74. LITHOLOGY AND ERUPTIVE STRATIGRAPHY OF CRETACEOUS OCEANIC CRUST, WESTERN ATLANTIC OCEAN

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INTRODUCTION

One of the major goals of crustal drilling in the Atlantic Ocean has been to determine directly the petrologic and magnetic constitution of acoustic basement, and to gain a better understanding of the processes of crustal construction at the Mid-Atlantic Ridge. A serious problem during early phases of crustal drilling had been the low recovery of basement materials, severely limiting structural and petrological interpretations. Prior to 1977, average basement recovery in the North Atlantic Ocean ranged from a low of 8 per cent at DSDP Site 333 to a high of 47 per cent at Site 335. Recovery was strongly biased toward thick, massive units, and non-consolidated materials such as breccia and interpillow sediment were almost certainly underrepresented in the cores. In addition, critical contact zones such as glassy pillow rinds and intrusive contacts were rarely preserved. Hence, the drill core provided only limited information on the constitution of the oceanic crust, and in the absence of geophysical logs, the relative proportions of the different constituents had to be estimated from the drilling record (Aumento, Melson et al., 1977).

Early drilling in the North Atlantic Ocean and elsewhere suggested a possible direct correlation between crustal age, hole conditions, and core recovery. A deep penetration attempt was therefore planned in crust of Cretaceous age in the western Atlantic Ocean in the hope of obtaining a deeper and more complete sample of the crust than had been possible so far. During this deep drilling attempt, on Legs 51, 52, and 53, three major basement holes were drilled at the southern end of the Bermuda Rise from December, 1976 to April, 1977 (Figure 1). Depths of 206.0 meters, 365.5 meters, and 544.0 meters below the top of acoustic basement were attained in Holes 417A, 417D, and 418A, respectively. As hoped, average recovery was high, ranging from a low of 62 per cent in Hole 417A to a high of 72 per cent in Hole 417D. Most importantly, nearly complete recovery was obtained in many intervals providing continuously cored sequences of oceanic crust. High recovery was obtained irrespective of lithology, in massive basalt, pillow sequences, breccia zones, and intercalated sedimentary layers. Thus, for the first time it is possible both to interpret crustal processes in terms of the relative proportions of lithologic constituents and to examine structural and lithologic evidence for tectonic dislocation.

This paper aims to: (1) document lithologic associations in Cretaceous crust at Sites 417 and 418; (2) provide an interpretative summary of the igneous units and their contact relationships; (3) critically evaluate criteria for tilting or rotation of crustal sequences, as proposed in models for ocean crust construction; and (4) interpret the eruptive stratigraphy in terms of crustal construction processes. We draw largely from the work of shipboard scientists on Legs 51 through 53, and attempt to summarize their contributions to the Initial Report volumes. However, the views expressed in this paper are those of the authors and do not necessarily reflect those of all of the shipboard scientists.

BASEMENT LITHOLOGY

Pillow basalt comprises the bulk of the drilled sections at Sites 417 and 418; the remainder consists in decreasing order of massive basalt, breccia, and interlayered sediment (Table 1). Narrow, subvertical dikes were encountered near the bottom of Holes 417D and 418A. The relative proportions of the different lithologies are similar in all three holes, and there are no regular downhole changes in rock type. Twenty-eight lithologic units were identified in Hole 417A, 22 in Hole 417D, and 25 in Hole 418A (see Site Chapters, this volume).

Pillow Basalts

Pillowed units are recognized by the frequent occurrence of curved chilled margins with glassy, or once-glassy, rinds and by the presence of quenched groundmass textures in the basalts. Most pillows are between 35 and 50 cm in vertical thickness (Table 2), but individual pillows may be as much as 1.5 meters and as little as 10 cm thick. Individual cooling units bounded by either glassy selvages or abrupt changes in grain size across unrecovered intervals were classified as single pillows if less than 1 meter thick.

A thin, black glassy rind, 1 to 2 cm thick, forms the outer pillow margin (Plate 1, Figures 1 through 3); this may be fresh or partly altered to smectite. Typically, the glass selvages spall off along concentric fractures and the glass chips collect between pillows where they alter readily, forming elongate slivers of palagonite (Plate 1, Figure 2). Some pillow interstices are filled with small masses of palagonite with a "perlitic" texture (Plate 1, Figure 2). The glassy rind grades into a fine-grained, dark colored variolitic zone, usually 2 to 4 cm wide, which in turn grades into the more coarsely crystalline pillow interior.

