32. TRACE AND MAJOR ELEMENT GEOCHEMISTRY OF BASALTS FROM LEG 81[1]

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ABSTRACT

Fifty-two samples of basalt from the four holes drilled on the Leg 81 transect across the Rockall margin were analyzed by X-ray fluorescence for Rb, Sr, Y, Zr, and Nb. On the basis of these results 13 samples were chosen for major and supplementary trace-element analysis. The results show no progressive change in the character of the volcanism, from Hole 555 in the continental domain through Holes 552 and 553A in the dipping reflector sequence to Hole 554A on the outer high. Two distinct magma types are present, apparently reflecting heterogeneity of the underlying mantle, but both types are present in both Holes 553A and 555, while Hole 552 and Hole 554 are each composed of a single type. Both magma types have a clear ocean-floor basalt signature when examined by discrimination diagrams, as does the basalt from Deep Sea Drilling Project Site 112, which formed at the same time as the Leg 81 basalts slightly farther south along the spreading center. In contrast, the basalts of East Greenland, formed at the same time, are more enriched in incompatible elements and have a within-plate geochemical signature, as is found in some basalts of Iceland today. Clearly the present distinction in geochemistry between the basalts of Iceland and those erupting well south on the Reykjanes Ridge was already established when continental splitting took place.

INTRODUCTION

One of the major aims of Leg 81 of the Deep Sea Drilling Project (DSDP) was to sample both the series of dipping seismic reflectors that occurs in the western margin of the Rockall microcontinent (Roberts et al., 1979) and the adjacent outer high, which is thought to be related to the initial formation of the oceanic crust in the area. Oceanward-dipping seismic reflectors are now known to be a feature characteristic of many passive continental margins (Talwani, Udintsev, et al., 1976; Gerard, 1981; Hinz, 1981) and are well seen on the East Greenland margin (Featherstone et al., 1977), which is the conjugate margin of the Rockall Plateau. Both the dipping reflectors and the outer high were successfully sampled during Leg 81 and proved to consist for the most part of both submarine and subaerial basaltic lava flows.

These basalts can potentially provide crucial information about the evolution of volcanic activity during continental breakup. Previous work shows two distinct (and contradictory) models. One, pioneered by Gass (1970), considers breakup to be exemplified by the southern Red Sea and African Rift Valley. Here breakup was preceded by copious volcanism evolving from alkaline to tholeiitic as the split grew, eventually turning to oceanic volcanism. The early volcanism would be classified as having within-plate geochemistry by discrimination diagrams such as those of Pearce and Cann (1973) and was attributed by Gass (1970) and later workers to thermal plumes rising from the mantle along the line of the split. Such copious precursor volcanism is concentrated at points along the rift, and there are long stretches of young margin (such as that of the central Red Sea) where signs of early volcanism of this type are lacking. The other model, not yet set out so formally, would place the generation of oceanic basalts of mid-ocean ridge basalt (MORB) type early in the splitting process. Thus Esson et al. (1975) showed that magmas of MORB type were available in Skye in the British Tertiary Province, even though the rifting there never reached continental splitting, and the eventual split occurred on the Rockall margin, much farther to the west. Drilling in the mouth of the Gulf of California on Leg 64 of the DSDP showed that submarine MORB basalts can be found within a few kilometers of subaerially weathered granitic basement (Saunders et al., 1982), although the general applicability of this observation might be challenged because of the predominantly transform nature of opening in the Gulf of California. Similarly, of course, the model of Gass might be criticized for being based on subaerial evidence, while most margins are rapidly submerged and remain so.

In an attempt to shed more light on the problem, and especially to understand as far as possible the processes operating in the Rockall area, 52 basalts samples were chosen for analysis from Holes 552, 553A, 554, and 555 of Leg 81. The position of the holes is shown in Figure 1. This chapter presents the results of those analyses and discusses their relevance to this important problem.

RESULTS

The 52 samples were chosen from the core recovered in Holes 552, 553A, 554, and 555 using the shipboard core descriptions. The samples were chosen from the centers of flow units to avoid as far as possible the effects of secondary alteration. All 52 samples were analyzed by X-ray fluorescence spectroscopy for the elements Pb, Th, U, Rb, Sr, Y, Zr, Mo, and Nb, using our Philips PW1410 instrument, calibrated with a basalt sample spiked with standard additions of the ele-

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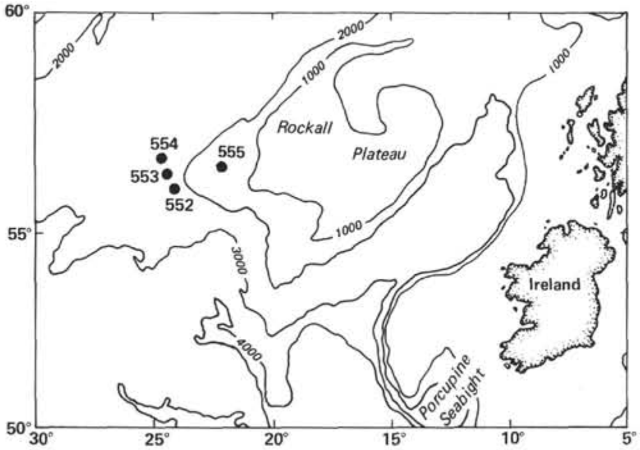

Figure 1. Map showing the locations of holes drilled during DSDP Leg 81.

ments in question and checked with a selection of standard rocks. The detection limit for U, Th, and Pb using this method is 4 ppm, whereas for Rb, Sr, Y, Zr, Nb, and Mo it is 0.7 ppm. Precision at the 0- to 5-ppm level is ±0.3 pm, whereas at the 100-ppm level it is ±2 ppm. On the basis of these analyses, 13 representative samples were selected for further analysis by atomic-absorption spectroscopy, adding major element analyses and a further range of trace elements (Li, Ni, Co, Cr, Zn, Cu, and V). Details of the analytical methods may be obtained from Peter Oakley on request.

The results obtained are given in Table 1 (trace elements) and Table 2 (major elements). Pb, U, Th, and Mo were below the limit of sensitivity for the method and have therefore been omitted from Table 1. Some interelement relationships are shown in Table 3.

PETROGRAPHY

Although the petrography of rocks from Leg 81 is the subject of detailed study elsewhere (Harrison et al., this volume), we undertook a thin-section examination of our samples to check for evidence of cumulus phases and secondary alteration.

The rocks form a homogeneous group of fine-grained, aphyric to microphyric, usually vesicular basalts. Microphenocrysts make up no more than 10% of the rocks and are commonly of labradorite and more rarely of augite set in a microlitic matrix with iron oxide as a common accessory, particularly in samples from Hole 552. Pseudomorphs after olivine microphenocrysts are scarce but are present in basalts from every hole. One sample, from the center of a massive flow unit at the bottom of Hole 555 (Sample 555-97-4, 75–77 cm), is a medium-grained subophitic dolerite, containing labradorite, augite, and rare pseudomorphed olivines, with accessory magnetite. The lack of large phenocrysts and the low abundances of microphenocrysts suggest that the lavas are close to liquid compositions.

The degree of alteration is variable, with samples from Hole 552 showing the most pervasive alteration. The margins of flows are usually most highly altered, and the variation we observe in degree of alteration may be related to flow thickness. The principal secondary phases are brown-yellow smectites and a distinctive green celadonite. These occur in the groundmass and as linings or fillings to vesicles, where the celadonite appears to be the later phase. The presence of these clay minerals is characteristic of low-temperature alteration produced by ocean-floor weathering. The dolerite from Hole 555 con-

Table 1. Rb, Sr, Y, Zr, and Nb analyses for 52 samples from Holes 552, 553A, 554A, and 555, DSDP Leg 81.

