15. MAGNETIC PROPERTIES AND INCOMPATIBLE ELEMENT GEOCHEMISTRY OF SOME IGNEOUS ROCKS FROM DEEP SEA DRILLING PROJECT LEG 64[1]

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INTRODUCTION

I received five unoriented samples of igneous rocks from four Sites of Leg 64 of the Deep Sea Drilling Project (DSDP). I have measured several magnetic properties, alkalis (K, Rb, and Cs), alkaline-earth (Ba and Sr) element concentrations, and $^{87}Sr/^{86}Sr$ ratios of these samples. This study reports the results.

MAGNETIC PROPERTIES

The experimental method is described by Verma and Banerjee (in press). All magnetic measurements were taken at the rock magnetism laboratory, University of Minnesota. Tables 1 and 2 present these results.

Natural remanent magnetization (NRM) intensity (J_n) varies from 0.374 to 10.6 $\times 10^{-3}$ emu•cm^{-3}. Corresponding anhysteritic remanent magnetization (ARM) intensity (J_a) ranges from 0.498 to 11.0 $\times 10^{-3}$ emu•cm^{-3}. Thus, J_n and J_a show somewhat similar ranges of variation. Dolerites from Site 478 possessing lower J_n values are more altered than the other samples. Viscous remanent magnetization (VRM) acquisition experiments conducted for about 30,000 min. show rather small but measurable VRM components. The VRM growth curves consist of two or three distinct segments of generally increasing slopes. Such growth curves have been obtained by other investigators in other sites (Lowrie, 1974; Kent and Lowrie, 1977; Verma and Banerjee, in press). Least-square fitting of the data permits their extrapolation for 10^5 min. (J_{vex}). The results show that these younger dolerites are considerably less viscous than the diabases (dolerites) from Leg 63 (Verma and Banerjee, in press). The gabbro from Hole 481A shows a VRM acquisition similar to the dolerites in the present study.

I tested the stabilities of the three magnetizations (NRM, ARM, and VRM) by stepwise alternating field (AF) demagnetization. Figure 1 shows the demagnetization curves. The ARM and NRM show similar demagnetization curves, especially for the latter three samples. But the VRM consistently shows much lower stability. Thus, a large part of the NRM in these rocks may be the original thermal remanent magnetization (TRM) component, and VRM may not be a serious problem for these samples.

The weak-field susceptibility (χ) of these samples ranges from 11 to 31 $\times 10^{-3}$ emu (cm^{-3} • Oe^{-1}). The Koenigsberger ratio (Q_n) ranges from 0.039 to 1.0 and is much lower than the average Q_n (=7.92) reported by Lowrie (1974) for a large number of DSDP basalts. But the present values are within the range of variation observed for the diabases of Leg 63 (Verma and Banerjee, in press). Thus, the induced magnetization component seems to be important for the dolerite and gabbro.

The saturation magnetization (M_s) shows a narrow range of 0.38 to 1.0 emu/g, but saturation remanent magnetization (M_r) varies from 0.031 to 0.21 emu/g and shows a greater variation than M_s. The M_r/M_s ratio implies multidomain (MD) grains for the dolerite in Sample 478-53-3, 13–16 cm and pseudosingle domain (PSD) grains for the other samples. Figure 2 shows a plot of M_r/M_s versus H_{cr}/H_c. Our samples fall near the field of diabases of Leg 63 (Verma and Banerjee, in press), and in fact they extend this field considerably but still seem to be distinguishable from the field of basalts of Leg 63.

