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ABSTRACT

Basalts from Sites 319, 320 and 321 have LIL-element (K, Rb, Cs, Ba, Sr, REE) and Sr isotopic characteristics which are typical of tholeiites produced on spreading ridges, as determined by comparison with new analyses of 25 young ridge basalts dredged from Atlantic, Pacific, and Indian ocean ridges. There is some suggestion that the Leg 34 basalts become more "depleted" through time (lower K, higher K/Rb, K/Ba, etc). No evidence was found at the three Leg 34 sites for any off-ridge volcanism of the trans-alkali basalt type.

INTRODUCTION

Basalt produced at mid-ocean ridges (MORB) has been recognized for several years as being distinctly different from basalts produced in other tectonic environments. While the differences are small, they are nevertheless adequate for distinguishing MORB from other basalts and there is currently considerable debate over the explanation of these differences. While the geographic variation of MORB chemistry is well studied, largely from dredge hauls along the ridges, the variation back in time is only poorly understood. Older MORB are usually only accessible by drilling, and frequently this older material is badly altered. The basalts drilled on Leg 34, covering an age range of about 15-40 m.y., are less altered than most DSDP basalts and provide an ideal suite of samples to compare with zero age MORB. This paper will present such a comparison. utilizing major elements, the LIL (large-ion-lithophile) trace elements, and Sr isotope ratios.

TECHNIQUE AND RESULTS

Major element analyses were performed by microprobe on four glass samples (Table 1); no glass was available from Site 321.

Analyses of K, Rb, Cs, Sr, Ba, and the rare earth elements (REE) were carried out on a few selected samples by isotope dilution (details may be found in Hart and Brooks, 1974; Shimizu, 1974), and the results are given in Tables 2 and 3. Sr concentrations on a complete suite of Leg 34 samples were determined by X-ray fluorescence and are reported in Table 4. The Sr isotopic ratios (Table 2) were performed on a 6-in. automated mass spectrometer by techniques described in Hart et al., 1973. In addition to the Leg 34 samples, LILelement and Sr isotopic data on a large number of young MORB dredge samples are reported in Table 5 for comparison purposes.

DISCUSSION

Sr Concentrations

Sr is relatively insensitive to alteration by seawater (Hart, 1969; Pearce and Cann, 1973; Thompson, 1973) and so may be used for the Leg 34 basalts to characterize inter- and intrasite variations. The data of Table 4 are plotted as a function of depth at the three sites in Figure 1. While there is some overlap between sites, each site has a relatively distinct range of Sr concentration, with Site 320 having the highest average concentration (126 ppm); Site 321 the lowest (92 ppm); and Site 319 an intermediate value (111 ppm). At Site 320 there is a slight tendency for Sr concentration to increase with depth; the other two sites do not show any clear trend with depth. Even single cooling units may show considerable variation, as in the unit at Site 319 between 11 meters and 30 meters. While most of this unit shows values in the range 105-115 ppm, three samples fall above 125 ppm. These high values may be related to local accumulation of plagioclase phenocrysts. Overall, the Sr concentrations of Leg 34 basalts are within the range of typical MORB (see Table 5), and significantly lower than Sr concentrations found in sub-alkaline tholeiites from oceanic islands or island arcs where concentrations are typically greater than 200 ppm. In relatively fresh rocks, Sr concentrations can be used to discriminate MORB from basalts from almost all other environments (one exception being Iceland, where low Sr tholeiites are also found; Hart and Schilling, 1973).

