Reports

Lherzolite, Anorthosite, Gabbro, and Basalt Dredged from the Mid-Indian Ocean Ridge

Abstract. *The Central Indian Ridge is mantled with flows of low-potassium basalt of uniform composition. Gabbro, anorthosite, and garnet-bearing lherzolite are exposed in cross fractures, and lherzolite is the bedrock at the center of the ridge. The lherzolites are upper-mantle rock exposed by faulting.*

In August and September 1968, R.V. *Argo* carried out a geological-geophysical investigation of a 2000-km segment of the seismically active Mid-Indian Ocean Ridge system (Fig. 1). Our study included bathymetric, magnetic, and seismic reflection (by air-gun) measurements and hard-rock sampling by dredging. Sites for dredging rock outcrops were selected on the basis of concurrent topographic, reflection, and magnetic exploration, and earlier topographic–magnetic–heat flow data collected during the International Indian Ocean Expedition 1960–65.

The Central Indian Ridge trends nearly north-south between the equator and 20°S. Another topographic trend, northeast to southwest, is displayed by numerous elongated steep-sided deeps or fractures that intersect and cut through the ridge (*1*). Figure 1, with contours at 2000-m intervals, was abstracted from very much more detailed charts. These show unequivocally that the northeast-trending deeps are real and that, between the major deeps, segments of the seismically active ridge trend northwest to north-northwest.

Segments of the Central Indian Ridge display magnetic-anomaly patterns similar to those of other mid-ocean ridges, but no detailed anomaly correlations have been made. Shallow focus earthquakes are common along this part of the ridge, but assignment of epicenters to ridge crest or cross fracture has not been possible. Measurements of heat flow vary considerably over short distances (*2*). Most of the high values are near the ridge crest but may represent localized volcanism, and some low values near the crest may lie in cross fractures.

Characteristically the northeast-trending deeps consist of troughs as much as 1000 m deeper than the regional level. However, in the main fractures local relief is much greater, up to 3500 to 4000 m, and bordering summits reach within 500 to 2000 m of the sea surface (Fig. 2A). Where the fracture intersects the mid-ocean ridge crest, the floor contains very little detectable sediment; our rocks were dredged in such areas. Farther from the crest are sediments, slightly contorted to horizontally bedded within the deeps. Several of the cross fractures have been traced or extended westward to the Mascarene Plateau where they appear to offset that aseismic structure (*1*). Though the cross fractures may mark transform fault zones segmenting the active Central Indian Ridge, the apparent offset of the aseismic Mascarene Plateau and the ridge crest initially indictates that they have also functioned as transcurrent faults (*1*). The cross fractures show little magnetic relief, which suggests that they are major fault zones in which brecciation or alteration has expunged magnetic patterns.

South of 20°S, the Southeast Indian Ridge exhibits the same geophysical characteristics as the Central Indian Ridge, except that heat flow is generally higher. Bathymetric exploration has been too scant to delineate major cross fractures, but magnetic profiles suggest less complexity here than is found farther north (*3*).