Sample (interval in cm)	Element				
	Rb	Sr	Y	Zr	Nb
Hole 552					
21,CC (6–9)	1.3	123	59	211	6.1
22-1, 13–17	0.6	124	51	206	6.5
22-2, 66–68	0.9	116	70	213	6.3
23-1, 133–135	2.1	117	64	195	6.1
Hole 553A					
38-1, 39–41	1.2	106	27	93	3.2
38-2, 75–76	2.9	81	25	64	3.4
39-1, 81–83	1.6	91	28	68	3.3
40-2, 79–81	0.6	77	38	120	3.1
42-2, 67–69	0.4	77	23	55	3.3
43-1, 99–101	11.9	62	22	77	3.1
45-1, 51–53	20.7	63	32	67	3.9
45-3, 79–81	5.2	82	24	57	3.2
46-2, 115–117	1.9	69	26	53	3.2
47-3, 30–32	0.2	77	31	75	3.9
49-3, 75–77	0.8	73	34	76	3.3
50-2, 107–109	0.7	64	24	48	2.3
51-2, 80–82	0.1	67	24	49	2.5
52-2, 68–70	1.5	69	24	49	3.7
53-1, 123–125	1.9	72	23	49	2.5
53-3, 116–118	2.9	87	27	69	3.7
54-1, 94–96	1.8	82	32	66	2.4
54-4, 60–62	1.5	79	30	67	3.5
55-1, 99–101	10.4	67	16	45	2.3
55-2, 75–77	3.3	65	51	45	2.3
55-4, 130–132	0.8	69	27	54	3.1
56-2, 64–66	0.7	76	26	49	2.7
57-1, 106–108	1.1	81	15	45	2.2
58-1, 79–81	3.9	78	21	48	2.5
59-1, 57–59	1.6	79	14	44	2.7
59-4, 64–66	2.0	64	21	46	3.0
Hole 554A					
7-1, 40–42	8.9	91	22	52	3.9
7-4, 27–29	7.0	80	22	52	3.2
8-1, 85–87	1.9	94	24	57	3.2
9-1, 79–81	8.1	93	27	58	3.5
10-1, 69–71	9.4	81	24	61	3.5
11-1, 9–11	7.8	96	27	62	3.9
12-1, 7–9	11	93	30	59	3.9
13-1, 2–4	7.5	88	26	61	3.2
14-1, 2–4	10	97	32	61	3.4
14-1, 97–99	2.4	93	24	63	3.6
Hole 555					
69-3, 37–39	1.7	106	36	101	3.5
70-1, 109–111	1.3	103	24	58	3.3
76-1, 85–87	1.9	90	26	50	2.9
76-4, 82–84	1.0	88	26	52	3.4
77-2, 65–67	4.4	74	28	71	3.0
82-1, 19–21	5.4	92	31	68	2.9
82-2, 2–4	24	80	29	68	2.8
82-2, 140–142	18	88	28	64	3.6
86-1, 126–128	8.5	112	22	64	3.2
90-3, 125–127	1.1	100	50	127	3.7
93-2, 48–50	3.8	109	29	67	3.1
97-4, 75–77	2.9	78	25	50	3.7

Table 2. Major and supplementary trace element analyses of 13 selected samples from Holes 552, 553A, 554A, and 555, DSDP Leg 81.

	Sample (interval in cm)												
	552-22-2, 66–68	553A-40-2, 79–81	553A-45-3, 79–81	553A-51-2, 80–82	553A-53-3, 116–118	553A-54-4, 60–62	553A-59-1, 57–59	553A-59-4, 64–66	554A-7-4, 27–29	554A-14-1, 2–4	555-69-3, 37–39	555-76-1, 85–87	555-82-2, 2–4
Major element oxide (wt. %)													
SiO_2	46.9	52.5	49.4	49.3	49.1	49.6	47.5	49.2	50.1	48.3	49.2	48.3	50.0
Al_2O_3	11.8	14.3	14.9	14.3	15.2	14.4	14.2	14.3	14.1	15.1	14.4	13.9	12.8
Fe_2O_3	7.58	7.37	5.96	2.74	5.43	4.66	7.67	3.56	2.90	6.10	3.64	3.76	3.07
FeO	10.19	6.33	7.24	9.23	6.81	8.32	5.52	7.96	9.27	7.29	8.69	6.88	6.78
MnO	0.13	0.25	0.16	0.27	0.31	0.31	0.13	0.26	0.21	0.25	0.23	0.23	0.22
MgO	7.89	5.50	7.12	7.53	6.75	6.73	9.96	8.29	6.99	5.05	6.40	7.96	7.75
CaO	5.53	7.61	8.76	11.5	8.98	0.41	7.98	11.4	11.4	11.7	10.9	11.9	10.3
Na_2O	2.64	2.90	2.46	2.07	2.55	2.47	2.16	1.89	2.28	2.38	2.52	2.61	2.22
K_2O	0.09	0.07	0.19	0.03	0.03	0.04	0.04	0.03	0.15	0.36	0.04	0.09	2.20
TiO_2	3.30	1.42	1.21	1.07	1.45	1.46	0.95	0.94	1.12	1.16	1.71	1.06	1.27
P_2O_5	0.30	0.16	0.02	0.06	0.09	0.09	0.05	0.06	0.07	0.13	0.12	0.06	0.08
H_2O^+	2.90	1.77	1.93	1.21	2.54	2.21	3.28	1.35	0.49	1.52	1.53	2.44	2.32
Total	99.25	100.18	99.35	99.31	99.44	99.70	99.44	99.24	99.08	99.34	99.38	99.19	99.01
Trace elements (ppm)													
Li	12	7	7	6	5	6	6	7	8	11	7	8	6
V	700	408	435	406	523	503	339	370	406	423	478	386	384
Cr	95	45	88	136	52	49	335	337	60	239	212	349	110
Co	47	75	52	55	55	59	58	52	58	64	55	52	54
Ni	44	37	65	76	47	51	91	95	48	62	78	75	51
Cu	260	92	167	161	110	144	310	152	146	154	236	180	176
Zn	163	126	157	103	143	136	86	92	103	120	111	86	104
Fe_2O_{3T}	18.9	14.4	14.0	13.0	13.0	13.9	13.8	12.4	13.2	14.2	13.3	11.4	10.6
Mg/Mg + Fe	0.45	0.43	0.50	0.53	0.51	0.49	0.59	0.57	0.51	0.41	0.49	0.54	0.59

Table 3. Interelement ratios for 13 selected Leg 81 basalts.

Sample (interval in cm)	Mg/Mg + Fe	Ti/Zr	Ti/Y	Zr/Y	Zr/Nb	Ti/V	Y/Nb
Hole 552							
22-2, 66–68	0.45	93	283	3.0	34	28	11
Hole 553A							
40-2, 79–81	0.43	71	224	3.2	39	21	12
45-3, 79–81	0.50	128	304	2.4	18	17	7.5
51-2, 80–82	0.53	131	267	2.0	20	16	9.6
53-3, 116–118	0.51	126	322	2.6	19	17	7.3
54-4, 60–62	0.49	131	293	2.2	19	18	8.6
59-1, 57–59	0.59	130	407	3.1	16	17	5.2
59-4, 64–66	0.57	122	267	2.2	15	15	7.0
Hole 554A							
7-4, 27–29	0.51	129	305	2.4	16	17	6.9
14-1, 2–4	0.41	115	219	1.9	18	17	9.4
Hole 555							
69-3, 37–39	0.49	101	283	2.8	29	21	10
76-1, 85–87	0.54	128	246	1.9	17	17	9.0
82-2, 2–4	0.59	112	262	2.3	24	20	10

tains, in addition to the clays, minor amounts of chlorite, which was probably produced during an earlier phase of high-temperature alteration.