The thermomagnetic properties are summarized in Table 2 and Figure 3 shows the thermomagnetic curves. The dolerites show reversible or slightly irreversible curves, whereas the gabbro shows an irreversible thermomagnetic curve. The Curie temperature (T_c) ranges from 147 to 508°C. We can infer, based on the low T_c of 147°C, that the dolerite in Sample 477A-2-2, 8–10 cm contains titanomagnetites with a very low degree of oxidation. The dolerites from Hole 478 show reversible (or slightly irreversible) M_s-versus-T curves and considerably higher T_c (~500°C). They seem to document earlier observations by Hall and Ryall (1977) and Verma and Banerjee (in press). Following Hall and Ryall (1977), we might attribute such high T_c to high-temperature initial cooling oxidation causing the original titanomagnetites to split into magnetite and ilmenite (magnetite causing the high T_c). The gabbro from Hole 481A (Sample 481A-15-4, 18–20 cm) also show a high T_c (~509°C; heating cycle), but upon cooling they show a concave curve with the lowest well-defined T_c (~186°C; cooling cycle). Upon reheating, the concave curve persists, but, curiously, the minimum T_c increases to ~215°C.

GEOCHEMISTRY

The experimental method is given in Verma (in press). All geochemical measurements (Table 3) were conducted at the Graduate School of Oceanography, University of Rhode Island. The average values of "normal" ridge basalts are also included for comparison. The concentration of trace elements varies considerably. Dolerites show altered mesostasis by clay

[1] Curray, J. R., Moore, D. G., et al., *Init. Repts. DSDP*, 64: Washington (U.S. Govt. Printing Office).

[2] Earlier publications of the author are under the name of Surendra Pal.

Table 1. Magnetization characteristics of Leg 64 igneous rocks.

Sample	Rock Type	J_n	J_a	J_v	J_{vex}	MDF_n	MDF_a	MDF_v	J_a/J_n	J_{vex}/J_n	MDF_a/MDF_n	MDF_v/MDF_n	χ	Q'_n	Q_n
474A-43-2, 75–77 cm	dolerite	10.6	10.9 [b] 11.1	1.96 (30,000)	2.4	56	36	7.6	1.0	0.2	0.6	0.1	31	0.34	0.76
477A-2-2, 8–10 cm	dolerite	9.27	3.81	0.495 (30,000)	0.65	91	40	8.7	0.4	0.1	0.4	0.1	20	0.46	1.0
478-41-1, 71–73 cm	dolerite	0.374[a]	0.498	0.023 (30,400)	0.032	234	245	48	1.3	0.1	1.0	0.2	11	0.034	0.076
478-53-3, 13–16 cm	dolerite	0.458	0.771	0.085 (30,000)	0.11	72	56	8.4	1.7	0.2	0.8	0.1	26	0.018	0.039
481A-15-4, 18–20 cm	gabbro	2.62[a]	2.15	0.345 (30,000)	0.47	336	339	46	0.8	0.2	1.0	0.1	16	0.16	0.36

Note: J_n is intensity of NRM in 10^{-3} emu•cm^{-3}; J_a is intensity of ARM in 10^{-3} emu•cm^{-3}; J_v is intensity of VRM acquired on demagnetized state in 10^{-3} emu•cm^{-3} (time of acquisition is given underneath in parenthesis, in min.); J_{vex} is intensity of VRM extrapolated for 10^5 min.; MDF_n is median destructive field for NRM in Oe; MDF_a is median destructive field for ARM in Oe; MDF_v is median destructive field for VRM in Oe; χ is weak field susceptibility in 10^{-3} emu•cm^{-3}; Q'_n is the modified Koenigsberger ratio, J_n/χ; Q_n is the Koenigsberger ratio, $J_n/0.45\ \chi$.

[a] This NRM intensity (J_n) has been corrected for a small antiparallel magnetic component.

[b] Duplicate measurements.