The only seismic refraction measure-

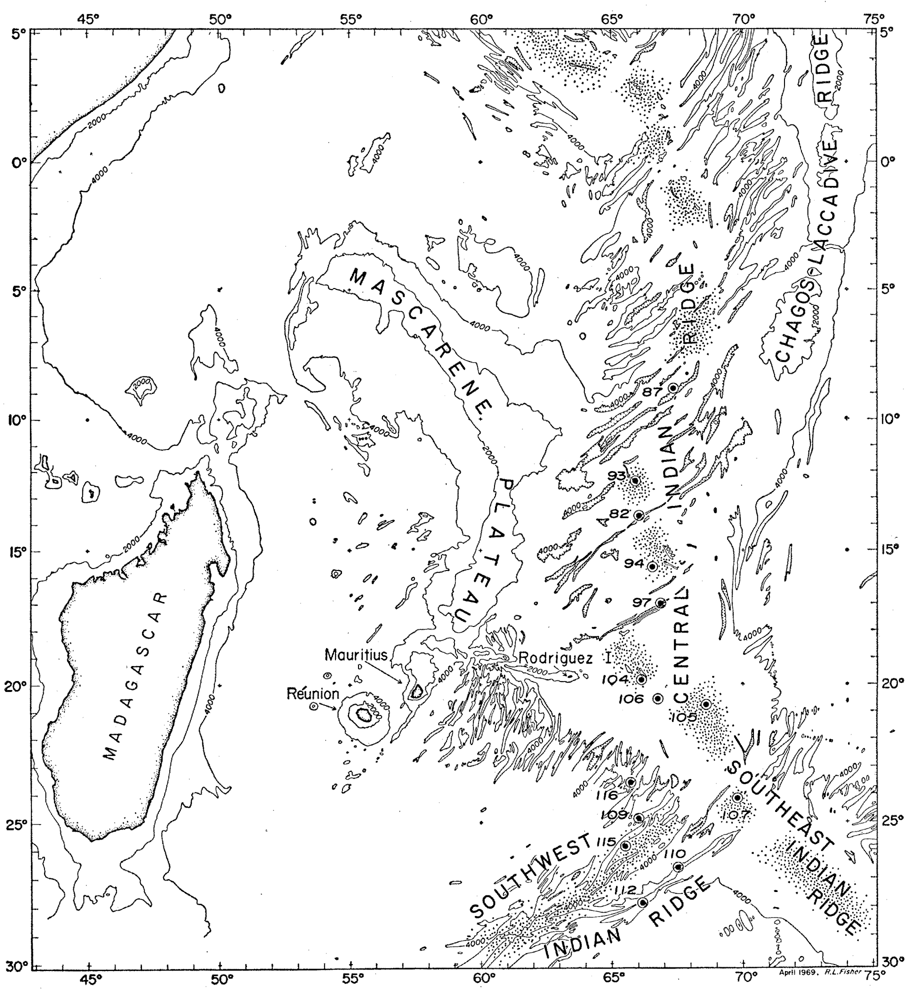

Fig. 1. Bathymetric map, at 2000-m contour interval, for part of the western Indian Ocean. The stippled zones mark the generalized ridge crests from topographic and magnetic data. Igneous rocks were dredged in 1968 at the 14 numbered stations.

ments of crustal structure on the Central Indian Ridge lie on an east-west line near 6°S. Francis and Shor report normal oceanic sections with crustal thickness of 4 to 7 km and subcrustal velocities of 8.0 and 8.4 km/sec within 150 to 200 km of the crest of the ridge (*4*). At the crest, sonobuoy refraction work indicates a layer of undetermined thickness with a velocity of 7 to 7.5 km/sec lying beneath 2 to 3 km of volcanics (?) with a velocity of 4.5 to 5 km/sec (*5*). Additional Russian work in 1967 in the "rift zone" indicates a rock complex with velocities of 9 to 10 km/sec about 15 km below sea level. At 5° to 6°S the ridge is intersected by several northeast-trending deeps (*1*). Therefore these seismic crustal data probably represent measurements in such cross fractures.

The Southwest Indian Ridge shows frequent shallow earthquake activity, but neither the topographic highs nor the seismicity extends northeast beyond the intersection with the Central Indian Ridge near 25°S, 70°E (*6*). Northeast-trending lineations predominate in the sector we have mapped, and the major deep trending southwest from 25°30′S, 70°E may be either the central rifted zone of the Southwest Indian Ridge or part of the transverse fracture system as developed north of 20°S. The northeast portion of the Southwest Indian Ridge differs in magnetic pattern from the usual mid-ocean ridge; our work confirms that a central anomaly is absent and demonstrates that the usual flank anomalies are not developed. This may indicate that the Southwest Indian Ridge is either not spreading or spreading very slowly (*3, 7*). Seismic refraction of this portion of the Southwest Indian Ridge is being studied at three stations (*5, 8*). Crustal structure is very similar to that found near 6°S, with a layer having a velocity from 7.2 to 7.4 km/sec only in the central zone.

Most of the rocks recovered from the Carlsberg Ridge, the Central Indian Ridge, and the Southwest Indian Ridge have been fresh to variously altered low-potassium basalts (*9*). The ages of the low-potassium basalts obtained by dredging have not been determined.

Russian work was carried out near 5° to 6°S in 1964 and near 6° to 8°N and 5° to 6°S in 1967. In addition, serpentinites, harzburgites, and dunites from the Southwest Indian Ridge were reported (*10*). Hekinian (*9*) described several fragments of serpentinite gleaned from sediment cores 180 km southwest of Rodriguez.

Table 1. Rock types dredged from the Central and Southwest Indian ridges. B, basalt; D, diabase; G, gabbro; A, anorthosite; L, lherzolite (peridotite); H, harzburgite (peridotite); and S, serpentinite.

Station	Position (°S) (°E)	Depth (meters)	Setting	Rock types
82	13°39′, 66°06′	3900–3600	Near base of north scarp in cross fracture	G, H, S
87	9°00′, 67°17′	2050–1935	Summit of north lip adjacent to Vema Trench	B, D
	9°03′, 67°21′	6060–5865	Near base of north wall of Vema Trench	S
93	12°25′, 65°56′ to 12°24′, 65°54′	3540–3880–3730	At base of scarp, central portion of rifted zone	B, L, S
94	15°33′, 66°45′ to 15°33′, 66°43′	2955–2815	In rifted zone, 40 to 50 km west of ridge crest	B
97	17°03′, 66°52′ to 17°05′, 66°49′	4880–4240	Lowermost flank and bottom of cross fracture northeast of Rodriguez Ridge	D, G, A, L, H, S
104	19°50′, 66°03′ to 19°50′, 66°02′	2810–2800	Central portion of rifted zone	B
105	20°45′, 68°38′ to 20°46′, 68°37′	2880–3130–3075	Eastern flank	B
106	20°34′, 66°45′	3560–3900–3570	Central portion of rifted zone at or near intersection with major but ill-defined fracture zone	B
107	24°21′, 69°50′	2925–2915	New flow filling central portion of rifted zone	B
109	24°52′, 65°59′ to 24°54′, 65°59′	4650–4530	In lineated topography northwest of Southwest Indian Ridge	B
110	26°37′, 67°32′ to 26°37′, 67°31′	5100–4990	In bottom of southwest-trending fracture zone on southeast flank(?) of Southwest Indian Ridge (possibly central zone)	B
112	27°50′, 66°12′	3350–3310	Near base of small peak adjacent (on south) to this fracture zone	B
115	25°50′, 65°31′	4480–4420	In valley or swale on north flank of Southwest Indian Ridge	B
116	23°30′, 65°43′ to 23°31′, 65°42′	3990–4090	Abyssal hills northwest of flank of Southwest Indian Ridge	B

Table 2. Percent of K_2O, Na_2O, and TiO_2 by weight and petrographic descriptions of basalts dredged from the Central and Southwest Indian ridges, Circe expedition, 1968.

