Reports

Composition of Basalts from the Mid-Atlantic Ridge

Abstract. *Studies of volcanic rocks in dredge hauls from the submerged parts of the Mid-Atlantic Ridge suggest that it consists largely of tholeiitic basalt with low values of K, Ti, and P. In contrast, the volcanic islands which form the elevated caps on the Ridge are built of alkali basalt with high values of Ti, Fe^{3+}, P, Na, and K. This distinct correlation between the form of the volcanic structures, elevation above the sea floor, and composition suggests that the islands of alkali basalt are derived from a parent tholeiitic magma by differentiation in shallow reservoirs. The volume of low-potassium tholeiites along the Mid-Atlantic Ridge and elsewhere in the oceans appears to be many times that of the alkali basalts exposed on oceanic islands. Tholeiitic basalts with about 0.2 K_2O appear to be the primary and predominant magma erupted on the oceanic floor.*

Studies of four dredge hauls, collected along parts of the Mid-Atlantic Ridge between latitudes 22° South and 5° North, indicate that all of the rocks recovered are tholeiitic basalts with from 0.08 to 0.32 percent K_2O by weight. Published analyses of basalts from three other dredge hauls taken at widely separated sites along the ridge also indicate that very similar tholeiites with low potassium contents are the only basalts and the principal rock type (*1, 2*). The distribution of these dredge sites along the Mid-Atlantic Ridge and their position relative to volcanic islands are shown in Fig. 1. Chemical analyses of the dredged basalts and specific depths of our dredge sites and of those reported by Correns are given in Table 1. The depths of the dredge hauls described by Nichols are estimated from the locations cited in his text (*2*).

Several features of these tholeiites from the Mid-Atlantic Ridge are of special interest. One is the striking similarity in chemical composition of these basaltic rocks dredged from widely separated sites along the ridge. The relatively low concentrations of Ti, Na, K, and P in all of the analyzed specimens are especially noteworthy.

Recently, we drew attention to tholeiites of nearly identical composition cored from the experimental Mohole and dredged from fault scarps, ridges, and low hills in the Pacific Ocean (*3*). Students of Hawaiian geology have also noted the basement of tholeiite upon which the Hawaiian shield volcanos have been built (*4, 5*). In effect, these tholeiites appear to be the predominant rock type along submerged ridges, scarps, and hills in the Atlantic Ocean, the Pacific Ocean, and in the Indian Ocean (*6, 7*).

Another feature of special interest is the marked contrast in composition between the tholeiitic basalts from the submerged parts of the Mid-Atlantic Ridge and the olivine-bearing alkali basalts that dominate the volcanic islands on and near the Ridge. The islands in the Atlantic Ocean along or near the Mid-Atlantic Ridge, with the exception of St. Paul's Rocks, are composed almost entirely of olivine alkali basalt, with very subordinate andesite, trachyte, and phonolite (*8*). St. Paul's Rocks are composed of serpentinite and serpentinized peridotite, and have been presumed by Hess and others to represent a fragment of mantle extruded by convective overturn (*9, 10*).

Our present knowledge of the nature of pyrogenic rocks of the Mid-Atlantic Ridge may be summarized as follows. (i) Islands on and near the Ridge are composed almost entirely of alkali basalt relatively enriched in K, Na, Ti, Fe^{3+}, and P. Very subordinate derivative alkali-andesite, trachyte, and phonolite also appear in close association with the alkali basalt. (ii) In contrast, the more submerged parts of the Mid-Atlantic Ridge appear to be composed very largely of tholeiitic basalt with very low potassium content. (iii) Minor amounts of peridotite and serpentinite such as that at St. Paul's Rocks also exist at several localities along the Ridge and have been dredged from scarps and trenches. Most of these ultrabasics also are probably cumulative rocks formed in conjunction with the differentiation of the associated basalts, although a more primitive origin is not impossible.

