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Igneous Rocks of the East Pacific Rise

The alkali volcanic suite appear to be differentiated from a tholeiitic basalt extruded from the mantle.

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The East Pacific Rise is a major segment of the worldwide complex of oceanic rises and ridges (Fig. 1). In large part these oceanic ridges and rises appear to form medial bulges between the continents; but in part they deviate from this pattern. The northern part of the East Pacific Rise merges with and may continue under the Cordillera of western North America (*1*).

The physical properties of oceanic rises and ridges are commonly attributed to the expansion, upwelling, and partial melting of the earth's mantle along the rising flanks of large convection cells (*2*). Features of the rises and ridges are thus linked with processes of mantle flux, crustal differentiation, and continental drift (*3*). Very clearly, parts of the mantle are being extruded along the rises as voluminous outpourings of lava. Studies of these volcanic effusions provide important clues to the nature of the mantle and of the primordial crustal matter which is further differentiated into continents (*4*). But these clues also may be masked by processes of igneous diversification associated with oceanic volcanism. For example, the volcanics on the islands of the East Pacific Rise range in composition from basalt to obsidian. And it has not been clear to what extent this compositional variation reflects magmatic differentiation from a single primary magma type, or whether two or more magmas of differing composition are erupted from the mantle. If these questions about the nature of the primary magma or magmas can be resolved, we may define with greater accuracy the properties of their source regions, the scope of magmatic differentiation, and the nature of the subcrustal material continuously added during crustal evolution and growth.

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Until very recently, concepts regarding the igneous rocks of the East Pacific Rise have been derived largely from work on scattered islands and from the volcanic debris found in sediments on its crest and flanks (*5*). In recent years, however, expeditions of the Scripps Institution of Oceanography have successfully dredged widely separated submarine lava flows along the Rise, associated fracture zones, and nearby submarine volcanoes (*6*). Basalt also has been cored in the experimental Mohole, near the northern intersection of the Rise and the continental slope of North America (Fig. 2) (*7*). Complementary to the submarine work, additional reconnaissance and sampling also have been undertaken on the previously little-known islands of Guadalupe, the Revillagigedos, Clipperton, and Pinta of the Galapagos Islands.

We present a summary of geologic studies of the islands, of dredge collections of igneous rocks along the Rise, and of rocks cored in the experimental Mohole. These data are related to preexisting petrologic information on the East Pacific Rise and to concepts of the origin and diversity of the igneous rocks on this and other segments of oceanic rises and ridges.

Volcanic Rocks

In general, dredging along the Rise in depths of water ranging from 1500 to 3500 meters has produced only a tholeiitic type basalt (*8*) with only 0.1 to 0.25 percent K_2O. This same low-potassium basalt also is the only igneous rock that has been recovered from the fracture zones which cut the Rise and which have been cored in the experimental Mohole at a depth of some 3700 meters. Consequently, low-potassium (oceanic) tholeiite appears to be the only basaltic magma which has erupted in any volume in more than 1500 meters of water along the Rise, and very possibly it is the dominant igneous rock in the "intermediate" layer of oceanic crusts.

In contrast, field studies of the islands and dredge hauls from the upper parts of the larger submarine volcanoes (seamounts) demonstrate the predominance of high-alkali basalt on these higher volcanoes. Commonly the alkali basalt is accompanied by other members of the alkali volcanic suite—andesine- and oligoclase-andesites and trachytes. Rarely, sodium-rich rhyolites appear. These rocks show a progressive enrichment in the alkalis and silica, at the expense of magnesium, calcium, and iron. Low-alkali, high-calcium, tholeiitic basalts as well as high-magnesium (picritic) and high-alumina (plagioclase-rich) basalts also occur at least locally on the islands and larger submarine volcanoes but are in general quite subordinate to the alkali basalts. The data are consistent with the interpretation we have offered recently for other parts of oceanic rises and ridges: that low-potassium tholeiites are the dominant if not the only magma erupted from the mantle (*9*). The alkali volcanic suite is formed principally or only as cappings to higher seamounts and islands, and it is derived from primary tholeiitic magma by magmatic differentiation in the higher volcanic edifices of the oceans.

Sodium-rich rhyolite, the volcanic equivalent of certain circumoceanic granites, occurs on Easter Island, and rhyolite glass, anorthoclase (high-alkali feldspar), and quartz have been described from sediments along the Rise (*5, 10*). These "granitic" volcanics contribute to the extreme diversity of igneous rocks developed along the Rise, but they probably represent less than 1 percent of the volcanic rocks on the Rise. Their close association with other members of the alkali suite on typically thin oceanic crust suggests that they must be products of a unique or extreme magmatic differentiation from the voluminous accompanying basalt.

Features of the Rise

The general form of the East Pacific Rise, its associated and neighboring islands, fracture systems, and the sites of recent dredge hauls and drill holes are shown in Fig. 2. Structural and geomorphic features of the Rise have been discussed in some detail by Menard (*1*). It forms a vast, elongate bulge in the Pacific Ocean floor, the northern part of which merges with the southwest coast of North America in the vicinity of Baja California (Fig. 2). The principal islands in this region are Guadalupe and the Revillagigedos. To the southwest, the East Pacific Rise contains a series of spurs or bifurcations, the most northerly of which extends east to Central and South America. This northerly spur, the Cocos Ridge, contains the Galapagos and Cocos islands. At and near latitude 30°S, there are three major spurs, the Tuamotu Ridge, the Easter and Nazca Ridge, and the West Chile Rise (Fig. 2). Easter and Sala y Gomez islands rise above the ocean at this intersection of ridges, rises, and spurs. At latitude 55°S, the Rise curves westward and becomes a major segment of the Mid-Ocean Rise system between Antarctica and New Zealand (*11*).

At intervals, the vast East Pacific Rise is cut and displaced by large east-west fracture zones, especially the Mendocino, Murray, Clarion, Clipperton, Marquesas, and Easter fractures (Fig. 2). Most of these fracture zones appear to be seismically active. Heat flow along and across the Rise is quite variable, ranging from 0.14×10^{-6} to 8×10^{-6} cal cm^{-2} sec^{-1} (*12*). In general, highest values are obtained along the crest of the Rise and lowest values along the flanks. Average heat flow along the crest is 3×10^{-6} cal cm^{-2} sec^{-1}. This is about twice the oceanic average (*13*). Seismic studies of the Rise suggest that the oceanic or "third layer" of the crust is thinned along the crest of the Rise, but the velocities in the mantle are lower than average at depths of typical oceanic mantle (*14*).

The extremely thin oceanic crust along the crest of the Rise has the elastic properties of basalt (*14*). If this is the case, the basalt extruded through it from the mantle onto the ocean floor should be an essentially uncontaminated melt or partial melt of the mantle. In this respect oceanic basalts are better subjects for study than those extruded through thick, differentiated, continental crusts, which may easily contaminate the basalt and obscure its primordial legacy.