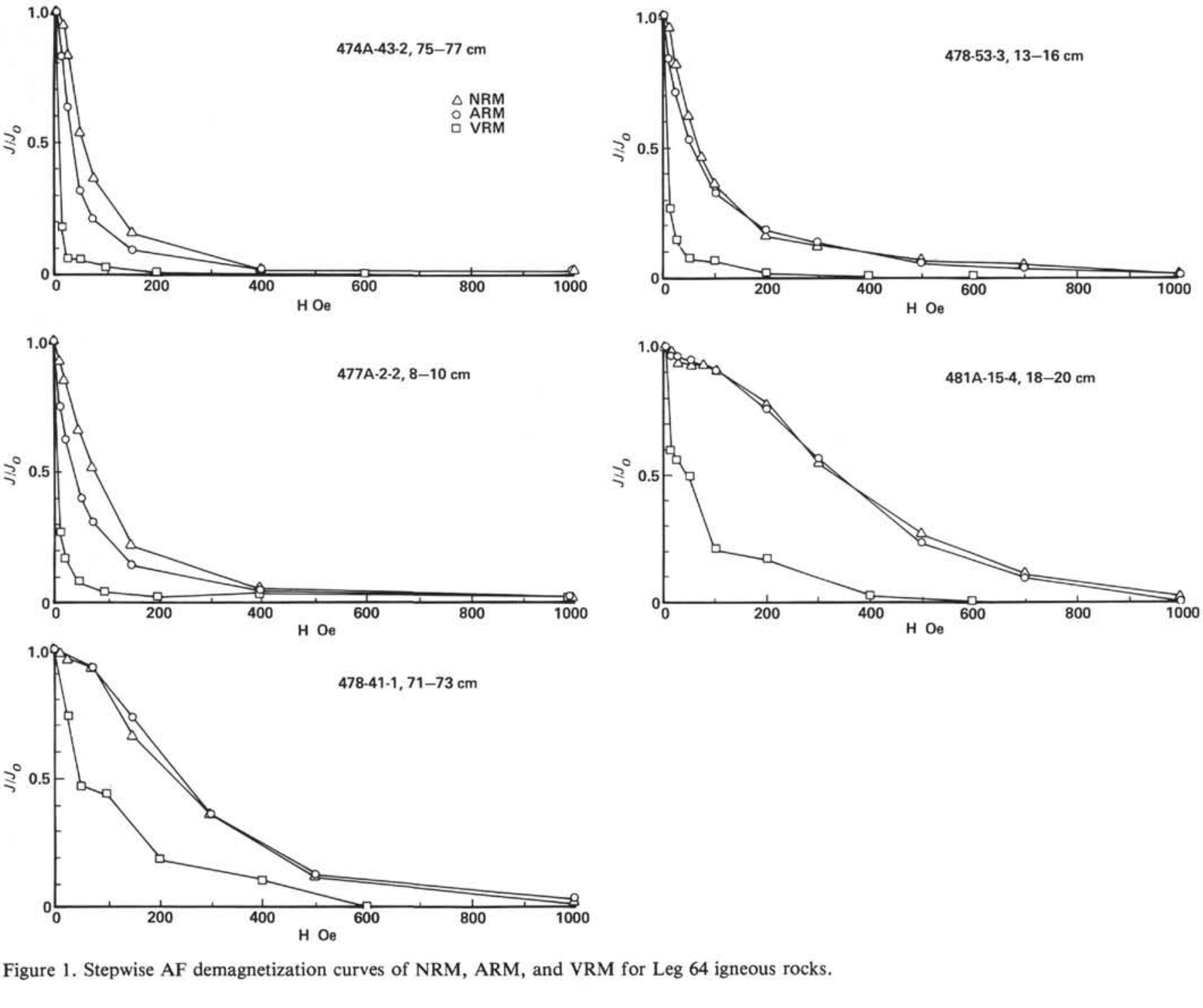

Figure 1. Stepwise AF demagnetization curves of NRM, ARM, and VRM for Leg 64 igneous rocks.