Sample	K_2O (%)	Na_2O (%)	TiO_2 (%)	Petrographic description
87-2A	0.12	2.70	1.21	Porphyritic olivine basalt. Olivine phenocrysts resorbed and partially serpentinized
87-2A1	0.13	2.73	1.18	Same
93-1	0.18	2.76	1.06	Fresh porphyritic olivine basalt flows. Groundmass glassy. Vesicles: round
93-1A	0.10	2.81	1.09	Same
93-4	0.20	2.80	1.10	Same
94-2	0.24	2.51	1.29	Fine-grained olivine basalt. Crystallite groundmass, in part palagonitic. Vesicles: round
94-2A	0.22	2.62	1.34	Same
97-1	0.22	4.18	2.18	Albitized diabase dike in altered gabbro (Table 1).
104	0.14	2.34	1.08	Fresh porphyritic olivine basalt. Groundmass glassy. Vesicles: round and irregular
104-A	0.16	2.46	1.10	Same
104-4A	0.17	2.35	1.10	Same
105	0.15	2.40	1.25	Porphyritic basalt. Groundmass glassy. Vesicles: round, partially filled with palagonite
105-A	0.17	2.46	1.23	Same
106-A	0.11	2.28	1.09	Fine-grained, porphyritic olivine basalt. Groundmass of crystallites. Vesicles: round
107	0.14	2.68	0.97	Fresh porphyritic olivine basalt. Groundmass glassy. Vesicles: irregular
107-A	0.16	2.73	1.01	Same
109	0.20	2.52	0.97	Fine-grained olivine basalt. Vesicles: round to irregular
116	0.20	2.55	1.04	Fine-grained plagioclase, augite basalt. Vesicles: round
110	0.36	3.80	1.68	Fine-grained olivine basalt. Vesicles: round to irregular. Palagonitic
112	0.41	3.94	1.71	Porphyritic olivine basalt. Groundmass of crystallites. Vesicles: round to irregular
115-1	0.31	3.30	1.22	Fine-grained porphyritic basalt (in part palagonitic). Plagioclase phenocrysts. Vesicles: round

In 1968 we dredged rocks from the following environments: (i) the central portion of the "rifted" zone commonly associated with the "single" magnetic anomaly, (ii) the transverse fracture zones, (iii) the flank areas of the Central Indian Ridge, and (iv) the probably older (?) or anomalous Southwest Indian Ridge (Table 1). Fourteen dredge hauls were successful at the stations indicated in Fig. 1.

Basaltic rock is the predominant rock type exposed within the rifted zone and was recovered in 12 dredge hauls. Basalt flows are common along the Central Indian Ridge. Most flows are predominantly low-potassium olivine basalts (oceanic tholeiite). Most of the basalts collected are fresh and were obtained from pillowed flows. However, textural features of a few samples suggest that the rocks are from sills or dikes, and one sample was recovered as a dike in a huge block of gabbro. A new flow filling a valley is shown on an airgun record in Fig. 2B.

In general, the basalts show a chilled, glassy surface. Features of the lavas, even at great depth, suggest extreme fluidity. Many samples contain two or three thin layers of glassy flow superimposed one upon the other. The forms recovered indicate that as the lavas erupted, cooled, and cracked, the still-liquid portions breached the thin crust to form a succession of glassy layers. Cavernous pieces of basalt from which the fluid lava was evacuated appear in many samples. Where the lavas were extruded through abyssal muds, the rock was chilled in exotic curled, rolled, folded, and bulbous forms. Some samples of basalt recovered from the ridge crest have fragments of red mud baked onto and partially engulfed by lava (Fig. 3A).

All of the basalt flows are porphyritic and contain phenocrysts of plagioclase (labradorite to bytownite) and olivine set in a glassy groundmass (tachylite). All the samples, even those recovered at depths of 4000 to 5000 m, contain some vesicles. Most of the vesicles are round, but some are elongate or irregular.

At the dredge sites along the Central Indian Ridge, over a distance of nearly 2000 km, the basalts are mineralogically similar and exceedingly uniform in chemical composition. The partial chemical analyses (Table 2) and two complete chemical analyses (Table 3) of basalts widely separated along the Central Indian Ridge indicate the relative uniformity in composition of the fresh, glassy, basaltic flows characteristic of this ridge and are similar to those of basalts from all of the oceans (*11*). Samples 109 and 116 (Table 1), dredged near the intersection of the Central and Southwest Indian ridges, are "normal" low-potassium basalts.

