop of the sample highly tenuous.

^{87}Sr/86Sr ratios measured for 25 of the samples indicate a total range from 0.7028 in a tholeiite from the Reykjanes Ridge to 0.7034 in an alkali basalt from Iceland and are consistent with other published ratios from the region. A positive correlation between ^{87}Sr/^{86}Sr and Ce/Yb ratios indicates the existence of systematic isotopic and elemental variations in the mantle source region. An approximately fivefold variation in Ce/Yb ratio observed in basalts with the same ^{87}Sr/^{86}Sr ratio implies that different degrees and types of partial melting have been involved in magma genesis from a single mantle composition. ^{87}Sr/^{86}Sr ratios above 0.7028, Th/U ratios close to 4 and La/Ta ratios close to 10 distinguish most basalts erupted in this part of the North Atlantic Ocean from normal mid-ocean ridge basalt (N-type MORB) – although N-type MORB has been erupted at extinct spreading axes just to the north and northeast of Iceland as well as the presently active Iceland-Jan Mayen Ridge.

Comparisons with the hygromagmatophile element and radiogenic isotope ratios of MORB and the estimated primordial mantle indicate that the mantle sources producing Iceland basalts have undergone previous depletion followed by more recent enrichment events. A veined mantle source region is proposed in preference to the mantle plume model to explain the chemical variations.

Introduction

The unique position of Iceland astride and actively spreading mid-ocean ridge has stimulated several geochemical studies of the basic lavas (Schilling, 1973; Hart et al., 1973; Sigvaldason, 1974a; Sun and Jahn, 1975; O'Nions et al., 1976; Bailey and Noe-Nygaard, 1976; Wood, 1978). The results of these studies, and the discussions they have provoked in the literature (eg., O'Hara, 1973; 1975; Flower et al., 1975; Langmuir et al., 1978) have made a large contribution to the current debate concerning the petrogenetic processes operative in the sub-oceanic mantle. In fact, the nature and scale of the variation in the hygromagmatophile (*hyg*) or incompatible trace elements and radiogenic isotopes measures in basalts from Iceland and the Reykjanes Ridge have significantly influenced the formulations of most models concerned with hot spot magma genesis. However, none of the studies published to date have considered the complete range of basic lavas erupted in the province, nor analysed a wide range of *hyg* elements in conjunction with major elements and Sr isotopes. For this reason it has previously only been possible to establish on a general scale the nature of spatial geochemical variations within the province.
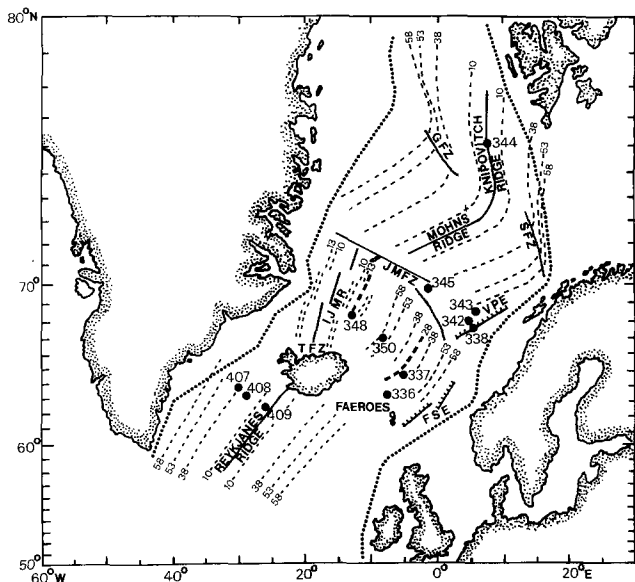
Fig. 1. Map of the North Atlantic and Norwegian Sea (adapted from Talwani and Edholm, 1977). *Solid lines* are the presently active mid-ocean ridges; *the thick dashed lines* are extinct spreading axes; *thin dashed lines* are age lineations determined from the magnetic anomaly patterns (ages are given in million years); *dotted lines* are the approximate continental margins. *GFZ* Greenland Fracture Zone; *SFZ* Senja Fracture Zone; *JMFZ* Jan Mayen Fracture Zone; *VPE* the Voring Plateau Escarpment; *FSE* Faeroes – Shetland Escarpment; *IJMR* Iceland – Jan Mayen Ridge; *TFZ* Tjörnes Fracture Zone. The drill sites of DSDP leg 38 (Talwani et al., 1976) and IPOD leg 49 (Luyendyk et al., 1978) are marked

The aim of the present study has been to integrate the results from a large number of samples representative of the range of basic lavas erupted spatially and temporally in Iceland and, where available, from the surrounding ocean floor. The sample localities are shown in Figs. 1 and 2. By considering the major and trace element analyses of these samples in conjunction with Sr isotope analyses of selected samples we have attempted to define the scale of geochemical variation within the province and use the results to assess the role of various magmatic processes in the genesis of the lavas. These data also have important implications for the nature and previous history of the mantle source regions.

Geological Setting

The anomalously shallow Reykjanes Ridge, spreading at approximately 10 mm per year, is atypical of slow spreading mid-ocean ridges in having a central high rather than a rift valley and a non-perpendicular orientation to its spreading direction. Shih et al. (1978) have recently shown by seismic studies that the Reykjanes Ridge consists of a number of en echelon fissure swarms (ca. 20 km long and less than 5 km wide) *not* connected by transform faults. Chemical studies of samples dredged from the ridge crest have suggested that the bathymetric changes are accompanied by a systematic increase in the *hyg* element and radiogenic isotope concentration of the basalts towards Iceland (Schilling, 1973; Hart et al., 1973; Sun et al., 1975). A geochemical study of the drill
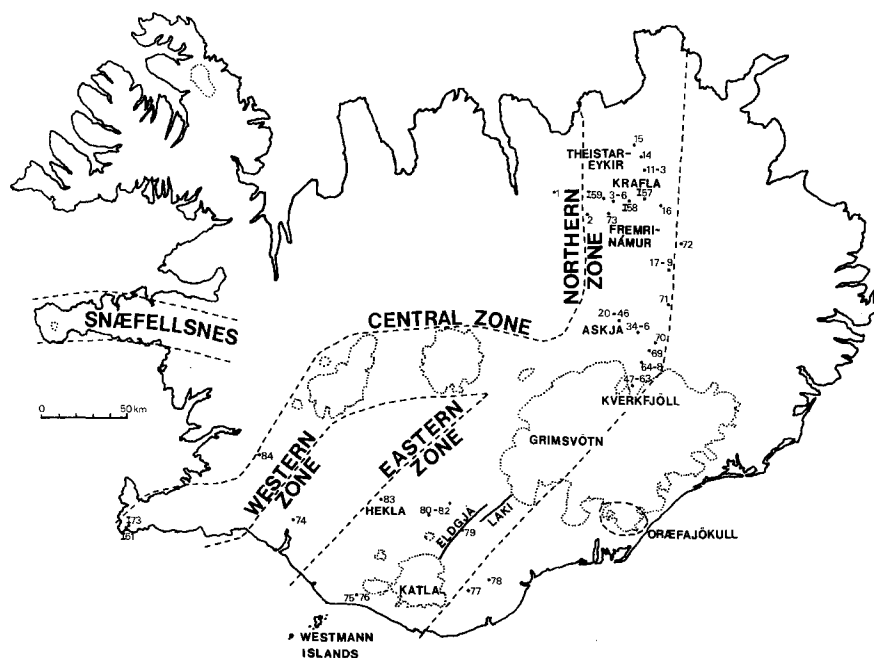
Fig. 2. Map of Iceland showing the location of the active volcanic zones (*dashed lines*) and the nomenclature used for them in this report. Numbers refer to the samples used (the prifix ISL has been dropped from these numbers)

cores recovered by IPOD leg 49 (Wood et al., 1978) has confirmed that the basalts erupted on the Reykjanes Ridge are more enriched in *hyg* elements and radiogenic isotopes than 'normal' mid-ocean ridge basalt (*N*-type MORB) but indicated that the change in their chemistry with latitude is not as systematic as the earlier studies of dredged material indicated. Certainly basalts with a significant range of *hyg* element and radiogenic isotope compositions have been erupted in the 63° N region of the Reykjanes Ridge in the last 40 m.y.

Postglacial volcanism in Iceland is confined to well defined zones (Fig. 2) which are significantly broader than the active zones of the submarine MAR. Jakobsson (1972) described broad spatial variations in the types of basalt erupted in Iceland: The western, central and northern zones consist of tholeiitic lavas and represent the trace of the MAR through Iceland, the eastern zone contains tholeiitic lavas erupted from fissures (eg. Laki and Veidivotn) in the north, with transitional and alkalic lava series erupted in the south from fissures (eg. Eldgjá) and central volcanoes (eg. Hekla and Katla) (Robson, 1956; Sigvaldason, 1969; Sigurdsson, 1970); the Snaefellsnes Peninsula consists of tholeiitic, transitional and alkalic lavas (Sigurdsson, 1970).

All the exclusively tholeiitic zones contain fissure swarms arranged en echelon. For example, the northern rift zone is tectonically dominated by five active volcanic centres and their associated fissure swarms which are up to 70 km long and between 5 and 10 km wide (Sigurdsson and Sparks, 1979, Fig. 1) – these are (from north to south) Theistareykir, Krafla, Fremri Námur, Askja and Kverkfjöll (Fig. 2). The basalts erupted in these fissure swarms tend to be more evolved, i.e., they have $Mg/Mg + Fe^{2+}$ atomic ratios (Mg numbers) between 0.4 and 0.5 (Sigurdsson and Sparks, 1978), than those erupted on the Reykjanes Peninsula, which have Mg numbers greater than 0.5 (Jakobsson et al., 1979).

Recent activity in the Krafla swarm (Bjornsson et al., 1977) has provided an insight into the mechanism of crustal extension in the northern zone. Fissure eruptions seem to be the result of the lateral injection of magma from a high level reservoir beneath the volcanic centres into the fissure swarms. Sigurdsson and Sparks (1978) have shown that several historic and prehistoric fissure eruptions were synchronous with caldera collapse in the related volcanic centres. They interpret these active fissure swarms as the surface manifestation of a crustal structure similar to that described from the Tertiary lava pile of eastern Iceland (Walker, 1974, Fig. 3), which indicates that spreading axes have been limited in space and time throughout Iceland's history (Gibson and Piper, 1972; Walker, 1975).

The abundance of central volcanoes and the silicic and intermediate lavas associated with them is a fundamental difference between volcanism in Iceland and that of the MAR. Although the origin of the silicic magmas has been a controversial issue (e.g., Carmichael, 1964; O'Nions and Gronvold, 1973; Sigvaldason, 1974b), trace element and Sr isotope data are consistent with the derivation of at least the majority of silicic lavas from basic parental magmas by crystal fractionation in crustal magma reservoirs (Wood, 1978). The abundance of mix-lavas, mix tephra eruptions and composite intrusions associated with central volcanic activity in Iceland suggests that magma mixing is a common occurrence in the crustal magma reservoirs (Blake et al., 1965; Sparks et al., 1977).

Magmatism in the active tholeiitic zones also includes monogenetic, basaltic shield volcanoes erupting primitive (i.e., Mg number > 0.6) olivine tholeiites and sometimes picrites and coarsely plagioclase and olivine porphyritic lavas (Sigvaldason, 1974a; Jakobsson et al., 1979). Some of the shield volcanoes have formed in areas peripheral to the fissure swarms. In the Tertiary lava pile primitive tholeiites thought to have been erupted from shield volcanoes dominate the surface of the lava pile by covering basalts previously erupted from fissure swarms (Wood, 1976, 1979).