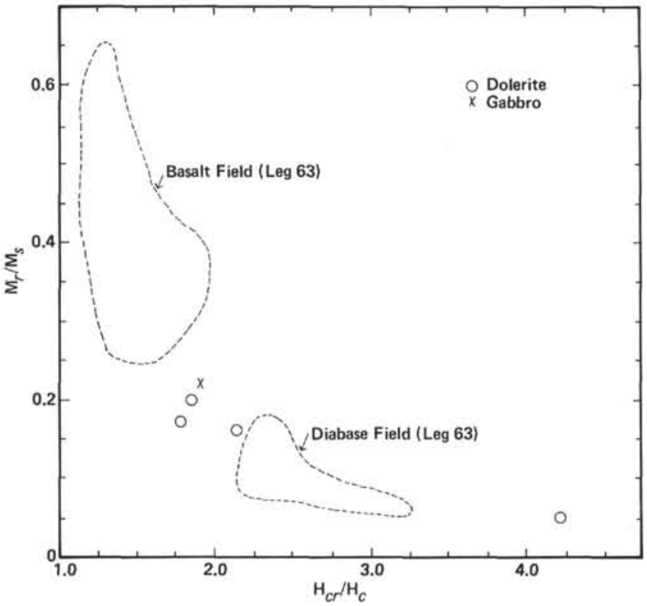

Figure 2. Plot of M_r/M_s against H_{cr}/H_c. (Basalt and diabase [dolerite] fields of Leg 63 rocks are also given for comparison.)

minerals and veins altered by zeolites. This is particularly significant for the dolerites from Hole 478. But the gabbro from Hole 481A seems to be less altered than the dolerites.

Potassium, rubidium, and cesium are highly susceptible to seawater alteration; Ba and Sr are affected to a lesser degree (Hart, 1969; Hart et al., 1974). Large changes in Ba concentrations have also been observed at other DSDP sites (Rice et al., 1979; Verma, in press), but differences in Sr concentrations (of almost a factor of two) are not caused entirely by alteration. There seem to be prealteration differences in the trace elements of these rocks, perhaps related in large part to fractional crystallization. Most element ratios are similar to those found in normal ridge basalts, although significant differences exist for K/Cs and Rb/Cs ratios—perhaps because of seawater alteration. But dredged rocks from the Gulf of California also show rather low K/Cs and Rb/Cs ratios (López et al., 1978; Verma, unpublished).

The whole-rock $^{87}Sr/^{86}Sr$ ratio varies from 0.70256 ± 5 to 0.70293 ± 3. As $^{87}Sr/^{86}Sr$ is also susceptible to seawater alteration, this ratio and the Sr content are also measured on the leached samples (residues from acid leaching) to determine whether any of this variation in $^{87}Sr/^{86}Sr$ is "primary." The method for leaching is described in Verma (in press).

The $^{87}Sr/^{86}Sr$ of dolerites from Holes 474A and 477A decreased slightly. The ratio on leached gabbro is significantly higher than the ratio for the two dolerites. The gabbro $^{87}Sr/^{86}Sr$ ratio is similar to the ratio for one dolerite from Hole 478 (Sample 478-41-1, 71–73 cm). This dolerite shows no decrease in $^{87}Sr/^{86}Sr$ ratio after leaching. The other dolerite from this hole (Sample 478-53-3, 13–16 cm) shows an even higher $^{87}Sr/^{86}Sr$ ratio in the leached sample (although the error in this measurement is rather large and could not be improved after repeating the run), implying perhaps that the leached sample is left with significantly more altered phases than the whole rock. After leaching, the dolerites from Hole 478 show a greater weight loss than the other three samples.

The $^{87}Sr/^{86}Sr$ ratio on leached samples varies from 0.70240 ± 4 to 0.70280 ± 6 (omitting the anomalously high ratio obtained for Sample 478-53-3, 13–16 cm). With only a few analyses at hand, it is not possible to attribute any spatial significance to these isotopic differences. But the variation in prealteration $^{87}Sr/^{86}Sr$ is within the range reported for normal ridge basalts (White and Schilling, 1978). Lopez et al. (1978) and Terrell et al. (1979) studied major and trace element geochemistry of rocks dredged from the Gulf of California and reached a similar conclusion: The samples are normal ridge basalts.

SUMMARY

The younger and less-altered dolerite and gabbro are less viscous than the older and more altered diabases from Leg 63. The rocks from Leg 64 show a wide range

Table 2. Hysteresis and thermomagnetic characteristics of Leg 64 igneous rocks.