In most pillows the phenocryst distribution is very uneven. Pillow interiors are often aphyric, grading outward

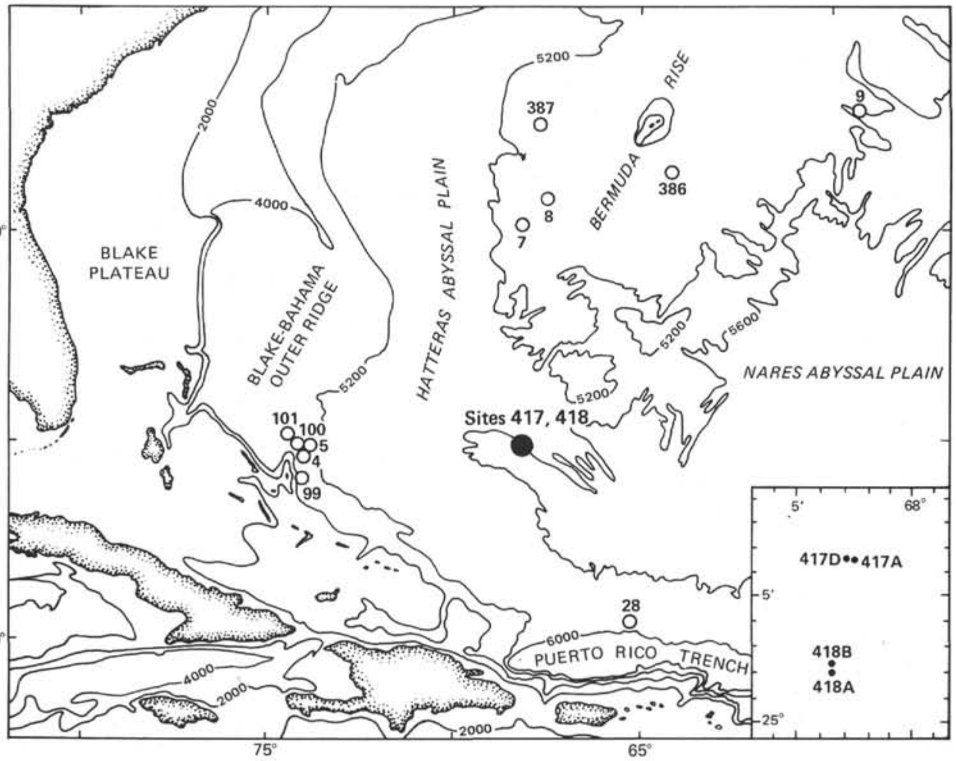

Figure 1. *Index map showing location of Deep Sea Drilling Project Sites 417 and 418.*

TABLE 1
Lithologic Summary of Holes 417A, 417D, and 418A

Lithology	Cored Thickness (m)	Recovered Thickness (m)	Percentage Recovery	Relative Proportions Cored (%)	Relative Proportions Recovered (%)
		Hole 417A			
Pillowed basalt	138.63	92.05	66.4	67.3	71.8
Basalt breccia	37.26	24.74	66.4	18.1	19.3
Massive basalt	23.11	10.34	44.7	11.2	8.1
Basalt pebbles	7.0	1.05	15.0	3.4	0.8
Total	206.00	128.18	62.2 (av.)	100.0	100.0
		Hole 417D			
Pillowed basalt	253.0	179.11	70.8	69.2	67.8
Basalt breccia	20.5	18.80	91.7	5.6	7.1
Massive basalt	89.0	63.71	71.6	24.4	24.1
Sedimentary rock	2.0	1.50	75.0	0.5	0.6
Dikes	1.0	0.93	93.0	0.3	0.4
Total	365.5	264.05	72.2 (av.)	100.0	100.0
		Hole 418A			
Pillowed basalt	366.60	252.23	68.8	67.4	64.5
Basalt breccia	31.15	19.89	63.9	5.7	5.0
Massive basalt	140.70	114.22	81.18	25.9	29.2
Sedimentary rock	0.55	0.37	67.3	0.1	0.1
Dikes	5.00	4.62	92.4	0.9	1.2
Total	544.00	391.33	71.9 (av.)	100.0	100.0

TABLE 2
Chilled Margins, Pillows, and Pillow Thicknesses in Holes 417A, 417D, and 418A