Several features of the basalts dredged from the Central Indian Ridge are noteworthy: (i) all of the flows are porphyritic and contain plagioclase and olivine as phenocrysts; (ii) all contain a few round vesicles which indicate the presence of gas (H_2O, CO_2, SO_2, F, Cl ?); (iii) the Na_2O and K_2O contents are low, 2.6 and 0.20 percent by weight, respectively; (iv) the fresh basalts are reduced, with $Fe_2O_3/FeO \cong 0.13$ and total Fe content, as Fe_2O_3, is about 9 percent by weight; (v) silica content is relatively uniform but varies from about 49.5 to almost 52 depending upon the number of phenocrysts in the sample analyzed, Al_2O_3 varies from 16 to 18 percent, and CaO is 11.5 percent by weight; and (vi) the freshest basalts are essentially water free.

Gabbros, anorthosite, peridotites,

Table 3. Chemical compositions of lherzolites, gabbros, anorthosite, and basalts from the Central Indian Ridge, Indian Ocean.

Component	Lherzolite			Gabbro				Anorthosite	Basalt	
	97-W	93-3	93-3 (water-free)	82-1	97-B	97-D	97-S	97-X	93-1	107
				*Weight percent**						
SiO_2	44.15	38.29	43.87	50.45	50.50			56.43	51.39	49.56
TiO_2	.03	.01	.01	.30	.48			.18	1.10	.97
Al_2O_3	3.59	2.74	3.14	18.03	15.18			26.10	16.33	17.60
Fe_2O_3	1.60	4.65	5.33	1.27	2.86			.51	.94	.87
FeO	5.23	2.25	2.58	4.68	4.73			.63	7.09	7.20
MnO	.10	.06	.07	.11	.09			.01	.19	.15
MgO	34.84	35.32	40.45	8.11	9.44			.92	7.93	8.65
CaO	5.50	3.75	4.30	11.60	13.60			8.34	11.44	11.68
Na_2O	.19	.20	.23	2.95	2.24	2.02	2.40	6.36	2.76	2.68
K_2O	< .02	< .02	< .02	.07	.10	.06	.08	.07	.18	.14
H_2O^+	3.02	10.27		1.83	.75			.23	.26	.14
H_2O^-	.51	1.19		.31	.16			.01	.03	.01
P_2O_5				.01	.04			tr	.10	.14
Total	98.78	98.75		99.72	100.17			99.79	99.74	99.79
				Parts per million†						
B		69								
Ba	3	2		10	12	9	12	37	29	20
Co	90	99		30	34	38	33	< 2	27	26
Cr	6400	4800		100	290	980	290	370	350	300
Cu	2	25		19	45	91	29	4	62	63
Ga	< 5	< 5		30	11	10	11	13	12	14
Mn	850	580		1600	1030	910	1100	150	1300	950
Ni	3500	3300		100	210	350	190	34	130	130
Sc	23	12		50	48	54	57	15	49	39
Sr	72	260		120	130	120	140	320	130	240
Ti	190	76		1900	2300	2000	3400	970	6600	4800
V	88	51		160	120	130	130	39	180	120
Y	< 20	< 20		< 20	< 20	< 20	~ 20	< 20	39	33
Yb	< 2	< 2		2	< 2	< 2	2	< 2	4	3
Zr	< 20	< 20		< 30	21	20	26	~ 20	84	61

* Analyst, C. G. Engel. † Analyst, E. Bingham (California Institute of Technology) except 82-1 which was analyzed by A. L. Sutton (U. S. Geological Survey, Denver, Colorado). Ag < 1, Be < 10, Cd < 200, La < 100, Mo < 10, Pb < 50, Sn < 50.

serpentinites, and talc were recovered from the northern portion of the Central Indian Ridge. Here the ridge is cut by huge northeast-trending cross fractures that provide windows into the deeper oceanic crust or even the upper mantle.

Coarse-grained, massive gabbros were dredged from the deep flanks or bottom of cross fractures at 13°39′S, 66°06′E and 17°04′S, 66°50′E. At Station 97, at depths of 4880 to 4240 m within the cross fracture (Fig. 2A), the collection consists of approximately 1200 kg of gabbro and peridotite accompanied by minor anorthosite. The largest sample, a block of gabbro measuring 24 by 76 by 56 cm, is deuterically altered and is cut by a dike of albitized augite diabase 15 cm across (Table 2, sample 97-1). The haul at Station 97 also includes abundant fresh gabbro which is coarse-grained and equigranular with constituent grains of plagioclase (bytownite), clinopyroxene, and olivine. These minerals average about 7 mm in length.