Sample	M_s	M_r	M_r/M_s	H_c	H_{cr}	H_{cr}/H_c	χ_i	χ_p	χ_i/χ_p	T_c	Remarks
474A-43-2, 75–77 cm	1.0	0.17	0.17	48	79	1.6	3.6	1.3	277	262	h.c. Reversible
	0.98	0.18	0.18	51	80	1.6	3.4	1.3	262		c.c. Heated to 280°C at 5°C/min. (reheated to 560°C; still reversible)
477A-2-2, 8–10 cm	0.38	0.061	0.16	56	128	2.3	1.1	0.86	128	147	h.c. Reversible(?)
	(0.38)	(0.060)	(0.16)	(59)	(133)	(2.3)	(1.0)	(0.83)	(120)		(h.c.; reproducibility test)
	0.40	0.057	0.14	44	98	2.2	1.3	0.66	197		c.c. Heated to 530°C at 2.5°C/min.
478-41-1, 71–73 cm	0.61	0.12	0.20	196	341	1.7	0.63	1.3	48	508	h.c. Reversible(?)
	0.56	0.073	0.13	96	180	1.9	0.76	1.1	69		c.c. Heated to 550°C at 10°C/min.
478-53-3, 13–16 cm	0.62	0.031	0.05	39	170	4.4	0.78	1.1	71	491	h.c. Reversible(?)
	0.58	0.037	0.06	46	155	3.4	0.80	1.0	80		c.c. Heated to 550°C at 10°C/min.
481A-15-4, 18–20 cm	0.95	0.21	0.22	141	253	1.8	1.5	0.83	181	509	h.c. Irreversible
	0.72	0.12	0.17	72	183	2.5	1.7	0.90	189	186	c.c. Heated to 600°C at 5°C/min.; concave cooling curve; reheated: concave curve persists, but $T_c \equiv$ 215°C

Note: M_s is saturation magnetization in emu•g^{-1}; M_r is saturation remanent magnetization in emu•g^{-1}; H_c is coercive force in Oe; H_{cr} is remanent coercive force in Oe; χ_i is strong field initial susceptibility (M_r/H_c) in 10^{-3} emu•g^{-1} Oe^{-1}; χ_p is strong field susceptibility (mean slope of saturation curve) in 10^{-5} emu•g^{-1} Oe^{-1}; T_c is Curie temperature in °C; h.c. is heating cycle; c.c. is cooling cycle. The first row (h. c.) of hysteresis data pertains to the unheated (original) sample. The second row (c.c.) of data corresponds to the sample heated to obtain thermomagnetic curves. For Sample 477A-2-2, 8–10 cm, the first two rows of data pertain to unheated samples and show the reproducibility of measurements.