Hole	417A	417D	418A
Pillowed section drilled (m)	138.6	253.0	366.6
Recovered pillowed basalt (m)	92.1	179.1	252.2
Upper chilled margins (No.)	127	227	390
Lower chilled margins (No.)	75	148	245
Lateral chilled margins (No.)	95	109	112
Undifferentiated chilled margins (No.)	0	0	46
Ratio upper/lower chilled margins	1.69	1.53	1.59
Maximum number of pillows (total chilled margins)	297	484	793
Probable maximum numbers of pillows (total upper and lower chilled margins)	202	375	635
Minimum number of pillows (upper chilled margins)	127	227	390
Minimum vertical thickness of average pillow (cm)	31	37	32
Probable minimum vertical thickness of average pillow (cm)	46	48	40
Maximum vertical thickness of average pillow (cm)	73	79	65

into marginal phyric zones. In other pillows the chilled margins are nearly aphyric and the largest phenocrysts occur in the center of the pillow. The phenocryst distribution probably reflects flow segregation within pillows that acted as lava tubes during eruption. Gravitational segregation should lead to accumulation of phenocrysts either in the top or bottom of individual pillows, whereas flow of lava through a tube could produce the observed complex distributions. This interpretation is supported by the flow orientation of microphenocrysts in some specimens. Another possibility is that the pillows acted as lava tubes in the early stage of eruption, and were filled at a later stage after a change in the phenocryst content of the lava.

Vesicles vary in size and abundance through individual pillows. Small vesicles, usually less than 0.1 mm in diameter, occur in the glassy selvages and chilled margins. In the coarser-grained pillow interiors, vesicles commonly range up to 1 to 2 mm across and tend to be concentrated in the area between the pillow center and the upper chilled margin. Segregation vesicles (Smith, 1967), with a meniscus of glassy material, are most common just inside the chilled margin.

Groundmass textures range from glassy to intersertal. The glassy rinds grade through a 1- to 2-mm-wide transition zone into glass containing small, sub-spherical varioles which become larger and more abundant inward, gradually merging into a zone of dark-brown cryptocrystalline material. This in turn grades into a quenched mixture of clinopyroxene and tiny plagioclase needles. The quenched groundmass becomes coarser grained and better crystallized inward, where it is characterized by radiating sheaves of clinopyroxene and very minute, submicroscopic magnetite crystals. The plagioclase microlites typically have a "swallow-tail" habit (Bryan, 1972) or open crystal form and may occur in "bow-tie" intergrowths with olivine or clinopyroxene in the pillow interiors.

Because of incomplete recovery neither the exact number of pillows nor the average pillow thickness can be obtained precisely; however, they can be estimated from a study of glass selvages. Recognizable selvages have been identified as upper, lower, or lateral pillow margins, and the results are tabulated in Table 2. These data show that upper pillow margins are consistently recovered with greater frequency than lower margins. At Sites 417 and 418, the ratio of upper to lower margins in the core is between 1.5 and 1.7, suggesting that lower margins are more easily destroyed during drilling than upper margins, and these are therefore selectively less recovered.

Average pillow thickness can be estimated by tabulating thicknesses of complete pillows and by estimating the number of pillows in a given depth interval. Twelve complete pillows were recovered in Hole 417A, 30 in Hole 417D, and 33 in Hole 418A (Table 3). These have an average vertical thickness of 36.1 cm, 44.3 cm, and 43.6 cm, respectively. The minimum number of pillows in any sequence is equal to the number of upper glass margins recovered (Table 2). The average vertical pillow thickness derived from dividing the total recovered thickness of pillow basalt by the estimated number of pillows ranges from a minimum of 31 cm to a maximum of 79 cm, with a probable minimum thickness of 40 to 48 cm. These values compare well with the average vertical thickness of complete pillows (Table 3). From these calculations we conclude that the actual mean vertical thickness of pillows at Sites 417 and 418 is between 36 and 79 cm, and is most probably about 50 cm.

TABLE 3
Complete Pillows Identified in Holes 417A, 417D, and 418A

Hole	Number of Pillows	Vertical Thickness Range (cm)	Mean Vertical Thickness (cm)	Standard Deviation (cm)
417A	12	28 – 50	36.1	7.6
417D	30	13 – 80	44.3	18.8
418A	33	10 – 107	43.6	23.9

The overall similarity in calculated and observed pillow thicknesses in the three holes is striking, suggesting some uniformity in the emplacement mechanism, the rheology of the cooling lava and its crust, and the slope on which the pillows formed. The lower average vertical thickness of pillows in Hole 417A may reflect extrusion onto a steeper slope than existed at Holes 417D or 418A, consistent with the interpretation that Hole 417A is located on a small basement high.

Dips of pillow margins were measured in all three holes in order to gain some insight into pillow morphology and slopes of depositional surfaces. Correlations were attempted between dips of pillow margins and paleomagnetic inclinations to test the hypothesis that pillow dips reflect tectonic rotation. In Hole 417A, 102 margins were measured; in Hole 417D, 208 and in Hole 418A, 464. The inclinations are plotted in histograms in Figure 2. In Hole 417A, the measured dips have a strong maximum at low angles, between 0 and 15 degrees, probably corresponding to the subhorizontal upper and lower pillow margins. There is a more or less regular decrease in the number of surfaces with steeper dips. Because the paleomagnetic inclinations in the upper part of Hole 417D (Cores 22 through 42) are much steeper than those in the lower part, the measured pillow dips are plotted separately for these intervals (Figure 2). The two data sets are clearly different, with median values differing by about 20 degrees; in the upper sequence, pillow dips have a well-defined maximum at about 40 degrees, and in the lower sequence most of the dips are less than 20 degrees. Dips of pillow margins in Hole 418A show no strong frequency maximum, and dips from all pillowed units are similar, regardless of paleomagnetic inclination (Figure 2).