The form and extent of the Mid-Atlantic Ridge as defined by the 2000-fathom (3600-meter) contour are shown in Fig. 1, as are the location of associated volcanic islands, St. Paul's Rocks and known dredge hauls. Ewing and Ewing, and Heezen have described the Mid-Atlantic Ridge as a broad swell, several hundred miles wide with a rugged crest rising about 2000 fathoms above the eastern and western Atlantic basins (*11, 12*). One of the most striking features of the Ridge is its median position between the Americas on the west and Europe and Africa on the east. Extensions of the Ridge continue northward through Iceland into the Arctic Ocean and southeastward into the Indian and Pacific Oceans (*13*). Precise soundings taken across the Ridge indicate the presence of a rift zone which seems to follow closely the crest of the Ridge, at least in those areas explored to date. Seismic data suggest that the rift zone coincides with a belt of earthquakes, at least within the accuracy of epicentral determinations (*9, 10*). Heat flow along the ridge appears to vary widely; values as low as 0.3×10^{-6} cal cm^{-2} sec^{-1} and as high as 6.5×10^{-6} cal cm^{-2} sec^{-1} have been recorded (*14*). Many investigators have suggested that the Mid-Atlantic Ridge is composed of rocks derived from the mantle, and extruded into a ridge-like form by the rising limbs of two large juxtaposed convective cells (*10; 11*, p. 308). These investigators envision major convective patterns that are inferred to have breached a super-continent previously floating in the middle Atlantic. The westerly cell is presumed to have dragged one large fragment of this super-continent, the Americas, to their present position. The opposed, easterly cell, has purportedly dragged the other continental fragment, Europe and Africa, eastward to their present sites.

Expanding upon the effects of this postulated major convective pattern, Hess has suggested that much of the

Mid-Atlantic Ridge and the oceanic layer itself may be serpentinite, and serpentinous peridotite similar to that found on St. Paul's Rocks (*15*). Most other workers have suggested that the ridge is largely, if not wholly, analogous in composition to the volcanic islands scattered along its crest and flanks (*7, 11, 16*). These volcanic islands are, from south to north, Bouvet, Gough, Tristan da Cunha, St. Helena, Ascension, and the Azores (Fig. 1).

Continuing studies of these islands during the past several decades have indicated very clearly the dominance of one rock type, alkali basalt, having the approximate composition indicated in Table 1, column 11. These alkali basalts not only dominate the Atlantic islands; they are, with the notable exception of the Hawaiian chain, the dominant rock on most islands throughout all of the oceans (*17*). The chemical characteristics of these rocks are striking and include a K_2O content (as percent by weight) that commonly exceeds 1.0 and averages about 1.5, and a Na_2O content that commonly exceeds 3.0 and averages about 3.3. Their TiO_2 content usually exceeds 1.7 and averages about 3.0; P_2O_5 varies from 0.3 to as much as 0.7 and averages about 0.45 percent by weight. The CIPW norms (*18*) of many of these alkali basalts contain nepheline or acmite or both, and nepheline and other feldspathoids are actually reported as constituent minerals in the groundmass of some samples.

Chayes has suggested from extended statistical studies of published chemical analyses, that more than 90 percent of oceanic basalts can be distinguished from circum-oceanic basalt on the basis of either their TiO_2 content being greater than 1.75, or the normative Ne+Ac content being greater than zero, or both (*19*). Nearly all of the analyses available to Chayes were necessarily of alkali basalts taken from oceanic islands. The tholeiitic basalts recently obtained in dredge hauls in the Atlantic, Pacific, and Indian Oceans suggest that Chayes' generalization may be valid only for the oceanic islands and seamounts—that is, the highest volcanic edifices in the oceans. On most of these islands and on many seamounts there is no doubt that alkali basalts like those of Table 1, column 11, predominate over all other igneous rocks by one to ten orders of magnitude. In the Atlantic Ocean the ratio of alkali basalts to all other rocks, presumably derivative largely via differentiation, ranges from 10 : 1 to 100 : 1, and the average ratio for all Atlantic islands is probably about 50 : 1 (*17, 20*). In these instances the subordinate rock types are largely alkali-andesite, trachyte, and phonolite, with traces of serpentinite, peridotite, rhyolite, and pyroxenite.

