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Deep Crustal Drilling in the North Atlantic Ocean

Drilling shows that the uppermost half kilometer of North Atlantic oceanic crust is unexpectedly complex.

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Summary. Oceanic crustal drilling by R.V. *Glomar Challenger* at 15 sites in the North Atlantic has led to a complex picture of the upper half kilometer of the crust. Elements of the picture include the absence of the source for linear magnetic anomalies, marked episodicity of volcanic activity, ubiquitous low temperature alteration and evidence for large scale tectonic disturbance. Comparison sections in the Pacific and much deeper crustal drilling are needed to attack problems arising from the North Atlantic results.

Until recently, our knowledge of oceanic basement rocks (conventional layers 2 and 3 of the oceanic crust) was based largely on seismic refraction studies and dredge hauls from mid-ocean ridge crests and fault scarps. Many early holes drilled by the *Glomar Challenger* for the Deep Sea Drilling Project (DSDP) reached and sampled basement, but usually only to depths of 10 meters or less. Models for the constitution and origin of the deeper parts of the oceanic crust have been based on comparison of crustal seismic velocities with laboratory measurements of rock elastic wave velocities and on the study of ophiolite complexes that are often regarded as sections of old oceanic crust.

Deep crustal drilling by *Glomar Challenger* in the Atlantic Ocean beginning in 1974, and observations made from submersibles in the median rift of the Mid-Atlantic Ridge at 36°N, have provided many new data with which to test previous models. Penetration of basement to depths greater than 500 m has been achieved at three sites and a number of shallower holes have also been drilled (Fig. 1 and Table 1).

The purpose of this article is to review the results of crustal drilling in the Atlantic Ocean and to test previous models with the new data (*1-3*). Since there will be no more drilling for at least 2 years, we also speculate on the nature of the oceanic crust and suggest questions that may be investigated by future drilling (*4, 5*).

The Model of the Oceanic Crust Prior to DSDP Leg 37

In early seismic refraction studies, the oceanic crust was interpreted in terms of a layered structure with the deeper layers having progressively higher compressional wave velocities (*6, 7*). The ocean floor sediments constituted layer 1 and the exposed basalts of the mid-ocean ridges represented the top of a 1.0- to 2.5-kilometer-thick sequence, designated layer 2. Beneath this layer, a ubiquitous 6-km-thick layer (layer 3) separated the upper crust from the mantle. Later, more detailed seismic refraction studies led to further subdivision of this simple three-layer model. In young crust, along or near mid-ocean ridge crests, an upper low-velocity layer 2A was recognized (*7, 8*). This layer, which is 0 to 1.0 km thick and has compressional wave velocities of 2.5 to 3.8 kilometers per second, overlies a lower layer 2B, with compressional wave velocities of about 5.0 km/sec. A similar twofold subdivision was also proposed for layer 3 (*9, 10*).

More recently, the refraction data have been interpreted in terms of gradual rather than stepwise increases in velocity with depth (*10, 11*). This interpretation has been given strong support by Kennett and Orcutt (*12*) and Orcutt *et al.* (*13*) from synthetic seismogram analyses. Thus, seismic "boundaries" in the crust are considered transitional in character, and distinct lithologic layers, each defined by narrow ranges of compressional wave velocities, probably do not exist.

Prior to crustal drilling, information regarding the lithology and constitution of the oceanic crust was based largely on dredge hauls from mid-ocean ridges and on comparisons of elastic wave velocities of known rock types measured in the laboratory with compressional wave velocities determined by refraction seismology (*14, 15*). The lower part of the crust was believed to consist of gabbro or mixtures of gabbro and peridotite, whereas the upper crust was believed to consist largely of pillow basalt despite the fact that compressional wave velocities of basalt in situ are much lower than the velocities of basalt samples measured in the laboratory. Fresh basalts have an average velocity of 6.0 km/sec (*15*), whereas upper crustal velocities may be as low as 2.5 km/sec. The lower velocities in situ were variously attributed to weathering and fracturing of the crustal basalts or to the presence of interlayered low-velocity sedimentary material or breccia.

Samples of oceanic basement dredged from mid-ocean ridges indicated that the

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upper crust is composed predominantly of basalt, much of which has a pillowed form typical of subaqueous eruptions. Early studies of these rocks suggested that they comprise a distinct, relatively uniform low-potassium variety of tholeiitic basalt (*16*). Further study of rocks recovered by dredging and shallow crustal drilling confirmed that oceanic basalts form a relatively homogeneous group with well-defined chemical characteristics, but with a range of compositions including ferrobasalts and some alkali olivine basalts (*17*). Cann (*18*) suggested that much of the observed chemical variation could be explained in terms of shallow-level fractional crystallization involving calcic plagioclase, forsteritic olivine, and augite. At several locations on the Mid-Atlantic Ridge, ultramafic rocks were dredged from the basement surface (*19, 20*) and from various fault scarps (*20–22*). These are partly serpentinized peridotite-gabbro complexes, some showing amphibolite facies metamorphism.

Many dredged basalts from the Mid-Atlantic Ridge showed evidence of either weathering or metamorphism (*19, 21–23*). Weathered rocks, characterized by alteration of glassy groundmass material and glassy pillow rinds, increase in abundance away from the ridge axis (*19*). Metamorphosed basalts showing pervasive alteration, including replacement of phenocryst phases by secondary minerals, are most abundant in the median rift, particularly along scarps facing the inner rift walls and along transform faults (*21*).

Magnetic surveying showed that strongly two-dimensional linear anomalies occurred over most of the ocean floor. The sharpness of the anomalies suggested a shallow source, and the division of the oceanic crust into alternately normally and reversely magnetized parallel prisms, with one prism per anomaly, was suggested as the explanation of the anomaly patterns (*24*). The high intensity of magnetization of ridge-crest dredge haul basalts (*25*), and the interpretation of near-bottom magnetic anomalies caused by topography (*26, 27*), suggested that a 200- to 500-m-thick layer at the top of basement, possibly equivalent to layer 2A of refraction seismology, was sufficient to account for the anomalies. However, basalts sampled away from the ridge crests in early shallow DSDP drill holes yielded relatively low magnetization intensities and magnetization directions divergent from expected values, requiring a source layer of about 1 km in thickness (*28*).

The possibility that seawater circu-

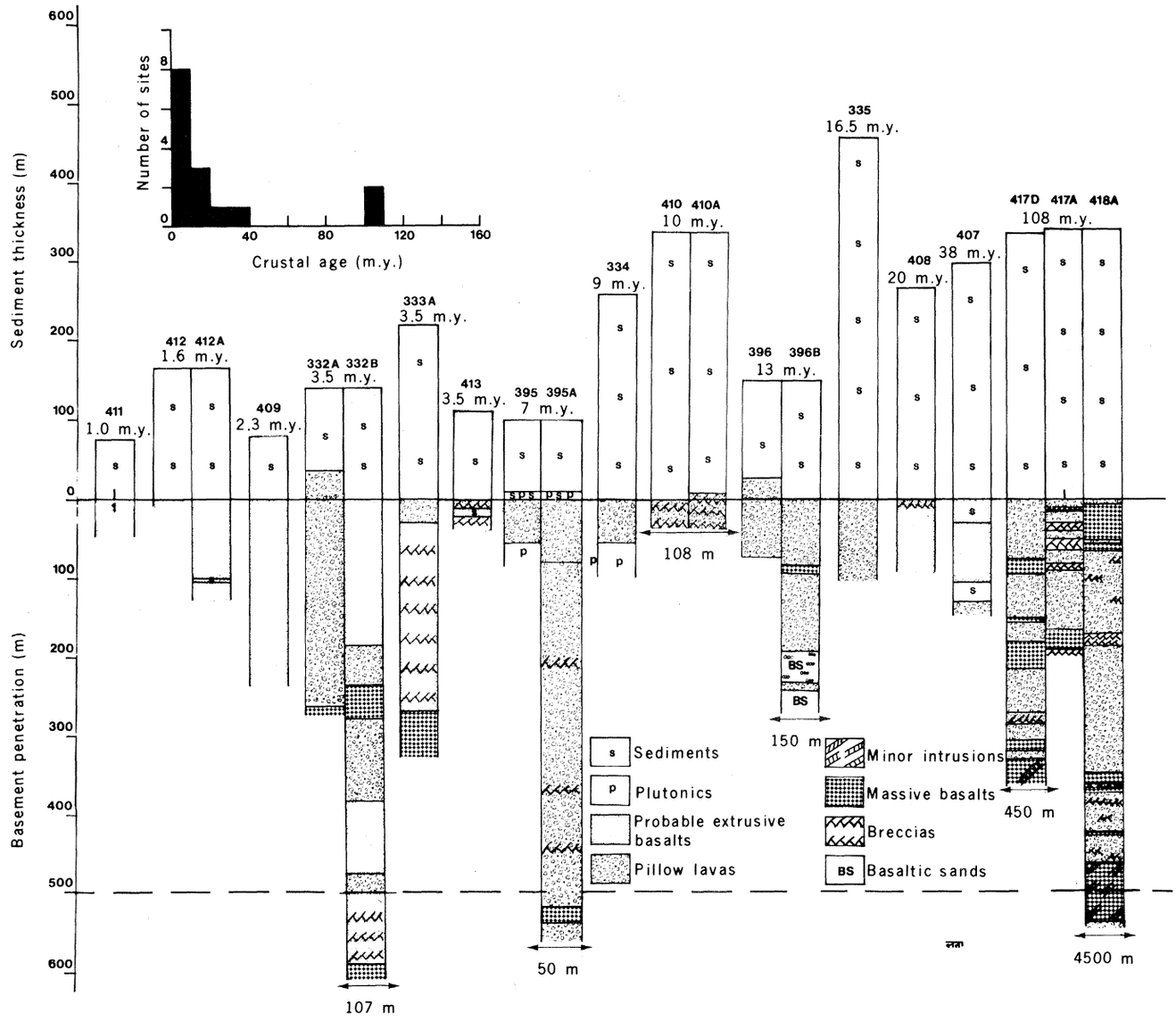

Fig. 1. Lithologic profiles in age sequence for North Atlantic basement drill holes. Inset: distribution of drill site ages.

lates to depth in newly formed oceanic crust was favored as an explanation for very irregular conductive heat-flow patterns found in ridge crest areas (*27, 29*). Alteration of newly formed oceanic crust through seawater circulation provided explanation for the decay of magnetization away from the Mid-Atlantic Ridge crust (*25*) and for the physical and chemical changes in basalts with depth and age (*30*). It was widely thought, as it is today, that ophiolite sequences represent sections of oceanic crust and upper mantle (*31*), a suggestion supported by the results of dredging on major oceanic fault scarps and by the similar velocity structures of ophiolites and oceanic crust.