Neither the grade nor degree of alteration are very high, and many trace elements can be expected to remain nearly immobile under these conditions (Cann, 1970; Humphris and Thompson, 1978). However K and Rb will certainly have been mobile (Hart, 1971), as to a lesser degree may have been Mg and Sr (Matthews, 1971; Staudigel et al., 1980). Elements mobile during ocean-floor weathering must be used with care in any petrogenetic arguments.

GEOCHEMICAL VARIATION WITHIN AND BETWEEN HOLES

This section examines the geochemical variation within holes, to see whether there is any systematic change during volcanism, and between holes, to investigate whether there is any systematic progression in volcanism along the transect that might be related to the tectonic evolution of the Rockall margin. We concentrate on elements likely to be less mobile during the low-grade alteration that has affected the rocks.

Of the elements determined in all 52 samples, Zr, Y, and Nb are relatively immobile under these conditions, whereas Sr shows significant mobility only under conditions of extreme ocean-floor weathering (Staudigel et al., 1980), or during greenschist facies metamorphism (Pearce and Cann, 1973). Figures 2, 3, and 4 show Y, Nb, and Sr plotted in turn against Zr. On Figure 2 (Y against Zr), most of the samples from Holes 553A, 554A, and 555 plot in a single cluster around a Zr value of 60 ppm, which is rather low for ocean-floor basalts and at Y about 25 ppm, which is normal. Those from Hole 552 are consistently much more enriched in both elements, containing levels of Y, in particular, which, at about 60 ppm, are abnormally high for ocean-floor basalts. Some of the points for Holes 553A and 555 extend from the unevolved cluster toward the cluster for Hole 552 and suggest that all of the samples might be related by fractional crystallization of a single magmatic parent. Assuming Rayleigh fractionation and a bulk solid–liquid distribution coefficient (D) of 0.15 for Zr (Pearce and Norry, 1979), such fractional crystallization would involve 77% solidification of the less evolved liquids to produce the more evolved liquids of Hole 552 and would imply a bulk solid–liquid distribution coefficient for Y of 0.39.

That this is probably too simple a conclusion can be seen from a plot of Nb against Zr (Fig. 3). The main, unevolved cluster plots around Zr = 60 ppm, Nb = 3.5 ppm, while the evolved cluster is near Zr = 210 ppm, Nb = 6.5 ppm. If the two clusters are related by Rayleigh fractionation, with D_{Zr} = 0.15, this implies the

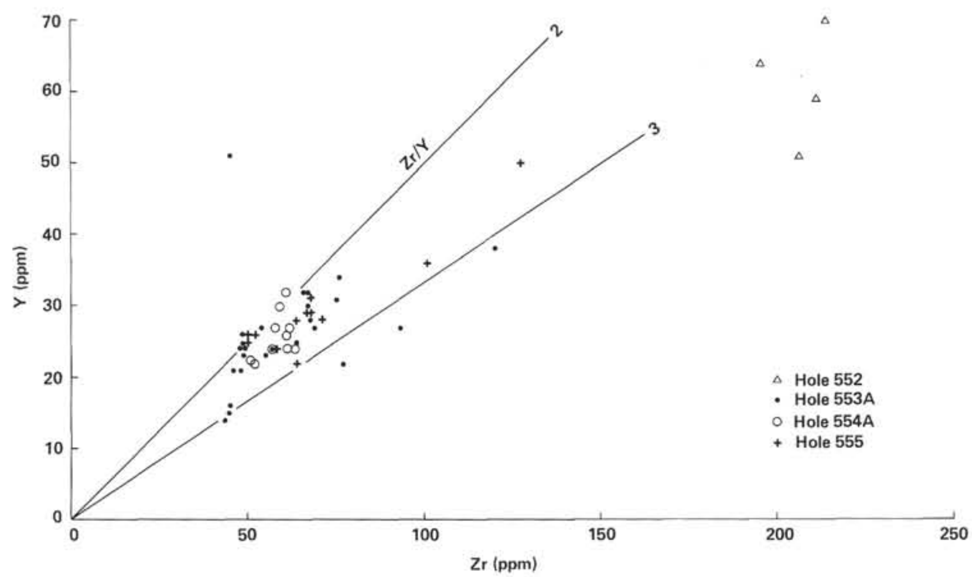

Figure 2. Plot of Y against Zr for 52 basalt samples from Holes 552, 553A, 554A, and 555, DSDP Leg 81.

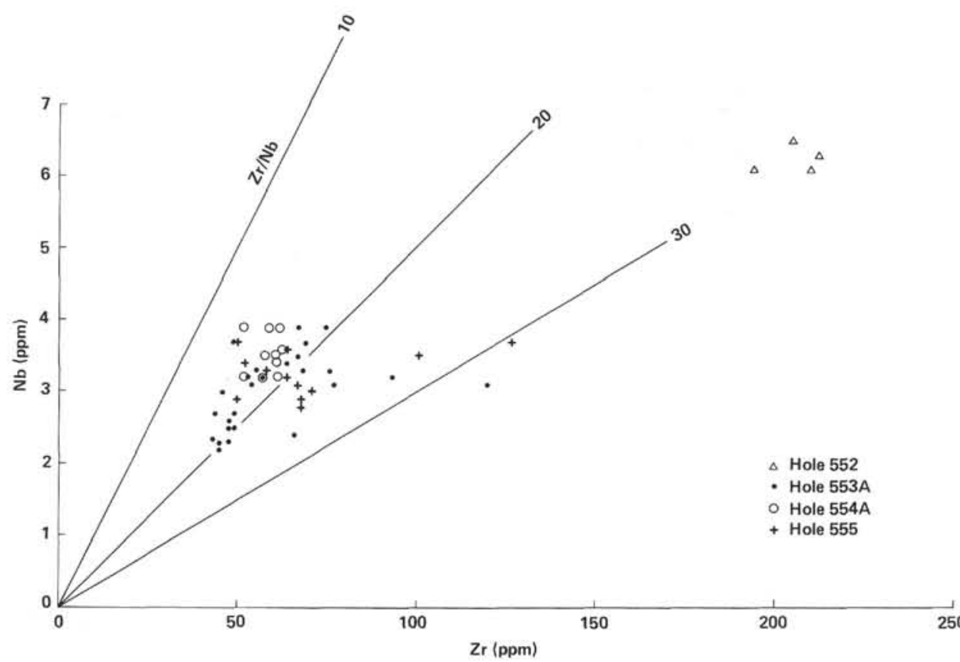

Figure 3. Plot of Nb against Zr for 52 basalts samples from Holes 552, 553A, 554A, and 555, DSDP Leg 81.

entirely unrealistic bulk solid-liquid distribution coefficient of 0.6 for Nb, and a change in Zr/Nb from about 17 to about 32. In addition, the more evolved samples from Holes 553A and 555 contain the same level of Nb as the less evolved samples. If these too were to be related in a simple Rayleigh fractionation scheme, this would imply the even more unrealistic bulk solid-liquid distribution coefficient for Nb of about 1. Where similar variations in Zr/Nb have been found elsewhere, they have been attributed, with supporting arguments from other elements, to the presence of heterogeneities in the mantle (Erlank and Kable, 1976; Macdonald, 1980).