Where distinguished, dips of upper and lower margins are nearly identical, suggesting that most of the pillows have a regular shape. However, different pillow shapes (spherical to tubular) will yield different frequency distributions of dip angles; spherical pillows would tend to have a frequency distribution favoring lower angles. Average pillow dips must also reflect variations in the dip of the depositional surface and may reflect a bias caused by drilling. Pillow sequences observed in the median valley of the Mid-Atlantic Ridge in the FAMOUS area (Ballard and van Andel, 1977) and in many ophiolite complexes are typically tubular and often have steep initial dips. For these reasons we believe that the dips of pillow margins measured in DSDP cores cannot be used to give reliable structural information, particularly since the azimuth of dip cannot be obtained.

Massive Basalt

Massive basalt is present in all three basement holes, comprising 8 per cent of recovered material in Hole 417A, 24 per cent in Hole 417D, and 29 per cent in Hole 418A (Table 1). A cooling unit was considered to be massive if no glassy selvages or chilled zones were encountered in 3 meters of well-recovered core. The massive units drilled at Sites 417 and 418 range from a few meters to nearly 40 meters in vertical thickness and are randomly distributed in the holes. Many units are bounded by upper and lower

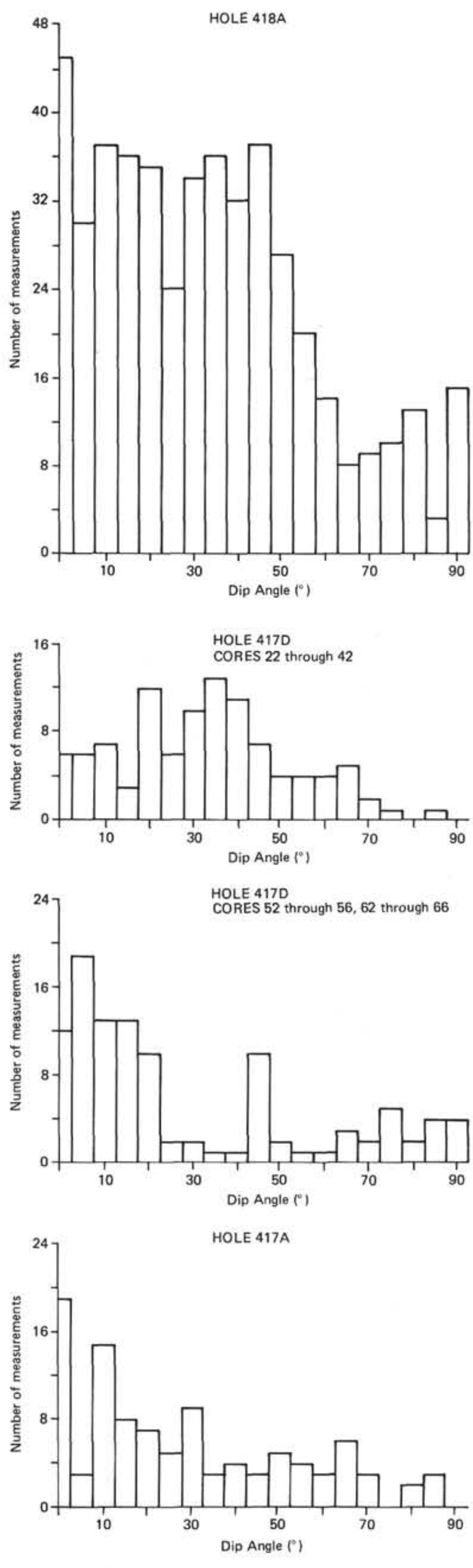

Figure 2. *Histograms of pillow margin dip angles in Holes 417A, 417D, and 418A.*

glassy selvages, but these are not always preserved. None of the massive units has well-developed breccia zones along its contacts. Internal cooling breaks are generally absent, although a few units have fine-grained "segregation" veins (Plate 2, Figures 1 and 2), perhaps due to mobilization of interstitial liquids during the last stages of cooling. A few massive units also contain internal vesicle zones (Plate 1, Figure 4). Where contact relationships are visible, the lower chilled zones of the massive units appear to be molded around rather than cutting across the underlying pillows, and overlying pillows rest conformably on the upper quenched surface.

