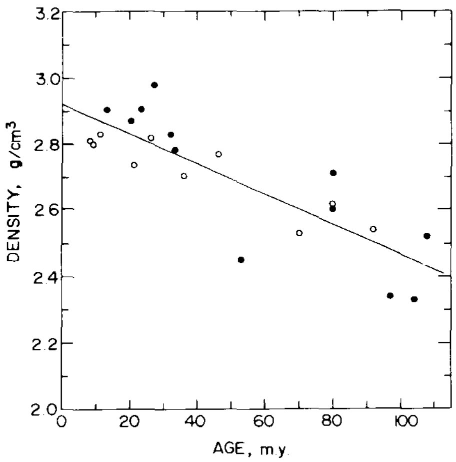

Figure 1. Mean density-age relations for layer 2 basalt. ○ = **sills and probable sills;** ● = **extrusive and probable extrusive rocks.**

Progressive Weathering of Submarine Basalt with Age: Further Evidence of Sea-Floor Spreading

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ABSTRACT

Densities of layer 2 basalt recovered during the Deep Sea Drilling Project have been found to decrease steadily with age, a finding ascribed to progressive submarine weathering in the context of sea-floor spreading. The least-squares solution for 52 density measurements gives a rate of decrease in density of $\Delta\rho/\Delta t = -0.46 \times 10^{-2}$ g per cm^3 m.y. = −16 percent per 100 m.y., which is in excellent agreement with earlier estimates based on observed chemical depletion rates of dredged oceanic basalt. Weathering of sea-floor basalt, should it penetrate to any considerable depth in layer 2, will decrease layer 2 seismic refraction velocities, act as a source of geothermal heat, and substantially influence the chemistry of sea water and the overlying column of sediment.

INTRODUCTION

Basalt extruded onto the sea floor during the formation of new oceanic crust, though suffering little subsequent mechanical erosion, should display evidence of progressive chemical alteration with age due to prolonged exposure to sea water. Direct evidence of this alteration has been observed in samples dredged from the sea floor (for example, see Hart, 1970, 1972; Hekinian, 1971). In a study of basalt samples retrieved from the uppermost few meters of oceanic layer 2 during Legs 2, 3, and 4 of the Deep Sea Drilling Project, we noted a pronounced decrease density of basalt with age at the rate of 18 percent per 100 m.y. (Christensen and Salisbury, 1972). This finding, attributed to increasing content of alteration products resulting from progressive submarine weathering, was regarded as tentative, due to the limited number of sites studied and to the uncertainty of the intrusive-extrusive relations at these sites.

These early results have now been substantiated by expanding the study to include basalt from DSDP Legs 5, 6, 7, 9, and 14, allowing a total of 52 density measurements from basalt recovered at 22 drill sites. Bulk densities of the Pacific basalt samples were obtained from the dimensions and weights of machined cores 1.3 cm in diameter and 2 to 4 cm in length. Vesicularity was less than 1 percent by volume for all cores. Density measurements, basement age (as interpreted from magnetic and paleontologic evidence), and contact relations for the basalt from each site are presented in Table 1. The relation between mean density and basement age for each site is shown in Figure 1.

DISCUSSION AND CONCLUSIONS

Although some scatter is present, the oceanic basalt samples plotted in Figure 1 clearly display a pronounced decrease in density with age. The least-squares solution for all points in Figure 1 give a rate of decrease in density of

$$\Delta\rho/\Delta t = -0.46 \times 10^{-2} \text{ g/cm}^3 \text{ m.y.} = -16 \text{ percent per } 100 \text{ m.y.},$$

in excellent agreement not only with our earlier findings (Christensen and Salisbury, 1972) but also with an independently computed value of

$$\Delta\rho/\Delta t = -0.38 \times 10^{-2} \text{ g/cm}^3 \text{ m.y.} = -15 \text{ percent per } 100 \text{ m.y.}$$

based on observed chemical depletion rates in dredged oceanic basalt (Hart, 1970; Hekinian, 1971). This observed decrease in density of layer 2 basalt with age is most logically explained in terms of the concept of sea-floor spreading. Young basalt, newly extruded at the ridge crest, is expected and observed (Christensen, 1972) to be fresh and dense; with increasing age and exposure to submarine weathering, the basalt displays increasing alteration and a resultant steady decrease in density.

Departures from the trend shown in Figure 1 are expected to be found in basalt which has undergone extensive hydrothermal alteration or which is the product of neovolcanism in old terrain. The effects of these two phenomena should be opposing; hydrothermal alteration (for example, chloritization) will generally lower the basalt density, whereas neovolcanism that is significantly younger than the sea floor will introduce basalt, generally as sills, that appears anomalously dense.