Because of the need for further evidence, the Sr-Zr diagram must be used (Fig. 4) despite the potential problem of the mobility of Sr. The mobility of Sr can be assessed in two ways, first by examining points that are clustered closely in the two preceding diagrams and second by comparing the relative positions of points in all three diagrams. Hole 552 and 554A basalts produce tight clusters in both Figures 2 and 3, and the clustering on Figure 4 is as good if not better. The relative position of points is also very similar. Thus the group of Zr-poor points from Hole 553A (Zr = 45-50 ppm) lies in the same relative position on all diagrams. For these rea-

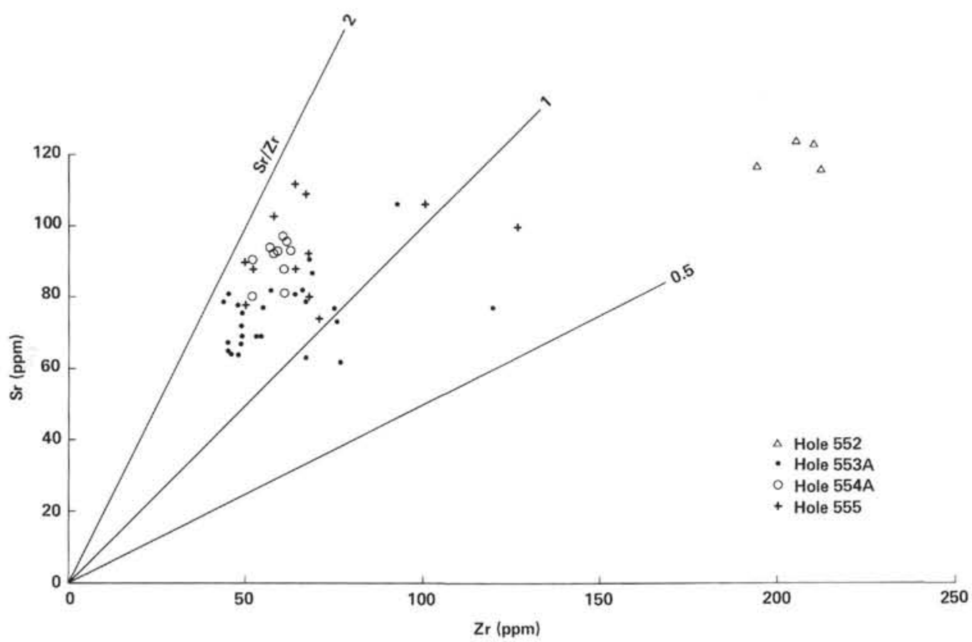

Figure 4. Plot of Sr against Zr for 52 basalt samples from Holes 552, 553A, 554A, and 555, DSDP Leg 81.

sons, it seems that mobility of Sr has not been important in this set of samples, except perhaps for one or two points that may be aberrant.

If this is accepted, then the diagram can be used to supplement Figure 3. In particular, the relative placing of the unevolved group, the evolved samples of Holes 553A and 555, and the highly evolved group from Hole 552 are very similar in both diagrams. This suggests strongly that the pattern on the Nb-Zr plot has a definite petrogenetic significance. It appears that the evolved magmas of Holes 553A and 555 are the most suitable precursors for the highly evolved magmas of Hole 552, as they have very similar Zr/Nb ratios and lie in the other diagrams in a suitable relation to each other. If a relationship by Rayleigh fractionation is assumed for these two groups of magmas (specifically, a mean of Samples 553A-40-2, 79-81 cm and 555-90-3, 125-127 cm on the one hand, and of all 552 samples on the other), and the bulk solid-liquid distribution coefficient for Nb is taken to be zero, then the transition from one group to the other would require a fraction solidified of 0.46, and bulk solid-liquid distribution coefficients of 0.18 for Zr, 0.47 for Y, and 0.52 for Sr. These values seem very reasonable, although that for Y is somewhat high and that for Sr low, suggesting that clinopyroxene would have to form rather a large part of any precipitated solid.

On this basis, the unevolved group of magmas would not be parental to either of the two groups considered above but would have a separate origin, probably from mantle of a different composition than that supplying magma to the more evolved groups. Two broad groups of magmas emerge from this analysis, one with Zr/Nb 15-20, sampled in Holes 553A, 554A, and 555 and represented by the large unevolved group on Figures 2, 3 and 4, and the other with Zr/Nb 30-40, sampled in Holes 552, 553A, and 555, represented by the more evolved groups. Both types of magma are represented at Sites 553A and 555, where some intermediate basalts are also found, possibly the result of mixing of the two types of magma in a magma chamber.

This conclusion is reinforced by the results from the 13 samples chosen for further analysis (Table 2). Selected elements are plotted against Zr in Figure 5. Many of the elements analyzed in this further group appear to have been mobile during alteration. This not only applies to K_2O, Na_2O, and CaO, which are mobile during the formation of clays, and the alteration of plagioclase but also apparently to both MgO and total iron. MgO is added to the rock from seawater to make smectites and other sheet silicates during this style of alteration, and Fe may be mobilized either in this connection or during the formation of pyrite in the basalt. Thus MgO appears to have been added to the basalt from Hole 552, which contains 18.9% of Fe_2O_{3T}, as is appropriate for its high content of incompatible traces, but also 7.9% of MgO, rather than 4.5-5%, which would be expected in lavas with such high Fe_2O_{3T}. Iron mobility seems to have affected particularly the basalts in the unevolved group. The result is that Mg/Mg + Fe cannot be relied on as an index of evolution, and certainly the plot of Mg/Mg + Fe against Zr shows a scatter of points that must in part be caused by this mobility.

However, the other elements plotted are believed to be more resistant to alteration, and the patterns of plotted points are consistent with such a conclusion. The plots of TiO_2, V, and P_2O_5 all show a very similar distribution of points to those of Y and Nb and are clearly of elements behaving similarly incompatibly. That of P_2O_5 has little character to it, presumably because P and Zr have similar distribution coefficients in all of the processes that have taken place. The plots of TiO_2 and V closely parallel the pattern of the same points on the Nb-Zr plot, and both clearly identify (even if in skeletal form, because of the smaller number of points) the dif-