By the early 1970's it was clear that the most valid means of testing this model of oceanic crust was by deep crustal drilling, and from this realization came the impetus for DSDP leg 37 and the crustal component of the recent International Program of Ocean Drilling (IPOD).

Location of Drilling Sites

Figure 2 shows the distribution of leg 37 and IPOD Atlantic basement sites. Geographically, the drill sites are concentrated on the crest of the Mid-Atlantic Ridge, with 12 of 15 sites (80 percent) in crust of 20 million years and younger age. The latitude range of sites on the ridge crest, from 23°N to 64°N, is considerable. Two of the remaining three sites (417 and 418) are isolated in both space and time from the ridge crest group. These are located on the southern end of the Bermuda Rise in crust about 108 million years old. This uneven distribution of sites allows the search for geographic variations in the crust along the ridge crest, but provides little opportunity to identify secular trends over most of the 180-million-year-age range of North Atlantic basement. The concentration of drilling sites along the ridge axis reflects an interest in drilling well-surveyed areas as close as possible to the locus of formation of new crust in the median valley. At present, sites cannot be located directly in typical median valley areas because from 30 to 100 m of sediment are required to hold the drill bit in one place long enough for a hole to be started in the basalt.

Table 1. Basement penetration, recovery, and lithology of crustal holes in the North Atlantic Ocean.

Hole	Basement penetration (m)	Overall basement recovery (%)	Percentage of total recovery: Definite evidence of extrusive pillow lava origin*	Probable evidence of extrusive origin†	Coarse-grained basalt‡	Definite evidence of minor intrusive origin	Plutonics	Other lithologies
					Leg 37			
332A	333	10	97	0	0	3	0	Minor nanno-ooze and chalk with glass and palagonite
332B	583	21	28	56	15	1	0	Basalt breccia in units 9 and 10
333A	311	8	9	72	20	0	0	Basalt breccia throughout
334	124	22	47	0	0	0	53	Minor limestone in basalts; nannofossil chalk in plutonics
335	108	38	100	0	0	0	0	Minor nannofossil chalk or limestone with volcanic glass and palagonite
					Leg 45			
395	92	11	80	0	0	0	20	
395A	576	18	94	0	0	4	2	Basalt breccia
396	96	33	100	0	0	0	0	
					Leg 46			
396B	255	33	73	4	3	0	0	Remaining 20 percent consists of two basaltic sand and gravel units with some pillows in the upper unit
					Leg 49			
407	158	19	19	81	0	0	0	Tuffaceous nanno-ooze interbedded with basalts near basement surface 24 m section of sandy calcareous mud at depth
408	37	34	0	100	0	0	0	Compacted hyaloclastite at top of basement
409	239	24	0	100	0	0	0	
410	48	24	0	100	0	0	0	Basalt breccia
410A	49	39	0	100	0	0	0	
411	46	9	0	100	0	0	0	
412	12	5	0	100	0	0	0	
412A	139	17	0	100	0	0	0	Minor limestone
413	40	8	0	100	0	0	0	Basalt may be talus
					Leg 51			
417A	206	62	72	0	0	11§	0	Basalt breccia 17 percent
					Legs 51 and 52			
417D	366	73	68	0	22§	1	0	Basalt breccia 10 percent
					Legs 52 and 53			
418A	544	72	65	0	27§	2	0	Basalt breccia 6 percent

*Abundant glassy partings, fine grain size, and vesicles. †Fine grain size and vesicles. ‡Thicker intrusive or ponded lavas. §Described as sills by scientific staff on leg 51, but similar lithologically to units described as flows by scientific staff on legs 52 and 53.

A previously unsuspected factor in basement drilling is a positive correlation between recovery and crustal age (Fig. 3). The increased recovery in older crust is probably due to increased lithification of the basement. Interflow sediments and breccias recover poorly when unlithified, but can be recovered easily when compacted and cemented by secondary minerals, as is evident from the high recoveries at old basement sites such as 417 and 418. Because most of the North Atlantic drilling sites are in crust ranging from 1 to 20 million years in age, conclusions derived from study of the cores are almost always based on recoveries of less than 50 percent. In addition, important zones such as igneous and tectonic contacts and interlayered sediments are only rarely recovered.

Oceanic Crust as a Lithologic Unit

Drilling results are generally in accord with the early crustal models, although the precise nature of oceanic basement is difficult to determine by drilling because of the generally low recovery. In young basement sections, core recovery averages about 20 percent and is biased toward massive units. However, recent drilling in old oceanic crust at sites 417 and 418 resulted in much higher recoveries (average about 70 percent), providing for the first time a fairly complete section of the upper part of "layer 2."

Material recovered by drilling consists chiefly of aphyric to coarsely phyric basalt with lesser amounts of basalt breccia, palagonite and sideromelane breccia, and nannofossil chalk and limestone (Table 1 and Figs. 1 and 4). In addition, plutonic complexes composed of gabbro and peridotite have been encountered at shallow depths at sites 334 and 395.

Most of the sampled basalts are from extrusive pillow complexes. Pillowed forms, quench textures, and the presence of abundant glass selvedge are taken as definite evidence of extrusive origin; fine-grained groundmass textures and the presence of microvesicles are considered evidence of probable extrusive origin.

The abundance of pillow basalts in the drilled sections is in accord with observations made from submersibles in the median rift of the Mid-Atlantic Ridge where outcrops consist of elongate, grooved, and striated pillows (*32*). Massive, relatively coarse-grained basalts average about 9 percent of recovered material, but they may make up as much as 27 percent of basement at some sites. These basalts may be either intrusive sills or thick, ponded lava flows, most probably the latter. We believe that they represent thick, ponded flows because: (i) despite their generally coarse-grained nature, they have "ophimottled" textures in which subophitic clots of plagioclase and clinopyroxene are surrounded by interstitial glass; (ii) where observable, contacts do not exhibit crosscutting relationships; and (iii) the massive units typically have chemical and magnetic characteristics similar to the enclosing pillow basalts, suggesting that they are coeval. We believe that these massive units represent flows that were erupted very rapidly, developing an upper crust similar to that formed on some Hawaiian lava lakes.

Only a few clear examples of intrusive bodies have been identified, and these make up less than 2 percent of recovered basement material (Fig. 4). Small dikes were encountered in both holes 417D and 418A at subbasement depths of approximately 350 and 500 m, respectively, and a possible sill has been reported from hole 395A. Other suggested sills are here considered to be massive flows, although in some cases the evidence is insufficient to make a definite assignment to either category. The dikes in holes 417D and 418A are narrow (about 30 centimeters), steep-sided bodies with chilled glassy margins that clearly crosscut the host rock. They are chemically and magnetically distinct from the enclosing basalts but are similar to flows higher in the section. The suggested sill in hole 395A is a massive, coarse-grained unit about 22 m thick. It is also chemically distinct from the enclosing basalts but similar to flows higher in the hole. Paleomagnetic inclinations in this body are close to the underlying pillow sequence but distinctly different from the overlying unit.

The recovered basalts range from aphyric to highly porphyritic with most containing about 10 percent phenocrysts. Olivine, plagioclase, and clinopyroxene are the most common phenocryst phases; spinel is also present in some olivine-rich units. Highly plagioclase-phyric basalts with individual phenocrysts up

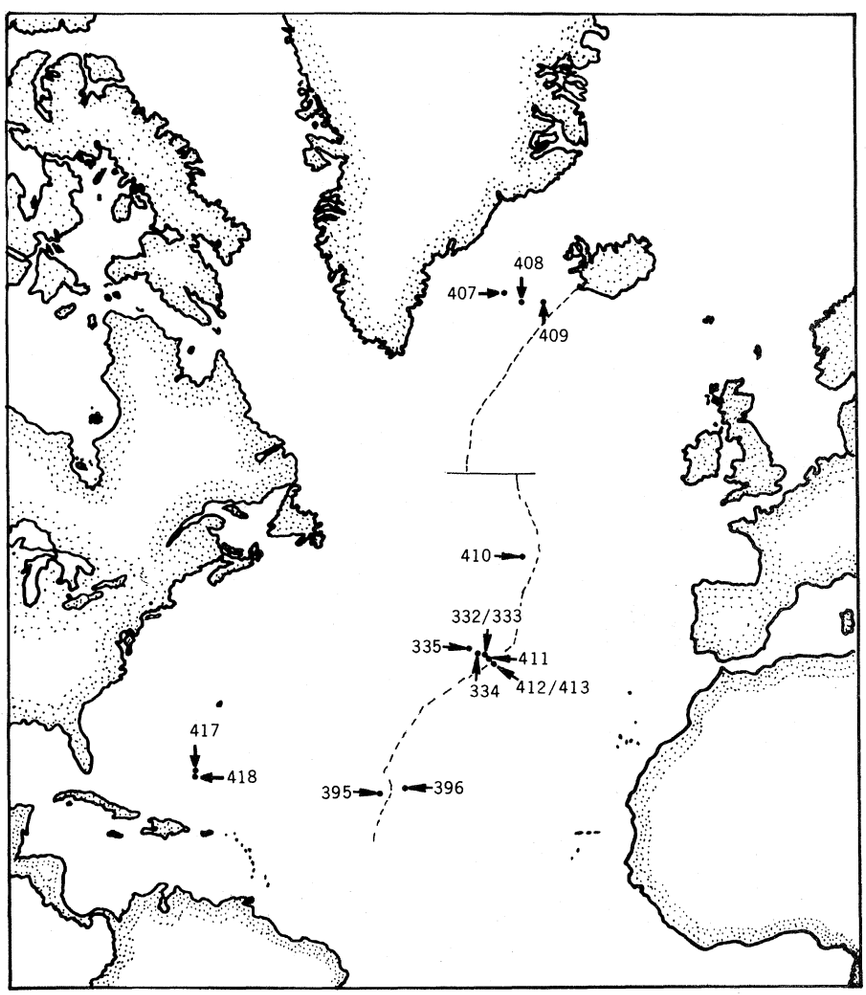

Fig. 2. Index map showing the location of North Atlantic basement sites.