Textures of massive units vary systematically from margin to center (Plate 3, Figures 1 through 3). At the glassy chilled margins textures are similar to those in pillow rinds, although the margins are often nearly flat and the glassy and variolitic zones are relatively thinner. The glassy selvages pass gradually into a brown, variolitic zone which in turn merges inward into a zone with fine-grained intersertal textures (Plate 3, Figure 1). Grain size continues to increase toward the central part of the unit, but the rock generally maintains an intersertal texture (Plate 3, Figure 2). As the grain size increases, plagioclase and clinopyroxene often develop clots with an ophitic to subophitic texture. These clots are generally surrounded by interstitial glass, giving rise to a characteristic "ophimottled" texture (Plate 3, Figure 3). Usually, the high interstitial glass content extends farther into a unit from the top than from the base, indicating asymmetric cooling. Only relatively thick units, probably greater than 30 meters, are holocrystalline. Unit 13 in Hole 417D is such a unit, with a subophitic texture. Interstitial material in this unit consists of apatite needles and probable alkali feldspar in patchy intergrowths.

Phenocryst distribution is variable in the massive units, but segregation is not as pronounced as in pillows. Small, skeletal microphenocrysts of olivine and plagioclase occur in the glassy selvages; those in the interior are typically larger and more euhedral. Some olivine accumulation was noted in the lower part of lithologic Unit 14C in Hole 418A, but in most units clear evidence for gravitational settling is absent.

The massive units drilled on Legs 51 through 53 have been variously interpreted by the shipboard parties as either sills or thick flows. Distinguishing between the two possible origins is difficult but we believe that most, if not all, of the massive units at Sites 417 and 418 are flows. No clear-cut intrusive contacts against pillow interiors were observed, and the lower glassy margins of many massive units appear to be molded around the underlying pillows. Many of the massive units have upper glassy margins which could have developed against water as well as against rock. Pillows appear to rest depositionally on the upper surface of at least one of the massive units. No contact metamorphism of glassy pillow rinds or sedimentary interlayers was observed along the contacts of massive units. The interiors of the massive units are medium-grained, but most have "ophimottled" textures characterized by interstitial glass. The presence of glass argues for a flow origin because even thin dikes, less than 30 cm wide, at Sites 417 and 418 have holocrystalline textures.

These observations lead us to conclude that cooling units more than 3 meters thick with a glassy or quench-textured groundmass are more likely to be flows than sills. A holocrystalline cooling unit lacking quench textures, greater than about 10 meters thick, may have formed as either a flow or sill. A holocrystalline cooling unit between 3 and 10 meters in thickness is most likely a sill, although proper insulation of a flow could lead to holocrystalline textures under some conditions.

Under what conditions can massive, non-pillowed flows form on the sea floor? Although subaerial flows have a significantly higher escaping volatile phase and solidify under less severe cooling conditions than submarine flows, the similarity in form and mode of formation of pillows and pahoehoe toes (Moore et al., 1973; Swanson, 1973) suggest that flowage processes in the two environments are similar. Observations of lava flows at Kilauea indicate that the rate of cooling is the principal factor determining whether flows advance as pahoehoe toes or sheet floods (Swanson, 1973). The slower a flow cools as it moves, the greater is the likelihood that it will form a thick massive unit. Observations show that the more rapid the rate of eruption and flowage, the slower is the rate of cooling. In the 1969 to 1971 Kilauea eruption, sheet floods were produced when eruption rates were about 10^6 m^3/hr, and pahoehoe flows formed when the eruption rates were about 10^4 m^3/hr. By analogy, we suggest that a rapid rate of eruption under water can produce a massive rather than a pillowed flow. A chilled carapace probably forms on the flow surface and is rafted along on the lava moving below.

Formation of lava tube systems composed of interconnected pahoehoe toes also strongly impedes cooling of lava flows at Kilauea (Swanson, 1973); virtually no cooling was measured during 12 km of transport in one such tube system. Lava pours through a tube system, spills out its mouth and forms a crusted lava pond in a flat area. Continued supply through the tube system adds more and more lava beneath the crust of the pond, hydraulically lifting the crust higher than its original position.

Studies of pillow formation (Moore et al., 1973) have shown that similar tubes can be formed from interconnected pillows. Such lava tubes might convey substantial volumes of lava through pillow sequences to low areas where lava ponds might be formed. Indeed, lava that forms a massive cooling unit may never have reached the actual sea floor, instead flowing through a tube system from vent to crusted pond. It could conceivably even intrude its own crust, possibly pillowed, which formed slightly earlier. However, in either case, the massive unit is formed during the same eruptive event that produced the surrounding pillows and not during a separate, later intrusive event.