The North Atlantic Ocean north of 60° N began to open between 60 and 40 m.y. ago and abnormally high magmatic activity during the initial stages of rifting produced the lava piles now exposed in the Faeroes and Kangerdlugssuaq, Greenland. The abnormally high magmatic activity has continued to the present day and resulted in the Greenland – Faeroe Ridge. Geochemical data for basalts from the Faeroes (Rasmussen and Noe-Nygaard, 1970) indicate that the basalt compositions erupted some 50 m.y. ago are similar to some Iceland basalts. A complex sequence of tectonic events has been involved in generating the Norwegian Sea floor to the north of the Greenland-Faeroes Ridge – at least three episodes of ridge jumping occured leading to the present asymmetry in the age of ocean crust adjoining the two continental margins (Talwani and Edholm, 1977). A geochemical study of basalts from the Norwegian Sea was undertaken to establish the persistence of the anomalous mantle underlying the Greenland-Faeroes ridge in space as well as time. The basement cores drilled by IPOD leg 38 (Fig. 1) were sampled for this purpose. These samples vary from *N*-type MORB to *hyg* element enriched basalts similar to those erupted in Iceland (Kharin, 1976; Schilling, 1976). However, all the basalts except some from holes 344, 348, and 350 have suffered significant secondary alteration and therefore only data for immobile trace elements can be considered to represent primary concentrations in these basalts.

Analytical Techniques

212 samples were studied petrographically and analysed for major and trace elements. $^{87}Sr/^{86}Sr$ ratios were obtained for 25 selected samples. The major elements and Zn, Sr, Y, Zr, Nb, Ba, and Ce were determined by X-ray Spectrometry (Tarney et al., 1978). The elements U, Th, Hf, Ta, Cs, Sb, Rb, Cr, Co, Ni, Sc, La, Eu, and Tb were determined by a non-destructive instrumental neutron activation technique (Chayla et al., 1973; Jaffrezic et al., 1979). All the samples were crushed in agate. Sr isotopes were determined by mass spectrometry at Leeds University. To overcome the effects of sea water – rock interaction on the IPOD leg 49 samples the leaching technique of O'Nions and Pankhurst (1976) was used.

Results

Major and trace element analyses of 27 representative basic lavas from the postglacial zones of Iceland are presented in Table 1 and a brief description of the petrography and locality of each is given in the appendix. Partial major and trace element analyses of 19 samples from IPOD leg 38 are given in Table 2 – complete major element and rare earth element analyses of the leg 38 basalts are published in the initial report volume (Kharin, 1976; Schilling, 1976). Selected samples from the Tertiary lavas of eastern Iceland (Wood, 1978) have been re-analysed during the course of this study to avoid systematic inter-laboratory errors. The agreement between the new analyses and the previously published data for these samples (analysed at Bedford College, London) is good. Sr isotope analyses are listed in Table 3.

Table 1. Major and trace element analyses of 27 lavas from Icelands' active zones

Sample	Krafla and Fremri Námur fissure swarms						Askja						
	ISL 4	I 59	I 58	ISL 10	ISL 14	ISL 15	ISL 20	ISL 21	ISL 28	ISL 29[b]	ISL 40	ISL 42	ISL 44
SiO_2	50.85	49.54	48.91	50.21	50.48	49.91	51.35	50.39	50.65	50.36	51.10	52.13	51.80
TiO_2	1.88	2.07	1.53	1.77	1.83	1.71	2.73	1.67	1.43	2.79	2.81	2.51	2.31
Al_2O_3	13.35	13.26	15.10	13.46	13.95	13.83	12.60	13.69	13.82	12.60	12.96	12.90	12.95
Fe_2O_3	1.84	2.42[a]	1.58[a]	1.64	1.55	1.63	1.97	1.55	1.48	1.91	1.89	1.87	1.77
FeO	12.26	12.39	9.94	10.91	10.34	10.85	13.11	10.38	9.89	12.75	12.60	12.45	11.80
MnO	0.23	0.24	0.19	0.21	0.20	0.21	0.25	0.20	0.20	0.25	0.25	0.24	0.23
MgO	5.72	5.83	7.59	7.06	7.01	6.90	4.87	6.90	7.41	5.48	4.87	4.88	5.36
CaO	11.20	10.32	12.08	11.79	11.89	12.15	9.36	11.88	12.30	9.48	9.66	9.37	10.39
Na_2O	2.52	2.34	2.17	2.60	2.62	2.63	2.98	2.51	2.48	2.47	2.92	3.09	2.72
K_2O	0.30	0.36	0.20	0.25	0.29	0.25	0.56	0.34	0.24	0.53	0.56	0.62	0.48
P_2O_5	0.17	0.21	0.16	0.16	0.18	0.16	0.31	0.20	0.14	0.37	0.30	0.31	0.24
Sum	100.32	98.98	99.45	100.06	100.34	100.22	100.09	99.71	100.04	98.99	99.92	100.36	100.05
$Mg/$ $(Mg+Fe^{2+})$	0.45	0.46	0.58	0.53	0.55	0.53	0.40	0.54	0.57	0.47	0.41	0.41	0.45
Sc	43.7	44.6	47.4	45.0	41.7	44.0	41.5	44.7	45.0	43.4	41.8	40.6	42.2
Cr	162	151	192	107	141	98	85	93	185	77	86	84	93
Co	54	58	—	53	51	52	48	52	51	52	48	48	52
Ni	71	67	106	62	62	63	27	54	67	22	25	29	54
Zn	107	121	89	91	86	90	120	87	82	116	123	113	103
Rb	4.7	4.9	4.0	3.7	4.6	3.3	10.2	6.5	3.9	16.5	10.9	12.6	10.3
Sr	155	154	168	163	194	160	186	196	169	204	187	191	195
Y	33	40	23	31	29	30	40	24	22	37	37	41	34
Zr	108	103	76	91	135	113	184	117	99	183	183	175	158
Nb	12	14	11	10	14	11	25	15	7	21	21	22	14
Sb	—	—	—	—	—	0.03	0.11	0.05	0.01	0.06	0.07	0.08	0.07
Cs	—	0.07	—	0.05	—	—	—	0.06	0.05	0.14	0.10	0.12	0.09
Ba	89	111	48	53	72	59	173	99	48	69	172	154	92
La	7.4	8.7	5.3	7.3	7.9	6.3	15.4	9.6	6.3	15.2	14.3	15.4	13.1
Ce	23	23	15	22	31	25	46	27	16	48	48	41	36
Eu	1.37	1.54	1.23	1.48	1.63	1.43	2.27	1.53	1.41	2.18	2.09	2.18	1.83
Tb	0.72	0.84	0.65	0.72	0.74	0.68	1.12	0.73	0.66	0.97	1.15	1.05	0.94
Hf	2.63	3.19	2.43	2.52	3.14	2.59	4.76	2.83	2.28	4.65	4.38	4.48	3.92
Ta	0.68	0.93	—	0.69	0.82	0.67	1.48	0.96	0.61	1.55	1.42	1.45	1.24
Th	0.67	0.78	0.56	0.60	0.82	0.66	1.40	0.82	0.57	1.44	1.35	1.62	1.27
U	0.13	0.20	—	0.12	0.16	—	0.42	0.24	0.15	0.41	0.36	0.43	0.38

[a]   These are analysed Fe_2O_3 values – in the remaining rocks Fe_2O_3 has been calculated using a Fe_2O_3/FeO ratio of 0.15
[b]   This basalt has suffered hydrothermal alteration and contains green clay minerals

Spatial Geochemical Variation

(a) Major Elements

Figure 3 is an alkali-silica plot for the samples analysed together with reliable data taken from the literature. Only relatively fresh samples are included, i.e., those with less than 1.5 w.% H_2O+. Basalts from the different postglacial zones and Tertiary areas of Iceland are distinguished revealing the general spatial variations mentioned above. Evolved tholeiites or ferrobasalts (Wood, 1978) erupted at the central volcanoes and associated fissure swarms in the northern zone follow low alkali enrichment trends (those from Kverkfjöll have slightly higher alkali contents than

those of the other centres of the northern zone). The tholeiites erupted from fissures in the northern part of the eastern zone (e.g., samples ISL 74 and ISL 78, Table 1) follow the same low alkali enrichment trends as those from the northern zone.

A very much higher proportion of the analysed Tertiary lavas have transitional compositions than those analysed from the active zones. There are at least three possible explanations for this: (1) biased sampling; (2) lava piles generated from centres erupting transitional lavas are thicker and maintain their position above sea level for longer periods than the more tholeiitic areas; (3) a greater proportion of transitional lavas were erupted during Tertiary times relative to the Recent activity.

Vadalda		Kverkfjöll and Kreppatungur				Eldgjá		Laki	Hekla			Reykjanes	
Isl 34	ISL 17	ISL 47	ISL 59	ISL 66	ISL 67	ISL 77	ISL 79	ISL 78	ISL 83	ISL 74	ISL 84	I 61	I 73
49.26	48.98	49.94	49.47	51.75	50.04	46.80	47.63	50.62	54.25	49.87	49.45	47.68	49.02
0.58	1.42	2.86	1.19	3.15	2.75	4.43	5.22	2.62	2.17	2.40	1.85	0.53	1.23
16.65	15.11	12.98	15.68	12.99	13.20	12.13	12.54	13.49	14.56	13.60	14.81	14.39	14.86
1.15	1.38	2.03	1.30	1.89	1.79	1.97	1.99	1.71	1.54	1.76	1.58	0.88[a]	1.88[a]
7.64	9.20	13.55	8.65	12.62	11.96	13.14	13.25	11.38	10.30	11.74	10.54	7.83	9.31
0.15	0.18	0.24	0.17	0.26	0.23	0.22	0.23	0.21	0.28	0.22	0.20	0.16	0.19
9.81	8.93	4.60	7.81	4.09	5.74	5.60	5.61	5.56	3.17	5.69	6.19	13.45	7.91
13.37	11.78	9.56	13.26	8.62	10.02	11.56	9.23	10.96	6.97	11.36	12.46	12.24	12.44
1.79	2.44	3.12	2.24	3.37	3.04	2.73	3.04	2.98	3.97	2.70	2.27	1.62	2.03
0.04	0.33	0.60	0.13	0.79	0.62	0.74	0.83	0.42	1.25	0.41	0.15	0.03	0.13
0.05	0.19	0.32	0.10	0.48	0.28	0.43	0.56	0.29	0.77	0.30	0.25	0.06	0.12
100.48	99.84	99.88	100.96	100.01	99.78	99.75	100.12	100.23	99.23	100.05	99.76	98.87	99.12
0.70	0.63	0.38	0.62	0.37	0.46	0.43	0.43	0.46	0.35	0.46	0.51	0.75	0.60
34.9	35.1	42.2	40.7	38.6	39.2	36.6	34.1	41.1	21.9	42.3	42.4	34.7	44.2
331	293	80	226	64	67	94	66	107	54	134	259	1,090	247
52	53	53	49	44	51	54	49	49	17	50	51	—	—
186	167	26	86	5	24	57	15	41	0	44	102	436	106
55	72	150	65	126	123	—	133	111	171	109	97	55	82
<1	5.2	11.9	1.6	13.4	12.7	12.2	15.7	6.0	23.8	6.5	<1	<1	<1
112	224	242	159	251	257	—	445	223	379	185	183	55	120
13	20	34	17	42	33	—	36	35	73	34	27	13	25
32	113	210	69	242	185	—	290	—	—	—	90	25	50
2	12	18	4	35	24	—	31	—	—	—	5	—	7
0.04	—	0.09	—	0.10	0.08	0.07	0.06	—	0.10	0.04	—	—	—
—	0.04	—	—	0.14	0.10	0.13	0.19	0.04	0.26	0.05	—	—	—
6	80	128	62	241	191	—	186	149	482	159	72	5	20
1.6	9.2	17.7	4.4	21.6	14.9	20.8	27.5	14.5	47.9	11.9	7.6	0.6	3.4
5	23	48	11	55	44	—	57	—	—	—	—	2	10
0.52	1.22	2.27	1.02	3.01	2.15	2.66	3.29	2.10	5.03	1.97	1.61	0.46	0.91
0.28	0.58	1.12	0.49	1.37	0.97	1.03	1.26	1.09	2.04	1.08	0.74	0.30	0.51
0.79	2.30	5.40	1.82	6.24	4.97	5.18	6.15	4.22	10.22	4.27	2.72	0.64	1.62
0.12	0.83	1.67	0.47	1.97	1.48	2.20	2.90	1.30	4.28	1.28	0.95	—	—
0.07	0.65	1.67	0.44	2.03	1.58	1.97	2.48	1.09	4.45	1.12	0.55	0.06	0.29
—	0.19	0.33	—	0.49	0.32	0.52	0.64	0.23	1.23	0.24	—	—	—

Major elements are in weight percent and trace elements in parts per million. Brief sample descriptions and localities are given in the appendix

(b) Trace Element

Figure 4 shows K versus Y and La versus Tb for the samples analysed in this study together with data from the shield volcanoes of the northern Iceland active zone (Sigvaldason, 1974a) in the former plot. There does not appear to be any systematic analytical differences for K and Y analyses given by Sigvaldason (ibid) and this study – i.e., samples from a given centre or associated fissure swarm analysed by both studies conform to the same trends. Such biaxial plots of a *more hyg* (or highly incompatible – K and La) trace element versus a *less hyg* (or slightly incompatible – Y and Tb) trace element are particularly effective in distinguishing the different basalt types and

associated fractionation series erupted in the province. Series related by crystal fractionation will approximate to straight line trends through the origin on these biaxial plots (Treuil and Varet, 1973; Weaver et al., 1972). In contrast, the significant differences in the bulk distribution coefficients (D) result in considerable variation in K/Y and La/Tb ratios among liquids produced by different degrees and types of partial melting (Gast, 1968; Wood, 1979).