to 15 millimeters in diameter are fairly common, having been recovered at sites 332 and 395 (*1, 2*). Similar basalts have been observed in the FAMOUS (French-American Mid-Ocean Undersea Study) area where they appear to be derived from vents along the flanks of the inner rift valley (*33*). Olivine-phyric or picritic basalts are common at site 332, where a 65-m-thick sequence of flows with numerous settling units is present. Olivine-phyric basalts have also been sampled in the FAMOUS area where they are related to the youngest eruptions along the rift axis (*33*).

Sediments are commonly interlayered with the extrusive basalts, particularly in the upper 200 to 300 m of basement. These are mostly fine-grained chalk or limestone showing varying degrees of induration. Recognizable nannofossils and foraminifers are preserved in many specimens; in others, recrystallization has obliterated all traces of fossils. In some cases, the nonfossiliferous material may simply be masses of secondary calcite rather than interpillow sediment. On leg 37, fossils from sediments within the basement are indistinguishable in age from those recovered from the oldest sediment above basement (*34*).

Commonly associated with the chalks and limestones are glassy breccias composed of sideromelane and palagonite fragments in a carbonate matrix. Some of these breccias have crude bedding, others are unbedded and poorly sorted, similar to peperites produced when hot basalt comes in contact with wet sediments (*35*). Glass-rich clastic debris was encountered within the basement section at site 396, indicating reworking and redeposition of fragmental material (*36*).

Lithic basalt breccias are present in many holes but it is difficult to determine their true abundance because they are difficult to recover in good condition. At sites 417 and 418, where the basement sequence is well indurated and recovery was high, lithic breccias comprise from 6 to 17 percent of the sampled section and average about 11 percent. These breccias consist of angular pillow fragments, often with glassy rinds, in a matrix of altered glassy material. They are lithologically similar to underlying pillow sequences and often grade into them; hence, they are considered to be pillow breccias formed during eruption rather than later talus accumulations associated with fault scarps. A breccia drilled at site 333, which may represent fault breccia, lacks glassy material.

The plutonic complexes encountered at sites 334 and 395 consist of gabbro and partly serpentinized peridotite, either harzburgite or lherzolite. Both complexes have associated breccias composed of rock and mineral fragments derived from the complex with a carbonate matrix containing poorly preserved nannofossils. At site 395 the complex consists largely of such breccia with only two thin (1 to 1.4 m) layers of unbrecciated peridotite. The breccia overlies, and is overlain by, the uppermost aphyric basalt of the basement section. The complex at site 334, which is at least 67 m thick, contains only a few breccia zones separating massive sequences of gabbro and peridotite. Most of the rocks here have a cumulus texture and there is some suggestion of rhythmic compositional layering. A tectonic foliation is present in both complexes and it predates the serpentinization.

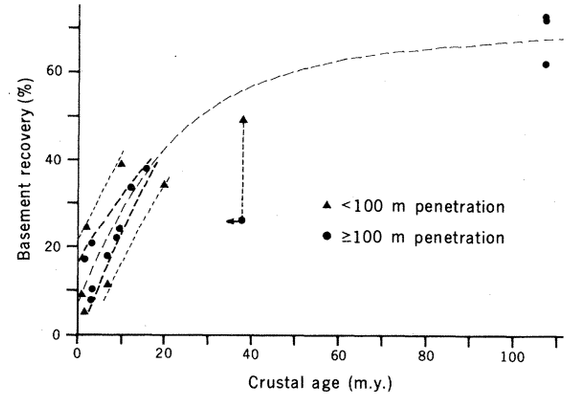

Fig. 3. Basement recovery plotted against age for holes drilled in the North Atlantic Ocean. Although holes of intermediate age are lacking, the graph suggests that high recovery can be expected from crust that is 50 million years or more in age.

The occurrence of these plutonic complexes at a shallow level in layer 2, their apparent interlayering with basalt flows, and the presence of tectonite fabrics and breccia zones within the complexes suggest that they were emplaced onto the floor of the median rift either by tectonic uplift or by diapiric intrusion prior to burial by extrusive basalts. Exposure to the sea floor at the time of basalt eruptions is supported at site 395 by the presence of breccia layers above and below unbrecciated peridotite and by the interlayering with basalts. The breccia layer in hole 395A could well be a talus deposit derived from an adjacent exposure.

Consequences of the Lithologic Nature of Oceanic Crust

Several attempts have been made to correlate the drilling results with the structure of the crust deduced from refraction seismology. The low velocities of the upper crust in situ, particularly layer 2A, are believed to reflect a high proportion of fractured basalt and interbedded low-velocity breccia and sediment. Drilling records indicate that basement at site 332 contains about 70 percent of such low-velocity material at the top, with the proportion decreasing to about 25 percent at 500 m subbasement (*37*). The calculated velocity profile for the hole corresponds closely to the refraction profile of the area determined by Whitmarsh [see (*38*)]. On the basis of these relationships we conclude that the uppermost basement section, with an average compressional wave velocity of 2.8 km/sec at this site, consists of extrusive basalt with a high proportion of fractured and porous basalt, basalt breccia and rubble, and some interlayered sediment. Layer 2B, with an average velocity of 5.0 km/sec, is believed to consist largely of extrusive basalt or brecciated material in which the fractures have been sealed. In hole 332B the top of the layer lies at about 500 m subbasement and has a calculated velocity of about 4.2 km/sec. No sharp lithologic change was found at the layer 2A-2B boundary and it seems likely that the apparent break simply reflects a gradual decrease in the proportion of low-velocity material.

A smaller proportion of interlayered sediment and breccia and aging of the oceanic crust probably accounts for the absence of an upper low-velocity zone in the Cretaceous crust drilled at sites 417 and 418. Here, interlayered breccias and sediments account for less than 20 percent of the section and, where present, they are well indurated and cemented. Compressional wave velocities measured in the breccias range from about 3.4 to 4.8 km/sec, notably higher than layer 2A velocities elsewhere. These rocks are not significantly more altered than younger rocks near the ridge crest, and the velocity differences are believed to reflect consolidation of the crust largely through compaction.

Several lines of evidence suggest that crustal construction at the Mid-Atlantic Ridge is episodic rather than continuous. At each drill site the cored basement section can be divided on mineralogical, ge-

ochemical, and magnetic characteristics into sharply distinguished, rather thick lithologic units, each composed of a number of individual cooling units such as pillows or thin flows. These lithologic units have a within-hole average thickness ranging from 44 to 61 m, depending on the manner in which the data are selected. Hence, if the upper 600 m of oceanic basement are typical of the upper 2 km, then on the basis of the preferred 61-m value some 30 lithologic units will, on average, constitute layer 2.

The internal consistency of stable paleomagnetic inclinations suggests that individual lithologic units probably formed in less than 100 years. If the 2-km-thick layer forms entirely within the median valley, the time required for its formation can be obtained from the ratio of the width of the inner median valley to the crustal formation rate. With this approach a range of 1 to 2 $\times$ 10^5 years is obtained for the Mid-Atlantic Ridge in the North Atlantic. This suggests an average interval between the formation of individual lithologic units of about 5 $\times$ 10^3 years. Thus it appears that the lithologic units form quickly from one eruption, or several closely spaced eruptions, and that the formation of each unit is followed by a period of local quiesence, that is, volcanic activity at any one place in the median rift is strongly episodic for time periods of less than 10^5 years. This conclusion is supported by the presence of altered or weathered zones at the tops of many crustal lithologic units, implying a relatively long residence time at the sea floor, and by the presence of individual volcanoes with different ages and compositions in the modern median valley (*32, 33, 39*). In some instances, uniform paleomagnetic inclinations characterize sequences of units composed of several distinct magma types, implying that two or more magma chambers of restricted size coexisted beneath the rift valley and erupted essentially contemporaneously, or that a single magma chamber was tapped at different levels.

An unexpected result of drilling is the almost complete lack of lateral lithologic and stratigraphic continuity in the crust. Generally, lithologic units cannot be correlated even between holes drilled only a few hundred meters apart (for example, 332A and 332B, 395 and 395A, 396 and 396A, 417A and 417D). In holes 332A and 332B, where some lithologically similar units occur in adjacent holes, the rocks have opposite magnetic polarities. This lack of stratigraphic continuity suggests that eruptions onto the sea floor are very local, building accumulations directly over the vent. This interpretation is supported by observations from submersibles in the FAMOUS area which revealed the presence of several areally restricted elongate hills parallel to the rift axis (*32, 40*). Numerous faults have also been observed on the walls and floor of the median rift (*32*), suggesting possible offset of the erupted sequences.