The marked contrast in chemical composition between the alkali basalts of Atlantic islands and the submarine tholeiites dredged from the Mid-Atlantic Ridge is shown in Table 1. The submarine tholeiites contain much less Ti, Fe^{3+}, Na K, and P, and more Ca than do the alkali basalts of the islands. There may be other, more subtle distinctions that might be delineated with much more data, such as the differences in content of silica, magnesia, and alumina that are suggested, but not proven, by the existing data summarized in the averages, Table 1, columns 10 and 11.

The differences in TiO_2 content are very marked. Titania in the dredged

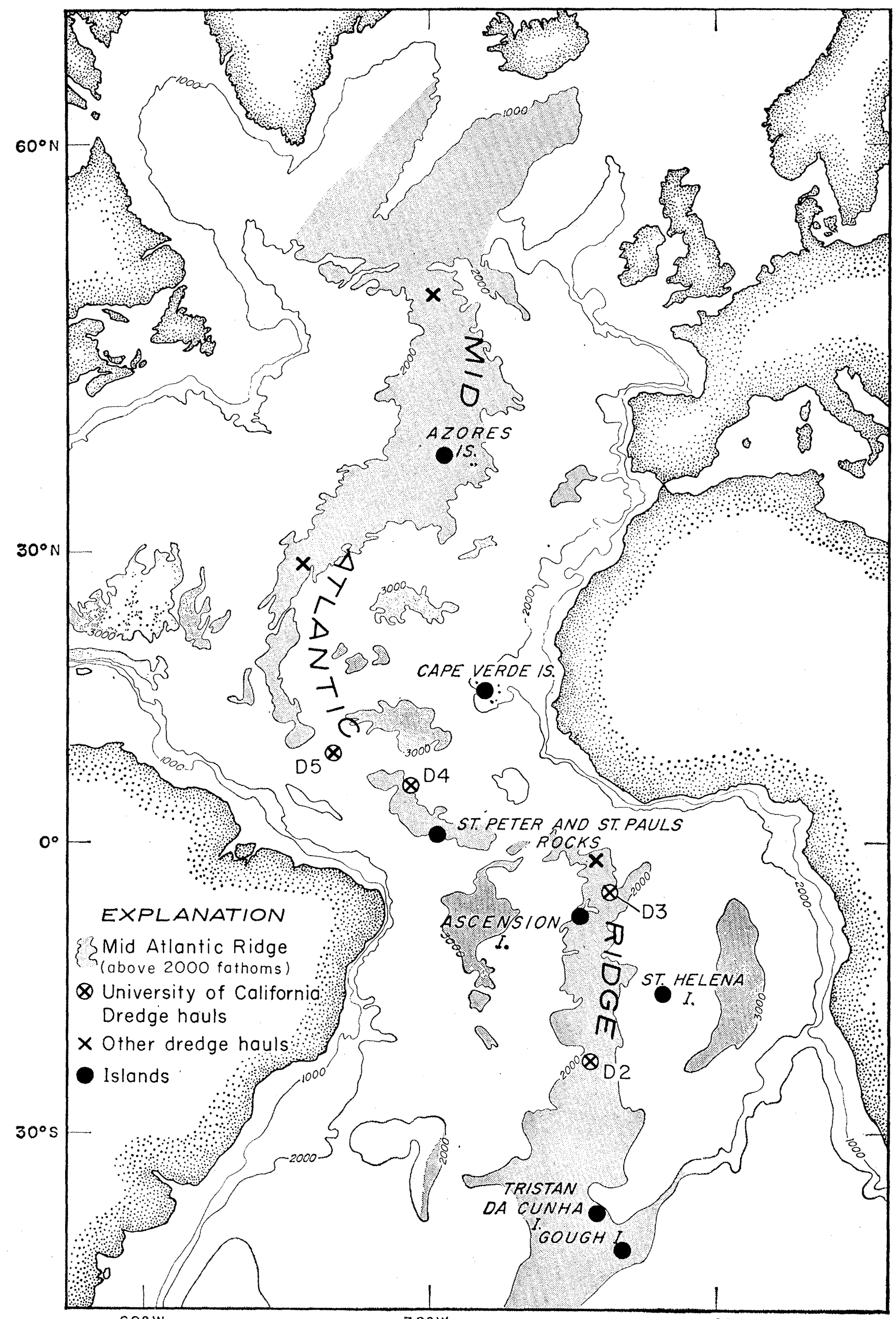

Fig. 1. A map of the Atlantic Ocean showing the Mid-Atlantic Ridge above 2000 fathoms (3600 m) and the location of dredge samples and islands discussed in the text.

tholeiites rarely exceeds 2.0 and the average for eight samples from widely separated localities is 1.23 percent of TiO_2 by weight (Table 1, column 10). This means, of course, that contrary to the suggestions in Chayes' study, the more deeply submerged oceanic basalts cannot be distinguished from circumoceanic basalts on the basis of their titania content; but the distinction, based upon titania, between alkali basalts of the higher volcanic cones in the oceans and circumoceanic basalts still stands (*17*). Over 90 percent of the alkali basalts of the oceanic islands do have a TiO_2 content greater than 1.75. Quite obviously, the other distinction cited by Chayes—that most oceanic basalts have nepheline or acmite or both in the norm—must also be restricted to basalts from the highest oceanic volcanoes. None of the tholeiites dredged from the more submerged parts of the oceans have either nepheline or acmite in the norm.

Phosphorus in the tholeiites dredged from the Mid-Atlantic Ridge ranges from 0.08 to 0.23 percent of P_2O_5 by weight, and averages about 0.15. This is about one-third the P_2O_5 found in alkali basalts of volcanic islands associated with the Mid-Atlantic Ridge (compare columns 10 and 11, Table 1). Actually, the ratio Ti/P in both tholeiites and alkali basalts is approximately the same, between 9 and 10, and, as Vogt noted long ago, these elements appear to vary sympathetically throughout many species of igneous rocks (*21*). Amounts of phosphorus in oceanic basalts appear to be of considerable value in interpretations of their origin and nature and analyses for phosphorus will have to be made with greater accuracy in the future.