The large variation in K for a single value of Y rules out the possibility of all the lavas being related to a single parental liquid by low pressure crystal fractionation. Nevertheless, lavas from a given centre or its associated fissure swarms do follow linear trends passing through the origin. It appears that the evolved

Table 2. Partial major and trace element analyses of 19 basalts from DSDP leg 38

	336	336	336	337	337	337	338	342	342
	41–1, 12–17	42–1, 147–150	44–2, 68–71	13–2, 144–148	14–2, 60–64	15–2, 140–144	43–2, 117–121	7–2, 143–147	7–5, 123–128
TiO_2	1.41	1.37	—	1.23	1.19	1.26	1.10	2.51	2.45
Fe_2O_3*	14.15	12.89	13.56	11.58	11.67	11.22	10.10	12.55	12.50
Na_2O	2.64	2.57	2.96	2.33	2.74	2.86	2.50	3.20	3.24
K_2O	0.16	0.20	—	0.50	1.32	0.47	0.15	0.57	0.64
P_2O_5	0.15	0.15	—	0.11	0.09	0.12	0.12	0.37	0.35
S_c	46.5	47.0	42.1	43.7	39.0	43.8	38.8	44.4	43.3
Cr	98	93	106	390	345	393	290	184	192
Co	55	49	50	48	56	60	46	57	74
Ni	60	57	50	125	162	168	94	79	113
Zn	87	79	—	88	87	79	65	108	118
Rb	<1	<1	9.0	6.2	19.5	5.6	<1	5.2	7.6
Sr	130	135	—	88	72	86	156	245	232
Y	29	26	—	30	25	30	15	35	38
Sb	—	—	—	0.18	0.13	0.22	—	0.04	0.03
Cs	—	—	0.14	0.25	0.29	0.14	—	0.03	0.10
Ba	88	128	—	143	167	145	118	202	275
La	3.8	3.5	7.0	3.2	2.9	2.8	3.4	14.4	14.7
Ce	9	—	12	7	6	—	—	28	29
Eu	1.35	1.14	1.16	1.05	0.92	1.03	1.01	2.19	2.19
Tb	0.73	0.69	0.55	0.68	0.61	0.67	0.47	1.05	1.01
Hf	2.47	2.02	2.93	1.66	1.54	1.71	1.54	4.61	4.33
Ta	0.25	0.23	0.53	0.21	0.21	0.22	0.28	1.16	1.12
Th	0.34	0.27	0.86	0.25	0.28	0.28	0.32	1.84	1.76
U	—	0.11	0.15	0.07	—	—	—	0.82	0.44

	343	343	344	344	344	345	348	348	350	350
	13–2, 15–19	16–3, 139–144	35–4, 74–78	36–3, 130–135	37–2, 137–140	33–2, 54–59	32–4, 99–101	33–1, 57–61	16–2, 29–33	16–2, 135–139
TiO_2	3.52	2.54	1.24	2.52	1.19	1.45	1.45	1.37	—	2.37
Fe_2O_3*	18.79	15.31	8.43	10.50	7.79	8.95	13.85	14.15	14.04	13.96
Na_2O	3.79	3.41	3.26	4.99	3.42	3.05	2.45	2.52	2.85	2.82
K_2O	0.48	0.16	0.41	1.17	0.48	0.73	0.07	0.07	—	0.30
P_2O_5	0.34	0.25	0.23	0.50	0.23	0.18	0.18	0.16	—	0.33
S_c	43.8	44.3	33.5	24.5	34.7	32.3	46.6	43.8	40.2	40.2
Cr	93	112	343	43	275	434	190	181	126	130
Ce	43	49	35	12	32	41	56	54	47	47
Ni	23	44	102	8	80	158	92	87	63	65
Zn	120	101	69	91	55	71	94	90	—	99
Rb	<1	<1	7.7	26.2	7.2	9.7	<1	<1	6.9	4.9
Sr	184	153	191	176	183	194	86	72	—	220
Y	36	32	24	60	22	21	34	29	—	38
Sb	0.09	0.05	0.03	0.05	0.06	0.25	—	—	0.06	0.05
Ce	—	—	0.24	0.36	0.16	0.23	—	—	0.44	0.93
Ba	392	189	219	516	200	119	66	120	—	239
La	13.4	8.3	8.3	24.0	7.9	9.2	3.1	2.6	14.9	14.4
Ce	28	19	16	44	14	20	—	—	—	—
Eu	2.05	1.63	1.22	2.55	1.12	1.22	1.26	1.14	2.00	2.09
Tb	1.08	0.94	0.60	1.47	0.58	0.59	0.77	0.71	1.00	1.00
Hf	4.05	2.83	1.98	5.79	1.90	1.80	1.89	1.81	4.20	4.21
Ta	1.31	0.76	0.99	2.82	0.86	0.67	0.19	0.19	1.21	1.24
Tb	1.32	0.73	1.09	3.33	0.89	0.60	0.14	0.17	1.33	1.43
U	0.18	0.17	0.27	0.88	0.19	—	—	—	0.33	0.33

Major element oxides are in weight percent and trace elements are in parts per million. Fe_2O_3* refers to total iron

Table 3. Initial $^{87}Sr/^{86}Sr$ ratios of 25 lavas

Locality	Sample	$(^{87}Sr/^{86}Sr)_i$
Krafla	ISL 6	0.70324 ± 5
	ISL 73 (silicic glass)	0.70324 ± 3
Askja	ISL 26 (silicic glass xenolith from 1875 Viti tuff)	0.70324 ± 4
	ISL 28	0.70312 ± 7
	ISL 42	0.70334 ± 5
	ISL 43	0.70336 ± 5
Vadalda shield	ISL 34	0.70319 ± 5
Ferjufjall	ISL 17 (olivine tholeiite from shield)	0.70334 ± 6
Kverkfjoll	ISL 51 (typical ferrobasalt)	0.70334 ± 5
	ISL 59 (single flow of plagioclase phyric olivine basalt)	0.70306 ± 6
Eldgjá	ISL 77	0.70344 ± 5
	ISL 79	0.70340 ± 5
Landmannalaugar	ISL 81 (silicic glass)	0.70344 ± 5
Eastern Iceland		
Nordfjordur	D57 (Wood, 1978)	0.70339 ± 3
Skagafell	F57 (Wood, 1978)	0.70340 ± 4
Laugarfell	V9 (Wood, 1978)	0.70320 ± 4
	V10 (Wood, 1978)	0.70337 ± 5
Reykjanes Ridge 63° N	(samples leached in HCl)	
IPOD 49 Hole 407	unit 407-1 (Wood et al., 1979b)	0.70339 ± 5
	unit 407-2	0.70329 ± 3
	unit 407-3	0.70322 ± 3
	unit 407-4	0.70327 ± 3
IPOD 49 Hole 408	408-35-1, 108-10 cm	0.70329 ± 5
IPOD 49 Hole 409	unit 409-1	(0.70279 ± 12)
	unit 409-2	0.70282 ± 7
	unit 409-3	0.70293 ± 4

All analyses are quoted relative to a value of 0.70800 for the Eimer and Amend $SrCO_3$ standard together with 2δ errors

basalts associated within a fissure swarm are related by crystal fractionation in high level magma reservoirs, but the parental magmas feeding each swarm show significant compositional variation. The relative compositional variations are the same as those shown by the alkali-silica diagram (Fig. 3), viz. the basalts become progressively enriched in the *more hyg* elements as the composition changes from tholeiitic through transitional types to alkalic compositions.

The K versus Y plot illustrates the lower *hyg* element abundances in the basalts erupted from the shield volcanoes relative to the basalts erupted at the

central complexes and fissure swarms. This is consistent with the more primitive compositions of the former. Some of these shields have erupted basalts with very low abundances of the more *hyg* elements – the most voluminous example is Theistareykirbunga (Sigvaldason, 1974a; Polyakov and Sobornov, 1975; O'Nions et al., 1976). Published data for the basalts from the fissure swarm associated with Theistareykirbunga are not all as depleted in the more *hyg* elements as those of the shield volcano itself.

If only the main compositional types of basalt associated with each of the five major centres of rifting in the northern active zone are considered then there appears to be a systematic change from Kverkfjöll in the southeast to Theistareykir in the northwest of this zone, i.e., the basalts become progressively depleted in the more *hyg* elements. Figure 4 shows that the basalts of Kverkfjöll follow a trend with K/Y = 160, those of Askja a trend with K/Y = 125, those of Fremri Námur and Krafla a trend with K/Y = 75 and those of Theistareykir a trend with K/Y = 30. However, this is a considerable oversimplification, e.g., basalts with K/Y ratios of 30 also form the Vadalda shield which lies approximately 10 km southeast of Askja (sample ISL 34, Table 1 and Fig. 4). Also, some of the subglacial, more magnesian basalts from Askja (e.g., sample ISL 28, Table 1) have slightly lower K/Y, La/Tb etc. than the ferrobasalts recently erupted at this centre. One basalt (sample ISL 59, Table 1) sampled in the Kverkfjöll fissure swarm has lower values of these ratios (e.g., K/Y = 64) than the rest of the ferrobasalt succession. Another lava of similar composition (samples ISL 69 and ISL 71) was found in the Kreppatunga part of this swarm. These basalts are plagioclase porphyritic (5–10% plagioclase megacrysts) olivine tholeiites (<2% olivine phenocrysts) and cannot be related to the ferrobasalts by crystal fractionation processes. Sigvaldason et al. (1976) have noted the large range of K concentration displayed by basalts from the Kverkfjöll region. Thus, although there are some clear spatial chemical variations in the northern active zone the entire range of magma types observed within the zone can be found coexisting locally.

