23. GEOCHEMICAL RESULTS FOR BASALTS FROM SITES 253 AND 254

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INTRODUCTION

Deep Sea Drilling Project Sites 253 and 254 are on the Ninetyeast Ridge (Site 253 on the western flank at 24°52.65'S, 87°21.97'E; and Site 254 near the intersection with Broken Ridge at the southern end of the Ninetyeast Ridge at 30°58.15'S, 87°53.72'E). The igneous rocks at the Ninetyeast Ridge sites (Sites 214 and 216) drilled on DSDP Leg 22 are quite different from typical mid-ocean-ridge basalt (Hekinian, 1974 and Thompson et al., 1974). The geochemical features which characterize the basalt at Sites 214 and 216 are:

1) High abundances of large-ion lithophile (LIL) trace elements such as strontium, barium, zirconium, and light rare-earth elements (REE); these elements are normally depleted in mid-ocean-ridge basalt (Table 1 and Figure 1).

2) High abundances of iron (total iron as FeO>13 wt. %) and titanium coupled with low abundances of calcium and magnesium (Table 2 and Figure 2).

3) Low abundances of trace elements such as chromium and nickel; these elements are normally enriched in mafic minerals (Table 1).

4) The association of oceanic andesites with the ferrobasalt at Site 214 (Figure 2).

Based on geophysical and age data, Sclater et al., 1974 and Bowin (1973) have established that the Ninetyeast Ridge does not mark the boundary between the Indian Ocean plate and the Wharton Basin plate, but rather it is a feature of the Indian Ocean plate. Bowin (1973) suggested that the Ninetyeast Ridge originated as a result of emplacement of gabbro and serpentinized peridotite beneath normal ocean crustal layers. He postulated that the localized emplacement was the result of a mantle plume which did not have conditions appropriate for formation of a large volcanic structure such as Iceland. Sclater et al., 1974 concluded that a plume or "hot spot" model could explain the origin of the Ninetyeast Ridge north of 8°S, but that south of 8°S a leaky transform-fault model was more likely.

Hekinian (1974) demonstrated that DSDP Leg 22 Sites 214 and 216 have geochemical similarities to the Indian Ocean islands of St. Paul and Amsterdam. Thompson et al. (1974) noted that Site 216 north of 8°S and Site 214 south of 8°S have geochemical similarities, and further, that their geochemical characteristics are the same features which distinguish Icelandic basalt from Reykjanes Ridge basalt (Schilling, 1973). Clearly, a petrological-geochemical comparison of the basalt of Leg 26 (southern Ninetyeast Ridge) Sites 253 and 254 with the basalt of Leg 22 (northern Ninetyeast Ridge) Sites 214 and 216 provides important information for understanding the origin and development of the Ninetyeast Ridge.

RESULTS

Four basaltic samples from Sites 253 and 254 were analyzed for trace elements (scandium, chromium, cobalt, hafnium, tantalum, and REE) by instrumental neutron activation analysis (Table 1). Petrographical descriptions, major-element data (Table 2), and some trace-element data for these samples are presented by Kempe (this volume, Chapter 14).

Site 253

Sample 253-24-1, 84-85 cm is an altered scoriaceous glassy basalt from a thin flow in an ash sequence. Several hundred meters of ash were cored below this flow so it is not a sample of basement rock. Olivine and plagioclase are phenocryst and microphenocryst phases in the glass. In major-element composition this basalt is more like Mid-Indian Ocean Ridge basalt (MIORB) than basalt from Sites 214 and 216 (Table 2). On a normative basis, Kempe (1973 and this volume, Chapter 14) has classified this rock as a quartz tholeiite. It is important to note that each of the four Leg 26 samples we studied is highly altered (cf. H_2O + CO_2 content in Table 2). Thompson (in press) has summarized data on the effects of low-temperature alteration on oceanic basalt. The major-element effects are increases in Fe_2O_3, potassium, and volatiles (H_2O and CO_2) accompanied by decreases in CaO, MgO, and SiO_2. The high degree of oxidation ($Fe_2O_3/FeO=0.6$) and high K_2O abundance of this basalt relative to MIORB probably have resulted from alteration. When the normative mineralogy has been recalculated on the basis of $Fe^{+3}/Fe^{+2} + Fe^{+3}=0.1$ this basalt lies very close to the silica-saturation boundary in the hypersthene-diopside-olivine ternary. The majority of dredged oceanic-ridge basalt lies within this normative ternary (Chayes, 1972).