The extensive recent volcanism along

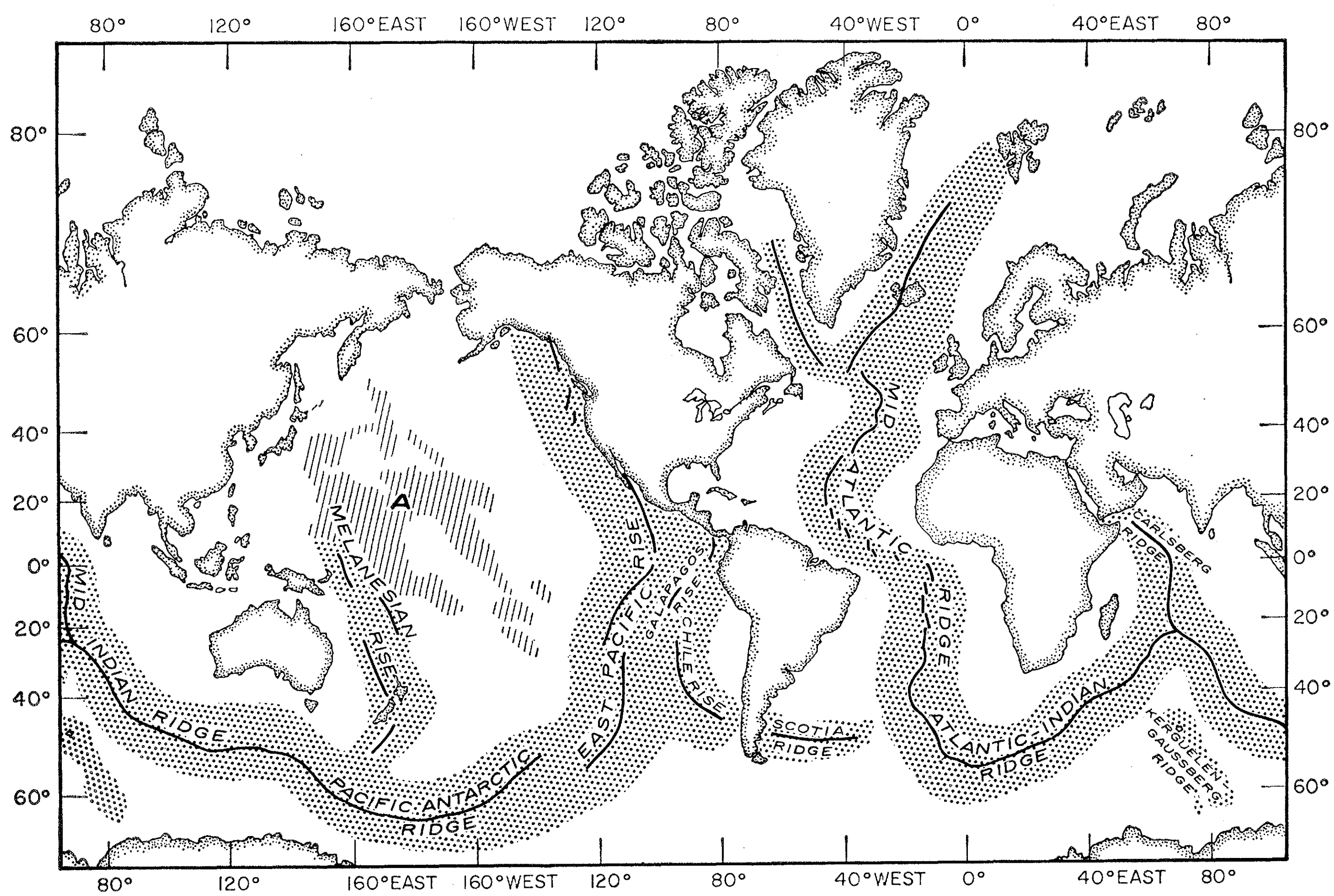

Fig. 1. The worldwide complex of oceanic rises and ridges and the great Pacific archipelagic apron [after Menard (*31*) and Heezen and Ewing (*11*)].

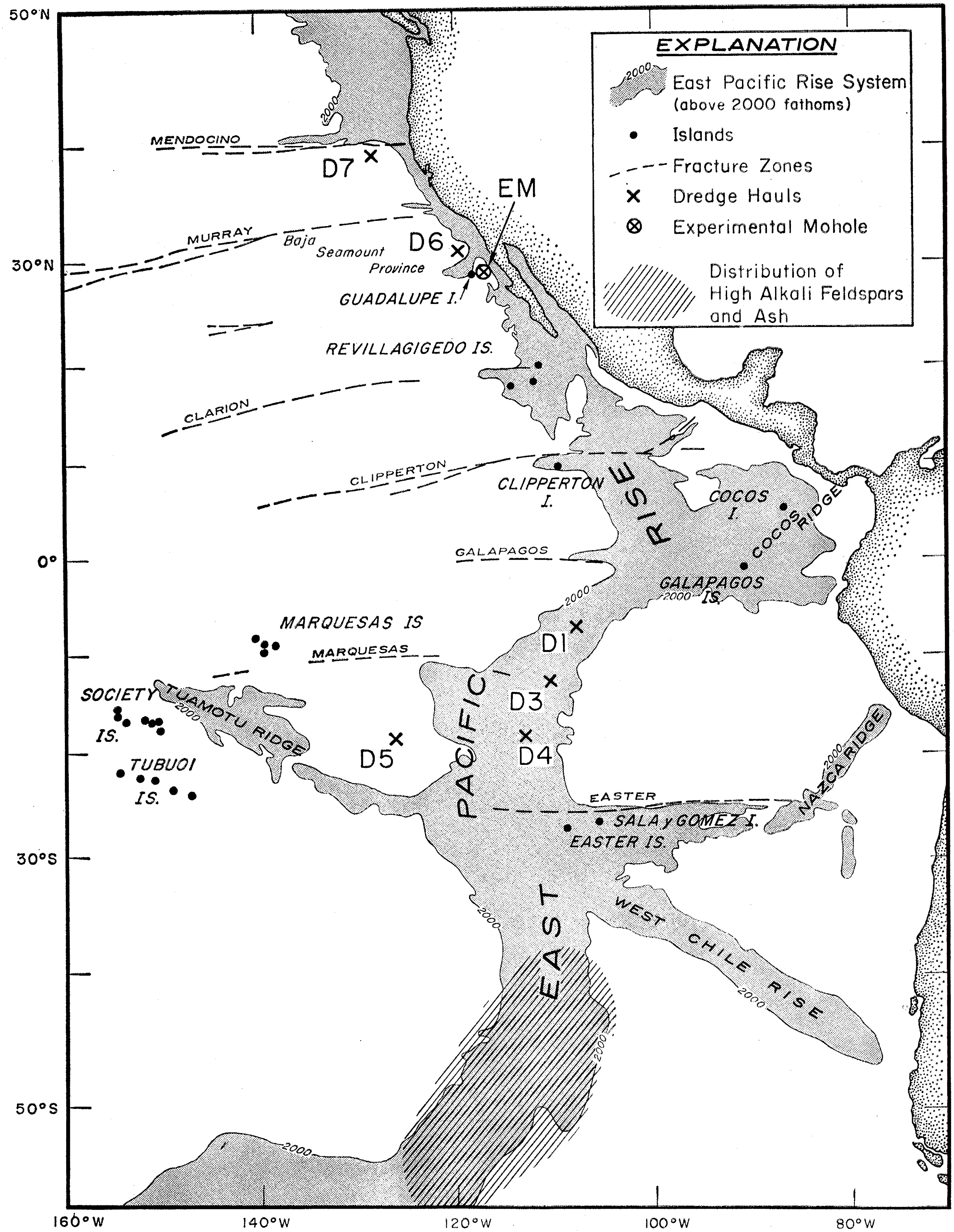

Fig. 2. The East Pacific Rise above 2000 fathoms, associated islands, fracture zones, the positions of dredge hauls, and the experimental Mohole. [Patterns of fracture zones from Menard (1). Distribution of high-alkali feldspar and ash from Peterson and Goldberg (5)].

the Rise is indicated by photographs of the ocean floor, abnormally high heat flow, and the properties of the dredge hauls discussed in a succeeding section. Samples of these volcanic eruptions are represented by tholeiitic basalts D1, D3, D4, and D5 (Table 1). Figure 3 and the cover photograph are of lavas dredged at localities D1 and D3. Analyses of representative rocks recently collected by University of California expeditions from Guadalupe, the Revillagigedos, Clipperton, Pinta (Galapagos), and Sala y Gomez islands are grouped in Table 2.