Pahoehoe lava flows with lava coils have been reported on the Galapagos rift (Lonsdale, 1977), and massive flows have been observed from submersibles in the rift valley of the East Pacific Rise (C. Rangin, personal communication). Here, they are typically found in topographic lows between pillowed flows, suggesting ponding of lava in much the same way as that observed at Kilauea. The paucity of massive flows in Hole 417A may reflect the fact that this hole penetrated a basement high where there was little opportunity for ponding of lava.

Breccia

Breccia makes up nearly 20 per cent of recovered material in Hole 417A, but averages only about 6 per cent in Holes 417D and 418A (Table 1). It occurs most commonly in thin layers associated with the boundaries of lithologic and magnetic units, or as minor interpillow accumulations.

The most common type of breccia consists of fragments of crystalline basalt, often with curved glassy rinds, in a matrix of smectite. Clasts range from about 1 to 30 cm across with the smaller fragments grading into the matrix material; clasts are angular, poorly sorted and matrix-supported (Plate 4, Figures 1 through 3; Plate 3, Figure 4). These breccias often grade into pillow sequences, and they are considered to be broken pillow breccias formed along flow fronts. The freshness of the rocks, their monolithologic nature, the preservation of delicate structures in the glassy selvages, and the abundant glass in the matrix argue against a tectonic origin.

A second, less common, type of breccia consists of loosely fitting fragments separated by a network of thin smectite–carbonate veins (Plate 4, Figure 4). Little relative movement has occurred between fragments, although slickensides are often present in the smectite-filled fractures. Whole single pillows, some with glassy selvages, may be fractured or brecciated in this fashion. These breccias are believed to result from compaction of loosely consolidated pillow piles, although they could possibly record minor tectonic events.

Hyaloclastic breccias are common in small quantities between pillows (Plate 1, Figure 2). They consist of small, angular, usually altered, glass fragments embedded in a carbonate or smectite matrix. The fragments are usually about 1 cm long and have a slightly curved, tabular habit. They probably represent glass chips formed by spalling of pillow rinds during quenching. Accumulation of these chips between pillows is followed by alteration of the glassy matrix, some of which may be replaced by carbonate.

Tectonic breccias, or those formed from accumulations of talus, were not positively identified in the cored materials from Sites 417 and 418 but may nonetheless be present in small quantities. Low fault scarps are present in the modern rift valley of the Mid-Atlantic Ridge, and some of these have small talus accumulations (Ballard and van Andel, 1977). Breccias formed in this way should be similar to pillow breccias, but they would have fewer fragments with glassy rinds and would lack a glassy matrix. Large tectonic scarps such as those associated with transform faults would probably yield breccia composed of a variety of rock types, such as metagabbro, greenstone, and serpentinite.

Sedimentary Rock

Sedimentary interbeds are sparse in the basement sequences at Sites 417 and 418, comprising less than 1 per cent of the recovered material (Table 1). This is significantly less than the amount of sediment estimated at previous sites (Hyndman, 1977). Most of the recovered sedimentary material at Sites 417 and 418 consists of indurated chalk or limestone occurring in small masses between pillows. Layering is generally not apparent, and most fossils have been destroyed by recrystallization. Many of these sedimentary rocks have incorporated fragments of fresh or altered glass. Baking is not obvious, but the sedimentary rocks are often indurated, probably as a result of silicification. Most of the sedimentary rocks are believed to be small masses dislodged from thicker accumulations by the bulldozing action of pillowed flows, rather than true sedimentary interbeds deposited directly on the underlying surface. Some may be secondary in origin, being deposited after formation of the pillow pile.

Dikes

Dikes were encountered near the base of Holes 417D and 418A at sub-basement depths of about 350 and 500 meters, respectively. In Hole 417D, two dikes with similar mineralogy and chemistry occur in Unit 13; in Hole 418A six dikes, comprising two mineralogical types, are present. The dikes have steep dips, glassy selvages, and cross-cutting relationships with massive, relatively coarse-grained flows (Plate 2, Figures 3 and 4). They are chemically, mineralogically and, in some cases, magnetically distinct from the host rocks. The dikes are typically about 30 cm wide and have very fine grained, nearly holocrystalline, intergranular groundmass textures; glass is common only in the narrow selvages at the margins. None of the dikes has quench textures but none is coarse grained or subophitic, suggesting that they cooled very rapidly. Phenocryst distribution is highly variable, probably as a result of flow segregation.

CRUSTAL CONSTRUCTION

Interpretation of Eruptive Units

The main purpose of this paper is to interpret the eruptive stratigraphy of the drilled sequences in Holes 417D and 418A, in order to gain a better knowledge of crustal construction processes at the Mid-Atlantic Ridge during the Cretaceous. Eruptive history can be deduced from lithologic, magnetic, and chemical breaks in the cored material and from petrogenetic interpretations of the core.