This Site 253 basalt is markedly higher in Al_2O_3 and lower in total iron and TiO_2 abundances compared to the basalts of Sites 214 and 216 (Table 2). Also the chromium abundance in this basalt is a factor of 10 higher than in basalt from Sites 214 and 216 (Table 1). These differences almost certainly reflect differences in the original magmas.

The abundances of transition-metal trace elements (scandium, chromium, and cobalt) in Section 253-24-1 basalt are similar to MIORB (Table 1), but, as at Sites 214 and 216, the LIL elements (such as light REE, zirconium, hafnium, and tantalum) are enriched in this basalt compared to the tholeiitic basalts typical of oceanic ridges (Table 1 and Figure 1). Some LIL-

TABLE 1
Trace Element Abundances in Ninetyeast Ridge Basalts[a] (ppm)

| Element | Leg 22 | | Leg 26 | | | | |
	Site 214	Sample 216-38, CC	Sample 253-24-1, 84-85 cm	Sample 253-58-1, 2-7 cm	Sample 254-36-3, 95-97 cm	Sample 254-38-1, 115-117 cm	Central Indian Ridge
Sc	46	42	50	53	42	42	39-70
Cr	43	25	460	640	360	140	180-460
Co	61	47	56	40	51	53	26-80
Ni[c]	53	45	–	310	200	–	130-320
Zr[c]	117	180	200	50	200	200	61-96
Hf	3.9	4.1	3.6	0.94	3.9	3.1	<2.7
Ta	1.9	3.0	0.66	0.11	0.71	0.42	<0.5
La	8.4	14.7	9.2	7.8	11.1	7.2	2-4
Ce	21.3	29.0	22.2	17.3	25.7	17.0	5.7-12
Nd	15.3	21.0	11.1	12.3	18.2	12.9	8.4-12.4
Sm	5.1	5.3	3.1	3.3	5.3	4.1	2.5-5
Eu	1.7	1.6	1.2	1.1	1.8	1.2	1-1.6
Tb	0.86	0.87	0.78	0.61	1.1	0.87	0.66-1.2
Yb	3.0	3.8	2.9	2.2	3.5	3.0	2.4-5.2
Lu	0.44	0.52	0.54	0.48	0.71	0.61	0.41-0.87

[a]Data except Ni and Zr obtained by instrumental neutron activation analysis, precision and accuracy ±10% for all but Tb and Lu ±25%.

[b]Average of 3 from Thompson et al. (in press).

[c]Data from Kempe (this volume).

[d]Sung and Frey, unpublished data.

[e]Abundance range for Sc, Cr, Co, Ni, Zr from Cann (1970), Engel and Fisher (1969); Hf and Ta maximum for ridge basalts from Frey et al. (in press,[b]); REE range from Schilling (1971).

element enrichment may be caused by low-temperature alteration (e.g., Hart, 1971; Thompson, 1974; Frey et al., in press). For example, potassium, rubidium, and cesium abundances are markedly increased by slight alteration; strontium and barium by moderate alteration; and light REE by severe alteration; whereas abundances of elements such as zirconium and hafnium appear to be only slightly affected even by severe alteration (Cann, 1970; Thompson, 1973). Because even zirconium and hafnium are enriched in Section 253-24-1 we suggest that this basalt is tholeiitic in major-element composition (i.e., similar to basalts formed at spreading ridges) but that it is enriched in LIL elements. It is a depletion in LIL elements which is the most distinctive feature of basalts formed at active oceanic-ridge spreading centers, but tholeiitic basalts with LIL-element enrichment have been found previously, e.g., in the Atlantic Ocean at 45°N on the Mid-Atlantic Ridge (Muir et al., 1964; Frey et al., 1968) and at Sites 2-10 of DSDP Leg 2 (Frey et al., 1973, in press). These conclusions about the magma chemistry for the Sample 253-24-1, 84-85 cm basalt are tentative until studies of fresh glass are made.