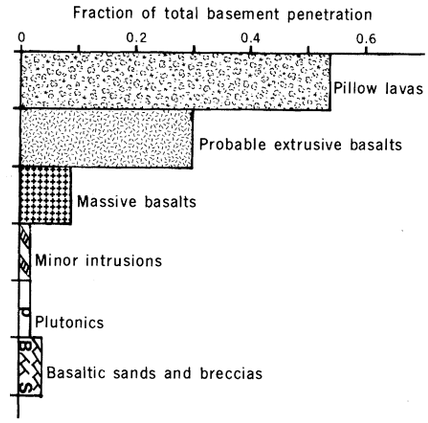

Fig. 4. A histogram showing the fraction of each major lithologic type in basement rocks recovered by crustal drilling in the North Atlantic Ocean. Breccias and sedimentary rocks recover very poorly, particularly in young crust, and are almost certainly underrepresented in the total.

The lower oceanic crust has yet to be sampled in situ by drilling, thus direct evidence of its structure and composition is lacking. Fresh gabbros, such as those encountered at shallow depth at sites 334 and 395 have compressional wave velocities of about 7.0 km/sec at ocean crustal pressures (*38*), close to the average lower crustal velocity of 6.7 km/sec derived from refraction seismology. Hence, layer 3 may consist chiefly of gabbro and metagabbro with the layer 2–layer 3 boundary representing a transition to predominantly extrusive basalt. However, Salisbury (*41*) argues from studies of ophiolite complexes that this velocity gradient represents a metamorphic front within a sheeted dike complex separating chloritized rocks above from amphibole-rich rocks below. Serpentinites can also have the required seismic velocities for the lower crust, but they are not considered important constituents because their Poisson's ratios do not match measured values in the crust (*42*). Also, such rocks would have highly variable velocities depending on the degree of serpentinization, and measured compressional wave velocities in the lower crust are quite uniform. A more precise determination of lower crustal materials must await direct sampling by deeper drilling.

Oceanic Crust as a Magnetic Material

It is clear that the simple model of uniformly magnetized crustal blocks of alternating polarity does not represent reality. Clear reversals of polarity with depth are observed in a number of the deeper holes [332A, 334, 395, and 418A; for example, see (*43*)]. In addition, inclinations often deviate systematically over long core intervals from expected dipole values by more than normal secular variation. Lateral magnetic heterogeneity is evident from marked differences in magnetization (including reversals) where adjacent basement holes have been drilled a few hundred meters apart. Natural remanent magnetization dominates the magnetization of the basalts, with induced and viscous magnetization being unimportant. A representative value for magnetization at most sites is 4 amperes per meter [40 $\times$ 10^{-4} electromagnetic units (e.m.u.) per cubic centimeter], typically much lower than values observed for median valley basalts. Reduction in magnetization with age is readily related to the rapid, pervasive low-temperature oxidation of the extrusive basalts by seawater at close to ambient temperatures. An unexplained exception to this general pattern is the relatively strong remanent magnetization of most basalts from the Cretaceous sites 417 and 418.

Magnetic intensity and stability correlate closely with grain size of the lithologic unit. Relatively weak but hard remanent magnetization dominates in the fine-grained extrusive basalts, whereas stronger but softer remanences with large viscous components dominate in the coarser-grained massive flows and plutonic rocks. The viscous magnetism was probably acquired largely during the normal polarity geomagnetic field of the last 7 $\times$ 10^5 years, but some components may have been acquired during drilling and recovery (*44*). The soft components are readily removed from all but a few plutonic rocks by the standard alternating-field paleomagnetic cleaning procedure. The abundance of fine-grained extrusives in basement sections means that magnetization in situ is dominantly hard, stable remanence in the upper 600 m of basement.

Figure 5 shows the remarkable scatter in magnetic inclinations and polarities found in all deep holes drilled thus far. No section of greater than 250-m depth is uniformly magnetized. Variation of magnetization intensity occurs on several scales from centimeters to tens of meters, and there are no consistent trends with depth. In the deeper holes, varia-

tion can be within one polarity or between polarities, or both. The variability of magnetization in these sections can be expressed numerically by the ratio of the effective magnetization, allowing for direction change, to the arithmetic average magnetization (Table 2). This ratio ranges from 0.1 to 0.8 with an average value of 0.4. If lateral differences between closely spaced holes are also considered this ratio will be reduced still further. In terms of the formation of the linear anomaly pattern, it is unlikely that the upper 600 m of basement is of much significance except, perhaps, in the vicinity of active spreading ridges where very intensely magnetized extrusives occur at the basement surface. This conclusion is supported by the poor agreement between the sense of the effective magnetization in the drilled holes and the associated linear anomalies.

It seems likely that linear anomalies reflect strongly magnetized, spatially well-organized lower sections of oceanic crust. One candidate for this lower layer, serpentinized peridotite, has average magnetization within the basalt range. This magnetization is, however, often dominated by or is entirely of viscous origin, and it seems unlikely that the polarity record could be preserved (*43*). Gabbros, which are also candidates for a deeper magnetic layer, have been reported as having stable magnetization (*45*). Doubt about the representative average magnetization intensity is a difficulty here. Reported values range from a geometric mean of 0.3 ampere per meter (3×10^{-4} e.m.u. cm^{-3}) (*45*) to 0.03 ampere per meter (0.3×10^{-4} e.m.u. cm^{-3}) (*46*). This wide range is likely to be a function of the small collections studied. If, when more samples are available, average magnetizations are found to be sufficiently strong and stable, the next problem will be to observe the spatial organization of magnetization. One way to do this might be for a submersible to take oriented samples from gabbro exposures on a transform fault scarp.

Because the magnetic structure of the upper oceanic basement in the North Atlantic differs so markedly from the predicted model, a comparison with the magnetic structure of Tertiary and younger subaerial flood basalts is useful. In both environments, magnetic reversals are common in vertical sections of flows and these help to define thick magnetic-lithologic units. Dikes often have polarities opposite from those of the host rocks, and many rocks exhibit overprinting of stable remanence by later viscous components acquired in the present field. The main difference between the two is the relative abundance of anomalous inclinations in oceanic crustal sections. In Iceland, for example, anomalous inclinations comprise only about 8 percent of the extrusive sections (*47*), and these are readily explained in terms of magnetization during geomagnetic polarity transitions. In contrast, inclinations that differ from expected values by at least 30° characterize more than 40 percent of the oceanic sections illustrated in Fig. 1. Rapid lateral and vertical variations in magnetization appear to be characteristic only of the oceanic crust, suggesting the existence of a unique tectonic environment associated with mid-ocean ridges. These variations are used as evidence for the structural model developed later in this article.

Igneous Processes in the Ocean Crust

Study of DSDP basement cores has generally confirmed and expanded petrologic models deduced from dredged basalts. However, unlike dredge hauls,

Table 2. Magnetization of basement sections for North Atlantic basement holes greater than 250 m in depth.

Hole	Basement penetration (m)	Effective average magnetization (EM) ($\times 10^4$ e.m.u. cm^{-3})	Arithmetic average magnetization of recovered rocks (AM) ($\times 10^4$ e.m.u. cm^{-3})	EM/AM	Sense of magnetic anomaly in vicinity of the hole
332A	330	−3*†	33	0.10	−
332B	582	−24†	37	0.66	−
333A	310	−11†	37	0.33	−
395A	575	−12*	40	0.29	+
396B	255	−6‡	22	0.29	+
417D	366	−72*	89	0.81	−
418A	544	+40§	120	0.3	Close to anomaly boundary

*These profiles contain one or more polarity reversals. †Intensities reduced for (supposed) nonmagnetic cavity, rubble, and sediment contributions. Similar reduction when carried out for the other holes will reduce both effective magnetization and the ratio parameter. ‡Calculated assuming that the sign of inclination is a reliable guide to polarity. §Based on 0 to 248 m interval. Net magnetization of remainder of section assumed to be zero since three or more reversals are reported as occurring.

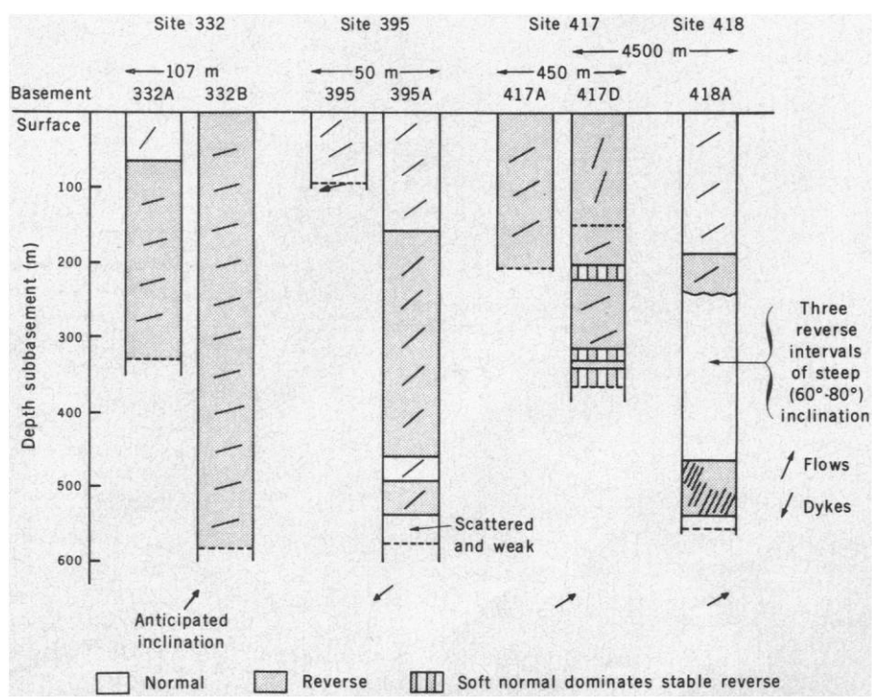

Fig. 5. A summary of the measured paleomagnetic inclinations and polarities in basalts recovered from the four most important basement sites in the North Atlantic.

drill core provides a detailed record of crustal stratigraphy and permits a chronologic reconstruction of geologic events at a given site.