Gabbro sample 97-B (Table 3) is slightly altered and contains chlorite and two amphiboles. One amphibole is reddish-brown, and the other is pale green and occurs as mantles around clinopyroxene. Gabbro sample 97-D (Table 3) is perhaps the least altered; only the olivine shows some alteration to serpentine and chlorite. Sample 97-D also contains the lowest amounts (percent by weight) of sodium and potassium (Na_2O, 2.02; K_2O, 0.06). Analysis of other samples of fresh gabbro indicate similar low amounts of potassium as oxide ranging from 0.06 to 0.10 percent. In contrast, most of the basalts contain about twice the potassium found in the gabbros and average about 0.20 percent K_2O. The average gabbro at Station 97 contains (percent by volume): plagioclase 63, clinopyroxene (augite) 25, olivine 5, opaque minerals 2, and chlorite and hornblende about 4. At Station 97 some of the gabbro is granulated to a coarse mortar gneiss, and other samples are slightly metamorphosed and contain clots and lenses of hornblende. The textural relations of the lenses of amphibole to primary pyroxenes, olivine, and plagioclase suggest that they are products of a higher grade "hydrothermal" metamorphism than indicated by the presence of chlorite. Sample 97-S contains minor clots of fresh hornblende. The sodium content of this rock is slightly higher than that of the unaltered gabbros. The most altered samples of gabbroic rocks in dredge haul 97 consist of fibrous talc and minor chlorite with only relict grains of augite.

Gabbro was also dredged from Station 82 (13°39′S, 66°06′E), 400 km north of Station 97 (Fig. 1). This station is on the northwest flank of another cross fracture, at a depth of 3900 to 3600 m. The gabbros recovered contain plagioclase and two pyroxenes, but not olivine. Hypersthene is partly altered to antigorite, but augite is fresh. Gabbro sample 82-1 (Table 3) contains the following minerals (in percent by volume): plagioclase 67.4, augite 16.0, hypersthene 16.6, chlorite and minor opaque minerals. Several samples of gabbro are altered to talc rock, and a few samples contain tremolite.

The gabbros dredged from deep in the cross fractures probably represent the intrusive (hypabyssal) equivalent of the tholeiitic basaltic flows sampled on the ridge surface. In general, the gabbros contain less Fe, Ti, K, Ba, Y, Yb, and Zr than the associated basalts (Table 3). Two possible explanations for the low concentration of these elements in the gabbros can be offered: (i) slow cooling may have permitted the escape of some of these elements in fluids, or (ii) the gabbro may be differentiated layers of large stratiform sheets. A sample of "porphyritic dolerite" dredged at a depth of about 2700 m from a fault scarp on the Mid-Atlantic Ridge is similarly low in these elements. Melson and others (*12*) note that this rock from the Mid-Atlantic Ridge is unusually coarse grained, and they speculate that such dolerites are fragments of hypabyssal intrusives or, perhaps, the central portions of thick flows.

The most abundant coarse-grained mafic rocks exposed in the cross fractures are gabbros, and without the field relations it is not possible to speculate about the extent or the degree of differentiation of these intrusive bodies. However, the haul at Station 97 also yielded pieces of anorthosite which consist primarily of plagioclase and minor reddish-brown hornblende.

The anorthosite is a light blue-gray granulated rock with coarse-grained labradorite partially resorbed and replaced by white or light-gray oligoclase. The bulk chemical composition of the anorthosite is similar to the plagioclase feldspar andesine (Table 3, sample 97-X). A modal analysis of 1000 counts indicates the anorthosite contains (in percent by volume): plagioclase, 94.7; reddish-brown hornblende, 5.2; and opaque minerals, less than 0.1. The largest blocks of anorthosite and gabbro are

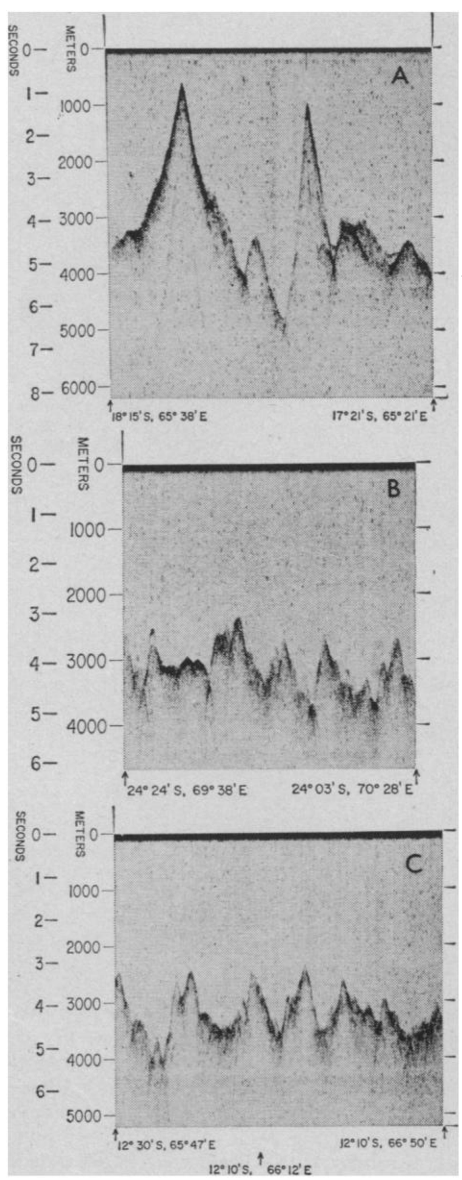

Fig. 2 (left). Airgun records, each with vertical exaggeration about ×20. (A) Profile across a northeast-trending cross fracture. Station 97 lies in the bottom of this deep. Length of section is about 105 km. About 200 to 300 m of gently dipping sediments lie in basins on the right (north) end of the profile, but no sediments were detected in the deep cleft. (B) Crest and upper eastern flank of the Southeast Indian Ridge. Length of section is about 95 km. The flattish area (dark) near the left edge is a fresh flow at the ridge crest from which very fresh basalts were dredged (Station 107; Fig. 3A). (C) Crest and upper eastern flank of the Central Indian Ridge. Length of section is about 130 km. Lherzolite is faulted into the deep valley of the central part of the ridge, at the left side of the photograph.