Sample 253-58-1, 2-7 cm is a sample of the porphyritic olivine basalt in which this hole terminated. The rock is very altered and abundant olivine has been replaced by talc and serpentine. The most distinctive chemical feature of this basalt is its high MgO content (14.8 wt. % on anhydrous basis) which reflects the high modal abundance (~15%) of olivine (Kempe, this volume, Chapter 14). Other major-element abundances such as low Na_2O and TiO_2 (Table 2) indicate that this basalt is

either a picritic cumulate or a basalt which has undergone very little olivine fractionation such as found on DSDP Leg 3, Sites 14 and 18 (Frey et al., in press). The high chromium and nickel abundances (Table 1) coupled with low zirconium, hafnium, tantalum, and REE abundances (Table 1 and Figure 1) also indicate a cumulate rock or a primitive relatively unfractionated magma. Despite the low abundances of LIL elements, this basalt is relatively enriched in light REE (Figure 1) similar to the upper flow (Sample 253-24-1, 84-85 cm). There is a possibility that this lower basalt is an olivine cumulate genetically related to basalts such as the overlying flows. For example, addition of 15% olivine (FO₈₅) to the basalt in Sample 253-24-1, 84-85 cm would account for the MgO enrichment in the basalt in Sample 253-58-1, 2-7 cm. Qualitatively the lower abundance of SiO_2, Al_2O_3, CaO, and Na_2O, and higher abundances of FeO* and MgO in Section 253-58-1 are consistent with olivine differentiation. We suggest that olivine accumulation is the explanation for the high MgO content in this basalt. Olivine accumulation would decrease the LIL-element abundances in the cumulate rock without causing significant relative REE fractionation. Again, any interpretation of the present data is tentative because of the high degree of alteration. Electron-microprobe analyses of fresh glass are needed to definitely establish whether this basalt is a cumulate or if it represents a mafic magma such as found in the Atlantic on Leg 3 (Frey et al., 1973, in press). Both of the basalts studied from Site 253 have low FeO*/MgO ratios (<0.9, Table 2). Since alteration processes tend to increase FeO*/MgO ratios (Thompson, 1973), this
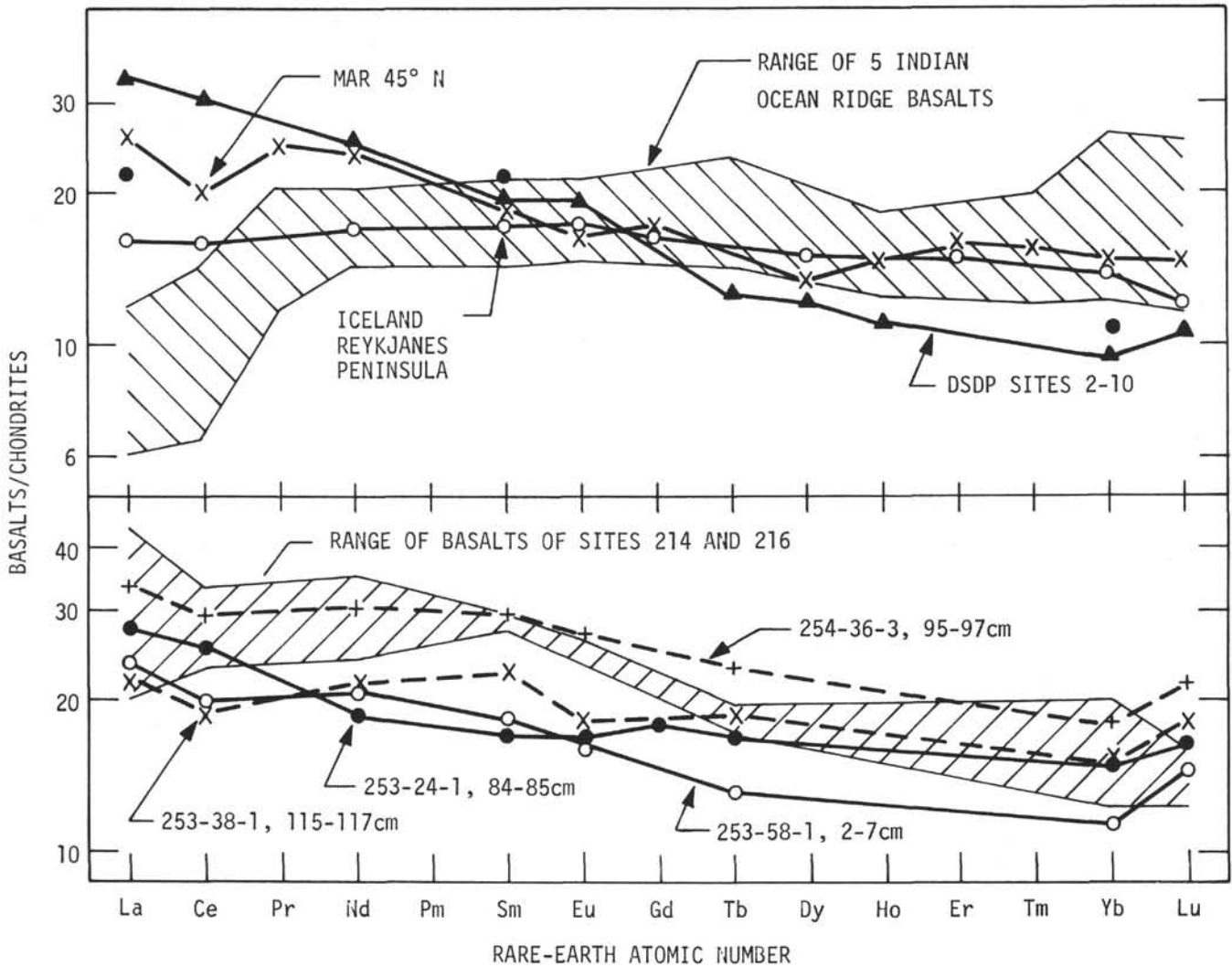
Figure 1. *Top – Comparison of REE abundances in tholeiitic basalts to a chondrite average. Basalts from MAR 45°N (Frey et al., 1968; Nichols and Islam, 1971), Reykjanes Peninsula, Iceland (Shimokawa and Masuda, 1972; for La, Sm, and Yb are averages from Schilling, 1973) and DSDP Site 2-10 (Frey et al., in press, a. b) are enriched in light REE relative to oceanic-ridge tholeiites. Bottom – Comparison of Ninetyeast Ridge basalts (DSDP Leg 22 Sites 214 and 216 and DSDP Leg 26 Sites 253 and 254) to a chondrite average.*