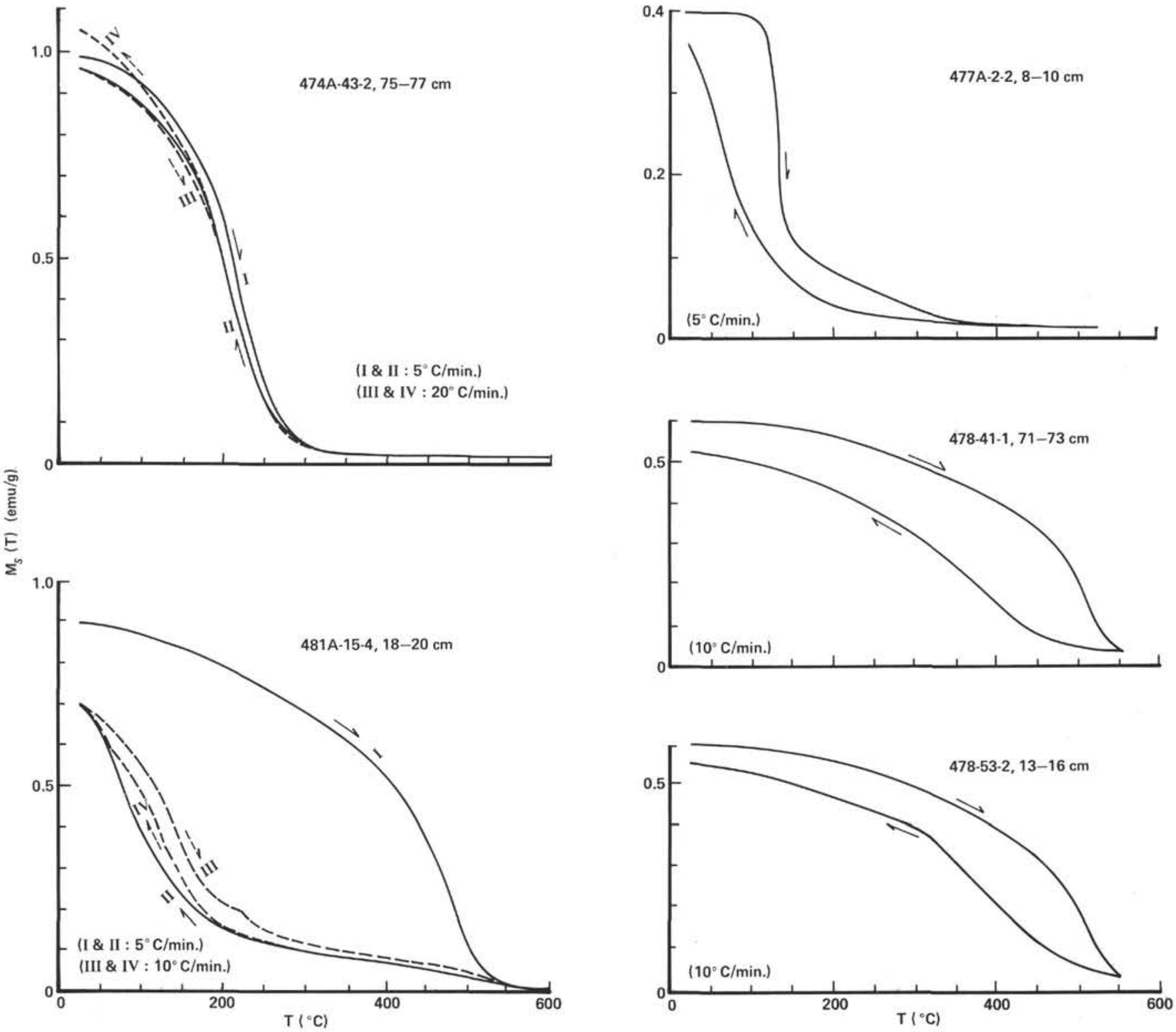

Figure 3. Thermomagnetic curves for Leg 64 igneous rocks. (Heating and cooling cycles are indicated by arrows; → and ←, respectively.) Heating and cooling rates are given in parentheses. Reheating and recooling curves are shown with dashed lines.

of Curie temperature (147–508°C), and their trace elements differ considerably. The $^{87}Sr/^{86}Sr$ ratio for leached samples shows a wide range (0.7024–0.7028), and these values seem to be primary (prealteration). But the ratios are comparable to those obtained for normal ridge basalts, suggesting that the source of the igneous rocks from the Gulf of California and the normal ridge basalts is similar.

ACKNOWLEDGMENTS

I am grateful to the shipboard scientists on DSDP Leg 64 for making the samples available and to S. K. Banerjee and J.-G. Schilling for experimental facilities and helpful comments. This work was supported partly by the University of Minnesota through V. Rama Murthy and partly by the National Science Foundation under grant OCE78-24690. I also thank D. V. Kent and S. S. Iyer for reading the manuscript.

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Table 3. Geochemical characteristics of samples of Leg 64 igneous rocks.