not layered or lineated. The anorthosite may occur (i) as late-stage dikes derived from cooling gabbroic magma, (ii) as layers of a stratiform sheet, or (iii) as an anorthosite massif. Because we do not know the field relations, we cannot establish how representative the haul at Station 97, wholly within the deepest portion of this cross fracture, is of the proportions of bedrock in this segment of the crust. To our knowledge, this is the first anorthosite recovered within the ocean basins.

The anorthosite could be as young as the associated Tertiary-Quaternary volcanics or as old as the Precambrian. Anorthosite or gabbroic anorthosite massifs on the continents range in age from 1.1 to 1.7×10^9 years (*13*). Emplacement of a coarse-grained gabbro-anorthosite complex in the crust of the Indian Ocean requires a steep thermal gradient, deep burial, or both. We could speculate that the overburden was a continent—now drifted away—and that we have dredged the open scar—the mantle.

The most intriguing sample of ultramafic rock was recovered from the central active portion of the Central Indian Ridge. At Station 93 we dredged a large quantity of very fresh, glassy basalt and much coarse-grained peridotite which is lherzolite (Table 3 and Figs. 2C and 3B).

Garnet-bearing lherzolite was dredged from the bottom of the huge cross fracture at Station 97 (17°06'S, 66°50'E; depth, 4880 to 4240 m). Thus, lherzolite is the "basement" rock exposed in the deep cross fractures and through which basalt is extruded on the central, active portion of the ridge.

The lherzolites are very coarse-grained rocks with fresh augen-like masses of forsteritic olivine enstatite, clinoenstatite (?), diopside (diallage), and minor grossular garnet enveloped in veinlets of serpentine and spinels. The primary mineral assemblage before serpentinization was olivine 50, enstatite 26, diopside 23, and spinels about 1 percent by volume. The garnet comprises about 1 to 2 percent of the rock and is pale pink to beige and irregular in form. S. R. Hart has identified the garnet as grossular or hydrogrossular with an Al_2O_3 content of 24 percent by weight and CaO about 37 percent. It is not clear if the garnet is a primary phase or a secondary mineral possibly formed during the pervasive serpentinization and shearing. Large pieces of lherzolite show a coarse lenticular to rodlike texture. This structure is most certainly secondary and related to movement along fracture zones. Chemically and mineralogically our lherzolites are similar to the "spinel peridotites" exposed on St. Paul's Rocks in the Atlantic (*14*) although our lherzolites are less sheared.

The lherzolite sample 97-W (Table 3) contains much less serpentine than does sample 93, but when 93 is calculated waterfree, it is almost identical in composition to 97-W. In both examples magnesium-rich clinopyroxene is fresh though both olivine and enstatite are more readily altered to serpentine. Both lherzolites approach in composition an "ideal" peridotite (and a "pyrolite") often postulated as the major rocks in the mantle under the oceans (*15*).

The association of coarse-grained gabbro, anorthosite, and the lherzolite dredged from the base of the deep cross fractures suggests several possible genetic and structural relations: (i) The gabbros are the intrusive equivalents of the eruptive basalts and occur as thick sills, dikes, or batholiths in the oceanic (basaltic) crust. The anorthosites are minor differentiates of the gabbroic magma. (ii) The anorthosites are fragments of large anorthositic to gabbroic massifs of unknown age, possibly older than 1000 million years. (iii) The gabbro and anorthosite represent the upper, less-dense portion of stratiform sheets, and the associated lherzolites are the heavy accumulate members. All of the