Selected samples from the Tertiary lava pile of eastern Iceland are shown on the La versus Tb plot (Fig. 4). The lavas associated with the central volcanoes (e.g. Thingmuli), follow the same trend as the main Kverkfjöll series. Other Tertiary lavas not erupted from central volcanoes and concentrated in the top 500 m of the pile, follow the same trend as the Krafla series. Thus, in terms of rare earth element (REE) ratios at least the Tertiary lavas fall within the same compositional range as those erupted in the adjacent Quaternary zone.
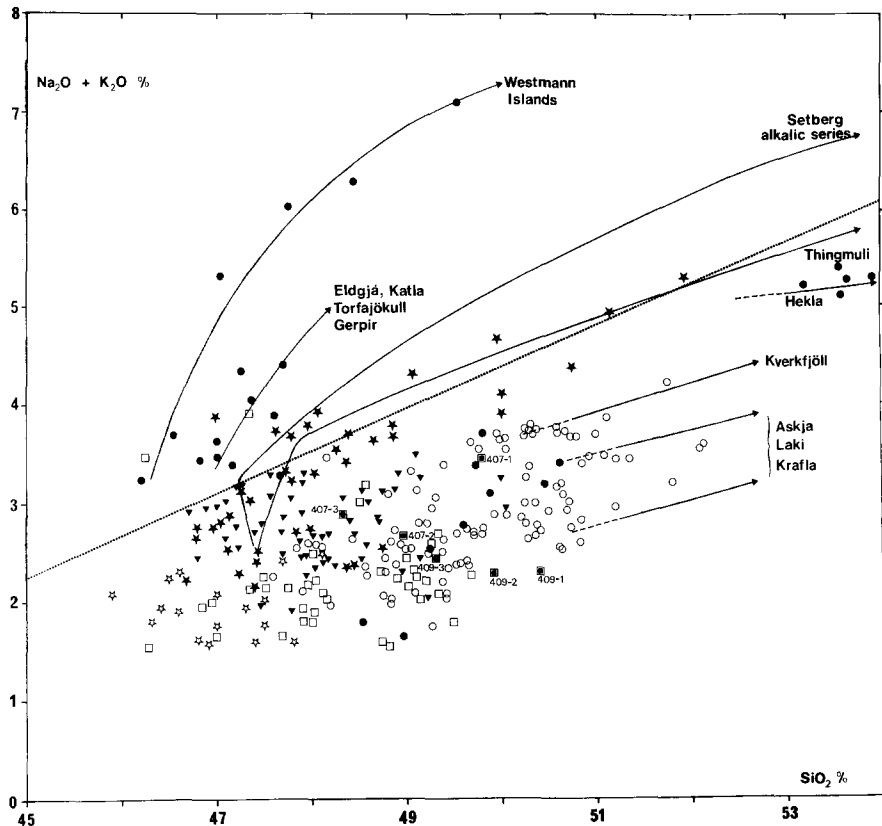
Fig. 3. Alkali-silica diagram for basic lavas from Iceland and the Reykjanes Ridge. The data comes from this study and Bailey and Noe-Nygaard (1976), Sigvaldason (1969; 1974a and b), Jakobsson (1972), Jakobsson et al. (1973, 1979), Sigurdsson et al. (1978), Wood (1978) and the trend of the Setberg alkalic series comes from (Sigurdsson, 1970). *Closed circles* are for the eastern active zone; *open circles* for the northern active zone; *open stars* for the central active zone, *open squares* for the western active zone; *closed inverted triangles* are for the Tertiary to Recent zone of northwest Iceland; *closed stars* are for the Tertiary to Recent zone of Eastern Iceland. Highly porphyritic basalts or basalts with H_2O+ contents above 1.5 wt.% have not been included
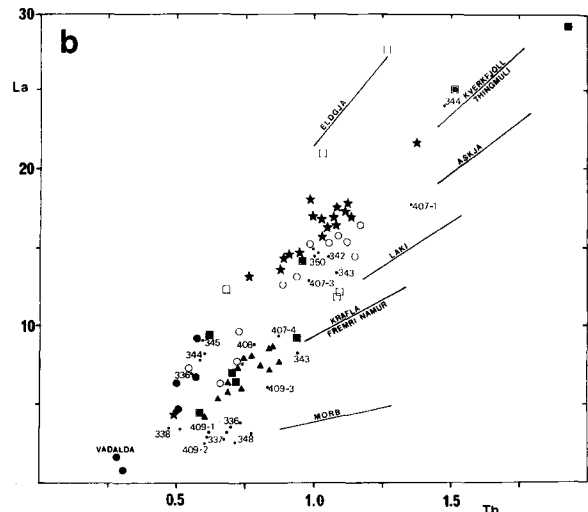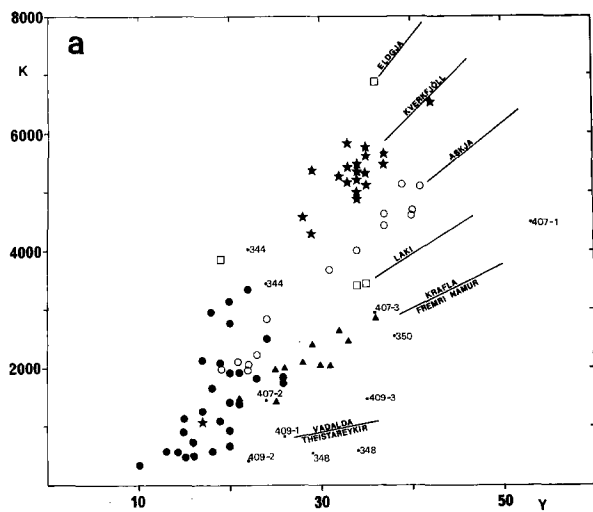
Fig. 4a and b. K versus Y and La versus Tb. (*N.B. Symbols used are different to that of Fig. 3*): closed circles are basalts erupted from lava shields in the northern active zone (the left diagram includes data from Sigvaldason, 1974a); closed stars are for the Kverkfjöll fissure swarm; *open circles* for Askja; *closed triangles* for Krafla and Fremri Námur fissure swarms; *open squares* for the eastern active zone; *partially filled squares* for Eastern Iceland series; *astericks* for western active zones; *small dots* for IPOD and DSDP samples, which are distinguished by hole numbers

The alkali basalts erupted in the southern part of the eastern active zone show the greatest relative enrichment in the more *hyg* elements (e.g. the Eldgjá basalts have K/Y ratios of 190). The tholeiitic lavas erupted from fissures in the northern part of the eastern active zones have *hyg* element compositions intermediate between the Askja and Krafla series (Fig. 4), e.g. the Thjórsárhraun lava (sample ISL 74, Table 1) has a K/Y ratio of 101. Schilling et al. (1978) have published REE data for Pleistocene to Recent basalts from the Langjökull area of central Iceland and the extinct Skagi zone of northwestern Iceland. La and Tb data for these samples (*not* plotted in Fig. 4) show that most of the basalts from the Langjökull area, which are almost exclusively from shield volcanoes (Sigurdsson et al., 1978), are similar to those from the Krafla series. Some of these basalts (i.e., the pillow basalts from the Arnarbaeli ridge), however, are very depleted in the more *hyg* elements and similar to those of Theistareykir (O'Nions et al., 1976) and Vadalda. The Skagi samples plot within the range of the Askja and Kverkfjöll series. The possibility of systematic analytical errors between our data and Schilling's cannot be totally ruled out, but analyses for samples from the same segments of the leg 38 cores analysed by Schilling (1976) and ourselves show good agreement for La and Tb. We therefore believe the above comparison to be justified. Similar comparisons between Schilling's data and our own can be made for the Reykjanes Peninsula and the rest of the western active zone. We have analysed only 3 samples from this zone (ISL 84, I61, I73, Table 1), but taken together with the samples analysed by Schilling (1973) it seems that this zone includes basalts which are both similar and more depleted in the light REE than those of the Krafla series. The Háleyjarbunga picrite (I61) is extremely depleted in the more *hyg* elements (Wood, 1979) and similar to the basalts from Theistareykir and Vadalda. Zindler et al. (1978) have reported basalts of similar composition from other shields on the Reykjanes Peninsula.

In general terms the basalt samples from the surrounding ocean floor show a similar diversity in Fig. 4. The samples most depleted in the more *hyg* elements, i.e., those from the top of hole 336, and holes 337, 348, and 409, follow similar trends to the Theistareykir series although they are more evolved. Indeed the basalts following this trend have many *hyg* element ratios similar to those of normal or N-type MORB (cf., Bougault et al., 1979; Sun et al., 1979). However, some of them have Sr isotope, Ta and Nb values which distinguish them from *N*-type MORB (see below). The basalts from the bottom of hole 336 and holes 338, 342, 343, 344, 345, 350, 407, and 408 plot within the range of the Krafla and Kverkfjöll

series (Fig. 4). This indicates that basalts enriched in the more *hyg* elements (*E*-type MORB) form substantial portions of the oceanic crust between 60 and 75° N in the Atlantic Ocean. The eruption of similar basalt compositions in the Faeroes (Schilling and Noe-Nygaard, 1974), Jan Mayen, Kangerdlugssuaq, and the Mohns Ridge (Schilling et al., 1974) lend further support to this conclusion. A thin basaltic andesite flow (?) was found interlayered with more primitive basalts in hole 344 on the Knipovitch Ridge (Kharin, 1976; Mohr, 1976). This basaltic andesite (sample 344-36-3, 130–135 cm, Table 2) has similar *hyg* element ratios to the coexisting basalts. This suggests a crystal fractionation relationship and perhaps the presence of other intermediate or even silicic lavas at this segment of the ridge.

Biaxial plots involving only the more *hyg* elements, e.g., U and Cs versus Th and Th and K versus Rb for fresh lavas from the Iceland Province are shown in Fig. 5. A number of intermediate and silicic lavas are included (at reduced scale) to emphasize the good linear relationships among these elements throughout the fractionation series. We note that the basalts which are very depleted in the more *hyg* elements have abundances of these elements which are below or close to the detection limits of the analytical techniques employed. These lavas may not necessarily have the same ratios of these elements as the rest of the lavas from the province. Notwithstanding this, the lavas for which data has been obtained all show good linear correlations among the more *hyg* elements despite the significant variations in REE and Sr isotope ratios (see below).

The elements plotted in Fig. 5 all have very low D values ($\ll 0.01$) for realistic mantle mineralogies and cannot be fractionated significantly from each other by partial melting or crystal fractionation processes. The ratios can therefore be considered as representative of their mantle sources (Treuil and Joron, 1975; Joron and Treuil, 1977; Treuil et al., 1977). Certain pairs of *hyg* elements have very similar ionic properties and consequently very similar D values, e.g., $Zr - Hf$, $Nb - Ta$, $Y - Tb$. Joron et al. (1978) have shown that although there is significant inhomogeneity in the sources feeding the MAR the ratios Zr/Hf, Nb/Ta and Y/Tb remain constant at 39, 16, and 42 respectively. These ratios are very similar to those measured in C1 chondrites and all basalts from the Iceland Province have these ratios. These data lend further support to the chondritic Earth model for the refractory elements (Ganapathy and Anders, 1974). Although the Th/U, Rb/Th, and Rb/K ratios are approximately constant in the lavas from the Iceland Province for which we have data, they are higher than those in average *N*-type MORB (Sun et al., 1979)
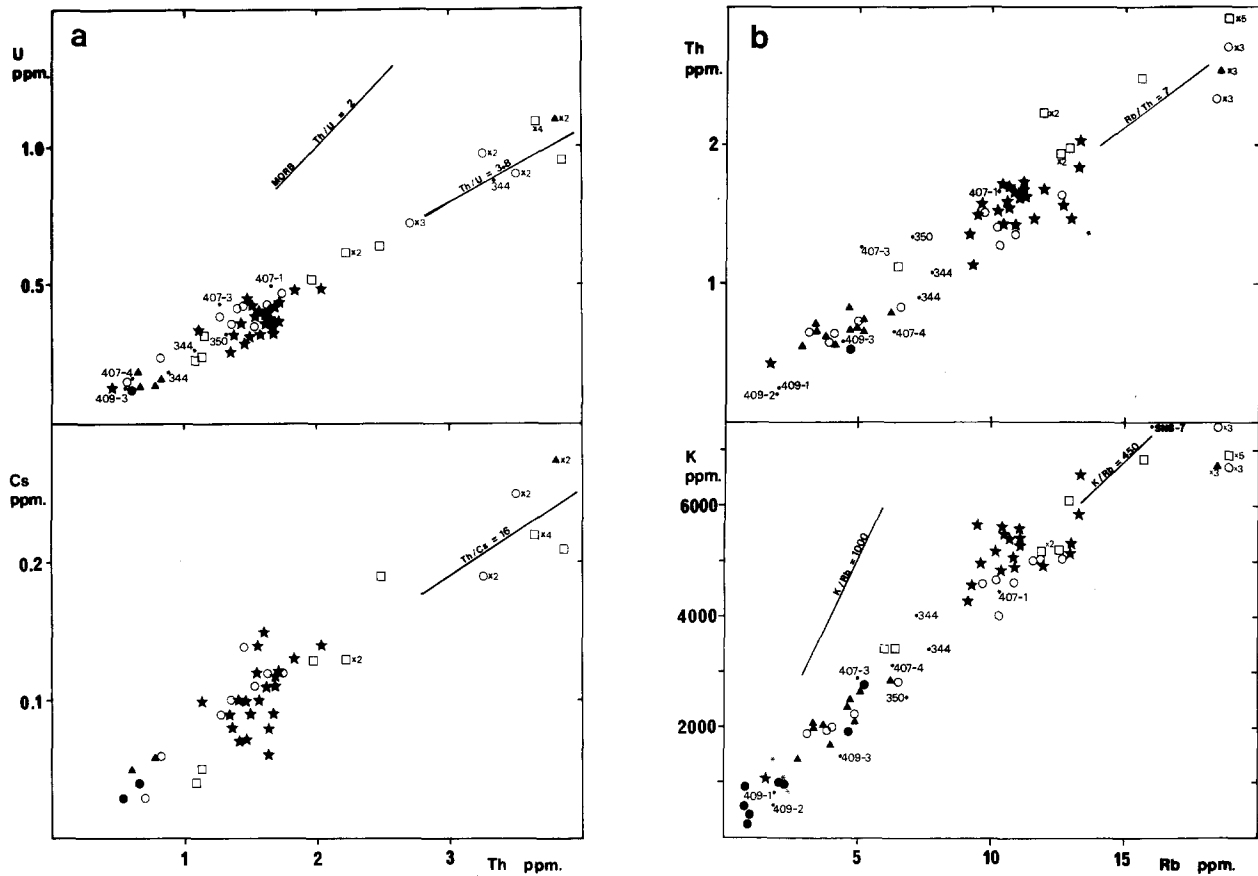
Fig. 5a and b. U and Cs versus Th, and Th and K versus Rb. Symbols as in Fig. 4. Silicic and intermediate lavas are shown at retuced scales with the magnitude of reduction marked