parameter clearly distinguishes these basalts from those at Ninetyeast Ridge, Sites 214 and 216 (Table 2).

Site 254

At Site 254, ~10 meters of basalt were recovered. Three types of basalt have been identified on the basis of petrography (Kempe, this volume, Chapter 14). Sample 254-36-3, 95-97 cm is an example of the stratigraphically highest basalt which is coarsely hyalophitic lava containing large (3 mm) feldspar and ophitic clusters of pyroxene and feldspar in an altered glassy matrix. Sample 254-38-1, 115-117 cm is from the lowest unit which consists of autobrecciated, very altered basalts. In this sample montmorillonite (determined by X-ray diffraction) is the dominant mineral. The major-element data indicate the presence of almost 8 wt. % H_2O (Table 2). Despite the abundance of montmorillonite, the

major-element abundances retain features characteristic of an igneous basalt rather than clay-alteration products. For example, although the K_2O abundance is the highest of the four samples studied, the K_2O/Na_2O ratio is <1, unlike clay minerals in marine basalts (Melson and Thompson, 1973). However, the low CaO content of this sample is certainly a result of alteration since CaO loss is characteristic of low-temperature alteration (Thompson, 1973; Melson and Thompson, 1973). Compared to the Site 253 basalts both of the Site 254 basalts have higher TiO_2, total iron, and lower Al_2O_3 abundances. Because these contrasts are not correlated with degree of alteration, they probably represent fundamental differences in the original magmas. These features (high TiO_2 and total iron, low Al_2O_3) are characteristic of the basalt from Sites 214 and 216. The Site 254 basalt appears to be intermediate

TABLE 2
Comparison of Major Element Abundances in Indian Ocean Basalts[a]