	474A-43-2, 75–77 cm Dolerite	477A-2-2, 8–10 cm Dolerite	478-41-1, 71–73 cm Dolerite	478-53-3, 13–16 cm Dolerite	481A-15-4, 18–20 cm Gabbro	"Normal" Ridge Basalts[e]	
K[a]	804 ± 4	1560 ± 10	1506 ± 9	3820 ± 25	3160 ± 20	1064	732
Rb[a]	1.20 ± 0.01	1.30 ± 0.01	1.95 ± 0.02	4.16 ± 0.04	5.09 ± 0.04	1.02	0.75
Cs[a]	0.17 ± 0.02	0.36 ± 0.05	0.33 ± 0.05	0.55 ± 0.06	0.15 ± 0.01	0.0131	0.009
Ba[a]	13.4 ± 0.1	21.4 ± 0.2	39.2 ± 0.4	64.7 ± 0.6	83.3 ± 0.5	12.2	6.2
Sr[a]	121.7 ± 0.3	234.4 ± 0.6	208.5 ± 0.5	222.0 ± 0.6	—	124	92
$^{87}Sr/^{86}Sr$[b]	0.70259 ± 5	0.70256 ± 5	0.70276 ± 4	0.70293 ± 3	—	0.70265	—
Rb/Sr[c]	0.00986 ± 9	0.00555 ± 4	0.00935 ± 10	0.0187 ± 2	—	0.0082	0.0082
K/Sr	6.61 ± 0.04	6.66 ± 0.05	7.22 ± 0.05	17.2 ± 0.1	—	8.58	7.96
K/Rb	670 ± 7	1200 ± 12	772 ± 9	918 ± 11	621 ± 6	1043	976
K/Cs	4700 ± 600	4300 ± 600	4600 ± 700	6900 ± 800	21100 ± 1400	81200	81300
K/Ba	60.0 ± 0.5	72.9 ± 0.8	38.4 ± 0.5	59.0 ± 0.7	37.9 ± 0.3	87	118
Sr/Ba	9.1 ± 0.1	11.0 ± 0.1	5.3 ± 0.1	3.4 ± 0.1	—	10.2	14.8
Rb/Cs	7.1 ± 0.8	3.6 ± 0.5	5.9 ± 0.8	7.6 ± 0.8	34 ± 2	78	83
Weight loss on leaching (%)	32.5	32.7	37.7	38.3	29.4		
Sr[a] (leached sample)	40.8 ± 0.2	77.5 ± 0.3	59.3 ± 0.2	65.2 ± 0.3	89.8 ± 0.4		
$^{87}Sr/^{86}Sr$[b] (leached sample)	0.70240 ± 4	0.70252 ± 5	0.70280 ± 6	0.70341 ± 14	0.70279 ± 7		
Sr *l.s.*/Sr w.r.[d]	0.34	0.33	0.28	0.29	—		

[a] All concentrations are in $\mu g \cdot g^{-1}$ (ppm).
[b] The $^{87}Sr/^{86}Sr$ ratios are normalized to $^{86}Sr/^{88}Sr = 0.11940$ and adjusted to SRM 987 $^{87}Sr/^{86}Sr$ ratio of 0.71021. The measured ratio for the SRM 987 standard is $0.71028_2 \pm 4_2$ (2σ, $n = 19$) during the period of about one year. In this period, the Eimer and Amend $SrCO_3$ standard gave a value of $0.708071_1 \pm 3_4$ (2σ, $n = 9$). The errors reported on individual $^{87}Sr/^{86}Sr$ ratios are two times the standard error of the mean ($2\sigma_\epsilon$) multiplied by 10^5.
[c] The quoted errors are the analytical errors multiplied by 10^5.
[d] Sr *l.s.*/Sr w.r. = Sr concentration in leached sample/Sr concentration in whole rock.
[e] First column: Average MORB values for trace elements and $^{87}Sr/^{86}Sr$ ratio are Hart's (1976) as cited in Staudigel et al. (1979). The element ratios are calculated from the trace element data. Second column: average of all normal ridge basalts given by White and Schilling (1978). The ratios are calculated from the trace element data.