and closer to reasonable estimates for these ratios in the bulk Earth (viz. 3.6, 9, and 300 respectively – Ganapathy and Anders, 1974).

This suggests that although the mantle sources being tapped in the Iceland Province are depleted in Rb relative to Th and K, they are not as depleted as N-type MORB sources. Figure 6 shows that there is a similar relationship between Th and La, i.e., although the basalts from the Iceland Province show little variation in Th/La ratio, they are depleted relative to Cl chondrites but not as depleted as N-type MORB. Some of the basalts from the IPOD leg 38 holes (i.e., 336, 342, 344) have higher Th/La ratios. These probably do represent actual differences in the mantle source region, especially in the case of hole 344 on the Knipovitch Ridge. They are also Fe poor like the basalts from MAR 45° N (Wood et al., 1978; Langmuir and Hanson, 1979) which have similar Th/ La ratios (Fig. 6).

(c) Sr Isotopes

The Sr isotope data given in Table 3 indicate that the spatial variation of major and trace element chem-

istry among Icelandic basalts is accompanied by significant variations in initial $^{87}Sr/^{86}Sr$ ratios. The alkali basalts from Eldgjá have the highest $^{87}Sr/^{86}Sr$ ratios (~ 0.7034) with the transitional basalts from the central volcanoes of eastern Iceland having similar or slightly lower values. The ferrobasalts from Askja and Kverkfjöll have similar $^{87}Sr/^{86}Sr$ ratios (~ 0.70335), which are higher than the $^{87}Sr/^{86}Sr$ ratios of basalts from these areas depleted in the more hyg elements as well as basalts from Krafla and Vadalda (< 0.70325). Silicic glasses ISL 73 and ISL 26 from Krafla and Askja respectively have $^{87}Sr/^{86}Sr$ ratios within the range of the basaltic rocks found at the corresponding centres. Also an alkali rich silicic glass from Landmannalaugar (part of the huge silicic massif to the north of Torfajökull) has the same $^{87}Sr/$ ^{86}Sr ratio as the Eldgjá basalts. These data are consistent with the generation of these silicic rocks by a crystal fractionation process from a basic magma of the same composition as the coexisting basalts. This is at variance with the conclusion of O'Nions and Gronvold (1973), which Wood (1978) has already questioned on trace element grounds.
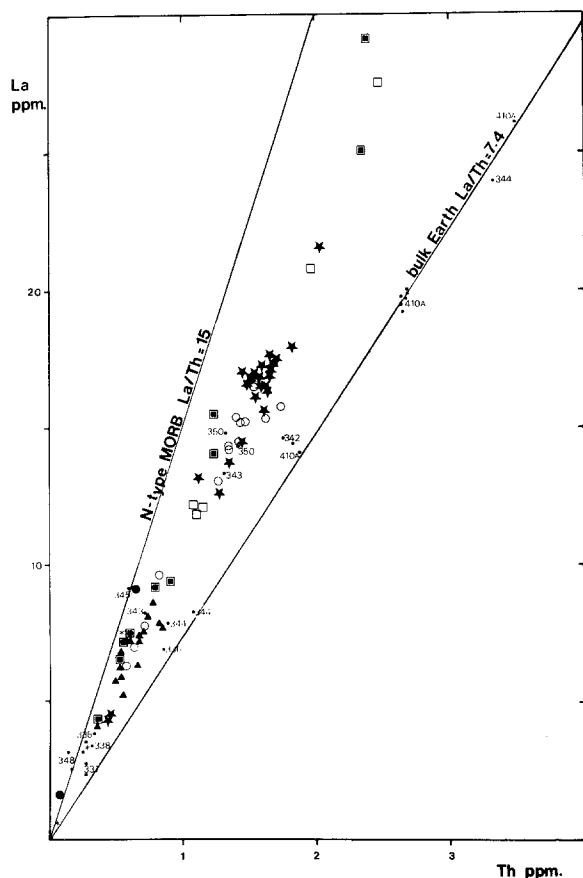
Fig. 6. La versus Th. Symbols as in Fig. 4. Basalts from MAR 45° N (IPOD hole 410A) from Wood et al. (1978). Bulk Earth ratio from Ganapathy and Anders (1974)

In order to make more extensive spatial comparisons of the $^{87}Sr/^{86}Sr$ ratios reported within the province we have compiled a list of all precise published analyses (Table 4), which shows the range of values found at certain localities. The data come from four laboratories, and systematic analytical discrepencies are known to exist between them (cf. O'Nions et al., 1976), although these are thought to be less than ± 0.0001. Fortunately these inter-laboratory discrepencies do not significantly obscure the variation occuring within the Iceland Province because it is of a significantly greater magnitude. Data for both basic and silicic samples have been included. As well as confirming the observations noted above these data show that the alkali basalts of Eldgjá, Torfajokull, Snaefellsnes Peninsula, Gerpir (E. Iceland) and the island of Jan Mayen have similar $^{87}Sr/^{86}Sr$ ratios (~ 0.7034) whereas the alkali basalt series of the Westmann Islands has significantly lower values (~ 0.7032). Only the western, central and northern zones include basalts with $^{87}Sr/^{86}Sr$ ratios close to 0.7030 – these are the lowest values found in Iceland. However, the basalts presently found at the crest of

the Reykjanes Ridge have $^{87}Sr/^{86}Sr$ less than 0.7030. Although some of the older basalts forming the western flank of the Reykjanes Ridge (i.e., IPOD holes 407 and 408) have higher $^{87}Sr^{86}Sr$ ratios (~ 0.7033) within the range of the Askja and Kverkfjöll series, which have similar REE ratios (Fig. 4).

O'Nions et al. (1976 Fig. 5) have previously reported a good positive correlation between $^{87}Sr/^{86}Sr$ ratio and $(Ce/Yb)_N$ ratio for tholeiitic lavas from Iceland and the Reykjanes Ridge. They noted that the alkalic series did not follow the same trend as the tholeiites. In Fig. 7 we have plotted $^{87}Sr/^{86}Sr$ ratio versus $(Ce/Yb)_N$ for the samples analysed by ourselves and also those analysed by O'Nions and co-workers. By plotting $(Ce/Yb)_N$ on a logarithmic scale we believe that a more meaningful relationship between these parameters is obtained and to which all the rock types erupted in the province conform (i.e., basic, silicic, tholeiitic, transitional, and alkalic). In the correlation described by O'Nions et al. (1976) they suggested that there was only very little variation in $(Ce/Yb)_N$ for a given $^{87}Sr/^{86}Sr$ ratio and interpreted this as evidence for approximately constant degrees of partial melting involved in the genesis of the tholeiites. Figure 7 does not substantiate this – in fact it indicates that $(Ce/Yb)_N$ varies by approximately a factor of *five* for any value of $^{87}Sr/^{86}Sr$, which implies that magmatic processes as well as source inhomogeneities are involved in generating the range of major and trace element chemistry described for this province.

Detailed numerical modelling of the major and trace element variations produced by crystal fractionation in the centres of Eastern Iceland (Wood, 1978) indicates that more than 90% crystal fractionation must occur in the generation of a silicic residual liquid from an Mg-rich olivine tholeiite parental magma. Even at such extreme degrees of crystal fractionation the Ce/Yb ratio increases by only a factor of 0.2 (this magnitude of variation is shown by the horizontal arrow in Fig. 7). Therefore crystal fractionation, which is extensive in most Icelandic central volcanoes, cannot explain the factor of five variation in $(Ce/Yb)_N$ for any value of $^{87}Sr/^{86}Sr$. The fact that silicic and basic lavas plot in similar positions in Fig. 7 supports this conclusion.

Partial melting is the process most capable of producing magmas with a range of $(Ce/Yb)_N$ of the required magnitude from a single mantle source. Wood (1979) has considered the partial melting process in detail for lavas from the Reykjanes Peninsula and inferred a dynamic partial melting relationship between lavas with the same radiogenic isotope ratios on the basis of numerical models for the REE. Unless degrees of partial melting significantly less than 10%

Table 4. Compilation of Sr-isotope data from the Literature

	$(^{87}Sr/^{86}Sr)_i$ range	Number of samples	References
Iceland – Jan Mayen Ridge			
Kolbeinsey	0.70290	1	4
Jan Mayen	0.70343–0.70348	3	4
Northern Postglacial Zone			
centres:			
Krafla	0.70312–0.70325	6	1, 2, 4
Askja	0.70312–0.70336	4	1
Kverkfjöll	0.70306–0.70334	2	1
shields:			
Leirhafnarfjöll	0.70304	1	2
Theistareykir (shield + centre)	0.70298–0.70315	5	3
Grjóthals	0.70305	1	2
Ferjufjall	0.70334	1	1
Vadalda	0.70319	1	1
Urdarhals	0.70321	1	2
Eastern Postglacial Zone			
Laki	0.70314–0.70319	3	1, 5, 7
Hekla	0.70320–0.70322	2	5, 7
Eldgjá	0.70333–0.70344	2	1, 7
Torfajökull	0.70344–0.70348	2	1, 5
Westmann Islands	0.70301–0.70319	9	2, 8
Central Postglacial Zone			
Kerlingarfjöll (centre)	0.70317–0.70318	2	5
Illahraun ⎫	0.70302	1	5
Kjalhraun ⎬ shields	0.70304	1	3
Hallmundarhraun ⎭	0.70304	1	2
Western Postglacial Zone			
Reykjanes Peninsula	0.70298–0.70321	16	2, 3, 5, 7, 9
Snaefellsnes Peninsula	0.70323–0.70345	10	2, 4, 7
Eastern Iceland Tertiary			
Gerpir (ca. 13 m.y. old)	0.70343–0.70349	3	6
Nordfjördur (ca. 10 m.y. old)	0.70339	1	1
Skagafell (ca. 9 m.y. old)	0.70340	1	1
Thingmuli (ca. 9 m.y. old)	0.70331–0.70338	2	6
Laugarfell (ca. 3 m.y. old)	0.70320–0.70327	2	1
Austurhorn (ca. 7 m.y. old)	0.70335–0.70339	3	6
Slaufrudalur (ca. 7 m.y. old)	0.70321–0.70326	3	6
Vesturhorn (ca. 6 m.y. old)	0.70334	1	6
Western Iceland Tertiary			
Breidadalsheidi (ca. 15 m.y. old)	0.70340–0.70348	3	6
Nordurardalur (ca. 6 m.y. old)	0.70330–0.70336	1	6
Thverarhlid (ca. 5.3 m.y. old)	0.70323–0.70327	1	6
Hvitarsida (ca. 3.1 to 4.3 m.y. old)	0.70323–0.70335	3	6
Esja (ca. 1.9 to 2.6 m.y. old)	0.70303–0.70316	5	6
Reykjanes Ridge			
North of 62° 30 N (Ridge crest)	0.70300–0.70318	12	2, 4
IPOD hole 409 (62° 36 N – 2.3 m.y. old)	0.70282–0.70299	5	10
IPOD hole 408 (62° 22 N – ca. 20 m.y. old)	0.70329	1	10
IPOD hole 407 (63° 56 N – ca. 40 m.y. old)	0.70329–0.70339	5	10
South of 62° 30 N (Ridge crest)	0.70263–0.70298	14	2, 4