Drilled basalts are compositionally similar to dredged basalts but have a somewhat wider range of composition, and several distinct basalt types may occur at a single drill site (*48, 49*). Some of the drilled basalts are chemically "primitive" [$100 \times Mg/(Mg + Fe^{2+}) \geq 70$] and may represent primary mantle-derived melts (*50, 51*). Most, however, are too chemically "evolved" to represent primary magmas and probably reflect modification of mantle-derived magmas by various degrees of crystal fractionation and magma mixing.

The effects of shallow level crystal fractionation on basaltic melts are well illustrated at site 332 where 13 magma groups have been recognized in two holes (*52*). Many of these basalts are highly porphyritic and most chemical differences between magma groups can be explained in terms of the addition or subtraction of observed phenocryst phases. Figure 6 shows the principal compositional trends resulting from fractionation of olivine and plagioclase, the most common phenocrysts, and these parallel the observed trends in the basalts. Some calculations suggest that clinopyroxene has also played a role in fractionation and three-phase fractionation in several magma groups is indicated by the phenocryst assemblage plagioclase + clinopyroxene + olivine. However, clinopyroxene occurs only rarely as a phenocryst phase and, where present, is usually rounded and corroded, suggesting that it is out of equilibrium with the host magma. Disequilibrium of phenocryst phases suggests that some of the observed chemical variations may be due to magma mixing (*53*).

Comparison of the observed phenocryst assemblages with experimental studies indicates that this crystal fractionation is a low-pressure (up to 3 kilobars) process taking place in the upper few kilometers of the oceanic crust. Hence, these fractionated basalts provide evidence for the existence of pockets of molten magma at shallow depths beneath the Mid-Atlantic Ridge.

High-pressure crystal fractionation is indicated by the orthopyroxene-bearing gabbros and peridotites encountered at sites 334 and 395 (*54*). The mineralogies of these rocks are those expected from high-pressure crystallization of olivine tholeiite magma (*51*), and the cumulus textures indicate accumulation of phenocrysts in a magma body. Derivation magmas formed by this process should be similar in large ion lithophile elements but different in $Cr/(Cr + Ni)$ and Cr/Mg ratios. Large differences in these ratios between some magmas obtained during leg 37 may be due to such a process (*52*).

The chemically "primitive" basalts found at some sites are characterized by high atomic $Mg/(Mg + Fe^{2+})$ values (≥ 0.70), high MgO (> 10.0 percent), and low TiO_2 (0.5 to 0.9 percent) and NaO (< 2.0 percent). These noncumulate "primitive" basalts are believed to represent primary mantle liquids that have risen to the sea floor with little or no modification. The existence of two or more such primitive magmas at one site (for example, site 332) suggests formation by different degrees or depths of partial melting in the mantle.

One possible model for magma generation and modification beneath the Mid-Atlantic Ridge is shown diagrammatically in Fig. 7. Primary olivine tholeiite magmas are formed by partial melting of mantle lherzolite at depths of approximately 30 to 35 km corresponding to a zone of low shear-wave velocity (*55*). Variations in the degree and depth of partial melting are believed to produce small differences in the original primitive liquids. Once formed, the buoyancy of these magmas causes them to rise upward through the overlying mantle. Some magmas rise directly to the sea floor with little or no modification; others are held temporarily in various magma chambers where they undergo varying degrees of crystal fractionation and magma mixing. Fractionation in deep magma chambers results in the formation of cumulate, orthopyroxene-bearing gabbros and peridotites, some of which may be later diapirically emplaced at shallow levels in the crust. Magmas trapped in shallow level magma chambers undergo low-pressure fractionation involving the phases olivine + plagioclase ± clinopyroxene ± spinel. Gabbros formed dur-

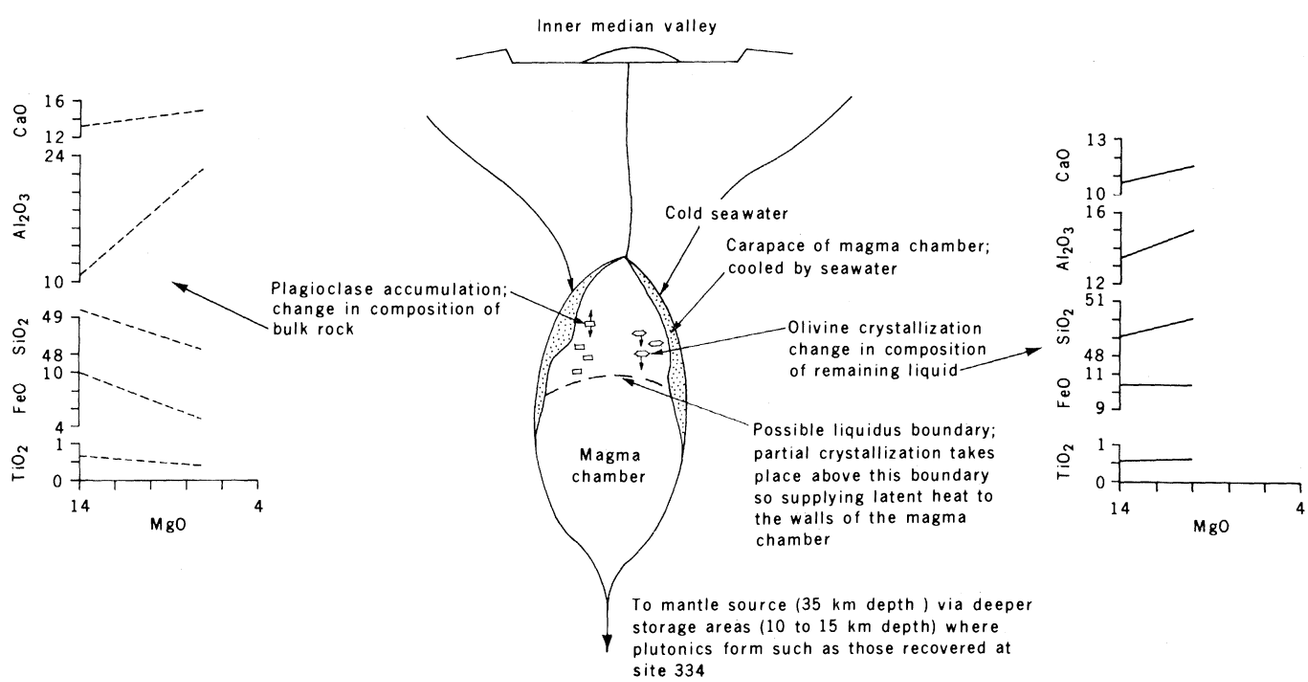

Fig. 6. Possible median valley magma chamber structure with principal compositional trends resulting from the fractionation of olivine (right) and plagioclase (left).

ing this stage are believed to be the major component of the lower crust or layer 3. Repeated injections of more primitive magma from depth into fractionating bodies results in mixed magmas characterized by zoned and corroded phenocrysts (*49*). Periodic eruptions from these subrift chambers onto the sea floor results in the complex basalt stratigraphy in layer 2 and probably leads to the formation of a sheeted dike complex in the vicinity of the layer 2–layer 3 boundary.

It is apparent that magmas erupted at any given locality long the Mid-Atlantic Ridge reflect a complex history of partial melting, fractional crystallization, crystal accumulation, and magma mixing. The highly varied and highly fractionated character of many drilled basalts suggests that they formed from magmas that evolved independently in a number of small, separate magma chambers rather than in one large one (*52*). The lithology and petrology of Atlantic sea floor basalts supports the conclusion based on paleomagnetic data that crustal construction along the Mid-Atlantic Ridge is episodic in nature. It seems clear that episodic crustal construction is characteristic of slow spreading ridges (2 to 2.5 centimeters per year), although more steady-state conditions may prevail at fast spreading ridges such as the East Pacific Rise.

Some evidence exists for secular compositional variations in basalts erupted from a given segment of the Mid-Atlantic Ridge (*56, 57*), but no clear trends are apparent. Generally, major and trace element variations among basalts at a given site exceed those between sites. However, Cretaceous basalts at sites 417 and 418 show significant differences in major element composition from modern basalts erupted at approximately the same latitude on the ridge, and similar compositional variations are observed along the FAMOUS–leg 37 flow line. The compositional variations are not systematic, rather there appears to be a random variation, particularly in lithophile elements, suggesting nonsystematic variations in mantle source rocks (*58*).

Geographic variation in basalt compositions has also been observed along the Mid-Atlantic Ridge (*57, 59, 60*). Schilling (*61*) has attributed rare earth element variations to various degrees of mixing between upper mantle material and deep mantle "blobs," whereas Bougault (*62*) and Dmitriev (*63*) have suggested two geographically distinct mantle source compositions along the ridge. Tarney *et al.* (*60*) suggest a range of mantle compositions variable on different scales for different elements.

Alteration of Oceanic Basalts

Alteration in drilled basalts has proved almost everywhere to be due to low temperature seawater-rock interaction. To date, evidence for higher temperature hydrothermal alteration has been found only at sites 332 and 395. In hole 332B, the presence of a characteristic alteration product of titanomagnetite in several thin zones suggests that passageways for water at 150°C may have been present in the past. In hole 395A, a 10-m-thick breccia zone has been reheated sufficiently by hydrothermal fluids to make the magnetic polarity of the clasts coherent.

The temperature range at which alteration can have taken place (0° to 20°C) is well defined by a combination of oxygen isotope paleotemperature determinations, the absence of anhydrite and other minerals found in active hydrothermal systems, and the presence of highly cation-deficient titanomagnetite which is known to be thermally unstable at 100°C over laboratory time scales.