The differences in degree of oxidation between the alkali basalts and the submarine tholeiites is equally marked. The dredged tholeiites that are devoid of obvious alteration have a ratio of Fe_2O_3/FeO of about 0.3 or less. Most alkali basalts from the volcanic islands and seamounts have a ratio of Fe_2O_3/FeO greater than 0.5 and in many of these alkali basalts this ratio approaches 0.7. These comparisons are complicated, however, by the marked oxidation, hydration and alteration found in most submarine lavas. Many basalts from both seamounts and sea floor are altered during and within a few hundred years of their initial contact with sea water. Mineralogical changes that frequently accompany this alteration are the successive replacement of olivine, opaque oxides, pyroxene, and finally plagioclase by clay minerals, zeolites, limonite, chlorite, and other hydrated minerals.

Analyses cited by Correns and by Nicholls are reported to be of unaltered basalt and basaltic glass, and the tholeiites analyzed in this study are relatively fresh. Nevertheless, the hydration and oxidation indicated by the analysis of sample D4 (Table 1, column 4) are probably the result of interaction of sea water and tholeiitic basalt. The abundant water recorded in several of the dredged basalts is a major reason for calculating the averages on a water-free basis (Table 1, columns 10 and 11).

Perhaps the most striking compositional differences between the tholeiites of the Mid-Atlantic Ridge, and the alkali basalts of the islands (and indeed most other basalts of the world), are those reflected by the contrasts in alkali content, especially potassium. The K_2O content of the submarine tholeiites varies from 0.08 to 0.32 and averages about 0.18 percent by weight (Tables 1 and 2). The total amount of Na_2O+K_2O averages about 3 percent and rarely exceeds 3.3 percent by weight. Few alkali basalts on Atlantic islands have less than 1.0 percent K_2O and the average is about 1.5 percent. Total Na_2O+K_2O in the alkali basalts commonly exceeds 4.0 and averages about 4.85 percent by weight. Most tholeiites on continents average at least 0.5 K_2O although there are some rare, and possibly significant exceptions (*22, 23*).