All data has been normalised to a value of 0.70800 for the Eimer and Amend standard and only analyses with 2σ errors $\leq \pm 0.00007$ have been included. The references of the data sources are: *1:* this study; *2:* Hart et al. (1973); *3:* O'Nions et al. (1976); *4:* O'Nions and Pankhurst (1974); *5:* O'Nions and Gronvold (1973); *6:* O'Nions and Pankhurst (1973); *7:* Sun and Jahn (1975); *8:* O'Nions et al. (1973); *9:* Zindler et al. (1978); *10:* Wood et al. (1978)
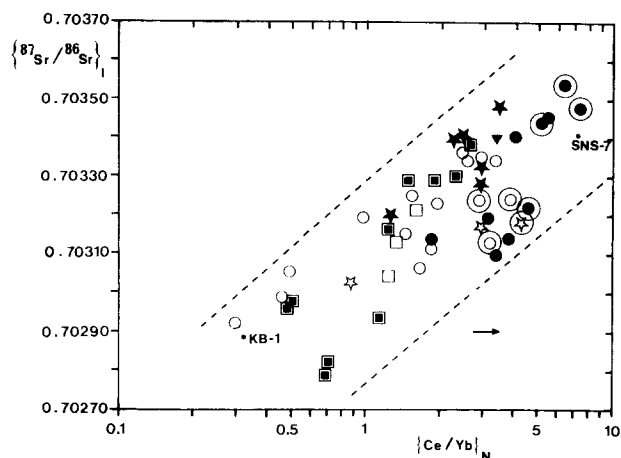
Fig. 7. Initial $^{87}Sr/^{86}Sr$ ratio versus chondrite normalised Ce/Yb ratio plotted on a logarithmic scale. Symbols as in Fig. 3 except that partially filled squares are for the Reykjanes Ridge samples. Silicic and intermediate lavas are encircled. Data comes from this study, O'Nions and Gronvold (1973) and O'Nions et al. (1976). Samples SNS-7 and KB-1 (O'Nions et al., 1976) from the Snaefellsnes Peninsula and Kolbeinsey Island, respectively, are distinguished. The horizontal arrow indicates the maximum magnitude and direction of variation in Ce/Yb which can be caused by more than 90% crystal fractionation of basic Iceland magmas (Wood, 1978)

are invoked (probably unrealistic for tholeiitic melts) batch partial melting cannot produce more than a two fold variation in $(Ce/Yb)_N$ ratio for realistic mantle source compositions. Dynamic partial melting (i.e., when small fractions of melt remain in the mantle residue which may suffer several episodes of melt extraction – Langmuir et al., 1977) can produce the range of $(Ce/Yb)_N$ observed in Iceland basalts (Wood, 1979).

Figure 7 also precludes the mantle plume model which invokes the mixing of two *magmas* (viz. the plume magma enriched in the hyg elements and radiogenic isotopes and the MORB magma) in varying proportions to explain all the basaltic lava compositions erupted in Iceland and along the Reykjanes Ridge (Schilling, 1973). In this model there should be no variation in $(Ce/Yb)_N$ ratio for a given $^{87}Sr/^{86}Sr$ ratio (Langmuir et al., 1978). For a binary source mixing model to be viable the sources must be mixed prior to melting.

Vertical Geochemical Variations

The concentration of the Mg-rich basalts in the top 500 m of the basaltic crust in Iceland (Wood, 1976) produces significant geochemical variations and, in

places, discontinuities in single vertical sections. There is also in many areas considerable variation on a smaller scale, i.e., a flow by flow basis. Figure 8 shows the variation of Mg-number and La/Tb ratio in successive lava flows for a vertical section from eastern Iceland (viz. profile V. Watkins and Walker, 1977) and IPOD hole 407. These sections show that ferrobasalts are interdigitated with Mg-rich basalts but the variation in La/Tb ratios precludes the derivation of all the lavas by crystal fractionation of a single primary magma. Sr isotope data presently available for the sections shown in Fig. 8 do not indicate any significant variations in $^{87}Sr/^{86}Sr$ ratio, but in other areas basalts with large differences in $^{87}Sr/^{86}Sr$ ratio are found coexisting in the field, e.g., basalt ISL 59 and the rest of the Kverkfjöll succession.

It is difficult to interpret the significance of such local variations because processes such as sub-surface, lateral flow of magma, which is clearly important in Iceland (Sigurdsson and Sparks, 1978), may lead to basalt series derived from widely seperated mantle sources being interbedded. For example, the Eldgjá and Laki fissures are less than 10 km apart in places and the markedly different lava compositions erupted from them co-exist in the field. Yet there is considerable geological and geochemical evidence to suggest that Eldgjá resulted from northeastward sub-surface magma flow from the magma reservoir underlying the Katla central volcano, and that Laki resulted from southwestward magma flow from the magma reservoir underlying the Grimsvötn central volcano, i.e. crustal magma reservoirs about 150 km apart (Sigurdsson and Sparks, 1978). In addition to this, many of the more voluminous lavas flow as much as 150 km from their eruptive sources, e.g. the Lakagigar eruption of 1783 (ISL 78). Thus, a vertical succession of interlayered basalts is not neccessarily derived from mantle directly underlying it.

For the above reasons we believe that chemical data for samples recovered by dredge hauls on the ocean floor must be treated more cautiously before they are accepted as representative of the basaltic crust or underlying mantle at a particular locality. Recent studies of dredge samples from the North Atlantic (e.g., Schilling, 1973; White and Schilling, 1978) have not considered the implications of *small scale* vertical and lateral variations in the chemistry of basalts erupted on the ocean floor. Using 2 or 3 samples per minute of latitude cannot provide a representative sampling of the basaltic crust. We propose that the geochemical 'gradient' suggested by data from dredged samples for the Reykjanes Ridge (Schilling, 1973) may not be as systematic as the data suggests.
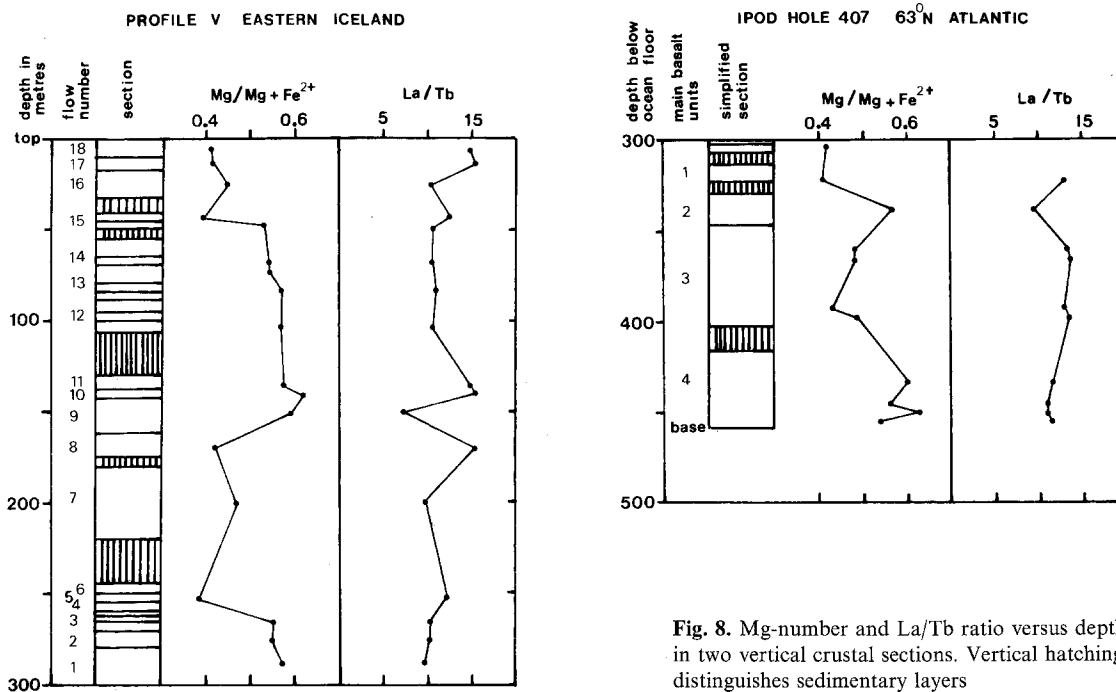
Fig. 8. Mg-number and La/Tb ratio versus depth in two vertical crustal sections. Vertical hatching distinguishes sedimentary layers

Significance of Mantle Source Heterogeneities

Like N-type MORB Iceland basalts have lower [87]Sr/[86]Sr and higher [143]Nd/[144]Nd ratios than the present day bulk Earth values of these ratios (~ 0.705 and 0.5126, respectively, O'Nions et al., 1978). Also they plot to the right of the geochron on the [207]Pb/[204]Pb versus [206]Pb/[204]Pb diagram (Sun and Jahn, 1975). These data are generally interpreted as being derived from mantle sources which have had Rb/Sr, Nd/Sm and Pb/U ratios lower than the corresponding bulk Earth values for substantial periods of Earth history. Thus both trace element and radiogenic isotope data indicate that Iceland mantle sources, or one of their components, have been depleted in the more *hyg* elements by a previous event(s). The range of [207]Pb/[204]Pb ratios in Iceland basalts (Sun and Jahn, 1975) indicates that this relative fractionation between the *hyg* elements occurred at least 2.5 b.y. ago when there was sufficient [235]U remaining to affect the [207]Pb/[204]Pb ratio.

However, there is also trace element evidence for enrichment relative to the bulk Earth. For instance, Fig. 7 implies that all the mantle sources and basalts with [87]Sr/[86]Sr greater than 0.7033 have a Ce/Yb ratio greater than the bulk Earth value. Depletion events would lower the Ce/Yb ratio in the mantle. It is therefore necessary to invoke an addition of Ce relative to Yb to explain the high Ce/Yb ratios of at least some of the Iceland mantle sources. Similarly the Th/U ratio of Iceland basalts is close to the bulk

Earth value (~ 3.6), but is too low to support the radiogenic [208]Pb found in them (Sun et al., 1979). This implies that one of the components of the Iceland mantle sources has had higher Th/U ratios than the bulk Earth for significant periods of Earth history. Thus, Iceland mantle sources consist of some components that have been depleted and others that have been enriched relative to the bulk Earth.