Larger Volcanoes

The composition of the island collections confirms the observations of earlier workers on the Galapagos, Cocos, and Easter islands, and on other scattered islands on the Rise. Basalts are overwhelmingly predominant. They compose some 85 to 95 percent of the igneous rock on the several islands. On most islands alkali-rich basalts are the dominant rock type. Tholeiitic basalts, picritic, and plagioclase-rich basalts occur with the alkali basalts, especially on Guadalupe, but in much smaller volumes.

The most common felsic derivatives of the basalts are andesine- and oligoclase-andesites and trachytes. Rocks of this alkali suite occur interbedded with alkali-rich basalts on the Galapagos, Cocos, and Clipperton islands, and also have been found on the Revillagigedos and Guadalupe (Table 2). Ultrabasic rocks (very high magnesium), especially dunite, peridotite, and pyroxenite, are, along with amphibolite, known only as inclusions, but the total volume of the ultrabasic and amphibolitic inclusions does not exceed 0.01 percent of the exposed rock on the islands. Hence relative abundances, by volume, of igneous rocks known from the islands along the Rise are, very approximately: basalt (with alkali-rich types predominant), 90 percent; andesine- and oligoclase-andesites, trachytes, and sodium-rich rhyolites, 10 percent; and ultrabasic rocks, less than 0.01 percent. Volcanic rocks of intermediate compositions, with silica contents between 53 and 59 percent by weight, are, as Chayes's computations have suggested, less abundant than more siliceous trachytes (*15*).

Much work remains to be done to quantify the relative abundances and interrelations of basaltic rock types. These proportions will also vary with the terminology and definitions used to separate basalt per se from the more alkalic members of the alkali suite.

Table 1. Composition of basalts dredged and cored from the East Pacific Rise and related fractures. Descriptions and locations: (D1) Porphyritic, bytownite basalt, with glassy to microcrystalline groundmass; 7°47′S, 108°10′W; depth 1700 m. (D3) Glassy to microcrystalline basalt; 12°52′S, 110°57′W; depth 2300 m. (D4) Fine-grained basalt; 18°25′S, 113°20′W; depth 3200 m. (D5) Porphyritic, labradorite basalt; 18°35′S, 126°30′W; depth 3000 m. (D6) Bytownite-labradorite basalt, alteration largely palagonite; 30°40′N, 119°15′W; depth 3025 m. (D7) Labradorite basalt, diabasic texture; 40°23′N, 127°59′W; Mendocino Ridge, depth 1260 m. This is sample PV 17 cited in Engel and Engel (*6*). (EM) Labradorite basalt, subophitic texture; 28°59′N, 117°30′W; experimental Mohole drilled on flat sea floor; depth of water, 3566 m; depth of basalt below sediment-water interface, 180 m (*7*).

Compound or mineral	D1	D3	D4	D5	D6	D7	EM
			Composition (percent by weight)				
SiO_2	48.53	49.80	49.64	49.28	49.80	49.94	49.13
TiO_2	0.76	2.02	1.37	1.38	0.99	2.27	1.23
Al_2O_3	22.30	14.88	16.19	16.96	17.42	14.85	14.97
Fe_2O_3	0.69	1.55	1.35	3.42	4.30	2.17	3.28
FeO	4.82	10.24	7.85	6.24	4.54	8.07	5.72
MnO	0.16	0.21	0.18	0.20	0.14	0.22	0.16
MgO	7.14	6.74	8.37	6.53	5.96	6.42	7.68
CaO	12.86	10.72	12.01	12.38	10.45	11.92	12.68
Na_2O	2.18	2.91	2.75	2.88	3.00	2.70	2.37
K_2O	0.06	0.24	0.11	0.17	0.25	0.26	0.16
H_2O^+	.38	.54	.30	.50	1.38	.63	1.06
H_2O^-	.01	.06	.01	.27	1.30	.67	1.25
P_2O_5	.07	.28	.09	.04	0.14	.18	0.15
Total	99.96	100.19	100.22	100.25	99.67	100.30	99.84
			Mineralogy (percent by volume)				
Groundmass			60.0		45.5		
Plagioclase	39.0	0.5	30.0	11.0	37.0	32.4	42.0
Pyroxene			Trace	1.0	8.5	60.0	49.0
Olivine	0.4		7.0	Trace			1.0
Opaque					4.0	5.8	5.0
Glass	60.6	99.5		88.0			
Vesicles			3.0			1.0	Trace
Alteration				Trace	5.0	0.8	3.0

Our reconnaissance studies of Guadalupe Island indicate that alkali-rich basalts, with andesine- and oligoclase-andesites and trachytes, are the oldest rocks exposed and represent over 95 percent of the island. The alkali basalts are fairly representative of alkali basalts of other oceanic islands: that is, they are characterized by SiO_2, 47 to 52 percent by weight; Na_2O, 3.5 to 5.0 percent; K_2O, 1.0 to 2.0 percent; TiO_2, 1.7 to 3.0 percent; and P_2O_5, 0.3 to 1.0 percent (Table 2). The ratio of Fe_2O_3 to FeO is also characteristically high, commonly exceeding 1.0 even in very fresh rocks (Table 2). This strongly oxidized nature of alkali basalts on oceanic volcanoes is characteristic and, as suggested in a later paragraph, may be an important clue to their origin.

Baja Seamount Province

Similar alkali basalts dominate the upper flanks and tops of the higher submarine volcanoes in the Baja Seamount Province, just northwest of Guadalupe, on the western flanks of the Rise (Fig. 2). In this region there are about one hundred large submarine volcanoes and many more smaller ones (*16*). Expeditions of the University of California have now made 46 dredge hauls from the upper flanks and tops of 31 of the larger submarine volcanoes in the region. Initial studies of some of these basalts are published separately (*6*). Representative analyses of alkalis (Na_2O and K_2O) of additional basalts are grouped in Table 3. Depth of dredge sites ranges from 600 to 1300 meters.

Basalts dredged near the tops of the larger submarine volcanoes that shoal within 1000 meters of the surface are quite altered by sea water and are pillowy in form, but in other respects they are identical to the vesicular, alkali-rich basalts found on the volcanic islands along the Rise. Large fragments of bedded ash have been dredged with the basalts. Hence lava and ash are inferred to be interlayered in much the same relations as on the islands (Fig. 4). Neither tholeiitic basalt nor trachytes have been dredged from the upper parts of seamounts. This suggests that these rock types are quite subordinate to the alkali-rich basalts on the surficial volcanic cappings.