Alteration of most drilled basalts is weak to moderate, and is apparently unrelated to age of the crust for ages greater than 1 to 2 million years. Easily altered phases such as basaltic glass and olivine persist in many drilled sections, even where the crust is over 100 million years old. On the other hand, alteration is already fairly extensive at the youngest sites, indicating rapid penetration of water into pillow piles and flows erupted onto the sea floor. Correlation of magnetization variation with time suggests that pillow interstices are water-saturated almost instantaneously; slower dif-

Extrusion of pillow basalts onto rift floor, producing mixtures of basalt, basalt breccia, and minor sediment. Olivine-phyric basalt erupted in rift axis and plagioclase-phyric basalt on flanks. Lower part cut by sheeted dike complex. Minor quantitites of diapirically emplaced plutonic rock.

Magmas trapped in shallow magma chambers undergo low-pressure crystal fractionation involving olivine + plagioclase ± clinopyroxene ± spinel. Small pockets of magma are isolated and undergo extreme fractionation to form plagioclase-phyric lavas. Other magma chambers receive periodic infusions of magma from depth resulting in mixing of magmas. Upper part of layer 3 cut by sheeted dike complex.

Zone of rising magmas in the upper mantle. Some magmas rise directly to higher levels, others are held temporarily in deep magma chambers. These undergo varying degrees of high-pressure fractionation involving olivine + plagioclase + clinopyroxene ± orthopyroxene to form gabbros, lherzolites, and harzburgites. Periodic influxes of primitive magma from depth results in varying degrees of magma mixing.

Zone of partial melting of mantle peridotite to form primitive olivine tholeiite magmas.

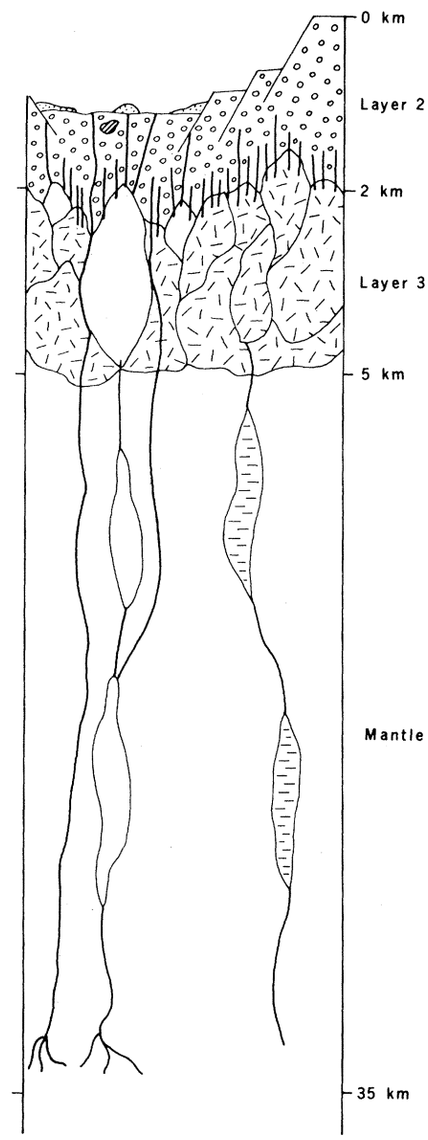

Fig. 7. One possible model for magma generation and modification beneath the Mid-Atlantic Ridge (not drawn to scale).

fusion then follows into the typically small (average diameter 0.45 m) pillows. The persistence of glass in the oldest rocks indicates that the crust must become nearly sealed at a relatively early stage, probably by precipitation of abundant secondary minerals in fractures and vesicles.

The only highly altered basalts encountered during drilling are those in hole 417A, drilled in crust of Cretaceous age. Here, a small basalt hill apparently projected above the sedimentary cover for many millions of years, allowing extensive seawater-basalt interaction (*64*). Basalts penetrated in hole 417D, drilled only 400 m from hole 417A, were apparently covered by sediments shortly after eruption and are relatively fresh.

In most sampled sections two distinct types of alteration are apparent, one superimposed on the other (*65*). In all cases, the earliest phase of alteration is a replacement of olivine and interstitial glass by brown or blue low-potassium smectite. This alteration is pervasive throughout the rocks and is spatially unrelated to fractures, pillow margins, or open channelways. Growth of this smectite results largely in hydration of the basalts with few other chemical changes. The second stage of alteration results from the passage of seawater through fractures and open channelways. Diffusion of water outward from these channelways produces alteration haloes often 20 to 30 times the width of the fractures. At most sites this is an oxidative alteration resulting in the formation of yellow or red smectite, abundant carbonate and zeolite, with lesser amounts of manganese and iron hydroxides. The yellow and red smectites are high-potassium, high-iron varieties and the growth of these leads to marked increases in K_2O and H_2O, and in the Fe_2O_3/FeO ratios. Most secondary carbonates are calcite, but iron-magnesian carbonates are common in hole 322B, leading to marked enrichment in MgO and FeO.

A two-stage sequence is not apparent in the rocks drilled in hole 417A, possibly because of the very intense alteration. These basalts contain abundant potassium-rich smectite, celadonite, potassium feldspar, zeolites, and carbonates resulting in high potassium enrichment (*64*). The alteration environment at this site was oxidizing at least in its later stages, reflecting decay of the original euxinic seawater composition with time.

Most of the alteration takes place relatively soon after eruption of the basalt. Pillows dredged from the inner median valley of the Mid-Atlantic Ridge show visible alteration along cracks together

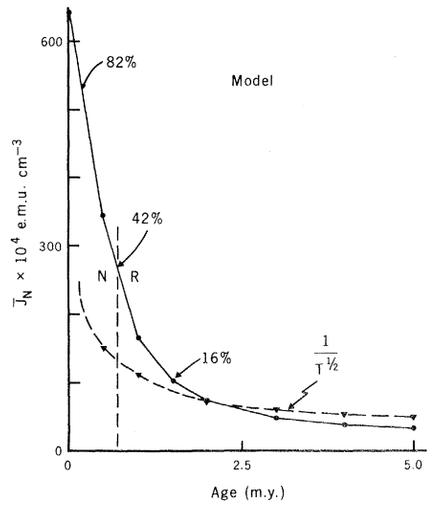

Fig. 8. Magnetic intensity of basalts from the North Atlantic Ocean plotted against age. The graph shows the approximation of the observed trend to a function of the form $J_N \propto t^{-1/2}$. *N*, Brunhes normal polarity epoch; *R*, Matuyama reverse polarity epoch.

with marginal gradients in potassium and uranium (*66*), and the absence of a prominent anomaly over some spreading centers has been attributed to alteration of the products of the most recent eruptive event (*67*). Basalts drilled in crust aged 3.5 million years at site 332 are altered as completely as older basalts at site 418, and the persistence of easily altered olivine and basaltic glass in very old rocks suggests that the crust was sealed off from circulating seawater at a relatively early stage.

The decay of magnetization by oxidation of titanomagnetite can provide quantitative estimates of alteration rates. It has been estimated from the modeling and inversion of magnetic anomalies that on the Mid-Atlantic Ridge an 18 percent decay of magnetization will have occurred by the time basalts have been transported from the median rift to the margins of the inner valley (Fig. 9). Elsewhere, we suggest that burial of centrally erupted material is likely to have occurred by this time (1 to 2 $\times$ 10^5 years), thus putting a limit on the degree of preburial alteration. Variations in decay time can be expected where eruptions occur along the flanks of the median valley as well as in the center.

The decay in magnetization appears to continue rapidly until about 1.5 million years, after which it proceeds much more slowly. This decay rate is matched closely by the observed decrease in magnetization of dredge samples away from the median rift. A model of magnetization decay based on the role of diffusion of alteration fronts into pillows, provides some insight into the progress of alteration as a whole in basement material consisting largely of pillows. Figure 9 indicates that on the Mid-Atlantic Ridge 66 percent of the decay has occurred by the time the basement material has arrived at the crestal mountains. A 95 percent decay level is reached by 5 million years, after which little change occurs. The observed decay in magnetization can be approximated by a single function of the form $J_N \propto t^{-\frac{1}{2}}$, where J_N is the natural remanent magnetization and t is time. It is considered significant that a temporal relationship of the same form describes the initial progress of diffusion of a fluid into a sphere, because drilling has shown that the upper part of basement is dominated by pillowed sequences.

The general absence of hydrothermal alteration in the drilled sequences is surprising because most heat-flow models for spreading ridges postulate extensive hydrothermal circulation in the oceanic crust (*68*), and hot springs are known to occur along rifts (*69*). Study of ophiolite complexes has shown that hydrothermal circulation was extensive in these bodies and was probably related to the formation of massive sulfide deposits (*70*). If hydrothermal alteration is taking place along spreading ridges it must occur generally at depths greater than 600 m and it is probably spatially restricted.

We postulate (Fig. 9) rapid, pervasive, nonoxidative alteration of extrusive pillow basalts and massive flows in the median rift. The youngest dredged basalts are typically fresh, but pervasive, nonoxidative alteration is present in most specimens over 0.75 million years in age (*71*). Fracturing of the basalts opens channelways through which cold seawater can pass, causing the second stage of alteration. This alteration is believed to be due to downward percolation of seawater on the flanks of the ridge, and throughout most of the Atlantic Ocean it must be oxidative in character. The only extensive nonoxidative alteration observed thus far is in holes 417D and 418A where Cretaceous basalts were erupted into a euxinic ocean. The oxidative alteration of similar basalts in hole 417A may reflect exposure of these rocks to the sea floor for a much longer time. As a result, these basalts were able to interact, at least in part, with later, oxygenated seawater.

Comparison with ophiolite complexes suggests that downward penetration of seawater extends to depths of 2.5 to 5 km (*70*). We suggest that most of the low-temperature alteration takes place in the first 1 to 2 million years following erup-

tion of the basalts and that alteration in older rocks proceeds very slowly. The persistence of easily altered basaltic glass and olivine, and the general absence of oxidative alteration in basalts at old sites suggests that the basaltic crust is sealed off from the overlying seawater at an early stage.