Figure 9 shows a plot of La versus Ta and illustrates the enrichment in Ta of most basalts from the Iceland Province relative to C1 chondrites and N-type MORB. Wood et al. (1979) have previously reported low La/Ta ratios in basalts from the 36°, 45°, and 63° N segments of the MAR. The basalts from the extinct spreading axes in the Norwegian Sea (viz. holes 337 and 348) are similar to N-type MORB and have La/Ta ratios close to 15. Basalts from holes 336, 338, and 345 also have La/Ta ratios close to this value. The relationship between the two basalt types in hole 336 (Table 2) is not clear, but the higher Th/La ratio of the basalt with higher *hyg* element contents (viz. 336-44-2, 68–71 cm) suggests that it is derived from a different mantle source. The relatively primitive basalt from hole 345 could be derived from a N-type MORB mantle source by smaller degrees of partial melting than that required to generate the basalts of hole 348. These data suggest that there is not necessarily a correlation between enrichment in the more *hyg* elements and the La/Ta ratio of the basalts, i.e., not all basalts with high La/Tb, K/Y, etc. are derived from mantle sources with low La/Ta
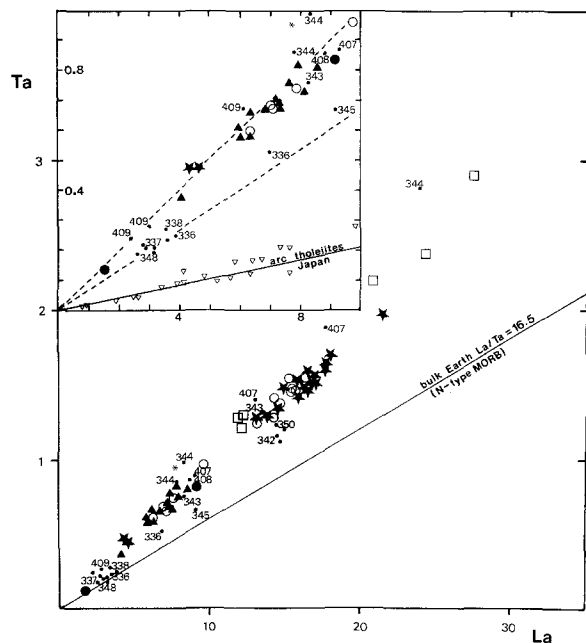
Fig. 9. Ta versus La. Symbols as in Fig. 4. Data for N-type MORB from Joron et al. (1978) and for Japan from Joron and Treuil (1977)

ratios. We note that some of the *hyg* element enriched basalts from Afar, Ethiopia also have La/Ta close to 15 (Treuil and Joron, 1975). Thus the event causing Ta enrichment may not be the same event that caused the enrichment of the other more *hyg* elements and consequently of radiogenic isotopes. Nb shows similar behaviour to Ta.

La, Ta, and Nb are not readily fractionated by partial melting processes – even by incipient melting, e.g., the mantle source of N-type MORB which appears to have had an incipient partial melt (ca. 1% melt, Hanson, 1977) extracted from it has not had its La/Ta ratio changed significantly from that measured in chondrites. Nevertheless, island arc tholeiites have very low Ta and Nb concentrations (La/Ta ratios about 50, Joron and Treuil, 1977) and La–Ta fractionation has clearly occurred during their genesis (Fig. 9). Ta and Nb are strongly partitioned into titanium minerals, e.g., sphene and ilmenite. The stabilities of Fe – Ti oxides are probably enhanced by the higher P_{H_2O} and f_{O_2} in the island arc environment relative to the midocean ridges. Current models for magma genesis at subduction zones (e.g., Best, 1975) require that a component derived by dehydration of the subducting lithospheric slab is involved. It is probably during this dehydration that the La–Ta and Nb fractionation occurs. In the basalts forming ocean crust layer 2 the small, highly charged cations of Ta and Nb are concentrated in the Fe – Ti oxides whereas

the more *hyg* elements with large cations (e.g. La, K, and Rb) are concentrated in the glass phase which is rapidly recrystallized to a range of hydrous ferromagnesian minerals. It is the breakdown of such phases in the subducted basalt that leads to dehydration. Thus, the large cations are lost during dehydration whereas the small, highly charged cations are retained. The refractory, dehydrated slab will therefore have a low La/Ta ratio. Perhaps it is the remixing of such material in the upper mantle that has produced the Ta- and Nb-rich mantle sources presently feeding substantial portions of the MAR. It should be remembered that much of the upper mantle beneath the North Atlantic Ocean has been closely involved with earlier Phanerozoic episodes of subduction associated with the closure of the Iapetus Ocean.

## Fractionation of the *hyg* elements relative to the Primordial Mantle

When discussing the compositional variation among basic lavas a reference composition is required to which all the lavas can be compared. The primordial mantle (i.e., present mantle + crust + hydrosphere + atmosphere) is useful in this context as it gives an indication of the fractionation events that have been involved in generating present mantle sources since the accretion of the Earth. Estimates of bulk Earth composition from the expected condensation sequence constrained by K/U ratio and bulk Fe and U abundances (Ganapathy and Anders, 1974) show good agreement with estimates made by summing the contributions of the atmosphere, hydrosphere, crust, mantle and core (Smith, 1977). The *hyg* element composition of the primordial mantle (Table 5) can be obtained from these estimates assuming that they were excluded from the Earth's core (except P). The ratios of the refractory elements in the calculated primordial mantle are close to C1 and C3 chondrites with approximately twice the absolute abundances.

The abundances of analysed *hyg* elements in some basalts normalized to the primordial mantle are plotted on a logarithmic scale in Fig. 10. The elements have been arranged in order of increasing D values, calculated for realistic mantle mineralogies using experimentally determined mineral – liquid Kd's where available (cf. Hanson, 1977, Table 2 for complication) or, estimated from relative enrichment factors in basalt series related to a single source composition (Wood et al., 1979). Obviously when certain phases are involved in magma genesis this order will change, e.g., residual plagioclase will cause Sr and Ba to move to the right.

Table 5. *hyg*-element composition of three mantle sources (ppm)

	Cs	Rb	Ba	Th	U	K	Ta	Nb	La	Ce	Sr	Nd	P	Hf	Zr	Sm	Ti	Tb	Y
Primordial Mantle	0.019	0.86	7.56	0.096	0.027	252	0.043	0.62	0.71	1.90	23	1.29	90.4	0.35	11	0.385	1,527	0.099	4.87
Average *N*-type MORB	0.0013	0.1	1.2	0.02	0.01	106	0.022	0.31	0.31	0.95	13.2	0.86	73.3	0.34	11.4	0.32	1,177	0.08	4.1
ISL 28	0.007	0.39	4.77	0.06	0.015	216	0.062	0.72	0.66	1.68	17.9	1.11	61.6	0.26	11.3	0.42	1,044	0.08	2.7

Hyg element contents (ppm) estimated for the primordial mantle and calculated for two mantle sources from basalt compositions using the batch partial melting equation assuming 10% partial melting and *D* values for a refractory harzburgite mantle residue $(Ol_{70}Opx_{25}Cpx_5)$ obtained from experimental Kd data for the elements Rb, Ba, K, Ce, Sr, Sm, and Yb (cf. Hanson, 1977, for compilation). *D* values for the other elements were estimated. Values for the primordial mantle are 1.4815 times the bulk Earth values of Ganapathy and Anders (1974) (assuming these elements are excluded from the Earth's core) except for: *Zr, Sr, Nb,* and *P* which are values calculated for the Archaean mantle (Sun and Nesbitt, 1977); *Cs* which is taken from Smith (1977); and *Hf* which is calculated from mean solar system *Zr/Hf* ratio of 31.3 Ganapathy et al. (1976)
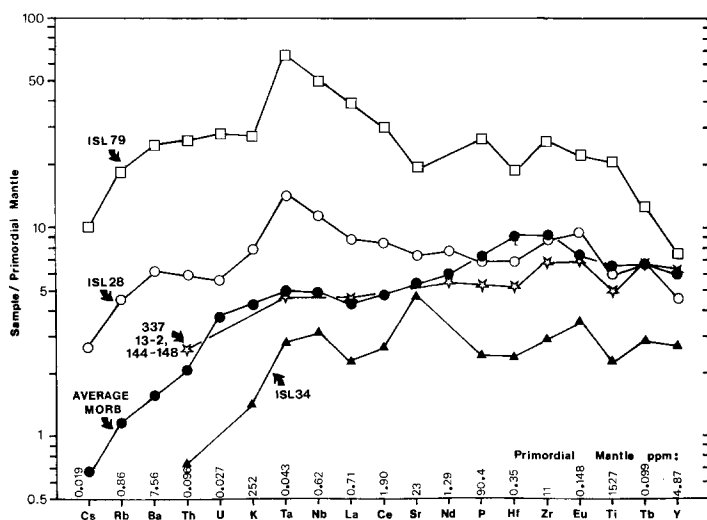
Fig. 10. *Hyg* element abundances in basalts normalised to estimated primordial mantle abundances. The elements are arranged approximately in increasing order of bulk partition coefficients between realistic upper mantle mineral assemblages and basaltic melts. See text and Table 5 for explanation

The composition of average *N*-type MORB (which has been compiled from data given by Sun and Nesbitt, 1977 and Bougault et al., 1979) plots as a relatively smooth curve in Fig. 10 indicating a progressive depletion of the *hyg* elements with decreasing *D* (cf., Sun et al., 1979, Fig. 4a). The *N*-type MORB samples from IPOD holes 337 and 348 plot quite closely to this average composition. In contrast most Iceland basalts (except the *hyg* element depleted picrites, e.g., ISL 34) show a progressive enrichment from Y to Ta and depletion from Ta to Cs. The two components of this pattern reflect the depletion – enrichment events which have been involved in the evolution of the mantle sources: the progressive depletion from Ta to Cs can be correlated with the time integrated depletions of ^{87}Rb and ^{144}Nd relative to ^{86}Sr and ^{147}Sm respectively (O'Nions et al., 1978); the present day light REE enrichment in the mantle sources forms part of the Y to Ta enrichment.

The picritic shield basalts have significantly lower abundances of the *hyg* elements than *N*-type MORB, which cannot be explained simply in terms of phenocryst accumulation – the positive Sr and Eu anomalies shown by ISL 34 are due to plagioclase phenocrysts. The low *hyg* element abundances are thought to be due to dilution caused by dynamic partial melting (Wood, 1979). However these basalts have higher Nb and Ta contents relative to La and the other more *hyg* elements and also higher ^{87}Sr/^{86}Sr ratios than *N*-type MORB (Table 4).

Approximate *hyg* Element Composition of the Mantle Sources

If one assumes that at least 10% partial melting is required to generate tholeiitic melts and such events leave refractory lherzolite or harzburgite residues,
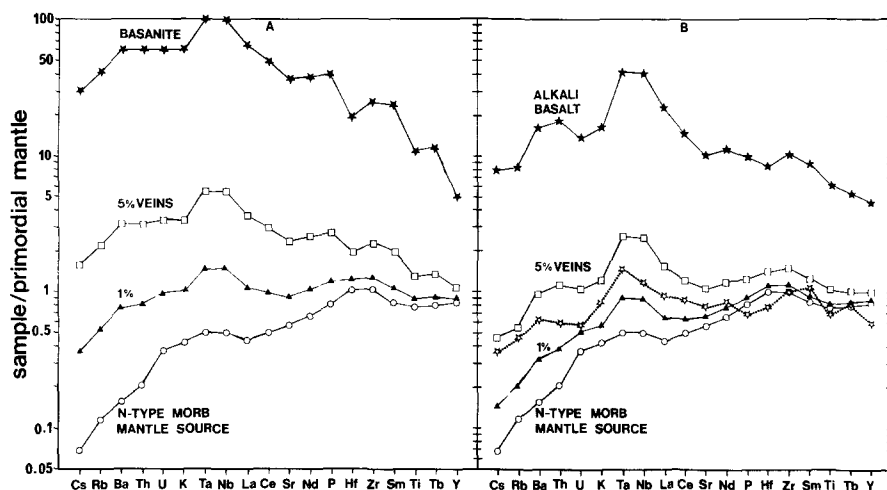
Fig. 11 A and B. Attempts to model the *hyg* element compositions of mantle sources consisting of a main (95%) depleted component (*open circles*) similar to the source of *N*-type MORB (Table 5) variably veined (up to 5%) by an undersaturated basic melt (*closed stars*). *Open squares* are for 5% veins and *closed triangles* are for 1% veins. In **A** the undersaturated melt used is a basanite (sample 2679, Frey et al., 1978), in **B** it is an alkali basalt from MAR 36° N (sample 413−1, Wood et al., 1979). *Open stars* are the calculated source composition of Iceland basalt ISL 28 (Table 5)

then minimum realistic estimates of the *hyg* element compositions of their mantle sources prior to melting can be obtained using the batch partial melting equation with 10% partial melting and *D* values for a harzburgite residue. In the absence of Kd data for some elements, the systematic variation of the elements in *N*-type MORB, arranged in the order shown in Fig. 10, justifies the extrapolation of the enrichment factors of the elements concerned from the calculated enrichment factors for adjacent elements. The calculated source compositions of average *N*-type MORB and Iceland basalt ISL 28 are given in Table 5. We consider the 10% partial melting used in the calculations to be lower than that actually occurring but it serves to counteract the effects of crystal fractionation on the basalt compositions used.