Rare-Earth-Element Patterns

Of the various LIL-elements, the REE are most insensitive to seawater alteration (Philpotts et al., 1969). The REE patterns for glass samples from Sites 319 and 320 are shown in Figure 2, along with two samples of MORB which represent the upper and lower limits of all MORB analyzed to date (Kay et al., 1970). The Site 319 and 320 patterns show the light REE depletion typical of most MORB, with no significant europium anomaly. There is a tendency for depletion of the heavy REE in these two Leg 34 basalts, and this is not common in MORB. REE patterns of the type shown in Figure 2 are

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Leg 54 Basan Glass Compositions							
	319-13-1, 59-64 cm	319A-2-1, 27-30 cm	319A Hole Cuttings	320B-3-1, 101-105 cm	Average MORB		
SiO ₂	51.52	51.00	50.20	50.65	49.6		
A1203	14.98	14.54	14.02	15.12	16.0		
Σ FeO	9.23	9.50	10.83	9.44	11.7		
MgO	7.82	8.12	7.26	7.99	7.8		
CaO	12.66	12.48	11.38	11.53	11.3		
Na ₂ O	2.60	2.56	2.91	2.91	2.8		
к ₂ о	0.04	0.04	0.08	0.09	0.2		
TiO ₂	1.19	1.24	1.93	1.57	1.4		
H ₂ O	-	-	-	0.23	-		
co ₂	-	-	-	0.00	-		
Cr_2O_3	0.03	0.04	0.03	0.03	-		
	100.07	99.52	98.64	99.56			

TABLE 1 Leg 34 Basalt Glass Compositions^a

^aBy microprobe.

TABLE 2LIL-Element Contents, Leg 34 Basalts

			320B-3-1,		
	319A-2-1,	27-30 cm	101-105	321-14-1,	Average
	Interior	Glass	Glass	42-45	MORBa
K (ppm)	1892	382	707	1131	1064
Rb (ppm)	5.17	0.188	0.665	1.334	1.02
Cs (ppm)	0.19	0.0085	0.0084	0.0226	0.013
Sr (ppm)	95 (XRF)	97.1	107.6	86 (XRF)	124
Ba (ppm)	2.79	1.323	6.73	16.38	12.2
K/Rb	366	2032	1063	850	1046
K/Cs	9940	45,000	84,000	50,000	81,000
K/Ba	678	288	105	69	109
87 _{Sr/} 86 _{Sr} b	0.70309	0.70266	0.70246	0.70288	0.70265
H ₂ O (total, %)	0.44	-	0.23	0.63	-
$H_2O+(\%)$	-	-		-	.34

^aAverage of 22 fresh basalts from four different ridges, Table 5.

^bPrecision $2\sigma = \pm 0.01\%$ relative to 0.70800 E+A standard.

not diagnostic of MORB, since light-depleted patterns may also be found in tholeiites from island arcs and some oceanic islands such as Iceland.

K, Rb, Cs, Ba Concentrations

These elements are all susceptible to seawater alteration, with Cs being one of the most strongly affected of all elements. However, in fresh glasses such as those from Sites 319 and 320, the alkali data should be reliable (Table 2). The sample from Site 321 was not a glass, but a holocrystalline sample with relatively low water content. The low Cs content of this sample suggests it is relatively free from alteration effects. The samples from all three sites are low in alkalies and Ba and show the high ratios of K/Rb, K/Cs, and K/Ba which are typical of MORB. In fact, the Site 319 glass is lower in K (382 ppm) than any other MORB thus far analyzed by accurate techniques. There appears to be a trend of increasing K and Ba concentration (and decreasing K/Rb, K/Ba ratio) with age represented by the three samples of Table 2; more analyses would be required to see if this effect is real.

To contrast the K, Rb, and Ba data of Leg 34 basalts with other MORB and basalts from other tectonic environments, concentrations of these elements have been plotted using the data of Tables 2 and 5, along with unpublished data of my own (Figures 3 and 4). In the K/Rb-K plot (Figure 3), Site 319 falls slightly outside the field of MORB (due to the low K content); Sites 320 and 321 fall in the central part of the MORB field. In general, MORB cannot be distinguished from arc tholeiites on the basis of K-Rb relationships. The Leg 34

TABLE 3					
Rare-Earth Element Concentrations,					
Leg 34 Basalt Glass ^a					

	319A-2-1, 27-30 cm	320B-3-1, 101-105 cm
Ce	5.84	11.34
Nd	6.68	8.85
Sm	2.595	3.22
Eu	1.109	1.248
Dy	5.22	-
Er	3.03	4.00
Yb	2.73	2.86

^aIn ppm.

basalts do fall outside the arc tholeiite field, though they show the same general trend of decreasing K/Rb with increasing K content that is shown by arc tholeiites, MORB, and the Reykjanes Ridge-Iceland suite.