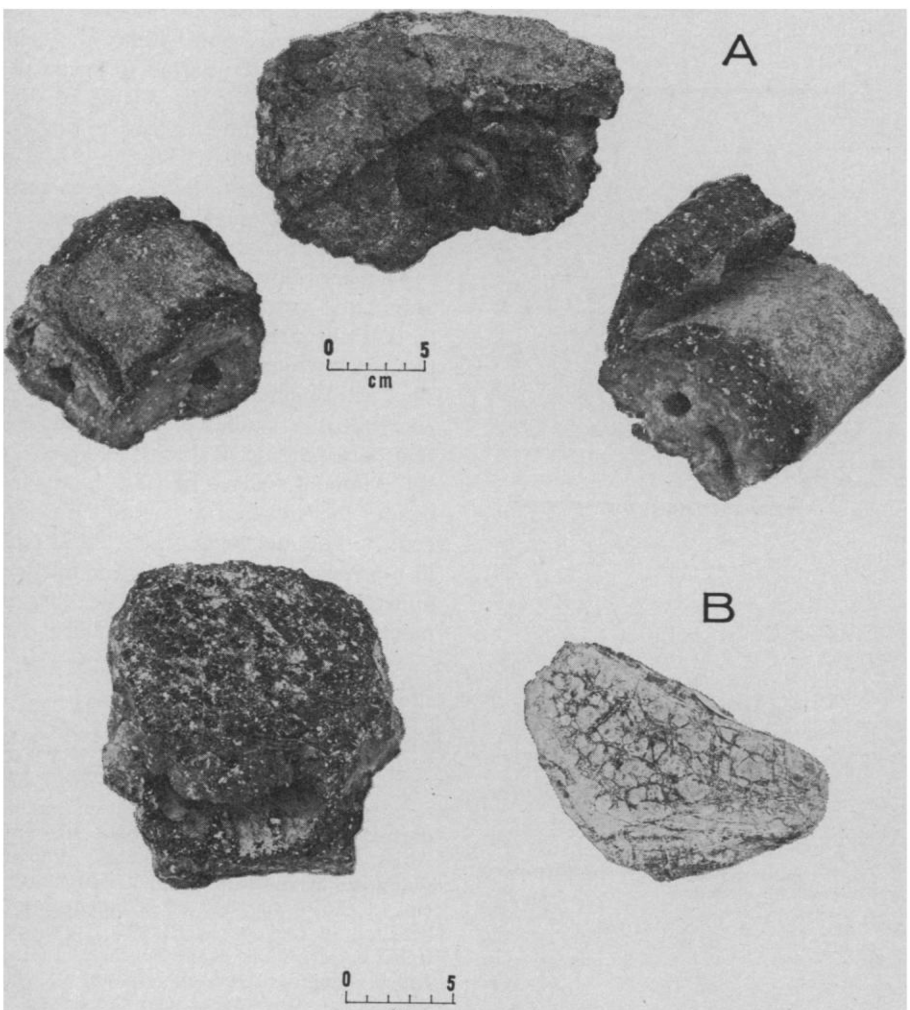

Fig. 3. Rocks from the rifted central portion of the mid-ocean ridge (Sample 107; depth, 2925 to 2915 m; position, 24°21'S, 69°50'E). (A) Fresh low-potassium basalt, Southeast Indian Ridge. Very fluid lava was extruded through the abyssal mud (dull tone) now baked on the lava surfaces. Note curled margins of porphyritic glass, tubules in the left and right samples, and "squeeze-out" in the center sample. (B) (Left) Fresh glassy basalt; (right) lherzolite (Table 3, sample 93-3; depth, 3880 to 3540 m; position, 12°25'S, 65°55'E). Lherzolite is the bedrock through which the basalt is extruded.

rocks are coarse grained, which probably indicates slow cooling of large bodies of basaltic magma. (iv) The lherzolites in the cross fractures and in the central rifted zone are upper mantle rock, either parental or residuate from which little or much basalt has been derived.

We are aware that the rocks dredged from the Central Indian Ridge are similar in many ways to Alpine ultramafic complexes and to various ultramafic-basaltic complexes thought to be slices of oceanic crust and mantle faulted into or on arcs and continental margins. However, the Indian Ocean rocks differ in that they are intruded into basaltic (oceanic) crust and therefore should be less contaminated with "sialic" elements. Studies of oceanic tholeiitic basalts in all of the oceans prove they are a kindred, uniquely different in composition from continental flood basalts and ophiolites of the Alpine-Tethyan belts. Very probably oceanic ultramafic-gabbroic-anorthositic complexes also are different in important compositional characteristics from the ultramafic-gabbroic complexes in most areas and in the Alpine-Tethyan belt.

CELESTE G. ENGEL
U.S. Geological Survey,
La Jolla, California 92037
ROBERT L. FISHER
Scripps Institution of Oceanography,
University of California at San Diego,
La Jolla, California 92037