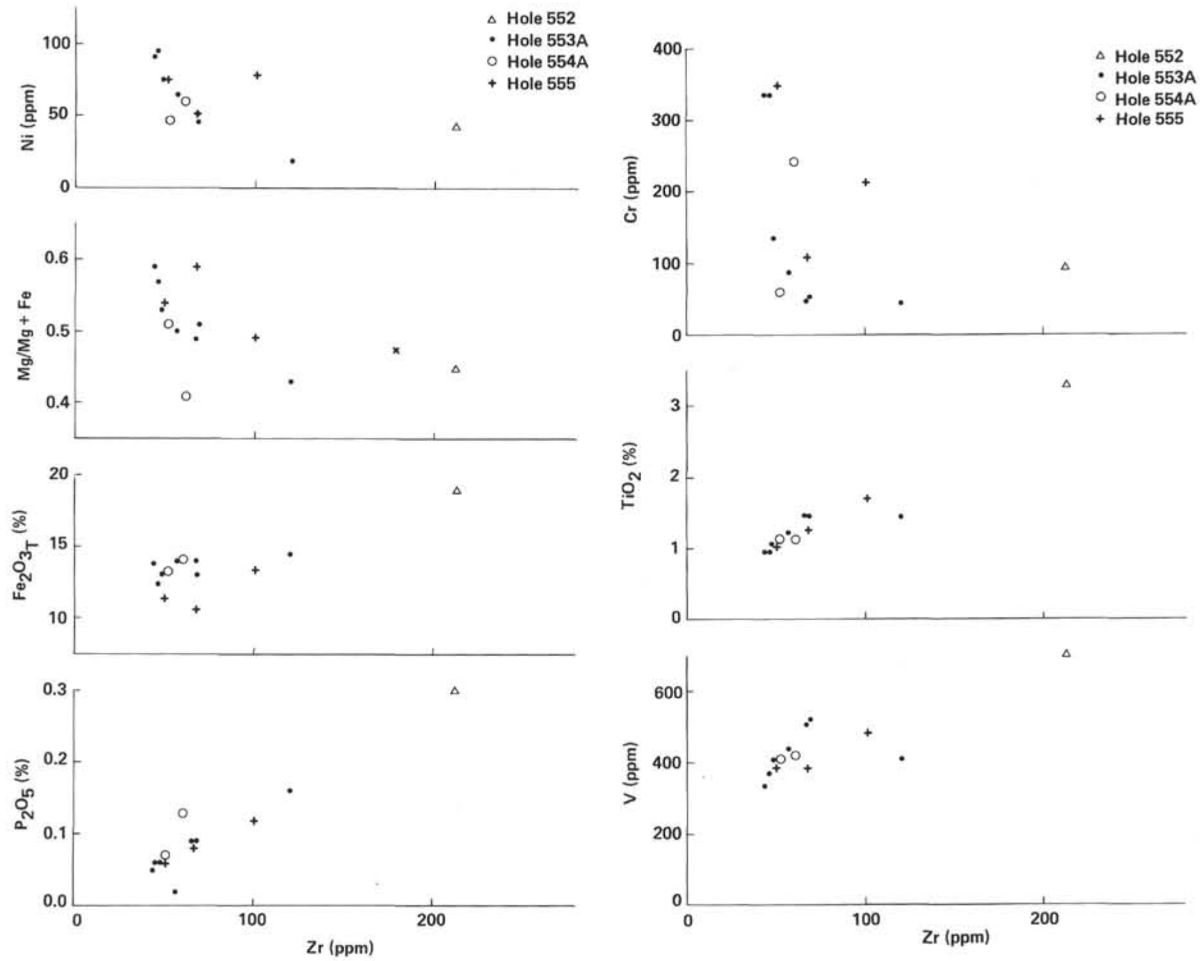

Figure 5. Cr, Ni, V, P_2O_5, TiO_2, Fe_2O_{3T}, and Mg/Mg + Fe plotted against Zr for 13 selected samples of basalt from Leg 81.

ferent magma types. Thus the variation in Zr/V ratios is closely parallel to that of Zr/Nb ratios, both pointing toward similar conclusions to those drawn above.

The plots for Cr and No also emphasize this variety, although for compatible rather than incompatible elements. Both plots are very alike, and their correspondence suggests little mobility of either element. Both show that, at levels of Cr and Ni corresponding to magnesian basalts, a range of Zr contents must have existed, unless there were, in the early stages of evolution of these magmas, large and synchronized changes in the bulk solid-liquid distribution coefficients for both elements. Since this is unlikely, the evidence here, too, suggests that the two groups of magmas are not related by crystal fractionation.

The chemical evidence thus provides two kinds of insight into the magmas of Leg 81. First, it emphasizes that two essentially different types of primary magma were available in this area, one enriched relative to the other in Zr, Y, Ti, P and Sr, depleted in V, and with similar Nb content. Intermediate magmas also occur. Second, it emphasizes the overall unity of the magmatism, since, although Hole 552 shows only the Zr-enriched type (with very small basement penetration) and Hole 554 only the Zr-poor type, the other two holes (with the greatest basement penetration), show both magma types in the same section. The diversity of magma types can probably, as has been said above, be related to mantle heterogeneity, such as has already been documented on Leg 49 of the DSDP (Cann et al., 1979) and south of the Azores (Bougault and Treuil, 1980).

The within-hole variation can be seen from the plots of Figures 2–5 but is also shown in Figure 6, where two variables have been chosen to plot against depth in each hole. The Zr/Nb ratio relates to the magma type present: values less than about 22 represent Zr-poor magmas, and values greater than about 30 Zr-rich magmas. Y abundance relates to the degree of evolution of a given magma type. In Hole 552, the magmas are both Zr rich and highly evolved, although the depth of penetration here was small and the interval from which basalt was recovered even smaller. In Hole 553A, the basalts in the lower part of the hole are generally of the Zr-poor type and become on average gradually more evolved from the bottom of the hole upward for about 100 m. The upper part of the hole is more varied, with Zr-rich and Zr-poor types of different degrees of evolution present together. Hole 554A is made up entirely of Zr-poor magmas, and here the degree of evolution decreases upward in the hole, in contrast to the lower part of Hole 553A. Hole 555 was sampled at less closely spaced intervals. In the upper part, thick volcaniclastics separate units of la-

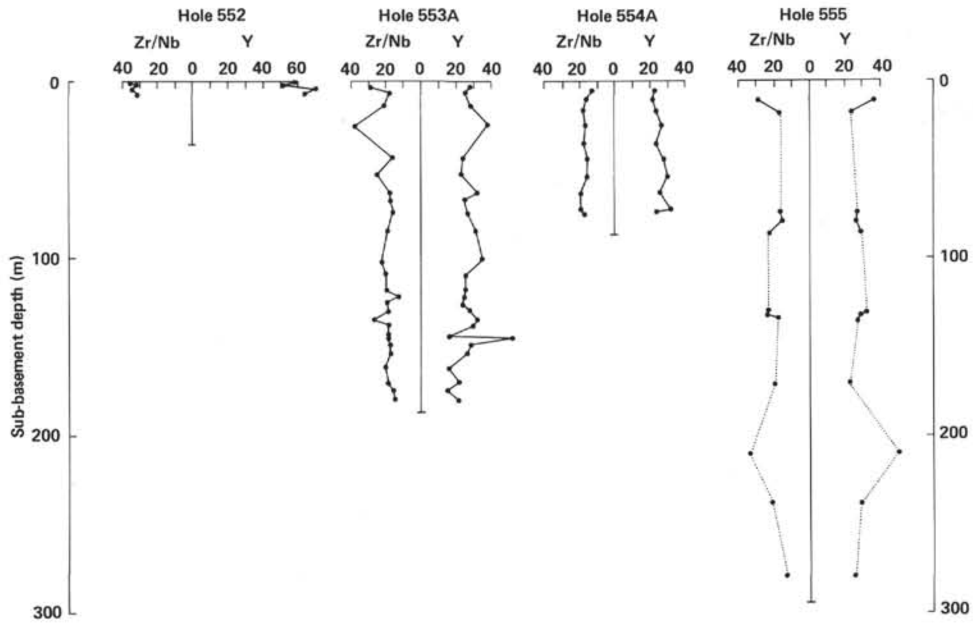

Figure 6. Zr/Nb and Y plotted against depth in hole for basalt samples from DSDP Leg 81.

va, and no description of the lower part was available to us when we chose the samples for analysis. However, it is clear that here both magma type and degree of evolution vary with depth in the hole, and no regular pattern is visible. It is thus not possible to see any consistency of either degree of evolution or magma type with depth in the section. However, these holes have sampled only the very upper part of the dipping reflector sequence, and a more systematic pattern might be evident if longer sections were available.

The variation of magmas between holes shows no regularity either. This is surprising because of the great range in tectonic position of the four holes. Hole 555 is apparently well onto continental crust (Site 555 chapter, this volume), while Hole 544A is on the outer high beyond the zone of dipping reflectors and clearly in the oceanic domain, if not clearly on oceanic crust (Site 554 chapter, this volume). Holes 552 and 553A occupy an intermediate position in the zone of dipping reflectors. Yet, as can be seen from Figure 6 as well as from the previous figures, the characteristics of the magmas sampled from Holes 555 and 553A are very similar, as is the irregularity with which these magmas occur within the section. There are only two possible indications that some changes may be taking place along the transect. One is the uniformity of the chemistry of Hole 554A, on the outer high. However, the penetration at the hole was not really deep enough to be sure that this uniformity is characteristic of the volcanic section here as a whole, and the magma type found here is also found abundantly in Holes 553A and 555. The other is the higher Sr level at Hole 555 than in other Zr-poor magmas in the transect. This may be related to continental crustal contamination and may be a sign of the position of Hole 555 in a continental setting. However, the high Sr might also be an effect of alteration by seawater.