In the K-Ba plot (Figure 4), Site 319 again falls outside the MORB field (showing the highest K/Ba ratio yet recorded for any basalt) while Sites 320 and 321 fall within the MORB field. The K/Ba ratio appears to be an excellent diagnostic parameter (in fresh samples) for distinguishing MORB from arc tholeiites and oceanic island tholeiites (such as Iceland and Hawaii). While the Leg 34 samples show a trend of negative slope on this plot (as they did in Figure 3), there is not as clear a trend in the arc tholeiite data. The Reykjanes Ridge-Iceland data show a trend of negative slope similar to the Leg 34 samples. Whether this is a trend which reflects mantle chemistry directly, or is a result of differentiation or mixing processes, is unknown at this time. The Reykjanes Ridge-Iceland trend has been interpreted by Schilling (1973) as mixing of two chemically different types of mantles (or of magmas from two different mantles).

Sr Isotope Ratios

The data for the three Leg 34 samples (Table 2) are compared in Figure 5 with data from other MORB (Table 5) and with data on basalts from other tectonic environments (unpublished data). On this plot, all three Leg 34 sites fall within the MORB field. As has been noted before (Tatsumoto et al., 1965; Hart, 1971; Hart et al., 1973), MORB generally have Sr⁸⁷/Sr⁸⁶ ratios lower than 0.7030 whereas most other basalts have ratios higher than 0.7030. There are several exceptions: basalts from the Mid-Atlantic Ridge at 45°N have ratios of 0.7033 (Table 5, not plotted in Figure 5), and several basalts from the Indian Ocean have ratios in the range 0.7030-0.7034 (Circe 104, Table 5, and data in Hedge et al., 1973). In addition, several oceanic islands have values as low as 0.7028 (St. Helena, Grant, et al., in preparation; Ascension, O'Nions and Pankhurst, 1974). Oceanic island basalts generally have K/Rb <600 though, so in a plot like Figure 5 the MORB fields and oceanic island fields remain separated (except for the peculiar "undepleted" basalts at 45°N on the MAR). It should be noted that there is a real variation in the Sr⁸⁷/Sr⁸⁶ of MORB from different localities, with welldocumented values as low as 0.7023 (Table 5), contrary to the statement by O'Nions and Pankhurst (1974) that

TABLE 4 Strontium Contents of Leg 34 Basalts						
Sample (Interval in cm)	Sr (ppm) ^a					
Hole 319						
13-1, 59-64 13-1, 77-80 13-1, 140-143	105 111 105					
Hole 319A						
$\begin{array}{c} 1\text{-1}, 48\text{-}51\\ 1\text{-1}, 139\text{-}142\\ 2\text{-1}, 27\text{-}30\\ 2\text{-}1, 111\text{-}114\\ 2\text{-}2, 114\text{-}117\\ 2\text{-}3, 86\text{-}89\\ 2\text{-}3, CC (p 15)\\ 3\text{-}1, 78\text{-}81\\ 3\text{-}2, 127\text{-}130\\ 3\text{-}2, 127\text{-}130\\ 3\text{-}2, 127\text{-}130\\ 3\text{-}3, 36\text{-}39\\ 3\text{-}3, 106\text{-}109\\ 3\text{-}4, 18\text{-}21\\ 3\text{-}4, 100\text{-}103\\ 3\text{-}5, 37\text{-}41\\ 3\text{-}5, 75\text{-}78\\ 4\text{-}1, 129\text{-}132\\ 5\text{-}1, 20\text{-}22\\ 5\text{-}1, 76\text{-}79\\ 6\text{-}1, 84\text{-}89\\ 6\text{-}1, 93\text{-}98\\ 7\text{-}1, 119\text{-}122\\ 7\text{-}1, 121\text{-}124\\ \end{array}$	$\begin{array}{c} 97\\ 107\\ 95\\ 106\\ 109\\ 134\\ 126\\ 112\\ 111\\ 109\\ 110\\ 113\\ 114\\ 109\\ 111\\ 111\\ 108\\ 129\\ 110\\ 120\\ 114\\ 105\\ 110\\ \end{array}$					
Hole 320B						
3-1, 54-57 3-1, 101-105 glass 3-1, 120-125 4-1, 130-133 5-1, 117-123 5 (bit sample)	120 108 123 120 128 138					
Site 321						
13-4, 119-124 14-1, 42-45 14-1, 99-102 14-2, 9-12 14-2, 127-130 14-3, 7-10 14-3, 92-96	96 86 99 99 90 90 90					
14-4, 7-10	87					