Occasional rounded fragments of peridotite and pyroxenite are dredged with the ash. These ultrabasic inclusions are most abundant in ash beds and cindery flank eruptions. This suggests that explosive or boiling volcanic eruptions are commonly required to fragment and eject peridotite and pyroxenite in any abundance. The peridotites are usually coarse-grained, friable, and composed of magnesium-rich olivines and chromium-rich hypersthenes. Most of the pyroxenites consist largely of medium- to coarse-grained clinopyroxene. In composition and texture these ultrabasic inclusions exhibit marked similarities to mafic layers found in the stratiform sheets (*17*). It seems quite probable that the oceanic ultrabasic fragments were initially formed by gravitative settling of olivine and pyroxene crystals in relatively shallow magma chambers within or just below the volcanoes during magmatic differentiation.

The only known tholeiitic basalts from upper parts of volcanoes in the Baja Province occur on Guadalupe Island. There the tholeiitic basalts occur as relatively late dikes, sills, and flows that fill and emerge from cracks that traverse the flanks of the larger volcanoes. A chemical analysis of one of these basalts from a recent flow on Guadalupe Island is given in Table 2, sample Gu 44. The rock is actually intermediate in composition between a typical tholeiite and an alkali basalt. It forms less than 5 percent of the island. In this respect Guadalupe presents an interesting contrast to the Hawaiian Islands, where the bulk of the exposed volcanoes are tholeiitic, and alkali-basalts, andesine-andesites, and trachytes occur principally as younger, superficial carapaces (*18*).

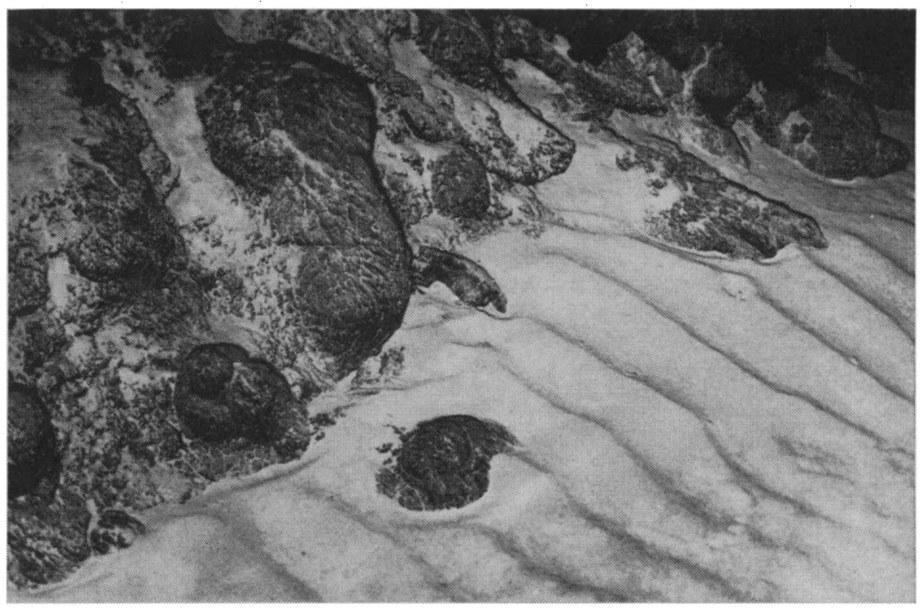

Fig. 3. Margin of incipiently pillowed and blistered tholeiitic basalt erupted from the earth's mantle on the west flank of the East Pacific Rise near station D3. Depth of water 3200 meters. [Fred Dixon]

Islands to the South

The proportions of tholeiitic basalts to alkali and other basalts present on the islands along the central and southern parts of the Rise are less well known; but tholeiities are present in much smaller volume on most islands. A small collection of rocks from the Revillagigedos and Clipperton islands made by Scripps expeditions consists only of alkali basalt and andesine-andesite. Analyses of typical examples are given in Table 2, samples PV 172, PV 176, and PV 305. LaCroix has described the trachytic central spine on Clipperton Island (*19*).

The basaltic lavas previously described from the Galapagos appear to be largely porphyritic, with either abundant plagioclase or olivine phenocrysts (*20, 21*). Plagioclase crystals (density 2.7) commonly float or sink very slowly in basaltic magmas. Olivine with a density of about 3.6 sinks relatively rapidly. Hence the possibility exists that analyses of these lavas reflect the effects of relatively localized crystal accumulation rather than common magma types. In any event, what appear to be two common types of basalt have either (i) high Al and Ca content, with a high ratio of K to Na, or (ii) moderate to high Mg content, with the ratio of MgO to CaO and the SiO_2 content intermediate between those of typical olivine-rich (picritic) and tholeiitic or alkali basalts. The analysis we have made of a major basalt flow from Pinta Island in the northern Galapagos is an example of type (i), plagioclase-rich, with high CaO and Al_2O_3 content (Table 2, sample PV 300).

Definite alkalic trends of igneous differentiation are indicated in the Galapagos by the work of Chubb and Richardson who report (i) analcite as an interstitial mineral in some of the Galapagos basalts, and (ii) oligoclase-andesite and trachyte present in subordinate amounts on San Salvador (James Island) (*20*). The work of Banfield and others also suggests that some of the youngest fissure and flank eruptions are tholeiitic (*21*). Previous studies by Chubb and Richardson of Cocos Island, which lies northeast of the Galapagos, on the Cocos Ridge, indicate that in this group alkali basalts are the predominant exposed volcanic rocks (*20*).

The two islands, Easter and Sala y Gomez, on the East Pacific Rise near latitude 28°S are of considerable interest. Published studies of Easter Island suggest it is largely alkali basalt (*10*). The rhyolitic ash, pumice, and obsidian for which the island is famous are found on a small satellitic cone (Orito) and associated with alkali basalts and andesine-andesites on Tano Kao, one of the three larger volcanoes of the island. As noted earlier these "granitic" lavas and pumice form less than 0.1 percent of the volcanic pile, are in part interbedded with basalts, and are obviously part of an interrelated volcanic episode on a typically oceanic crust. Accordingly, they are presumed to be differentiated from the basalt.

The major basaltic flows exposed on Sala y Gomez have been sampled and studied petrographically by Fisher and Norton (*22*). We have analyzed three of these rocks and all of them are enriched in alkalis. An analysis of one appears in Table 2 (sample PV 301).

Deeply Submerged Lavas

Data on igneous rock erupted upon the more deeply submerged parts of the East Pacific Rise include (i) dredge hauls along the eastern part of the Mendocino scarp; (ii) the basalt cored in the experimental Mohole some 100 kilometers east of Guadalupe Island; (iii) a dredge haul along a small fault scarp ridge approximately 150 kilometers northwest of Guadalupe Island; and (iv) four dredge hauls along the

Table 2. Composition of extrusive igneous rocks from islands of the East Pacific Rise. Descriptions and locations: (Gu 44) Labradorite, olivine basalt, from small, late flow, south end. (Gu 22) Labradorite, alkali basalt flow, at base of dike-cinder cone complex, southeast shore. (Gu 15) Labradorite-andesine, alkali basalt flow forming the north flank of the Barracks Creek Volcano, north end. (Gu 77) Labradorite-andesine, alkali basalt, with pronounced flow structure, in sequence forming the east flank of volcano 2.5 km south of Barracks Beach. (Gu 52) Labradorite-andesine, alkali basalt, at Lobster Camp Cove, east side. (Gu 57) Oligoclase-anorthoclase, trachytic flow in steeply dipping sequence underlying Gu 52, Lobster Camp Creek. (Gu 84) Pumaceous glass, from pumice interbedded with alkali basalt flows, southeast part; rock includes 0.5 percent hornblende, biotite, and tridymite. (PV 172) Labradorite-andesine, alkali basalt flow, Partida Island; rock includes 2.0 percent apatite, and 3.0 percent biotite. (PV 176) Oligoclase-anorthoclase trachyte, San Benedioto Island. (PV 305) Andesine alkali basalt, obtained in dredge haul on east slope; depth 400 m. (PV 300) Bytownite basalt. (PV 301) Andesine-oligoclase andesite, from upper flow (*22*). Analyst, C. G. Engel.