Lithologic units defined on the basis of structural character (pillowed, massive, brecciated), cooling breaks, and phenocryst mineralogy may correspond to either single or multiple eruptive events. Conversely, a single eruption may form several lithologic units. Any genetic relationship between pillowed and massive flows and eruptive style is of particular interest. Differences in lithology may reflect variations in eruptive rate or simply the topography of the depositional surface; massive units may result from lava ponding during certain phases of an eruption that otherwise formed pillows. Breccia units are also diverse, and their interpretation is uncertain. Tectonic breccias may form by accumulation of talus along scarps and, in drilled crust, reflect periods of volcanic quiescence. Flow breccias probably form along advancing flow fronts and would record an active eruption. Other breccias may form simply by compaction of loosely consolidated pillow piles and have little stratigraphic significance.

Basalt compositions appear to be characteristic for successive eruptive sequences, although phenocryst redistribution and secondary alteration often affect the chemical composition of all but the rapidly quenched glassy selvages. Thus, fresh sideromelane compositions provide the most useful discriminants for the recognition of magma compositional groups. Compositions of glass selvages are often very uniform within a given eruptive unit, so that even a small change in composition can be used to recognize different magma batches.

Phenocryst contents may vary significantly within individual cooling units owing to flow or gravitational segregation, but the overall assemblage generally reflects the bulk composition of the rock. Appearance of a new eruptive sequence is usually accompanied by a change in the phenocryst assemblage.

If the effects of viscous magnetism are removed by AF demagnetization, downhole changes in stable NRM inclinations should reflect changes in pole position through time or rotation of the crustal section after formation. In either case, inclination changes may represent periods of volcanic quiescence. Changes in magnetic inclination or polarity, particularly when coupled with lithologic or chemical changes, are used to distinguish individual eruptive units and also major breaks in the eruptive sequence.

Using the criteria listed above we have defined both eruptive units, representing the products of a single eruption, and major eruptive sequences representing series of related eruptive units (see Flower et al., this volume). Ideally, an eruptive unit sampled by drilling should have: (a) uniform glass composition, (b) whole-rock compositional variation consistent with the effects of phenocryst fractionation and accumulation, (c) uniform magnetic polarity and stable inclinations, (d) lithology consistent with the chemical composition, and (e) no major sedimentary or clastic intercalations. In practice, both chemical composition and magnetic inclination can vary during a single eruption if a zoned magma reservoir is tapped and if tilting and rotation of eruptive products occurs along growth faults.

Major eruptive sequences represent a series of contiguous eruptive units that can be related to a single fractionation system by least-squares modeling of glass and whole-rock compositions (Flower et al., this volume; Byerly and Sinton, this volume; Flower and Robinson II, in preparation). These sequences represent stratigraphic "packages" bounded above and below by significant breaks defined by changes in glass composition and magnetic inclinations or polarities (Flower and Robinson II, in preparation). In many cases these boundaries are marked by breccia zones, sedimentary interlayers, and zones of intense oxidative alteration, all of which imply lengthy contact of the basalt pile with sea water, and by implication, a hiatus in the eruptive activity.

Eruptive Stratigraphy of Basement

In this section we review the lithologic, magnetic, and chemical stratigraphy of Holes 417D and 418A in terms of eruptive units and major eruptive sequences. From the stratigraphy, we infer a chronologic sequence for the emplacement of the basalt units. Glass chemical types referred to are those of Byerly and Sinton (this volume).

Hole 417D

Flower et al. (this volume) identified a maximum of 24 and a minimum of 13 individual eruptive units in Hole 417D. These are grouped into three major eruptive sequences separated by major stratigraphic discontinuities (Figure 3).

Eruptive Sequence III (base of hole to 642 m sub-bottom)

This sequence includes all lithologic units below Unit 9C and comprises at least 60 meters of massive basalt with two intercalated pillow layers (Figure 3). Phenocrysts are largely plagioclase and olivine, with some clinopyroxene toward the base of the sequence. Glass compositions represent moderately TiO_2-rich liquids (group H), becoming slightly more fractionated upward. Whole-rock compositions are variable, reflecting both fractionation and accumulation of phenocrysts. Magnetic inclinations are all negative but show fairly regular shallowing with decreasing depth. If these units were erupted in rapid succession as suggested by their relatively uniform compositions, the pattern of inclinations could reflect progressive tilting of the basalts during their emplacement, although such steep tilts have not been observed from submersibles on the sea floor. The progression from early mafic lava to later differentiated lava is unusual compared to most eruptive sequences, but the basalt sampled at the bottom of the hole is probably not representative of the earliest part of the eruptive episode.