^aXRF technique, precision $\pm 3\%$.

14-4, 61-66

MORB tend to be very uniform at a value of ~ 0.7029 . An exceptionally low value of 0.7012 was reported by Hedge and Peterman (1970) for MORB from the Gorda Rise; reanalysis of powder from the same sample at DTM gave a more normal value of 0.7024.

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The differences between Sr isotope ratios in MORB and other basalts (for example those from oceanic islands) has been ascribed to derivation from a mantle which is chemically heterogeneous (Tatsumoto et al., 1965). Further work, in particular a detailed study of basalts from Iceland and the Reykjanes Ridge (Hart et al., 1973), has been similarly interpreted. The only serious alternative to this heterogeneous mantle model is

 TABLE 5

 Analytical Data for Basalts Dredged from Mid-Ocean Ridges

Sample	Location and Reference	K (ppm)	Sr (ppm)	Ba (ppm)	H ₂ O+ (%)	K/Rb	K/Cs (x10-3)	K/Ba	87 _{Sr/} 86 _{Sr} a
RR average ^b	MAR 62°-60° N	438	77.8	9.4	_	639	41.3	46.6	0.70276 ±5
1-2	MAR 46°N (1)	1986	116	78.0	0.12	355	24.8	25.5	0.70326 ±7
56-2	MAR 46°N (1)	1625	102	-	0.43	361	24.2	-	0.70330 ±30
4519-34	MAR 46°N (2)	5420	252	141.60	0.85	524	25.9	38.3	0.70328 ±6
44-2-1	MAR 23°N (3)	1685	134.4	8.63	0.52	1078	106.6	195.2	0.70268 ±8
111327	MAR 11°N (4)	813	123	9.94	0.36	1232	116.1	81.8	0.70238 ±9
111273	MAR 11°N (4)	963	122	5.37	0.43	1748	181.7	179.3	0.70251 ±8
AD5-5	MAR 10° N (5)	560	118	3.10	0.63	981	22.9	180.8	0.70268 ±7
AD5-18	MAR 10°N (5)	1140	145	8.6	0.44	1122	92.7	132.5	0.70263 ±13
AD3-3	MAR 6° S (5)	1780	133	13.9	0.56	1204	82.4	128	0.70233 ±6
D10-SRH1	JFR 45°N (6)	1671	111	19.45	0.15	907	81.5	85.9	0.70253 ±10
D2-SRH A	JFR 44°N (6)	2154	166	39.0	0.35	628	54.8	55.2	0.70227 ±8
P6702-44	EPR 6° S (7)	502	95	2.67	0.20	2041	125.5	188.0	0.70268 ±5
PD1P	EPR 8°S (8)	430	138	7.1	0.10	695	44.3	60.6	0.70253 ±7
AMPH 3M	EPR 13°S (8)	900	111	10.1	0.19	800	56.2	89.1	0.70254 ±14
AMPH 4A	EPR 18°S (8)	500	108	3.72	0.16	1285	96.2	134.4	0.70260 ±12
5111 · 7	CIR 5°N (9)	1480	145	11.82	0.58	1477	118.4	125.2	0.70284 ±8
Circe 93	CIR 12°S (10)	1350	126	23.7	0.28	589	49.6	47.0	0.70291 ±10
Circe 104	CIR 20°S (10)	770	95	13.44	0.23	596	45.8	57.3	0.70321 ±13
Circe 107	CIR 24°S (10)	960	157	16.71	0.25	765	61.5	57.4	0.70296 ±8
Average MORI	3c	1064	124	12.2	0.34	1046	81.0	109	0.70265