Compound or mineral	Guadalupe Island							Revillagigedo Islands		Clipperton Island	Pinta Island	Sala y Gomez Island
	Gu 44	Gu 22	Gu 15	Gu 77	Gu 52	Gu 57	Gu 84	PV 172	PV 176	PV 305	PV 300	PV 301
					Composition (percent by weight)							
SiO_2	47.13	48.00	50.08	50.48	51.26	60.30	60.57	50.32	60.83	49.71	46.47	52.48
TiO_2	1.84	3.20	2.90	2.25	2.82	0.94	0.23	2.45	0.91	3.05	1.74	1.77
Al_2O_3	12.54	17.42	18.77	18.31	16.29	18.08	17.07	18.99	16.49	14.34	20.92	16.86
Fe_2O_3	4.72	6.17	4.10	3.21	5.51	4.21	1.94	3.69	1.65	6.86	1.62	3.65
FeO	6.26	4.64	5.13	6.03	4.91	1.17	1.63	4.50	5.58	5.30	6.17	4.86
MnO	0.19	0.13	0.15	0.21	0.15	0.18	0.23	0.11	0.23	0.17	0.19	0.16
MgO	13.19	4.55	4.50	4.21	4.01	1.38	.42	3.03	1.08	2.17	5.87	4.10
CaO	10.17	9.60	7.30	7.21	7.87	3.14	.83	8.26	3.13	8.19	12.84	5.47
Na_2O	2.25	4.00	4.16	4.80	4.08	6.80	6.18	4.14	6.38	4.50	2.63	5.43
K_2O	0.65	1.30	1.79	1.93	1.65	2.91	5.84	2.09	3.36	1.94	0.43	2.82
H_2O^+	.35	0.42	0.38	0.46	0.36	0.39	4.90	0.50	0.17	1.55	.42	0.72
H_2O^-	.30	.15	.01	.38	.40	.38	0.39	.83	.01	0.69	.30	.54
P_2O_5	.36	.54	.79	.74	.77	.29	.07	1.03	.30	1.38	.36	.85
Total	99.95	100.12	100.06	100.22	100.08	100.17	100.30	99.94	100.12	99.85	99.96	99.71
					Mineralogy (percent by volume)							
Groundmass		47.5	67.0		81.5				22.5	90.0	50.0	20.0
Feldspar	37.0	28.5	22.0	70.0	15.0	96.0		76.0	4.5*	5.0*	25.0	70.0
Pyroxene	25.0	0.5	4.0	14.5	1.0	2.0†		16.5	2.0†	5.0	1.0	Trace
Olivine	14.5	1.0	3.0	8.0	2.0			2.5			1.5	7.0
Opaques	3.5	2.5	4.0	7.5	0.5	2.0	Trace	5.0	1.0			3.0
Glass							51.5		22.0			Trace
Vesicles	20.0	20.0					48.5		48.0		22.5	

* Anorthoclase. † Aegerine-augite.

central and west flanks of the Rise between latitudes 8° and 20°S. There are also the widely dispersed fragments of felsic ash, anorthoclase, and quartz found in pelagic sediments along the southerly crest and flanks of the Rise (*5*). The locations of all of these sites are shown in Fig. 2. Exact locations and depths of dredge sites are given in Table 1, with chemical and petrographic analyses of the rocks obtained.

The lavas dredged from sites D1 to D4 must be very recent, probably less than a few hundred years old. Their surfaces consist of very fresh vitreous glass or of unaltered fine-grained to microcrystalline basalt. Photographs of several of the dredge sites and examination of the collections indicate the scarcity of encrusting sediment and the absence of hydrated manganese oxides, even in crevices and cracks. At locality D3, photographs and dredged fragments show that the thin marginal parts of flows are extruded over, and form a cast of, ripple-marked sediments. Flows vary widely in thickness, but most appear to be less than 9 meters thick and some marginal parts are only 3 or 4 centimeters thick. Hence the lava must have been extremely fluid.

Both photographs and specimens indicate the abundance of pillowy and ropy lava forms, many with pervasively crackled but only slightly vesiculated surfaces. Vesicular and cindery textures are far less pronounced than in the lavas dredged from the highest parts of the large submarine volcanoes or exposed on the islands. There is consequently a general decrease in vesiculation and boiling eruptions at greater depths of water, a relation noted by Moore in the vicinity of Hawaii (*23*).

Dredge hauls from scarp ridges (D6 and D7, Table 1) and the experimental Mohole (EM, Table 1) are more altered, partly brecciated and cracked, and in places veined and replaced by calcite, hydrated manganese oxides, palagonite, zeolites, and other secondary minerals. Both paleontologic and radiometric studies suggest that the core EM may be as old as upper Miocene, that is, some 3 to 3.5 $\times$ 10^7 years (*24*). The specimens from the fracture and fault ridges are as yet undated, but judging from their appearance and alteration they also may be at least as old as Miocene.

All of the dredged rocks are low-potassium, tholeiitic basalts. Considering the diversity in age and of geologic features from which they are taken, the similarities in composition are indeed striking (Table 1). Perhaps the most conspicuous chemical features are (i) the low average values for K_2O, 0.19 percent by weight; TiO_2, 1.5 percent; P_2O_5, 0.15 percent; (ii) the high ratios of Ca to Mg and Na to K; and (iii) the value for SiO_2, 50.0 percent by weight. Several of the tholeiitic glasses also contain as much as 17 percent alumina and a ratio of Fe^{3+} to Fe^{2+} of less than 0.15. The C. I. P. W. norms (*25*) calculated from these analyses indicate most of the basalts are essentially saturated, that is, they contain either a little normative quartz or only a little normative olivine.

The rather uniform chemical compositions of the tholeiites are reflected in very similar constituent minerals. The dominant minerals are augite, calcic plagioclase, and opaque, iron-rich oxides (Table 1). Olivine appears as scattered, partly resorbed, and corroded crystals. The medial parts of thicker flows and fragments of both fracture zones and the experimental Mohole core have diabasic to sub-diabasic textures (Table 1, samples D7 and EM). Most of the basalt dredged from the Mendocino scarp is sufficiently coarse-grained to be called a gabbro.

Causes of Diversification

In a previous report we have drawn attention to the fact that tholeiites with the same textures and composition are the only basalts as yet dredged from the more deeply submerged parts of the Mid-Atlantic Ridge and the Carlsberg (Arabian-Indian) Ridge in the Indian Ocean (*9*). The similarities in composition of the oceanic tholeiites from oceanic rises and the Mid-Ocean ridges in the Pacific, Atlantic, and Indian oceans are indicated by comparisons of the "average" oceanic tholeiities given in Table 4. Because these extrusions of basalt along the flanks and deeper parts of oceanic ridges and rises are relatively monotonous in composition and probably exceed by 10^3 or more the volume of alkali basalts known from the seamounts and islands, we have suggested that low-potassium tholeiite may be the only magma generated in the mantle (*9*). The alkali-rich basalts, andesites, trachytes, and traces of rhyolite on the islands and in the pelagic sediments, as well as the alkali-rich basalts from the larger submarine volcanoes, appear to be derived from the tholeiitic magmas, largely through gravity differentiation.