To summarize, the main result from this assessment of within-hole and between-hole variation is not that there is a variety of magma types available in the transect (although this is the case), but that magmatism along the transect was remarkably consistent in overall character both in time and space. No evolution from one kind of magma to another can be seen in the splitting process. It appears that as the magmatism began, so it continued from the continental into the oceanic domain.

TECTONIC AFFINITIES OF THE MAGMAS

Given the consistent character of the magmatism throughout the transect, the next question is whether the magmas show any compositionally clear tectonic affinity. In particular whether they resemble chemically the within-plate/hot-spot type of basalt (WPB), or the ocean-floor basalts (OFB) of normal mid-ocean ridges. This can be examined using the methods of Pearce and Cann (1971, 1973) based on the elements, Cr, Ti, Zr, Nb, Y, and Sr, which are relatively immobile during low-grade alteration.

The tectonic discrimination of the chemical methods used is not exactly parallel to the tectonic distinctions drawn by geophysicists. Thus the WPB class of basalts is found not only in within-plate environments, such as Hawaii, but also in rifting/slow-spreading environments, such as the East African Rift Valley. Even in Iceland, which clearly forms a segment of the mid-ocean ridge system, some of the lavas may be classified chemically as WPB, apparently because of the anomalous character of the mantle beneath Iceland. Other lavas in Iceland, especially the more magnesian class of basalts (Sigurdsson et al., 1978; Wood, 1976, 1978), plot as OFB and along the Reykjanes Ridge south of Iceland there is a clear transition to a consistently OFB character, paralleling the transition described by Schilling (1973) in, for example, the degree of light rare earth element (LREE) enrichment. It should be stressed, however, that tectonic discrimination by the Pearce and Cann methods does not necessarily relate to the degree of LREE enrichment in basalts.

The OFB class of basalts is represented mostly along spreading centers as MORB in one or another of its varieties. However, it can also be erupted in zones of rifting as a precursor to spreading which may never take place (Esson et al. 1975).

Figure 7 is a modification into cartesian coordinates of the Ti–Zr–Y triangular plot of Pearce and Cann (1973), to which it is topologically identical (Cann and Heath, 1976). It is essentially used to distinguish WPB basalts from other basalts (OFB and arc basalts). All 13 samples for which analyses of the three elements are available fall outside of the WPB field. The nearest point to the field boundary is Sample 553A-59-1, 57–59 cm, an unevolved basalt from near the bottom of Hole 553A. All of the other points fall well away from the boundary.

Once the non-WPB basalts are separated, they can be plotted on a Zr/Sr versus Ti/Sr diagram (Fig. 8), again a cartesian transformation of the triangular Ti–Zr–Sr diagram of Pearce and Cann (1973). As expected, the points all fall into the OFB field rather than the arc field. If the basalts of Hole 555 have picked up some continental crustal Sr, it is not enough to push them over the field boundary.

Thus all of the basalts erupted on the transect, whether of the Zr-rich or Zr-poor groups, have close affinities with the basalts of mid-ocean ridges, showing that this kind of basalt was available early in the history of splitting within the continental domain, through the time of development of the dipping reflectors, to the building of the outer high.

REGIONAL COMPARISONS OF LEG 81 BASALTS

To assess the significance of the geochemistry of Leg 81 basalts, it is necessary to compare them with other basalts from the North Atlantic region. Particularly important in this respect are comparisons with basalts from the Faeroe Islands and Eastern Greenland, with which the Rockall basalts are broadly coeval. The other comparison must be with basalts currently being erupted along the Mid-Atlantic Ridge.

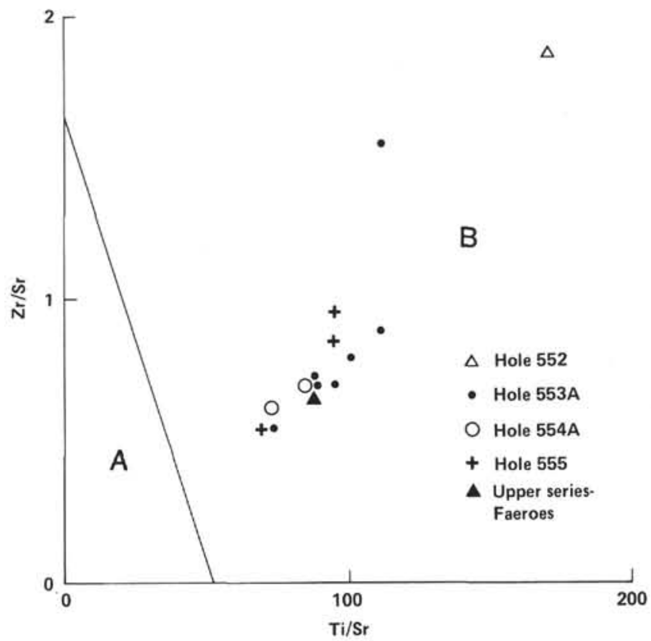

Figure 8. Zr/Sr versus Ti/Sr for selected basalts from the North Atlantic region. (A = field of volcanic arc basalts; B = field of ocean floor basalts.)

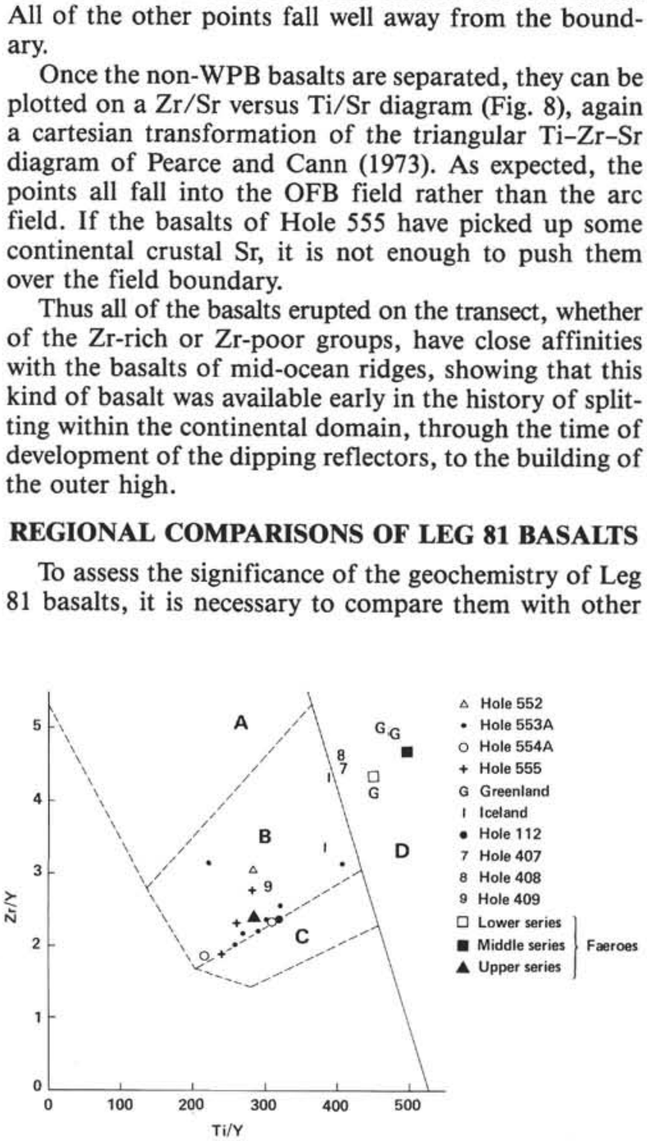

Figure 7. Zr/Y versus Ti/Y for selected basalts from the North Atlantic region. (A,C = fields of volcanic arc basalts; B = field of ocean floor basalts; D = field of within-plate basalts.)