The actual mineralogy and texture of the oceanic tholeiites varies widely, but diabasic textures appear to be characteristic of most of these rocks that are largely crystalline. Sample D5-5 (Table 1, column 4) is an augite diabase with approximately (in volume percent) 50.6 plagioclase, 39.2 pale pink augite, 1.6 olivine, 6.4 opaque minerals (largely titaniferous magnetite) and 2.2 fine-grained interstitial minerals and alteration products. We have found approximate analogues to this diabasic tholeiite in the core from the experi-

Table 1. Chemical composition of tholeiitic basalts dredged from the Mid-Atlantic Ridge and the average composition of alkali basalts from volcanic islands along the ridge.

Oxide	D2-1* 20°40'S 13°16'W	D3* 5°47'S 11°25'W	D4* 6°03'N 32°22'W	D5-5* 9°39'N 40°27'W	D5-18* 9°39'N 40°27'W	Correns† 1°56'S 12°41'W	Nicholls‡		Av. composition	
							28°54'N 43°19'W	50°44'N 29°52'W	Tholeiite§	Alkali Basalt‖
SiO_2	49.20	49.48	48.54	49.02	50.13	49.54	48.13	50.47	49.89	47.79
TiO_2	2.03	1.39	1.50	1.46	0.86	0.78	0.72	1.04	1.23	3.03
Al_2O_3	16.09	16.72	16.70	18.04	19.65	16.47	17.07	15.93	17.28	15.94
Fe_2O_3	2.72	1.16	3.56	1.58	1.86	2.30	1.17	0.95	1.93	3.76
FeO	7.77	7.58	4.95	6.22	4.77	7.55	8.65	7.88	7.00	7.46
MnO	0.18	0.19	0.18	0.13	0.12	0.19	0.13	0.13	0.16	0.15
MgO	6.44	8.20	7.12	7.85	5.95	7.91	10.29	8.75	7.90	6.83
CaO	10.46	11.14	11.31	11.51	12.57	11.43	11.26	11.38	11.51	9.77
Na_2O	3.01	2.66	2.98	2.92	2.77	2.62	2.39	2.60	2.77	3.28
K_2O	0.14	0.24	0.14	0.08	0.21	0.30	0.09	0.10	0.16	1.54
H_2O+	.70	.62	1.50	.64	.50	.95	.27	.53		
H_2O-	.95	.61	1.20	.57	.44	.27	.02	.06		
P_2O_5	.23	.12	0.21	.12	.19	.08	.10	.11	0.15	0.45
Total	99.92	100.11	99.89	100.14	100.02	100.39	100.29	99.93		
Depth (m)	2910	2380	2982	2388	2388	2000	3000	2000		

* Dredge hauls by the University of California Research Vessel Argo, on expedition Lusiad, July 1963, analysed by C. G. Engel. † Analysis of augite, olivine basalt reported by Correns (*1*, p. 83). ‡ Analyses of basaltic glass from Nicholls (*2*, p. 19, Table 2). § Average composition, calculated on a water-free basis, of analyses of basalts in columns 2 to 9 inclusive. ‖ Average composition, calculated on a water-free basis, of alkali basalts from volcanic islands along the Mid-Atlantic Ridge.

Table 2. Variations in Na_2O and K_2O in several suites of tholeiitic basalts dredged from the Mid-Atlantic Ridge.