Because of the observed relations between the form of the volcanic structure, its height, and the composition of constituent basalt, processes of differentiation may be confined largely to chambers within and immediately below large volcanoes. Some students of volcanology have invoked this same hypothesis to explain somewhat similar relations found in the Hawaiian Islands (*26*). The oxidized nature of even the freshest alkali basalts along the Rise suggests that the processes and paths of magmatic differentiation are influenced by oxidative and fluxing effects of infiltrating rain and sea water. Experimental studies of basaltic systems seem to corroborate the importance of oxygen pressures in influencing the course of magmatic differentiation (*27*). Gaseous transfer of elements, especially alkalis, upward in the magma chambers also may be a significant process. Certainly the effects of gravity must be profound, especially in causing the early formed crystals of magnesium-rich olivine and pyroxene to sink toward the chamber floor (*26*).

A crude analogue to this kind of gravitative differentiation exists in the great spoon- and funnel-shaped stratiform sheets. Several of these, for example the Skaergaard in Greenland, are differentiated from parental, low-potassium tholeiitic basalts chemically like the oceanic tholeiites (*17*). In many of these stratiform igneous complexes the final, the uppermost, product of gravity differentiation is an alkali-rich granophyre, or "red rock" (*28*). This "red rock" is the analogue to the oceanic trachytes. Each is a volumetrically subordinate differentiate from the parent tholeiitic magma. There are, of course, some important differences between the volcanic and stratiform lines of descent, but these appear to be due largely to differences in the physical and chemical conditions during differentiation. The important aspect of this comparison is that studies of stratiform sheets do demonstrate that alkali-rich differentiates not unlike oceanic trachytes are products of gravity differentiation, from low-potassium tholeiitic basalts, in surficial magma chambers. In the stratiform sheets, a major by-product is layers of peridotite and pyroxenite. Earlier in this discussion the suggestion was made that the peridotite and pyroxenite fragments found in the ash and flows of oceanic volcanoes may have had a similar origin. It hardly seems necessary to attribute most of these fragments to a deeper, more primitive source in the earth's mantle.

The interpretations cited above are as yet but working hypotheses. The 32 dredge samples and one core of tholeiitic basalt are hardly an adequate

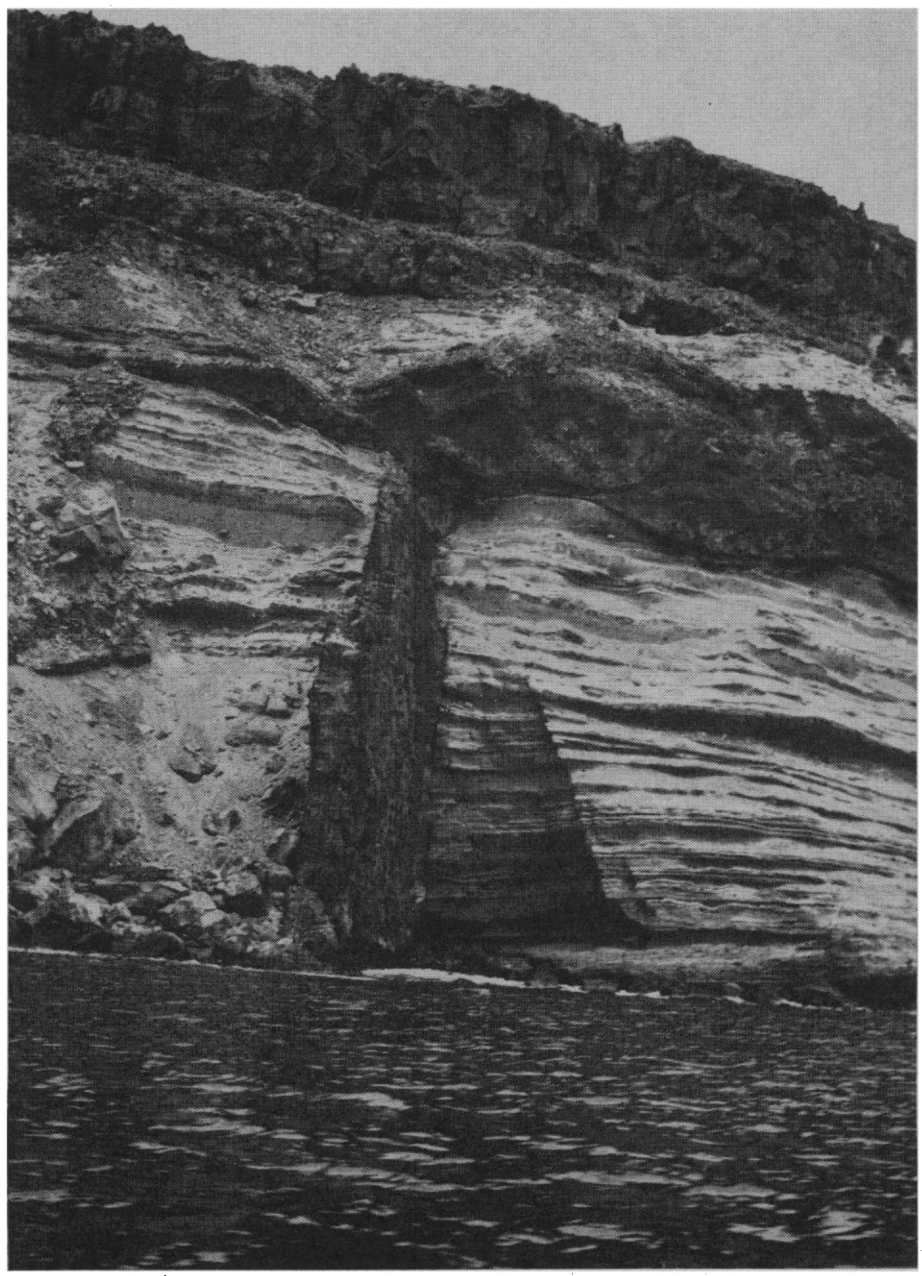

Fig. 4. Beds of volcanic pumice and ash cut and overlain by alkali basalt, south end of Guadalupe Island, eastern Pacific Ocean.

sample of the 65,000 kilometers of oceanic ridge, rise, and fracture systems. Conceivably, alkali-rich basalts also occur as primary magmas which are either more viscous or less commonly generated in the mantle. A higher viscosity could be adduced as the reason alkali basalts have been found only in volcanic cones. And if tholeiitic magmas are greatly predominant and more fluid, their extrusion as great floods and thin sheets may mask and swamp out the deeper, more bulbous and conical occurrences of alkali basalt. Additional dredge hauls and cores are required, especially from the truncated volcanoes (guyots) and from the smaller, incipient volcanoes and other abyssal hills.

From several experimental studies and some circumoceanic field relations it appears that primary magmas are composed of both tholeiitic and alkali-rich basalt. The field relations in Japan are noteworthy. There Kuno has noted a close spatial correlation between the distribution of tholeiitic and alkali-rich basaltic provinces and, respectively, the belts of shallow and deep-seated earthquakes in the mantle (*29*). Kuno suggests that alkali basalts are therefore derived at the deeper levels of seismic activity in the mantle, and the tholeiitic lavas at the shallower levels.