The Faeroe Islands are mostly composed of a 3-km thick sequence of plateau basalts, with a minimum age of 50–60 m.y. (Tarling and Gale, 1968). The stratigraphy, petrology, and geochemistry of the lavas have been described by a number of workers, all of whom accept a threefold division into lower, middle, and upper series, separated by minor unconformities (Noe-Nygaard and Rasmussen, 1968; Schilling and Noe-Nygaard, 1974; Bollingberg et al., 1976). The lower and middle series are dominated by Fe- and Ti-rich quartz tholeiites, enriched in incompatible elements and LREE. The upper series is composed predominantly of olivine tholeiites depleted in incompatible elements and LREE, although enriched lavas do occur (Gariepy et al., 1983).

The early Tertiary basalts of East Greenland are best developed on the Blosseville coast between Scoresby Sund and Kangerdlugssuaq (Brooks et al., 1976). The true thickness of the pile is difficult to determine because of faulting, and estimates vary from over 7 km (Soper et al., 1976) to an average thickness of 2 km (Nielson and Brooks, 1981). The pile certainly thins to a feather edge inland, where it overlies continental crust. Where the continental crust ends to the seaward is not entirely clear. It is certain, however, that the volcanic episode lasted less than 3 m.y. (Soper et al., 1976) and that it occurred immediately prior to magnetic Anomaly 24 (54 m.y.), which is found just offshore (Larsen and Jacobsen, 1982). The Rockall margin basalts have the same relationship to Anomaly 24 and thus appear to have erupted at the same time as the East Greenland basalts. The Greenland pile is divisible into a lower series of compound flows and interbedded pyroclastics, which contains some picrites, overlain by a generally thicker series of simple flows, the Plateau basalts, dominated by saturated Fe- and Ti-rich tholeiites (Brooks et al., 1976; Brooks and Neilson, 1982).

Representative analyses of basalts from the Faeroes and East Greenland are given in Table 4 together with means of the analyses from Hole 552 (highly evolved Zr-rich magma type) and Hole 554 (unevolved, Zr-poor magma type), representing the extremes of variation within the Leg-81 transect. There is a good correspondence between the major elements of all of the basalts, taking into account the probable mobility of Mg in the Leg 81 basalts, except for the upper Faeroese basalts and the East Greenland picrite. Incompatible elements give a somewhat different story, however. At an equivalent stage of evolution of the basalts, (measured by Y, Cr, and Ni contents, Mg/Mg + Fe or total iron) both the Faeroes and the East Greenland basalts are more enriched in incompatibles such as Zr, Sr, Ti, and Nb. Again mantle heterogeneity seems to be the cause of this difference, with the mantle supplying the Leg 81 basalts being significantly depleted in incompatibles relative to that supplying the basalts further north. It is interesting, though, that Zr/Nb is approximately the same in the Zr-poor lavas of Leg 81 as it is in the basalts of East Greenland.

The presence of picrites at the base of the East Greenland lava pile is unique in the North Atlantic region, although they do occur in other flood basalt sequences [e.g., Deccan (Krishnamurthy and Cox, 1977), West Greenland (Clarke and Pederson, 1976)], where they have been interpreted as representing parental magma derived more or less directly from the mantle. Although picrites were not recovered during Leg 81, the drilling only sampled at most the top 300 m of the lava sequence which may be as much as 7 km thick.

The basalts may be further compared on the tectonic discrimination diagrams. The Greenland and Faeroes analyses are plotted on Figure 7, where they clearly fall in the WPB field. The exception is the upper series lavas of the Faeroes which lie in the OFB field, confirming their similarity to MORB (Gariepy et al., 1983). It seems from this plot that the differences between the Leg 81 basalts and those from East Greenland and from the lower and middle series in the Faeroes are not simply a matter of enrichment or depletion in incompatible elements, but that there are more fundamental differences, similar to those between ocean-floor basalts and within-plate basalts. These differences are confirmed by the other element ratios of Table 5, where data for comparative basalts are listed.

Table 5 also gives comparative data for the basalt recovered from the bottom of DSDP Hole 112 (Shipboard Scientific Party, 1972). This site is on crust that must have been very close to the Leg 81 crust in Anomaly-24 time and formed at nearly the same time, although it now lies on the opposite side of the Rekyjanes Ridge spreading center. This basalt has many characteristics in common with the Leg 81 basalts, although a major-element analysis is not available. On Figure 7 it plots on the OFB side of the dividing line, close to several of the Leg 81 samples.

To extend this comparison further, it is useful to examine basalts that have been erupted along the ridge crest from Iceland to the Charlie-Gibbs Fracture Zone

Table 4. Chemical comparison of Leg 81 basalts with basalts from East Greenland and the Faeroe Islands.

	1	2	3	4	5	6	7	8	9
	Hole 552 Mean	Hole 554 Mean	Faeroese basalts			East Greenland basalts			
			Lower	Middle	Upper				
Major element oxides (%)									
SiO_2	46.9	49.2	48.8	49.5	47.4	47.3	47.3	47.7	47.1
Al_2O_3	11.80	14.61	12.90	14.50	14.80	13.40	13.19	13.33	10.72
Fe_2O_3	7.58	4.50	7.60	4.30	4.10	4.90	4.82	5.58	13.8
FeO	10.19	8.27	8.30	8.40	8.60	8.62	8.54	8.18	
MnO	0.13	0.23	0.20	0.20	0.20	0.18	0.21	0.20	0.16
MgO	7.89	6.02	5.90	7.20	9.60	6.31	6.55	6.31	11.80
CaO	5.53	11.55	10.40	10.90	11.80	10.79	11.40	10.74	9.44
Na_2O	2.64	2.45	2.40	2.30	1.80	2.35	2.48	2.03	2.0
K_2O	0.09	0.25	0.40	0.40	0.30	0.26	0.26	0.26	0.38
TiO_2	3.30	1.14	2.90	2.30	1.40	2.64	2.48	2.38	2.12
P_2O_5	0.30	0.08	—	—	—	0.30	0.25	0.26	0.31
Trace elements (ppm)									
Sr	120	90	300	250	150	272	253	335	192
Y	61	25	37	25	28	34	33	30	—
Zr	206	58	220	170	110	169	137	148	138
Nb	6.3	3.5	15	8	2	12	10	9	—
Cu	260	150	300	200	190	211	207	155	130
Co	47	61	70	50	60	45	47	48	62
Ni	44	55	120	120	260	95	93	48	480
V	700	414	430	280	290	330	342	343	270
Cr	95	200	120	230	430	175	160	109	730
Fe_2O_{3T}	18.9	13.7	16.8	13.6	13.6	14.5	14.4	14.6	13.8
Zr/Nb	33	17	—	—	—	14	14	16	—
Mg/Mg + Fe	0.45	0.47	0.41	0.51	0.58	0.46	0.47	0.46	0.63

Notes: 1, 2 = Means of analyses from Holes 552 and 554 (Tables 1 and 2, this paper); 3, 4, 5 = Lower, middle, and upper series Faeroese basalts (Bollingberg et al., 1976; Gariépy et al., 1983); 6, 7, 8 = East Greenland basalts from Scoresby Sund (6), Widemann's Fjord (7), and Nansen's Fjord (8) (Brooks et al. 1976); 9 = East Greenland picrite from Mikis Fjord (Brooks et al., 1976).