Note: (1) Aumento, 1968; (2) Muir and Tilley, 1964; (3) Melson et al., and Van Andel, 1968; (4) Melson and Thompson, 1971; (5) Engel and Engel, 1964a; (6) Melson, 1969; (7) Bonatti and Fisher, 1971; (8) Engel and Engel, 1964b; (9) Cann, 1969; (10) Engel and Fisher, 1969.

^a 2σ precision relative to 0.70800, E & A standard.

^bSix samples from Reykjanes Ridge, Hart and Schilling, in preparation. Error quoted is the standard deviation of the six analyses.

^cAverage of this table excluding three samples from 46°N.

the one proposed by O'Nions and Pankhurst (1974) which invokes isotopic disequilibrium or heterogeneity on a mineralogical scale. Because of the isotopic differences between basalts from the three Leg 34 sites, they would normally be interpreted as being derived from chemically different mantle. In other words, many of the major and trace element differences between the Leg 34 basalts may be primary, and a reflection of chemical differences in the mantle which supplied each of the sites. While some of the observed differences may be a result of crystal fractionation effects, there would be no need to explain all the differences in this way. Whether or not one can also explain the trace element and isotopic differences in terms of a mineral disequilibrium model (such as that of O'Nions and Pankhurst, 1974) must await further quantitative development of such models.

Alteration Effects

One test was made of the effect of seawater alteration on a drilled basalt. A core fragment from Hole 319A (see Table 2) was analyzed which contained both a chilled glass margin and holocrystalline interior.

The K content of the altered interior is 5 times and the Rb content 25 times that of the fresh glass (despite a water content for the interior sample of only 0.44%), and the K/Rb and K/Cs ratios are drastically lowered (factors of 5 in both cases). The Ba concentration has doubled in the altered interior, while the Sr concentration is

not significantly changed. The Sr isotope ratio is considerably higher in the altered portion (0.7031 versus 0.7027), presumably due to exchange with seawater Sr (Hart et al., 1974) which has an Sr^{87}/Sr^{86} ratio of about 0.7091. In general, these effects are similar to those reported in other studies (Hart, 1969; Philpotts et al., 1969; Thompson, 1973; Hart et al., 1974) except that the interior portion of this sample would not be judged so highly altered on the basis of its H₂O content alone.

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Figure 1. Strontium concentration versus depth, Sites 319, 320 and 321, Leg 34. Data from Table 4. Precision estimate of ±3% shown at bottom.



Figure 2. Rare-earth element patterns for two glass samples, 319A-2-1, 27-30 cm and 320B-3-1, 101-105 cm. Shown for comparison are the highest and lowest patterns reported for MORB, from Kay, et al, 1970. Note the lack of significant europium anomaly in the Leg 34 samples.

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Figure 3. K/Rb ratio versus K concentration of three Leg 34 basalts compared with zero-age MORB (ocean-ridge basalt), island arc tholeiites, tholeiites from the Reykjanes Ridge, Iceland, and Hawaii, and 5 tholeiites from the marginal sea behind the Marianas island arc. The MORB data are from Table 5; samples from 46°N on the Mid-Atlantic Ridge have not been plotted. Most of the other data is unpublished. The Iceland sample with very low K content is a Mg-rich basalt from the Reykjanes Peninsula.



Figure 4. K/Ba ratio versus K concentration of three Leg 34 basalts compared with basalts from other tectonic environments. See Figure 3 legend for additional details.

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Figure 5. Sr⁸⁷/Sr⁸⁶ ratio versus K/Rb ratio for three Leg 34 basalts compared with basalts from other tectonic environments. See Figure 3 legend for additional details.

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