The dual nature of primary basaltic magma also seems to be supported by some recent laboratory studies of basaltic systems in pressure vessels. Yoder and Tilley found, for example, that tholeiitic and alkali basalt magma types appear to be separated by equilibrium thermal divides at one atmosphere (*30*). In experiments at elevated pressures these equilibrium thermal divides appear to give way to a new set of divides resulting from a new mineralogy. Yoder and Tilley conclude,

> The change of the equilibrium thermal divides with pressure leads to the derivation of the two principal magma trends (tholeiitic and alkali basalt) from the same bulk composition. . . . In general, alkali basalt-type magmas are to be expected to be generated at greater depths than tholeiitic type magmas, from the same primary source rock.

This same correlation of depth (pressure) and composition of basaltic magma generated in the mantle is consistent with recent experiments of Davis and England (*31*). They note that the measured temperatures of melting of forsterite (Mg olivine) as a component in silicate systems should shift toward the melting-point of Mg_2SiO_4 with increasing pressure. Hence, at increasing depths, the partial fusion of peridotitic or other magnesium-rich mantle may yield magmas that are less tholeiitic (siliceous) and perhaps more alkalic.

Our prejudice at present is to favor the field data from the oceans, including the relations on the Hawaiian Islands (*18*) which suggest that oceanic tholeiites are the only magma extruded from the mantle. It is noteworthy that the recent dredge hauls obtained by Moore from submerged, faulted flanks of the Hawaiian volcanoes are tholeiites very similar to those from the oceanic rises and ridges (*23*). It appears that most or all of the archipelagic apron enveloping the Hawaiian Islands consists of low-potassium tholeiite (Fig. 1). Menard has noted the great extent of this apron and the enormous volume of constituent flood basalts (*32*). The composition and form of this apron, coupled with the detailed geologic work on the Hawaiian Islands, indicate therefore an overwhelming amount of low-potassium tholeiite, capped by a relatively minuscule, young carapace of alkali-rich derivative.

Table 3. Na_2O and K_2O content of alkali basalts dredged from guyots, seamounts, and ridges in the Baja Seamount Province.

Site	Position	Depth (m)	Na_2O	K_2O
Erben Guyot	30°50′N, 132°32′W	640		
PV 307			3.46	1.93
Fieberling Guyot	32°30′N, 120°45′W	1200		
PV 1470			2.76	1.58
PV 1500			3.97	1.56
Jasper Seamount	30°25′N, 123°48′W	840		
PV 1740			4.12	2.16
PV 1750			5.10	2.45
Unnamed Seamount	30°05′N, 126°56′W	1100		
PV 1840			4.10	2.00
PV 1900			3.77	1.97
Unnamed Ridge	30°12′N, 120°02′W	1300		
PV 1952			3.46	1.37
PV 1959			4.27	1.51
PV 1960			4.09	1.91
San Juan Seamount	33°03′N, 121°00′W	900		
PV 1640			4.00	1.71

Table 4. Average compositions of oceanic tholeiitic basalts from the Atlantic, Pacific, and Indian oceans (calculated water free). Atlantic: Average of seven tholeiitic basalts. One sample from Correns (*39*, p. 83); two from Nicholls (*40*, p. 19); and four (D1 to D5-5) from Engel and Engel (*9*). Pacific: Average of six samples from Table 1, this report. Sample D1 contains abundant plagioclase phenocrysts and is omitted from the average. Indian: Average of four samples from Wiseman (*41*) from the Carlsberg Ridge. Abyssal hill, one sample; 2000 km west of Australia, depth 4885 m, Korzhinsky (*33*).

Compound	Atlantic	Pacific	Indian	
			Carlsberg Ridge	Abyssal hill
SiO_2	49.78	50.25	51.81	51.13
TiO_2	1.29	1.56	1.88	0.35
Al_2O_3	16.92	16.09	15.56	15.20
Fe_2O_3	1.94	2.72	3.56	1.16
FeO	7.32	7.20	6.39	7.64
MnO	0.16	0.19	0.17	0.18
MgO	8.18	7.02	7.10	10.45
CaO	11.34	11.81	9.35	11.89
Na_2O	2.77	2.81	3.87	1.81
K_2O	0.16	0.20	0.11	0.19
P_2O_5	.14	.15	.20	*

* Not determined.

Crustal Composition

Quite obviously, immediate targets for field work are the abyssal hills and the deeper oceanic layers. Abyssal hills include incipient volcanoes, as well as faulted blocks and features of less obvious origin at depths in excess of 4000 meters (*16*). To date only one dredge haul from what may be an abyssal hill has been described (*33*). This haul, made by oceanographers of the Soviet Union, was obtained in 4885 meters of water at a locality "2000 kilometers west of Australia" (Table 4). The rock is very clearly a low-potassium tholeiitic basalt, essentially identical with those found on the deeper parts of oceanic ridges and rises.

The compositions of the so-called "second" or "intermediate" crustal layers of the rise are almost equally ambiguous. The low-potassium tholeiite cored in the experimental Mohole may represent the top of this second layer, although this is not clearly so. More probable constituents of oceanic layer 2 are the faulted fragments of basalt and diabase dredged by Scripps expeditions from four localities at the base and top of the Mendocino fracture zone. We have studied all these rocks and find that they are variously altered, generally coarser-grained, but otherwise typical low-potassium tholeiites.

Melting of the Mantle

The uniformity in composition of the nonporphyritic and glassy tholeiites from three oceans also suggests that they could be complete melts of the upper mantle. If so, we are provided with a direct measure of its composition, at least at depths of around 50 to 100 kilometers, where seismic observations suggest oceanic magmas are generated (*34*). This is, of course, neither a necessary conclusion nor one consistent with all the data.

The alternative, that they are partial melts, has some fascinating implications. Both the differentiation we infer for oceanic basalts and the secular differentiation of continents are characterized by the concentration of the radiogenic elements at and near the earth's surface (*4*). The low-potassium tholeiitic basalts of the oceans are almost surely the least radiogenic of all common igneous rocks. Although accurate measurements of uranium and thorium on these tholeiites are incomplete, it is possible to reason by analogy with the carefully studied low-potassium tholeiites (especially those from Hawaii) and from concepts of chemical coherence. The Hawaiian tholeiites with less than 1500 parts K per million commonly contain less than 0.2 part U, 0.4 part Th, and 0.5 part Pb per million (*35*). The ratio of K to Rb is about 1200 (*36*). The ratio of K to U appears to be about 10^4, as in other igneous rocks of the terrestrial crust and unlike the much higher ratio in chondritic meteorites. Hence as Gast, Wesserburg *et al.*, and others have noted, a chondritic composition seems improbable for the upper mantle (*37*). The petrologic data suggest a rock closely akin to calcium-rich achondritic meteorites.

The concept of partial melting also implies that the total mantle is even more impoverished in K, U, and Th than the least radiogenic oceanic tholeiite. The degree of impoverishment is presumably a function of the degree of partial melting. Hence, accurate measurements of U and Th and of the isotopic composition of Pb and Sr in oceanic tholeiites will impose more rigorous restrictions on hypotheses of the kind and origin of mantle materials, its secular differentiation, processes of magma generation, and heat flow (*37, 38*).