Table 5. Trace elements in Leg 81 basalts compared with other North Atlantic examples.

Sample	Ti	Sr	Y	Zr	Nb	Zr/Nb	Zr/Y	Ti/Y	Ti/Zr
Leg 81, Hole 552[a]	19,800	120	61	206	6.3	33	3.4	325	96
Leg 81, Hole 553A[a]	7,300	75	26	60	3.0	20	2.3	281	121
Leg 81, Hole 554A[a]	6,800	90	25	58	3.5	16	2.3	272	117
Leg 81, Hole 555[a]	8,100	93	29	69	3.3	21	2.4	279	116
Faeroes lower series[b]	17,400	300	37	220	15	10.8	4.3	460	79
Faeroes middle series[b]	13,800	250	25	170	8	14	4.4	549	81
Faeroes upper series[b]	8,400	150	28	110	2	33	2.3	291	76
E. Greenland 1[c]	15,800	272	34	169	12	14	5.0	465	93
E. Greenland 2[c]	14,900	253	33	137	10	14	4.2	450	108
E. Greenland 3[c]	14,300	335	30	148	9	16	4.9	476	96
E. Greenland picrite[d]	7,300	192	—	138	—	—	—	—	52
Leg 12, Hole 112[e]	6,000	94	19	45	1.0	45	2.4	316	133
Leg 49, Hole 407[f]	13,800	193	34	152	18	8.4	4.5	407	151
Leg 49, Hole 408[f]	10,100	201	25	115	15	7.6	4.6	403	146
Leg 49, Hole 409[f]	8,100	103	29	83	10	8.3	2.9	279	98
Iceland iron-rich[g]	18,800	299	48	206	27	7.6	4.3	392	91
Iceland magnesian[h]	8,800	194	23	77	10	7.7	3.3	383	114

[a] Leg 81 basalts (this chapter).
[b] Faeroe basalts (see Table 4, nos. 3–5).
[c] East Greenland basalts (see Table 4, nos. 6–8).
[d] East Greenland picrite (see Table 4, no. 9).
[e] Basalt from DSDP Hole 112, Leg 12 (54°01′N, 46°36.2′W); (Laughton, Berggren et al., 1972).
[f] Means of basalts from Reykjanes Ridge sites of Leg 49, all at about 63°N (Tarney et al., 1979).
[g] Representative basalts from Iceland from Wood (1976): B30, typical iron-rich basalt.
[h] Representative basalts from Iceland from Wood (1976); U2, typical magnesian basalt.

since Anomaly-24 time. Extensive studies have been conducted on the basalts of Iceland. These can be considered to fall into two broad classes (Sigurdsson et al., 1978)., a group rich in iron and titanium (FETI basalts) and a magnesian group, which sometimes shows primitive enough characteristics to be considered to have been derived directly from the mantle. A member of each class has been selected from the analyses of Wood (1976) and these are included in Table 5 and plotted on Figure 7. Both show WPB–OFB transitional characteristics, with the FETI basalt plotting on the dividing line and the more magnesian type within the OFB field. Their Zr/Nb ratios are considerably lower than for Leg 81.

A complete series of samples has been dredged from the spreading center between Iceland and the Charlie-Gibbs fracture zone, and has been the subject of intensive investigation by Schilling and co-workers (Schilling, 1973; Schilling and Sigurdsson, 1979). Unfortunately, only partial analyses of this collection have been published, and these do not include the critical elements of Table 5. Schilling and Sigurdsson (1979) relate the geochemistry to a number of factors, including liquidus temperature of the basalts. Their Figure 3 shows some chemical parameters plotted against latitude, and very clearly demonstrates the change in rare-earth patterns from Iceland southward. One of their samples, from about 57°N, must be very close to the point on the spreading center corresponding to the position at which the Leg 81 crust was formed. It has a LREE-depleted pattern, with $(La/Sm)_{EF} = 0.4$, which suggests a MORB geochemistry for the basalt, although, as was said earlier, the correlation between REE pattern and tectonic affinity is far from perfect.

Other evidence comes from the basalts drilled on DSDP Leg 49 at Sites 407, 408, and 409 on a transect westward from the crest of the Rekyjanes Ridge at about 63°N, relatively near Iceland. Means are given for each site in Table 5, taken from Tarney et al., 1979. In several ways the analyses are similar to those from Iceland, particularly in the Zr/Nb ratios which for both Sites 407–409 and Iceland lie close to 8. On Figure 7, the older sites (Site 407 in crust of age about 40 m.y. and Site 408 in crust about 20 m.y. old) plot close to the WPB/OFB boundary and close to the East Greenland basalts and the iron-rich Icelandic basalt. The mean for Site 409, however, plots well within the OFB field, close to the Leg 81 points.

It is quite clear that the Leg 81 lavas are significantly different from those of East Greenland, the Faeroes, and Iceland, which are, however, very similar to each other. This is to be expected since all three areas are closely associated with the Greenland–Iceland–Faeroes Ridge, which has been a topographic high probably continuously during the opening of the North Atlantic/Norwegian Sea (Talwani, Udintsev, et al., 1976). On any predrift reconstruction of the North Atlantic the crust drilled during Leg 81 would have lain well to the southwest of the Greenland–Iceland–Faeroes area on crust lacking the topographic and magmatic anomalies associated at present with Iceland. The other basalts forming at that latitude then and now (DSDP Site 112 and the Trident sample from 57°N) appear to share many of the characteristics of the Leg 81 basalts and are different from the basalts erupted further to the north. The basalts of the Leg 49 transect, lying closer to Iceland than to the Leg 81 sites, share many features in common with Iceland but, in Site 409 at least, have moved from the WPB/OFB transitional geochemistry of Iceland into the OFB field.

CONCLUSIONS

The basalts drilled on Leg 81 are derived from two distinct types of magma, one relatively rich in Zr and other incompatible elements and the other relatively poor in these elements. Hole 552 contains a very evolved Zr-rich magma type throughout the very short section penetrated. Hole 553A contains both magma types, with the Zr-poor type the most abundant and the Zr-rich type concentrated more in the upper part of the section. Hole 554A basalts are uniformly of the Zr-poor type, while Hole 555 again contains both types, although without any preferential distribution of either within the section. The two types of magma cannot be related by crystal fractionation and must reflect heterogeneity of the mantle source. Although two magma types are present, there is no systematic variation in magma type along the Leg 81 transect, and so no discernible evolution in magmatism during continental splitting. Both magma types have ocean-floor basalt affinities, and it seems as though this magma type was readily available for eruption very early in the splitting process, even at Site 555, which lies essentially within the continental domain. There is no sign of precursor within-plate or plume-type magmatism.

Comparison with other basalts from the North Atlantic province shows that the basalts of East Greenland and the Faeroes, although erupted at the same time and possessing very similar major-element characteristics, have a distinct trace-element signature with a strong within-plate or plume character. This character is shared by some of the present basalts of Iceland and, to a lesser degree, by basalts drilled just to the south of Iceland on DSDP Leg 49. Thus the character of the basalts erupted during splitting at those latitudes was probably already influenced by the same factors that give Iceland its topographic and magmatic anomaly at the present time. There too the character of the magmatism continues today as it was established when splitting occurred.

At the latitude of the Leg 81 transect, DSDP Hole 112 basalts show very similar geochemical characteristics to the basalts of the transect, and the indications are that chemically similar basalt is still being erupted at the ridge crest today.

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