Dredge	Depth (m)	Na_2O	K_2O
	Position: 22°40'S; 13°16'W		
D2-1	2910	3.01	0.14
D2-4	2910	2.98	.14
D2-10	2910	2.77	.31
D2-12	2910	2.35	.20
D2-16	2910	3.37	.32
D2-20	2910	3.60	.32
D2-22	2910	3.37	.15
D2-26	2910	2.95	.14
	Position: 5°47'S; 11°25'W		
D3-2	2380	2.66	.24
	Position: 6°03'N; 32°22'W		
D4-1	2982	2.98	.14
	Position: 9°39'N; 40°27'W		
D5-5	2388	2.92	.08
D5-11	2388	2.65	.14
D5-18	2388	2.77	.21

mental Mohole and in rocks dredged from the Mendocino Seascarp and the Gorda Escarpment in the Pacific Ocean (*3, 24*). Shand also has reported similar diabasic textures and mineralogy in basalts dredged from the Mid-Atlantic Ridge (*25*). Sample D5-18 contains large phenacrysts of plagioclase, hence its chemical composition, especially the high alumina, may reflect crystal accumulation.

Samples D3 and D4 (Table 1, columns 3 and 4) are vesicular, tholeiitic basalts with minor olivine as phenocrysts set in a very fine-grained groundmass. Sample D5-5 (Table 2) contains unique feathery crystals of augite, somewhat similar to the form of augite crystals in basalt cored in the experimental Mohole.

The uniformity in composition of submarine tholeiites from widely separated points along the Mid-Atlantic Ridge, coupled with the compositional contrasts between them and the alkali basalts of the associated islands, raise many questions. The Mid-Atlantic Ridge is but a segment of the vast Mid-Ocean Ridge system which appears to have extensions aggregating more than 40,000 miles (64,000 km) along the axes of the Atlantic, Indian, South Pacific, and Arctic Oceans (*13*). Although the volcanic islands scattered along these ridges are built almost entirely of alkali basalt, the several dredge hauls of igneous rocks from the flanks of the ridges, and from the surrounding sea floor are all essentially identical to the tholeiites we have analyzed (Tables 1 and 2).

Our studies in both the Atlantic and Pacific Oceans suggest that the major parts of this vast Mid-Ocean Ridge system are composed largely of tholeiite with a low potassium content, upon which locally differentiated alkali basalts have been extruded to form the higher volcanic carapaces. Moreover, tholeiites of low potassium content appear to be the dominant igneous rock throughout at least the upper parts of the entire oceanic crust.

The extent of alkali basalts below the surface, or perhaps more accurately, down the flanks of the Mid-Atlantic ridge, has yet to be determined; but they clearly dominate all volcanic cones built from 3500 to 5500 m above the ocean floor. Tholeiites with low values of Ti, Na, K, and P are predominant along the Mid-Atlantic Ridge to elevations of some 2500 m above the ocean floor. This seeming dependence of composition upon elevation appears to argue eloquently for the derivation of the elevated alkali basalt cones from a parent tholeiitic magma by gravity differentiation.

Some possible processes operative during this differentiation are elaborated in studies by Powers, Stearns, and Macdonald, Yoder, Tilley, and others (*5, 26*). Certainly the more equant shape and great height of the conduits inferred for the elevated volcanic cones would seem ideally suited to the crystallization and settling of olivine and subordinate pyroxene from a cooling column of lava leaving a more alkali basalt melt in the upper sections of the conduit. Lavas in these same conduits, and in associated craters and chambers, would also be most influenced by oxidative and fluxing effects of infiltrating rain and sea water. These concepts appear to be strengthened by the fact that the known fissure (flood) basalts throughout the earth's crust are largely tholeiitic in nature, with relatively low alkalis, water (+110°C) and ferric iron.

Hence, the height, shape, and origin of the conduit appear to be major factors in the diversification in basalts. But quite clearly, studies of the origin and differentiation of these and related volcanic rocks are in their infancy.

Note added in proof: Recent studies by Frey and Haskin (*27*) of rare earths in oceanic tholeiites from the Mid-Atlantic Ridge indicate "primitive" abundance distribution patterns, "barely altered from that characteristic of chondritic meteorites." The lack of marked fractionation of the rare earths in oceanic tholeiites, from a presumed primordial distribution, is completely consistent with the assumption that these tholeiites represent the primary magma erupted from the mantle.

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