References and Notes

1. R. L. Fisher, G. L. Johnson, B. C. Heezen, *Bull. Geol. Soc. Amer.* **78**, 1247 (1967); R. L. Fisher, C. G. Engel, T. W. C. Hilde, *Deep-Sea Res.* **15**, 521 (1968).
2. R. P. Von Herzen and V. V. Vacquier, *Phil. Trans. Roy. Soc. London Ser. A* **259**, 262 (1966); M. J. Langseth, Jr., and P. T. Taylor, *J. Geophys. Res.* **72**, 6249 (1967).
3. X. Le Pichon and J. R. Heirtzler, *J. Geophys. Res.* **73**, 2101 (1968).
4. T. J. G. Francis and G. G. Shor, Jr., *ibid.* **71**, 427 (1966).
5. Y. P. Neprochnov, I. N. Elnikov, B. V. Holopov, *Dokl. Akad. Nauk SSSR* **174**, 429 (1967).
6. M. Baranzangi and J. Dorman, *Bull. Seismol. Soc. Amer.* **59**, 369 (1969).
7. F. J. Vine, *Science* **154**, 1405 (1966).
8. T. J. G. Francis and R. W. Raitt, *J. Geophys. Res.* **72**, 3015 (1967).
9. J. D. H. Wiseman, *Publ. Brit. Mus. (Nat. Hist.) Geol. Mineral Invest.* **3**, 1 (1937); C. G. Engel, R. L. Fisher, A. E. J. Engel, *Science* **150**, 605 (196 J. R. Cann and F. J. Vine, *Phil. Trans. Roy. Soc. London Ser. A* **259**, 198 (1966); V. I. Chernysheva and P. L. Bezrukov, *Dokl. Akad. Nauk SSSR* **166**, 961 (1966); R. Hekinian, *Deep-Sea Res.* **15**, 195 (1968).
10. G. B. Udintsev and V. I. Chernysheva, *Dokl. Akad. Nauk SSSR* **165**, 1147 (1965).
11. A. E. J. Engel and C. G. Engel, in *The Sea*, A. E. Maxwell, Ed. (Interscience, New York, in press), vol. 4.
12. W. G. Melson, G. Thompson, T. H. van Andel, *J. Geophys. Res.* **73**, 5925 (1968).
13. N. Herz, *Science* **164**, 944 (1969).
14. W. G. Melson, E. J. Jarosewich, V. T. Bowen, G. Thompson, *ibid.* **155**, 1532 (1967).
15. D. H. Green and A. E. Ringwood, *J. Geophys. Res.* **68**, 937 (1963); H. H. Hess, *Nat. Acad. Sci.–Nat. Res. Counc. Publ. 1188* (1964), p. 169.
16. Officers and crew of R.V. *Argo* carried out arduous and meticulous navigational and maneuvering operations in the location and recovery of rock samples. E. Bingham (California Institute of Technology) provided the quantitative spectrographic analyses presented in Table 3. D. G. Crouch prepared the illustrations. Field work supported by the Office of Naval Research and NSF grant GA-4595. Laboratory analyses supported by NSF grants G-22255, GP-5469, GA-11080 and NAS-9-7894.

13 June 1969; revised 28 August 1969

Mars: Is the Surface Colored by Carbon Suboxide?

Abstract. *The reflection spectrum of Mars can be well matched from 0.2 through 1.6 microns (and farther) by polymers of carbon suboxide, reflection spectra for which have now been measured. We propose that the reddish color of Mars might be attributed to carbon suboxide, not the commonly considered limonite or other iron-bearing minerals.*

The planet Mars is conspicuously red even when seen without a telescope. This redness is accentuated by the predominantly blue color of most bright stars; Mars itself is colored more nearly a dull orange, popularly attributed to an iron-bearing mineral such as limonite (*1*). Some iron compounds show approximately the same color as Mars, but there are numerous spectral discrepancies, such as a reflectance minimum at 0.87 μ which is weak or absent on Mars (*2*). A better spectral match is shown by certain polymers of carbon suboxide, an uncommon material which may plausibly form in the atmosphere of Mars.

Carbon suboxide, or C_3O_2, is a noxious, clear liquid which boils at 7°C. Its linear molecules readily (and sometimes explosively) polymerize to form a sequence of heavier molecules, most of them quite hygroscopic. Their colors are graded through pale yellow, orange, reddish-brown, and violet, to nearly black. The first few members of this sequence can be formed from the monomer even at temperatures well below 0°C, under ultraviolet light or with various acidic catalysts.

For this investigation we prepared carbon suboxide by dehydrating finely powdered malonic acid in an excess of phosphorus pentoxide at 145°C (*3*). The gaseous products, which also included carbon dioxide and acetic acid, were collected in a cold trap. The carbon suboxide was then isolated by fractional distillation, transferred to a quartz-windowed cell, and polymerized either by ultraviolet light from a mercury lamp or thermally by being warmed to room temperature.

The polymers formed a multicolored coating on the quartz window. We illuminated this deposit by a quartz-tungsten lamp and measured reflection spectra with a Perkin-Elmer model 12C spectrometer, equipped with a LiF prism and a PbS detector. Comparison spectra were also recorded with the light reflected from sulfur, powdered silica, and magnesium oxide, the reflective properties of which have been described elsewhere (*4*). Measurements at wavelengths shorter than 0.8 μ were made with a second instrument—a grating monochromator adapted for this purpose with a 1P28 photomultiplier cell. The region from 0.6 to 0.8 μ was recorded on both instruments to provide unambiguous matching.

Figure 1 presents the spectral reflectivity of the polymer most closely matching the color of Mars. The agreement includes a slight decrease from 0.30 to 0.35 μ, low reflectivity for violet and blue light, the proper curvature from 0.35 to 0.8 μ, a moderate peak at 0.8 μ, a shallow minimum near 1.1 μ, and generally high reflectivity for longer wavelengths. The Mars reflectivity from 0.2 to 1.6 μ is taken from the review article by McCord and Adams (*5*). Although the Mars spectrum for longer wavelengths is less well established, there is a general rise in reflectivity to about 1.8 μ, followed by a decline of about 50 percent from 1.8 to 3.0 μ (*6*). The same is true of polymerized carbon suboxide.

Dollfus attempted to evaluate water vapor absorption in the martian atmosphere by measuring the integrated absorption across the water vapor band at 1.38 μ (*7*). His value of about 0.015 g/cm^2 of H_2O was an order of magnitude higher than has been estimated by other observers using higher spectral resolution (*8*). Moroz has also shown that the 1.38-μ absorption does not appear in the spectrum of the martian polar caps, so it cannot correspond to