Element	Site 214[b]	Site 216[c]	Site 253[d] 24-1, 84-85 cm	Site 253[d] 58-1, 2-7 cm	Site 254[d] 36-3, 95-97 cm	Site 254[d] 38-1, 115-117 cm	Carlsberg Ridge	St. Paul Island	
SiO$_2$	48.10	49.50	52.20	46.60	47.20	49.20	49.70	48.40	48.70
Al$_2$O$_3$	14.90	13.50	18.30	16.70	14.80	14.30	16.40	12.60	18.40
FeO*[a]	14.60	13.80	6.92	10.50	12.70	11.50	10.10	16.70	12.20
MgO	6.45	6.57	7.87	14.80	8.10	11.10	7.70	5.17	4.32
CaO	9.04	8.79	9.67	8.38	9.94	7.20	10.94	8.18	10.1
Na$_2$O	2.75	2.57	3.05	1.49	2.63	2.11	3.05	3.02	2.92
K$_2$O	0.37	0.90	0.32	0.40	0.16	0.74	0.18	0.46	0.45
TiO$_2$	2.35	2.75	0.98	0.74	2.62	1.72	1.67	3.58	1.76
P$_2$O$_5$	0.19	0.22	0.35	0.09	0.28	0.18	0.08	0.82	0.35
FeO*/MgO	2.26	2.10	0.88	0.71	1.65	1.13	1.31	3.23	2.82
H$_2$O+CO$_2$	5.83	3.79	5.94	7.51	5.46	8.25	1.09	2.25	0.60

[a]Values in wt. % calculated on anhydrous basis.
[b]Average of 6 (Hekinian, in press).
[c]Average of 7 (Hekinian, in press).
[d]Kempe (this volume).
[e]Average of 6 (Cann, 1969).
[f]Olivine basalts from St. Paul Island (Girod et al., 1971).
[g]FeO* is all Fe calculated at FeO.

between the group at Sites 214 and 216 and that at Site 253. For example, basalt at Sites 214 and 216 have FeO*/MgO ratios >2 and Site 253 basalt have FeO*/MgO ratios <1, whereas Site 254 basalt have FeO*/MgO ratios <1 but >2. In a comparison of the Site 254 basalt, Sample 254-36-3, 95-97 cm has a higher FeO*/MgO ratio, higher REE, hafnium, and tantalum abundances, and a higher degree of light REE enrichment (Figure 1) than Sample 254-38-1, 115-117 cm. These major- and trace-element trends are expected of crystal/liquid separation processes and indicate that Sample 254-36-1, 95-97 cm is a more fractionated basalt. The higher chromium abundance in Sample 254-36-3, 95-97 cm is not consistent with this interpretation. As with the Site 253 basalt, the interpretation of igneous processes by use of chemical data from altered basalt is tenuous until the available unaltered glasses have been studied.

CONCLUSIONS

The studies of crystalline altered basalt from the Ninetyeast Ridge (Leg 22, Sites 214 and 216, Hekinian, 1973; 1974; Thompson et al., 1974; Leg 26, this volume) suggest that at least three types of igneous rock occur at the crest of the Ninetyeast Ridge:

1) Oceanic andesite (Site 214) which is readily recognized by an intermediate SiO₂ content (>55% SiO₂) and a higher alkali-metal content (Figure 2) when compared to basalt.

2) Iron-rich tholeiitic basalts (Sites 214, 216, and 254) which are readily recognized by their high FeO*/MgO ratios (Table 1 and Figure 2).
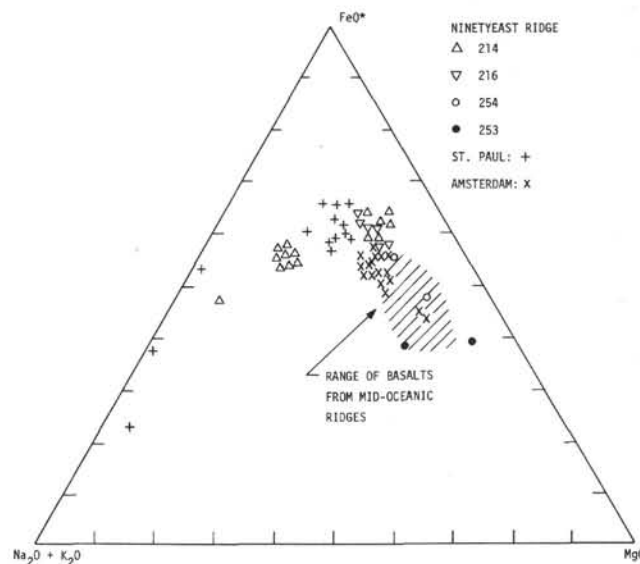