The general absence of hydrothermal alteration in drilled basalts indicates that uprising of hydrothermal fluids must be restricted to small plumes in the axial rift zones and to transform faults. Observations from the Troodos Massif in Cyprus show that the half-spacing between rising plumes in that complex was similar to the thickness of the permeable layer (2.5 to 5 km) (*70*). Other observations indicate that major fractures acted as important conduits for discharge of hydrothermal fluids and localization of mineralization. Presumably, the same relationships hold true in the oceanic crust, and hence hydrothermally altered rocks should be spatially restricted in layer 2.

Basement as a Structural Unit

One of the major surprises resulting from crustal drilling in the North Atlantic Ocean is the evidence for extensive tilting and rotation of crustal blocks. Minor faulting and tilting of crustal blocks were observed directly from submersibles in the FAMOUS area (*32*), but large-scale disruption of the crust was not evident from seismic refraction work, and the regularity of sea floor magnetic anomalies suggested a high degree of continuity in the crust.

The main evidence for the structural disruption lies in the lithologic heterogeneity of the crust revealed by closely spaced drill holes and in the abundance of anomalous stable paleomagnetic inclinations. The close correlation of lithologic and magnetic breaks in the crust with chemical discontinuities indicates that the structural disruption occurred in the median valley during the process of crustal construction rather than during the migration of newly formed crust from the median rift to the flanks of the ridge (*58*).

Heterogeneity in the basaltic extrusives between closely adjacent holes could result, at least in part, from episodic volcanism and overlapping of lava flows in the median rift. However, the presence of gabbro and peridotite breccias with a nannofossil chalk matrix beneath undisturbed thin pillow basalt sequences at sites 334 and 395 can only be explained reasonably by large-scale vertical faulting or diapirism. Again, at present there is no convincing alternative to large-scale block rotations as an explanation for the abundant anomalous paleomagnetic inclinations, if we assume original magnetization in a geocentric, axial dipole field. From the various lines of evidence a rather novel tectonic scheme can be deduced and this in turn can be used to construct a new model of inner median valley processes.

We start by attempting to model the magnetic inclinations in the three pairs of holes (at sites 332, 395, and 417) where both vertical and lateral data are available (Fig. 5). We show later that features observed at these sites are also found in a number of shallower holes. Hole 332B (Fig. 10A) can be modeled most simply in terms of a uniformly rotated block of at least 582 m thickness, but hole 332A combines a major downhole change in inclinations with a polarity reversal. These relationships can be explained by faulting subsequent to tilting of the major block followed by partial overlap by rather younger flows. Such a fault must crop out between holes 332A and 332B and should have a vertical component of movement of at least 25 m. It was possibly intercepted in hole 332A at a depth of 330 m subbasement. After faulting, a series of unrotated flows covered the down-dropped part of the block, perhaps being dammed against the resulting fault scarp. The unrotated flows are of normal polarity, in contrast to the reverse polarity of the rotated block, suggesting a 10^4- to 10^5-year hiatus between eruptions.

Blocks that appear to have been ro-

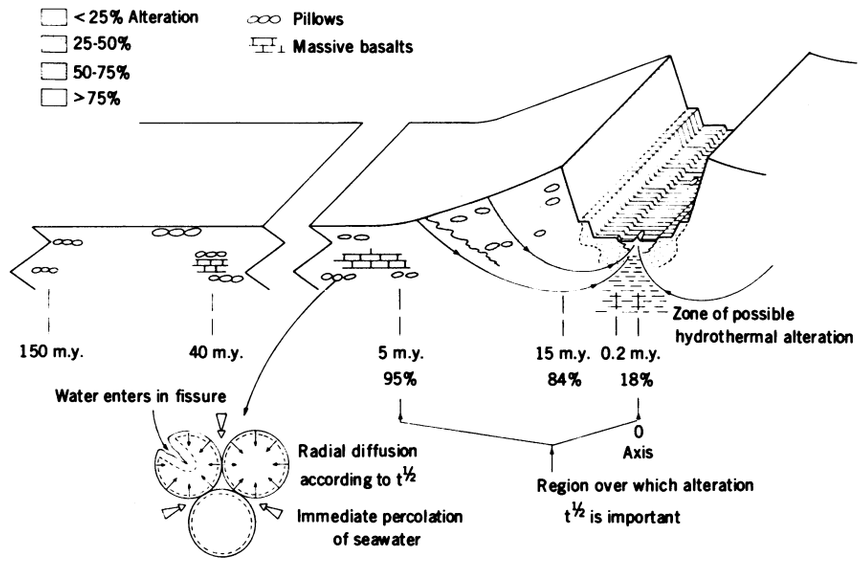

Fig. 9. A schematic model for alteration of oceanic crust showing the likely alteration processes, possible paths of water circulation, location of possible hydrothermal conduits, and the percentage of total alteration with age of the crust.

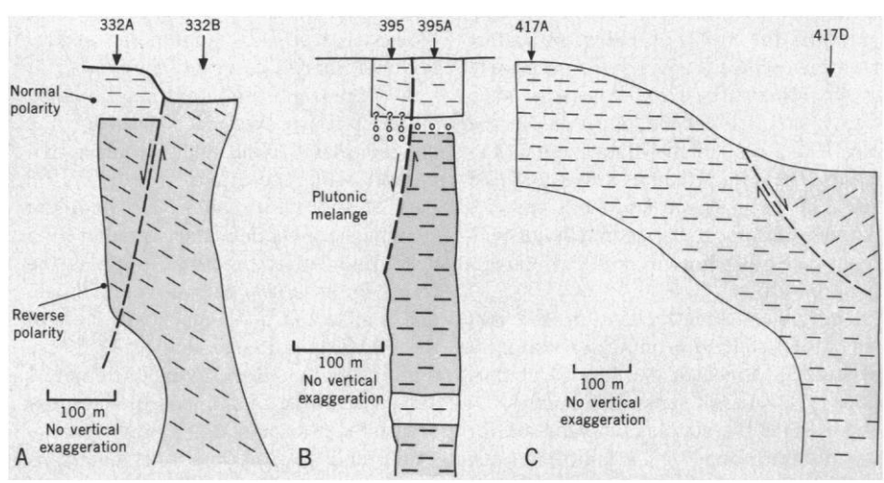

Fig. 10. Structural models providing one possible interpretation of the paleomagnetic inclinations measured at the three basement sites in the North Atlantic where two closely spaced holes were drilled. (A) Site 332. (B) Site 395. (C) Site 417.

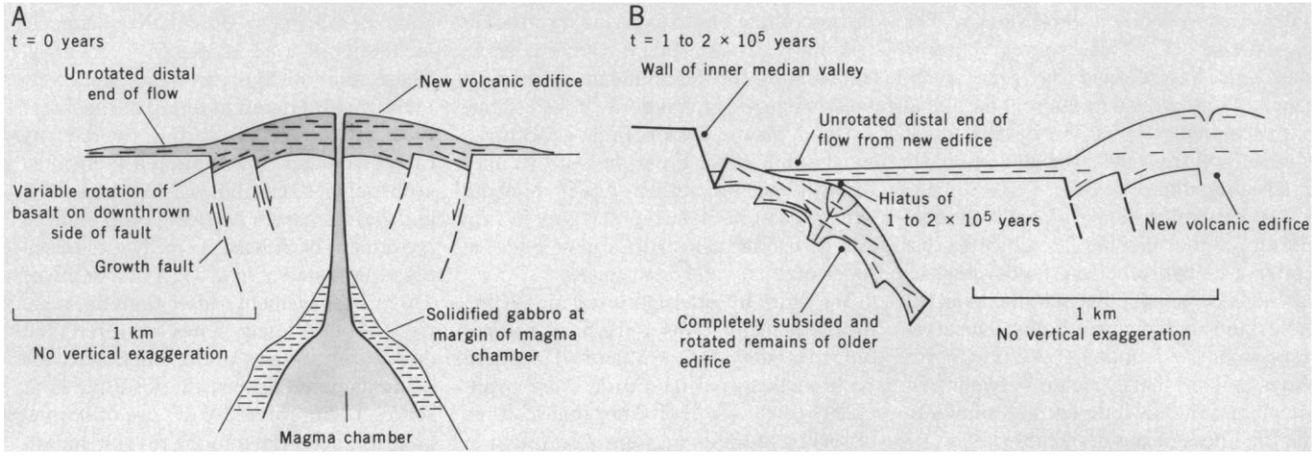

Fig. 11. A schematic model for tectonic rotation in the inner rift valley of the Mid-Atlantic Ridge. (A) Growth of a new volcanic edifice in the inner median valley. (B) Rotation and burial of an old volcanic edifice in the inner median valley.

tated uniformly also occur in holes 333A, 396B, and 417D and perhaps in some of the shallow holes in the 407 to 413 sequence. At site 333 there is evidence that rotation continued during initial sediment deposition on the block. Polarity change also occurs in holes 334, 395, 396B, 407, 410, and 418A.

Site 395 (Fig. 10B) yields additional evidence of tectonic dislocation in the median rift valley. Here, we see continuous increase of tilt with depth in extrusive basalts and the presence of plutonic mélange material. As at site 332, there are also anomalous stable inclinations and polarity changes with depth. There is no evidence for significant rotation of the deeper basalts at this site, although this is not excluded because the axis of rotation could be close to the paleomagnetic azimuth. Continuous increase in tilt with depth in extrusive basalts, which also occurs in holes 410A and 418A, suggests that inner median valley crust cannot withstand the load of a new volcanic edifice, and slowly subsides at the front of flows emanating from the edifice along a series of growth faults. The surface expression of such faults may have been observed in the FAMOUS area of the inner median valley of the Mid-Atlantic Ridge (*32*). At site 395 the marginal fault of a possible diapiric plutonic mélange may have been reactivated as a growth fault in the overlying basalts.