Despite these reservations, no clear distinction can be made in Figure 1 between weathering trends of basalt in sills and extrusive rocks. It is clear, however, that both sill and extrusive rocks decrease in density with age, suggesting that weathering continues unabated beneath the accumulating sediment pile, perhaps through an exchange process involving the overlying water-laden sediments.

Weathering of layer 2 basalt, should it prove extensive, would have several important geochemical and geophysical implications:

1. Since seismic wave velocities through submarine basalt have been found to vary linearly with density (Christensen and Salisbury, 1972), pervasive weathering of layer 2 basalt to a depth of a few hundred meters should be seen in refraction studies as a decrease in layer 2 seismic velocities with age. This effect has, in fact, been observed both in laboratory studies of seismic wave velocities through submarine basalt and in regional studies of refraction velocities in layer 2 (Christensen and Salisbury, 1972).

2. It has been apparent for some time that the chemistry of sea water and of the sediment column are influenced by chemical interaction with the underlying basement rocks. Once the depth of penetration of submarine weathering is known, this influence can be quantitatively evaluated.

3. Since weathering is an exothermal process, a source of geothermal heat in addition to radioactive decay resides in the

TABLE 1. BASALT DENSITY, BASEMENT AGE, AND INTRUSIVE/EXTRUSIVE RELATIONS FROM DSDP LEGS 2 THROUGH 7, 9, AND 14

Site	Bulk density (g/cm³)	Mean bulk density (g/cm³)	Age of oldest overlying sediment (m.y.)	Remarks	References
Leg 2					
10	2.611 2.619 2.632	2.621	80	Probable sill	Peterson and others (1970)
Leg 3					
14	2.762 2.780	2.771	46	Probable sill	Maxwell and others (1970)
15	2.892 2.920	2.906	23 (21*)	Probable extrusive	Maxwell and others (1970)
18	2.819 2.820	2.820	26	Probable sill	Maxwell and others (1970)
19	2.395 2.500	2.448	53 (53*)	Extrusive	Maxwell and others (1970)
Leg 4					
23	2.531 2.538 2.557	2.542	?	Sill†	Bader and others (1970)
Leg 5					
32	2.829	2.829	32 (38*)	Probable extrusive	McManus and others (1970)
36	2.900 2.909	2.905	13 (8*)	Probable extrusive	McManus and others (1970)
Leg 6					
54	2.867 2.869 2.873 2.877	2.872	20	Extrusive	Fischer and others (1971)
57	2.955 2.004	2.980	27	Extrusive	Fischer and others (1971)
Leg 7					
61.0	2.676 2.726 2.734	2.712	80	Probable extrusive	Winterer and others (1971)
61.1	2.562 2.605 2.641	2.603	80	Probable extrusive	Winterer and others (1971)
63.0	2.697 2.780 2.881	2.786	33	Extrusive	Winterer and others (1971)
66.0	2.336 2.348	2.342	97	Extrusive	Winterer and others (1971)
Leg 9					
77B	2.693 2.716	2.705	36	Sill	Hays and others (1972)
79	2.686 2.781	2.734	21	Sill	Hays and others (1972)
82	2.801	2.801	9	Sill	Hays and others (1972)
83	2.833	2.833	11	Sill	Hays and others (1972)
84	2.809 2.812	2.811	8	Sill	Hays and others (1972)
Leg 14					
136	2.52§ 2.52§	2.52	108 (155*)	Probable extrusive	Hayes and others (1972)
137	2.25§ 2.41§	2.33	104	Extrusive	Hayes and others (1972)
138	2.49§ 2.51§ 2.57§ 2.58§	2.54	92 (112*)	Probable sill	Hayes and others (1972)
141	2.52§ 2.53§	2.53	70	Probable intrusion	Hayes and others (1972)

* *Magnetic anomaly age.*
† *Omitted from Figure 1.*
§ *Densities from Fox and others (1972).*

upper levels of layer 2 (Hart, 1972). Weathering of submarine basalt, perhaps occurring in conjunction with devitrification and exothermal metamorphic reactions, may contribute significantly to oceanic heat flow, especially in older oceanic crustal regions.

4. Finally, the discovery of a heat source high in layer 2 which contributes materially to oceanic measurements of heat flow may necessitate a downward revision of geothermal gradient estimates in the oceanic crust and upper mantle.

Since drill penetration of layer 2 during the Deep Sea Drilling Project has been only shallow to date, it has not been possible to determine the depth of weathering from drill cores. From refraction data, weathering appears to have penetrated in some regions at least a few hundred meters, but since the depth of weathering may be in part fracture controlled, it is expected to be highly variable; in any case, direct evaluation is impossible without deep drilling at several localities in layer 2. Since the magnitude of each of the geochemical and geophysical effect noted above depends critically upon the depth to which submarine weathering has penetrated, quantitative evaluation of these effects must await direct sampling during the deep-drilling phase of the International Program of Ocean Drilling.

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