Figure 2. *FMA diagram (FeO* is total iron as FeO, units are wt. %) illustrating relative iron enrichment in Ninetyeast Ridge basalts and basalts from Amsterdam and St. Paul islands. The Na$_2$O + K$_2$O-rich rocks are the oceanic andesites at Site 214 and St. Paul Island. Range of mid-oceanic-ridge basalts from Hekinian (in press).*

3) Tholeiitic basalts (Site 253) similar in major-element abundances to oceanic-ridge tholeiites (Figure 2 and Table 2), but containing relatively high abundances of LIL elements such as light REE, zirconium, and

hafnium. These basalts are readily distinguished from LIL-element-depleted tholeiites by their REE distributions (Figure 1).

These three types of igneous rock are also known to exist in Iceland (Schilling, 1973; Jakobsson, 1972; Baldridge et al., 1973), the Faeroe Islands (Schilling, personal communication, and Noe-Nygaard and Rasmussen, 1968), 45°N (near the Azores) on the Mid-Atlantic Ridge (Muir et al., 1964; Aumento, 1969; Aumento and Loncarevic, 1969; Frey et al., 1968; and Nicholls and Islam, 1971) and in the Galapagos Islands (McBirney and Williams, 1969). The consistent appearance of these three rock types implies some similarity to the petrogenetic processes involved in forming oceanic islands and the aseismic Ninetyeast Ridge and a dissimilarity with the petrogenetic processes forming active spreading ridges away from oceanic islands. Hekinian (1973, 1974) has previously suggested that the type of volcanism encountered on aseismic ridges is similar to that of islands associated with ridges. Morgan (1971, 1972) has inferred that areas such as Iceland, Azores, and the Galapagos have formed as a result of a mantle plume.

Amsterdam and St. Paul islands, located southwest of the southern end of the Ninetyeast Ridge, may have a tectonic relationship to the Ninetyeast Ridge (Sclater et al., 1974). Morgan (1972) has also designated these islands as representing mantle-plume activity. The three igneous rock types described above are abundant on these islands (oceanic andesite and iron-rich tholeiites on St. Paul Island, Reinisch, 1909 and Girod et al., 1971; LIL-element-enriched tholeiite on Amsterdam, Gunn et al., 1971; see Figure 2). As at Iceland, the basalts on St. Paul Island have Sr^{87}/Sr^{86} ratios higher than those observed for oceanic-ridge basalts (>0.703 on Iceland, Hart et al., 1973; >0.704 on St. Paul Island, Girod et al., 1971). Based on the difference in strontium isotope ratios, Schilling (1973) has concluded that two different mantle magma sources are involved in generating Icelandic basalt and Reykjanes Ridge basalt. Schilling (1971) and Frey et al. (in press) have demonstrated the extreme difficulty of deriving the light-REE enrichment of Icelandic and Mid-Atlantic Ridge 45°N basalt from light-REE-depleted basalt characteristic of oceanic ridges. Girod et al. (1971) concluded that (1) the basalts of St. Paul Island separated from their mantle source at depths greater than oceanic-ridge basalt and (2) fractional crystallization was much more extensive at St. Paul Island (forming iron-rich basalt and oceanic andesites) than at oceanic ridges. Since sampling at four sites on the Ninetyeast Ridge has returned the rock types typical of oceanic islands like Iceland and Amsterdam-St. Paul, we suggest a similar model for the origin of the Ninetyeast Ridge. The geochemical data available for Ninetyeast Ridge rocks are those from altered rocks. Detailed testing of the model (separate magma source but more extensive fractional crystallization) requires future studies of unaltered glasses from cores from Sites 214, 216, 253, and 254.

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