Veined (Metasomatized) Mantle Model

The enrichment-depletion events recorded by the *hyg* element and radiogenic isotope compositions of Iceland basalts can be reconciled with a veined upper mantle source region, in which a refractory host mantle (depleted in *hyg* elements) is permeated (more or less evenly) by veins (up to about 5%) of an undersaturated melt (enriched in *hyg* elements) (Frey and Green, 1974). The model has the advantage of having a refractory, low density mantle (Oxburgh and Parmentier, 1977) and yet still capable of generating 'enriched' basalts. Figure 11 shows two attempts to model the *hyg* element composition of mantle sources formed by different degrees of veining of a *N*-type MORB source with an undersaturated basic melt.

In the model using the basanite veins the bulk source with 5% veins is light REE enriched and similar to the preferred source composition calculated by Frey et al. (1978) for the basanite itself. Even with only 1% veins the ratios between the more *hyg* elements in the veins dominate the bulk source composition (whereas the major element composition is dominated by the refractory host mantle). Similarly in the model using the alkali basalt from 36° N MAR as veins the bulk source with 5% veins has relative REE abundances very similar to those calculated by Langmuir et al. (1977) for the mantle source at this segment of the ridge. The calculated mantle source of Iceland basalt ISL 28 compares favourably with the veined mantle compositions.

The radiogenic isotope composition of a veined mantle will depend on six parameters. In the case of Sr for instance: (1) the $^{87}Sr/^{86}Sr$ ratio of the veins and host at the time of veining; (2) the absolute concentration of Sr in the two components; (3) the $^{87}Rb/^{86}Sr$ ratios of both components; (4) the abundance of the veins; (5) the age of the veining event; (6) the degree of isotopic equilibrium between veins and host. If the basanite liquid used in the model shown in Fig. 11 had an $^{87}Sr/^{86}Sr$ ratio of 0.705 (bulk Earth value) and veined at the present time a *N*-type MORB mantle source with a ratio of 0.7023 the ratios of the bulk sources (assuming isotopic equilibrium) with 1 and 5% veins would be 0.70295 and 0.70355 respectively. These are comparable with the range shown by Iceland basalts (cf. Table 4). In order for the Iceland basalt mantle sources to have present day $^{87}Sr/^{86}Sr$ and $^{144}Nd/^{143}Nd$ ratios lower than the

bulk Earth values any veining by undersaturated basic melts with Rb/Sr ratios near to bulk Earth values must have occurred relatively recently (within the last few hundred million years).

The two components of a veined mantle have compositions which are controlled by earlier fractionation events which, if one accepts that the transfer of melts and fluids have played the major role in the compositional evolution of the mantle, may also involve veining. Certainly variable degrees of veining of small portions of the Archaean mantle during degassing could explain amongst other things some of the variation in radiogenic ^{207}Pb found in present day basalts. Remelting of an undepleted or veined, fertile portion of the upper mantle could lead to re-enrichment of an overlying, depleted, refractory portion of the mantle. Many upper mantle nodules appear to be recording exactly this type of event in their major and trace element chemistry – lherzolites with refractory major element compositions are variably enriched in the *hyg* elements (eg. Frey and Green, 1974). This may explain the inverse correlations between major and trace elements shown by some basalt series, eg. the basalts erupted at 45° N MAR show a large range in the degree of light REE enrichment which is inversely correlated with total Fe concentration (Langmuir and Hanson, 1979; Wood et al., 1978). One explanation for this is that the host component of veined mantle sources for 45° N MAR basalts is significantly more refractory than the mantle source of *N*-type MORB. This will have two important consequences: (1) for a given amount of heat input or degree of adiabatic decompression the more refractory mantle will suffer smaller degrees of partial melting than the less refractory mantle; (2) As the host becomes more and more refractory the hyg element ratios of the bulk source become closer to those of the vein component for a smaller proportion of veins. The melts generated from such a source will be similar to the vein component in *hyg* element contents but have refractory major element compositions. The basalts drilled on the Knipovitch Ridge (hole 344) show similar tendancies to light REE enrichment and Fe depletion relative to Iceland basalts and may be derived from more refractory veined mantle.

With the data presently available it seems that the veined mantle model can satisfactorily explain most of the *hyg* element and radiogenic isotope variation displayed in basalts from Iceland and the North Atlantic Ocean. When the possibilities for variation in the composition of both components of the veined source, the time and the degree of veining are taken into account it is apparent that a large range of local and regional inhomogeneities in the upper mantle could be readily generated.

Summary and Conclusions

1. A spectrum of basalts occur in Iceland, including types enriched and depleted in the light REE and other more *hyg* elements. ^{87}Sr/^{86}Sr variation correlates positively with ratios such as Ce/Yb and K/Y, indicating mantle source inhomogeneities. Nevertheless, basalts with the same ^{87}Sr/^{86}Sr ratio display a significant range of Ce/Yb values indicating that the processes which produced melts from each source composition were variable.

2. Spatial variation occurs in the chemistry of basalts erupted in Icelands' different active zones. In the northern zone there is a progressive enrichment in the more *hyg* elements and radiogenic isotopes from northwest to southeast in this zone, although local variations complicate this trend. Considerable crystal fractionation occurs in high level magma chambers beneath the central volcanic complexes. The intermediate and silicic lavas associated with the central complexes have trace element and Sr isotope compositions which are consistent with their derivation by crystal fractionation from some of the coexisting basaltic magmas.

3. Substantial chemical variations often occur in vertical sections through the lava pile in Iceland and the surrounding ocean floor (IPOD holes 336, 407, and 409). The variations are such that the lavas in a single section cannot be derived from a single parental magma by crystal fractionation processes.

4. Basalts with compositional equivalents occurring in Iceland have been recovered from the surrounding ocean floor by drill holes 342, 343, 345, 350, 407, and 408. All Iceland and Reykjanes Ridge basalts can be distinguished from N-type MORB by having La/Ta ratios significantly less than 15 (usually close to 10) as well as ^{87}Sr/^{86}Sr ratios greater than 0.7027. Using La/Ta criteria it is evident that basalts sampled by holes 336, 337, 338 and 348 have affinities with *N*-type MORB. The basalts from the Knipovitch Ridge (hole 344) have affinities with Iceland basalts for most *hyg* elements but their more refractory major element compositions (i.e., low Fe) and low La/Th ratios are similar to some basalts erupted at the 45° N segment of the MAR.

5. Relative to estimates for the composition of the primordial mantle some of the more *hyg* element contents in Iceland basalts suggest depletion (e.g., Rb), whilst others suggest enrichment (e.g., light REE). The isotopic ratios also suggest previous fractionations relative to the bulk Earth. Ta and Nb are enriched to a greater degree than the other more *hyg* elements. This may be a consequence of refractory titanium phases involved at some stage of mantle source evolution.

6. The data presented here are consistent with a veined mantle source model in which the host component of the mantle (ca. $\gg 95\%$) is a refractory residue of incipient melting depleted in the more *hyg* elements. The vein component is an undersaturated melt derived from a mantle source which has not suffered depletion, or (more likely) has been previously re-enriched. The two components have remained isolated for most of the Earth's history in order to maintain different $^{207}Pb/^{204}Pb$ ratios. By varying the compositions of the two components of the veined mantle and the time of the veining a large range of source compositions can be generated.

Appendix 1

Description of Samples Presented in Table 1

ISL 4   Postglacial fissural flow east of Lake Myvatn. Fine grained, glassy sample with microphenocrysts of Ol (3%), Pl (3%) and Cpx (2%).

I 59   Myvatnseldar lava (1724–1729). Sampled at its vesicular surface, it is fine grained with a sub-ophitic texture.

I 58   Postglacial lava crossing road about 10 km east of Myvatn. Medium grained sample with microphenocrysts of Pl (6%) Ol (5%) and Cpx (1%).

ISL 10   Postglacial lava sampled from the gorge on the west side of the river Jokulsá near Dettifoss. Aphyric, medium grained Ol basalt.

ISL 14   Postglacial lava sampled 1 km west of the river Jokulsa at Holmatungur. Sparsely Pl porphyritic (5%) with rare Ol and Cpx microphenocrysts (ca. 1%).

ISL 15   Thirty meter thick columnar jointed lava near Vesturdalur. Aphyric with rare Ol phenocrysts containing Cr spinels.

ISL 20   1961 Askja lava sampled near the flow front. Sub-aphyric with Pl and Cpx microphenocrysts and abundant Fe-Ti oxides in groundmass.

ISL 21   Subglacial, pillow lava from Askja (at the caldera entrance). Aphyric with rare microphenocrysts of Pl and Cpx.

ISL 28   Subglacial lava from Askja erupted after the formation of the old caldera. Fine grained, aphyric olivine basalt.

ISL 29   Subglacial lava from Askja erupted prior to the formation of the old caldera. Hydrothermally altered with sparse Pl and Cpx phenocrysts.

ISL 40   1923 Askja lava sampled within the old caldera. Aphyric, glassy basalt with rare Cpx and Pl phenocrysts.

ISL 42   Prehistoric lava from Askja (overlies ISL 28). Aphyric.

ISL 44   Pillow basalt from the SE flank of Askja. Sub-aphyric with Pl phenocrysts (1%) and rare olivine microphenocrysts.

ISL 34   Lava from the interglacial vadalda shield. Coarse grained basalt with intergranular texture and phenocrysts of Pl (9%) and Ol (5%).

ISL 17   Extensive lava from shield volcano sampled at Ferjufjall, east of Herdubreidarlfjöll. Medium grained with Ol phenocrysts (5%).

ISL 47   Dyke feeding recent subaerial flow on the summit of Virkisfell near the front of the glacier. Aphyric, glassy basalt.

ISL 59   Subglacial pillow basalt 2 km N.E. of hut on Virkisfell. Porphyritic with megacrysts of Pl (7%) and rare Ol in a glassy matrix.

LSL 66   Prehistoric lava overlying pillow sequence 15 km N.E. of the hut on Virkisfell to the east of road. Aphyric and glassy.

ISL 67   Dyke feeding pillow formation 18 km N.E. of hut on Virkisfell close to the road. Sub-aphyric and glassy with microphenocrysts of Pl (2%) Ol (1%) and rare Cpx.

ISL 77   Historic lava from Eldgjá collected from the road bridge across the Hólmsá river. Aphyric with rare Pl and Ol microphenocrysts.

ISL 79   Historic lava from the southwest end of Eldgjá. Aphyric.

ISL 78   1783 Lakagigar eruption from Laki. Sub-aphyric with sparse Pl phenocrysts and Ol and Cpx microphenocrysts.

ISL 83   1970 lava from Hekla sampled at the flow front. Sub-aphyric with laths of Pl giving the flow texture. Rare, small Ol microphenocrysts are mantled by Cpx.

ISL 74   Prehistoric Thjórsáhráun fissure lava sampled 15 km west of Hella (ca. 130 km from its site of eruption). Sparsely Pl phyric (3%) with rare Ol phenocrysts and Cpx microphenocrysts (1%).

ISL 84   Lava from the Thingvellir graben. Aphyric medium grained basalt with rare Ol microphenocrysts.

I 61   Postglacial lava from the Háleyjarbunga lava shield, Reykjanes Peninsula. Picritic basalt with phenocrysts of Ol (10%) and Cr-spinel (0.7%).

I 73   Sýrfell fissure lava, Reykjanes Peninsula. Sparsely porphyritic with phenocrysts of Pl (4%), Ol (3%), and Cpx (0.5%).

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