Summary

The apical parts of large volcanoes along the East Pacific Rise (islands and seamounts) are encrusted with rocks of the alkali volcanic suite (alkali basalt, andesine- and oligoclase-andesite, and trachyte). In contrast, the more submerged parts of the Rise are largely composed of a tholeiitic basalt which has low concentrations of K, P, U, Th, Pb, and Ti. This tholeiitic basalt is either the predominant or the only magma generated in the earth's mantle under oceanic ridges and rises. It is at least 1000-fold more abundant than the alkali suite, which is probably derived from tholeiitic basalt by magmatic differentiation in and immediately below the larger volcanoes.

Distinction of oceanic tholeiites from almost all continental tholeiites is possible on the simple basis of total potassium content, with the discontinuity at 0.3 to 0.5 percent K_2O by weight. Oceanic tholeiites also are readily distinguished from some 19 out of 20 basalts of oceanic islands and seamount cappings by having less than 0.3 percent K_2O by weight and more than 48 percent SiO_2. Deep drilling into oceanic volcanoes should, however, core basalts transitional between the oceanic tholeiites and the presumed derivative alkali basalts.

The composition of the oceanic tholeiites suggests that the mantle under the East Pacific Rise contains less than 0.10 percent potassium oxide by weight; 0.1 part per million of uranium and 0.4 part of thorium; a potassium:rubidium ratio of about 1200 and a potassium: uranium ratio of about 10^4.

References and Notes

1. H. W. Menard, *Science* **132**, 1737 (1960).
2. H. H. Hess, in *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, New York, 1962) pp. 599, 607; J. Ewing and M. Ewing, *Bull. Geol. Soc. Am.* **70**, 291 (1959); B. C. Heezen, in *Continental Drift*, S. K. Runcorn, Ed. (Academic Press, New York, 1962), vol. 20.
3. H. H. Hess, in *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, New York, 1962) p. 599; H. W. Menard, *Phys. Chem. Earth*, in press.
4. A. E. J. Engel, *Science* **140**, 143 (1963).
5. M. N. A. Peterson and E. D. Goldberg, *J. Geophys. Res.* **67**, 3477 (1962); V. H. Nieman, *Aufschluss* **14**, 327 (1963).
6. C. G. Engel and A. E. J. Engel, *Science* **140**, 1321 (1963).
7. ———, *Bull. Am. Assoc. Petrol. Geol.* **45**, 1799 (1961).
8. Tholeiite is commonly defined as a basaltic rock nearly or slightly oversaturated with silica (*25*). Constituent olivine is commonly partly corroded and replaced by pyroxenes.
9. A. E. J. Engel and C. G. Engel, *Science* **144**, 1330 (1964).
10. M. C. Bandy, *Bull. Geol. Soc. Am.* **48**, 1589 (1937).
11. B. C. Heezen and M. Ewing, in *The Sea* (Interscience, New York, 1963), vol. 3, p. 388; B. C. Heezen and H. W. Menard, *ibid.*, p. 233.
12. R. P. Von Herzen and S. Uyeda, *J. Geophys. Res.* **68**, 4219 (1963); R. P. Von Herzen and A. E. Maxwell, *ibid.* **69**, 741 (1964).
13. W. H. K. Lee, *Rev. Geophys.* **1**, 449 (1963).
14. R. W. Raitt, *Bull. Geol. Soc. Am.* **67**, 1623 (1956); H. W. Menard, *Science* **132**, 1737 (1960).
15. F. Chayes, *J. Geophys. Res.* **68**, 1519 (1963).
16. H. W. Menard, *Marine Geology of the Pacific* (McGraw-Hill, New York, 1964), p. 76.
17. H. H. Hess, *Geol. Soc. Am. Mem.* **80** (1960); L. R. Wager and W. A. Deer, *Medd. Groenland* **105**, 1 (1939).
18. G. A. Macdonald and T. Katsura, in "The crust of the Pacific Basin," *Am. Geophys. Union Monogr. No. 6* (1962); H. A. Powers, *Geochim. Cosmochim. Acta* **7**, 77 (1955).
19. A. La Croix, *Ann. Inst. Oceanog.* **18**, 289 (1939).
20. L. J. Chubb and C. Richardson, *Bull. Bernice P. Bishop Museum* **10**, 1 (1933).
21. A. F. Banfield, C. H. Behre, Jr., D. St. Clair, *Bull. Geol. Soc. Am.* **67**, 215 (1957).
22. R. L. Fisher and R. M. Norris, *ibid.* **71**, 497 (1960).
23. J. G. Moore, abstract, Geol. Soc. Am. Meetings, 27–28 March 1964, Seattle, Wash.
24. W. R. Riedel, H. S. Ladd, J. I. Tracey, Jr., M. N. Bramlette, *Bull. Am. Assoc. Petrol. Geol.* **45**, 1793 (1961).
25. W. Cross, J. P. Iddings, L. V. Pirsson, H. S. Washington, *J. Geol.* **10** (1902).
26. G. A. Macdonald, *Geol. Soc. Am. Bull.* **60**, 1541 (1949); H. A. Powers, *Geochim. Cosmochim. Acta* **7**, 77 (1955).
27. E. F. Osborn, *Am. Mineralogist* **47**, 211 (1962).
28. W. Hamilton, *Intern. Geol. Congr. 21st, Copenhagen, 1960, Norden* (1960), vol. 13, p. 59.
29. H. Kuno, *Bull. Volcanol.* **20**, 37 (1959).
30. H. S. Yoder, Jr., and C. E. Tilley, *J. Petrol.* **3**, 342 (1962).
31. B. T. C. Davis and J. L. England, *J. Geophys. Res.* **69**, 1113 (1964).
32. H. W. Menard, *Phys. Chem. Earth*, in press.
33. D. S. Korzhinsky, *Izv. Akad. Nauk SSSR, Ser. Geol.* **12**, No. 9 (1962).
34. J. P. Eaton and J. Murata, *Science* **132**, 925 (1960).
35. K. S. Heier and J. J. W. Rogers, *Geochim. Cosmochim. Acta* **27**, 137 (1963); C. Patterson, personal communication, March 1964.
36. P. Lessing, R. W. Decker, R. C. Reynolds, Jr., *J. Geophys. Res.* **68**, 5851 (1963).
37. P. W. Gast, *J. Geophys. Res.* **65**, 1287 (1960); G. J. Wasserburg, G. J. F. MacDonald, F. Hoyle, W. A. Fowler, *Science* **143**, 465 (1964).
38. S. P. Clark, Jr., and A. F. Ringwood, *Rev. Geophys.* **2**, 35 (1964); G. F. J. MacDonald, *J. Geophys. Res.* **64**, 1967 (1959); *ibid.* **67**, 2489 (1961).
39. C. W. Correns, *Chem. Erde* **5**, 8 (1930).
40. G. D. Nicholls, *Science Progr. London* **51**, 19 (1963).
41. J. D. H. Wiseman, "The John Murray Expedition, 1933–34," *Publ. Brit. Mus. Geol. Mineral. Invest.* **3**, 1 (1940).
42. We express appreciation for the interest and help of our colleagues at the Scripps Institution of Oceanography, University of California at San Diego, especially G. Arrhenius, Fred Dixon, Robert Fisher, Jeffrey Frautschy, R. P. Von Herzen, Carl Hubbs, H. W. Menard, and Roger Revelle. Research supported by ONR, NSF (gp 2364), University of California, and the U.S. Geological Survey.