The paleomagnetic data at site 417 (Fig. 10C) suggest a uniform rotation of at least 35° to 40° of the upper 150 m of hole 417D. A fault separating holes 417A and 417D is the simplest explanation for the rotation, and such a fault has been postulated at 491 m subbottom depth in hole 417D. However, lithologic and structural evidence of faulting, independent of the paleomagnetic inclinations, is inconclusive.

Where and when was this peculiar structural style, characterized by inclined faulting, large rotations of fault blocks, differential rotation within extrusive sections, and uplifted plutonic mélanges, imposed on oceanic basement? Earthquakes within oceanic crust are concentrated at ridge crests and on transform faults (*72*). Because the drill sites were selected away from known transform faults, we assume that most of the faulting and rotation occurs at the ridge crest. This interpretation is supported by the evidence for coeval volcanic and tectonic activity in the drilled sections. Ridge crest geology and other criteria impose a number of constraints on any tectonic model. We conclude that the available evidence points to tectonic disruption occurring largely in the inner median valley of the Mid-Atlantic Ridge. Major block faulting at the walls of the outer valley presumably either reactivates older fractures or only affects large blocks that already contain the special tectonic imprint described above.

In proposing a model for inner median valley activity (Fig. 7) we invoke the concept that volcanic and tectonic activity are, with hydrothermal activity, all part of the same convective heat-loss system. A convenient starting point for a description of the tectonic cycle is the formation of a new central volcanic edifice, similar to Mt. Venus or Mt. Pluto of the FAMOUS rift area (Fig. 11A). These features extend for several kilometers along the strike of the axis of the inner median valley, and are about 1 km in width and several hundred meters in peak elevation. Paleomagnetic study of extrusive sequences in drill cores suggests that formation time of such features is short (< 100 years) compared with the interval between edifice formation (~ 10^4 years). Observations in the FAMOUS area (*32*) suggest that the loading produced by many of the thicker flows from a newly formed edifice exceeds the strength of the crust, which then yields by normal faulting at the perimeter of the flow. Stoping of the roof of the magma chamber (*73*) might stimulate this surface collapse. Further eruptions from the same edifice will cause continued movement on the fault line. If a hinge line occurs between the fault and the source of the lava, rotation of the subsiding, loaded crustal segment will occur with the later flow-units being rotated less than earlier ones leading to continuous change in paleomagnetic inclination with depth. Preexisting crust beneath the new flow will be uniformly rotated at the maximum value occurring at the base of the flow. A fault that responds to increased loading in this manner is properly described as a growth fault. Mélanges of plutonics could be forced to the surface from shallow depths as a result of this subsidence causing further tectonic disruption.

At some time after termination of volcanic activity, the edifice as a whole begins to be transported toward one of the other walls of the inner median valley (*32*). Transport is accompanied by subsidence of the edifice as a whole, and it seems likely that subsidence will be accompanied by fault movement within and beneath the edifice (Fig. 11B). The amount and direction of rotation should reflect at least two factors: (i) asymmetry of the edifice which would lead to rotation in whatever direction was necessary to approach mechanical equilibrium, and (ii) increasing crustal strength away from the inner median valley which should

cause the greatest subsidence to occur along the trailing edge of an edifice. The overall rotation of an edifice is seen as the likely explanation for long, uniformly rotated basement sections. After an interval of from 1 to 2 × 10^5 years an edifice, now subsided to the level of the surrounding inner median valley fill or deeper, should have achieved mechanical equilibrium, and, in some instances, may be buried by thin, distal ends of flows from a younger active edifice. In the Neogene, for which the average duration of polarity epochs is 1.5 to 1.9 × 10^5 years, there will be a strong probability that the unrotated overlying flow will have the opposite magnetic polarity from that of the rotated underlying edifice. By this mechanism it is possible to account for thin, dipole-magnetized sequences capping some rotated basement sections, and to explain the deep tow observation that the tectonic dips of the surface of basement blocks are much less than those occurring at depth (*74*).

By the time the buried edifices have reached the outer edge of the inner median valley, the construction of at least the upper part of ocean basement is essentially complete and it only remains for segments to be removed from the median valley for permanent accretion, via the rift mountains, to the adjacent plate.

This model has several important consequences, some of which can be tested by further drilling.

1) The bulk of upper layer 2 in the North Atlantic should be a large-scale tectonic mélange of variously rotated blocks, each block consisting of the remains of a single volcanic edifice or part of such an edifice. The mechanism of rotation could be determined by locating basement drill holes symmetrically about an east-west slow-spreading center (Atlantic type) such as the Galápagos Rift. Opposed tilts at sites on opposite sides of the rift would suggest that lateral change in inner median valley crustal strength was the major factor in determining the direction of rotation. On the other hand, the absence of a relationship between sense of rotation and site location with respect to the rift would imply that edifice asymmetry was the dominant factor.

2) For north-south ridges, and all ridges if rotation is related to edifice asymmetry, high paleolatitude sites will now have shallower than dipolar inclinations and low latitude sites will have steeper than dipolar inclinations.

3) The upper parts of ophiolite sequences are often severely tectonized and a valuable test of our model of oceanic basement tectonics could be made by study of such a sequence if original structural components of ophiolites can be differentiated from those formed during obduction.

4) At many places in the North Atlantic the upper cap of basement should consist of a small number of subhorizontal flows that are much younger (1 to 2 × 10^5 years) than the deeper part of the layer.

5) It is unlikely that reliable estimates of absolute plate motion can be obtained from paleomagnetic inclinations in North Atlantic oceanic basement. Only thin caps are likely to be undisturbed tectonically and these are unlikely to contain sufficient information to allow secular variation to be removed by averaging.

6) If, as we suggest, the tectonic style described here is a consequence of the extreme weakness of inner median valley crust, constraints may be introduced to the current discussion of the nature and size of Mid-Atlantic Ridge magma chambers (*75*). The presence of shallow bodies of magmatic liquid appears to be the simplest way to weaken the bearing strength of the crust. While collapse of the crust close to a volcanic vent does not provide evidence to distinguish narrow, transient or broad, permanent magma chambers, the continued subsidence of edifices up to the margin of the inner valley, if substantiated, would appear to favor the presence of magma at shallow depths, at least sometimes, beneath most of the inner valley.

Questions

Here we list some important questions that remain to be answered (*76*).

1) The lithology, structure, and other properties at depths greater than 600 m subbasement are still unknown. Evidence of imminent changes with greater depth is present in the deepest drill holes, such as the decrease in magetization at the bottom of 395A and the occurrence of dikes in holes 417D and 418A. Do these dikes represent the upper part of a sheeted dike complex such as is seen in ophiolites? These questions can best be answered by deeper penetration by drilling which appears to be feasible in old crust. Sections in fault scarps are accessible to sampling by dredging or by submersibles but it is not known whether the crust in these areas is typical.

2) We do not yet know whether the geochemical and physical features of oceanic crust formed from a slow-spreading ridge such as the Mid-Atlantic Ridge are the same as those formed from fast-spreading ridges such as the East Pacific Rise. To date, shallow holes drilled in the Pacific have found what appear to be several of the magnetic complexities of North Atlantic crust such as reversals and continuous change of inclination with depth. However, very little information from direct sampling is available on the constitution and variability of the crust in the Pacific Ocean. Deep drilling attempts in the Pacific Ocean have thus far been unsuccessful, but these have all been in very young crust. Presumably, drill holes in old Pacific crust would yield the same improved penetration and recovery found at old sites in the Atlantic Ocean.

3) How close to reality is the tectonic mélange model that we have proposed for layer 2? The basic problem here is to identify an independent means of checking rotations of crustal blocks proposed on the basis of paleomagnetic data alone. Bideau *et al.* (*77*) have proposed a means of orienting sea floor basalts from segregation vesicles but his method has not been widely tested.

4) Where and what is the source of the linear magnetic anomalies on the sea floor? Drilling has shown convincingly that the source of the anomalies does not lie in the upper 600 m of oceanic crust as previously thought. Are the anomalies generated by considerable thicknesses of low-intensity material or is there some highly magnetic source layer at greater depth? If so, what constitutes the layer and why is it not tectonically (and thus magnetically) disrupted in the same way as upper layer 2? These questions can only be answered by deeper crustal drilling.

5) The absence of evidence for a steep geothermal gradient at any time in sampled basement is unexpected. Is this evidence of extensive downwelling of cold seawater through the crustal rocks? Are there zones of hydrothermal upwelling along the Mid-Atlantic Ridge and, if so, what are their locations and dimensions? Are massive sulfide deposits being formed along present-day spreading ridges as suggested by studies of ophiolite complexes? A combination of direct observation of spreading ridges by submersibles and deep drilling of young crust should provide information bearing on these problems. Drilling of very young crust must await the development of techniques for starting basement holes in the absence of a sediment cover and continuing successfully in brittle, highly fractured material.

6) Can better geochemical criteria be developed for recognition of primary

magmas and identification of specific processes of magma modification? What causes the apparent compositional variations in primary magmas along the Mid-Atlantic Ridge? Do similar geochemical anomalies persist in older rocks derived from specific ridge segments? What are the causes of geochemical differences between basalts generated along the ridge crest and in "plume" areas such as Iceland? Secular variations in oceanic basalts can be investigated by drilling a number of holes along a specific sea-floor spreading line in crust of progressively greater age. The effects of mantle "plumes" could be investigated by drilling a number of holes around a single "hot spot" such as the Azores.

It is apparent that crustal drilling to date has shown that the processes of generation and modification of oceanic crust are much more complex than originally thought. A continued program of crustal drilling, coupled with direct observation of the sea floor from submersibles, provides the best means of investigating the problems outlined above and of testing new models as they are developed.

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