Eruptive Sequence II (642 to 479 m sub-bottom)

This sequence encompasses lithologic Units 9C through the lower part of Unit 4 and consists of pillow basalt, pillow breccia, and three intercalated massive flows (Figure 3). All the rocks contain plagioclase, olivine, and clinopyroxene phenocrysts, those in the middle of the sequence containing relatively more clinopyroxene. The uppermost eruptive units, near the base of Unit 4, contain fairly abundant clinopyroxene and olivine phenocrysts. Glass groups D, E, and F are interpreted as reflecting a fractionation series ranging from highly fractionated, TiO_2-rich basalt at the base (F) to relatively mafic basalt (D) at the top (Byerly and Sinton, this volume; Flower and Robinson II, in preparation). Whole-rock compositions are more varied, showing complex effects of phenocryst redistribution. Magnetic inclinations are shallow negative and steepen slightly upward. We interpret eruptive sequence II as the extrusive products of a single reservoir system, showing progression from early fractionated, to later more mafic magma which may be derived from lower levels of the magma chamber. Despite the change in stable magnetic inclination of 488 meters sub-bottom, possibly indicating a quiescent interval, we tentatively include glass group D in this sequence because it appears to be cogenetic with E and F glass groups (Flower and Robinson II, in preparation). Alternatively, it might be a mafic basalt at the base of eruptive sequence I. Chemical and magnetic data on the breccias in Units 9B and 9C preceding the earliest flows in this sequence are sparse, but mineralogically they are similar to the overlying pillow basalt and may mark the first stage of eruption.

Eruptive Sequence I (479 to 343 m sub-bottom)

Represented by Units 4 (upper part) through 1, this sequence consists largely of pillow basalt with lesser massive flows and some breccia in the lower part. All of the rocks are plagioclase–olivine phyric; they usually contain sparse clinopyroxene phenocrysts, which are most abundant in Unit 3 near the middle of the sequence. Glass compositions include C, B, and A, which appear related to one another by fractional crystallization of olivine and plagioclase (Flower et al., this volume; Byerly and Sinton, this volume). Glass group C at the base represents a relatively fractionated liquid which becomes progressively more mafic upward through glass group B to a sub-bottom depth of 365 meters. Above this level average glass compositions are slightly more fractionated. Whole-rock compositions have consistently lower TiO_2/Al_2O_3 and usually higher $Mg/(Mg + Fe^{+2})$ ratios than the associated glasses, reflecting plagioclase and olivine accumulations before or during eruption. Magnetic inclinations are consistently steep and negative.

We have tentatively interpreted sequence I as starting at 479 meters sub-bottom with the change from glass group D to glass group C and as reflecting eruption from a single, zoned magma reservoir. Early eruptions produced relatively differentiated magma, becoming more mafic upward to about 367 meters sub-bottom. The last eruptions, represented by glass group A, again start with relatively differentiated magma which becomes slightly more mafic upward.

Hole 418A

In this hole Flower et al. (this volume) identified a maximum of 43 and a minimum of 32 individual eruptive units. We group these into seven major eruptive sequences, two of which, IV and V, may be subdivided. The eruptive sequences are bounded by changes in magnetic inclination or polarity and/or by significant changes in glass compositions and phenocryst abundances. We believe most of these boundaries represent lengthy quiescent intervals in view of the alteration profiles at the top of each sequence (Flower et al., this volume).

Eruptive Sequence VII (base of hole to 860 m sub-bottom)

The 8 meters of this sequence drilled consists of plagioclase-clinopyroxene-olivine-spinel-phyric pillow basalt, with a thin breccia zone at the top (Figure 4). The one glass analysis available (group N) shows moderately high TiO_2 and is distinctly more fractionated than glass in the overlying units. Whole-rock analyses have relatively low TiO_2/Al_2O_3 ratios and variable $Mg/(Mg + Fe^{+2})$ ratios but are interpreted as cogenetic (Flower and Robinson II, in preparation). Magnetic inclinations are negative and distinctly shallower that those of the basalts above the breccia zone at the top of the sequence. The breccia is more highly altered than rocks just above or below.

Eruptive Sequence VI (860 to 786.5 m sub-bottom)

The basalts of this sequence form a 74-meter-thick section consisting of three massive flows (Unit 14A through 14C) (Figure 4). The sequence is intruded by narrow dikes at two levels. The lava flows are moderately phyric with plagioclase, olivine, and clinopyroxene phenocrysts. Only one glass analysis (group M) is available from the massive units; the other glasses analysed in this depth interval are chilled dike margins (group L). Whole-rock compositions are variable, but suggest olivine and clinopyroxene accumu-

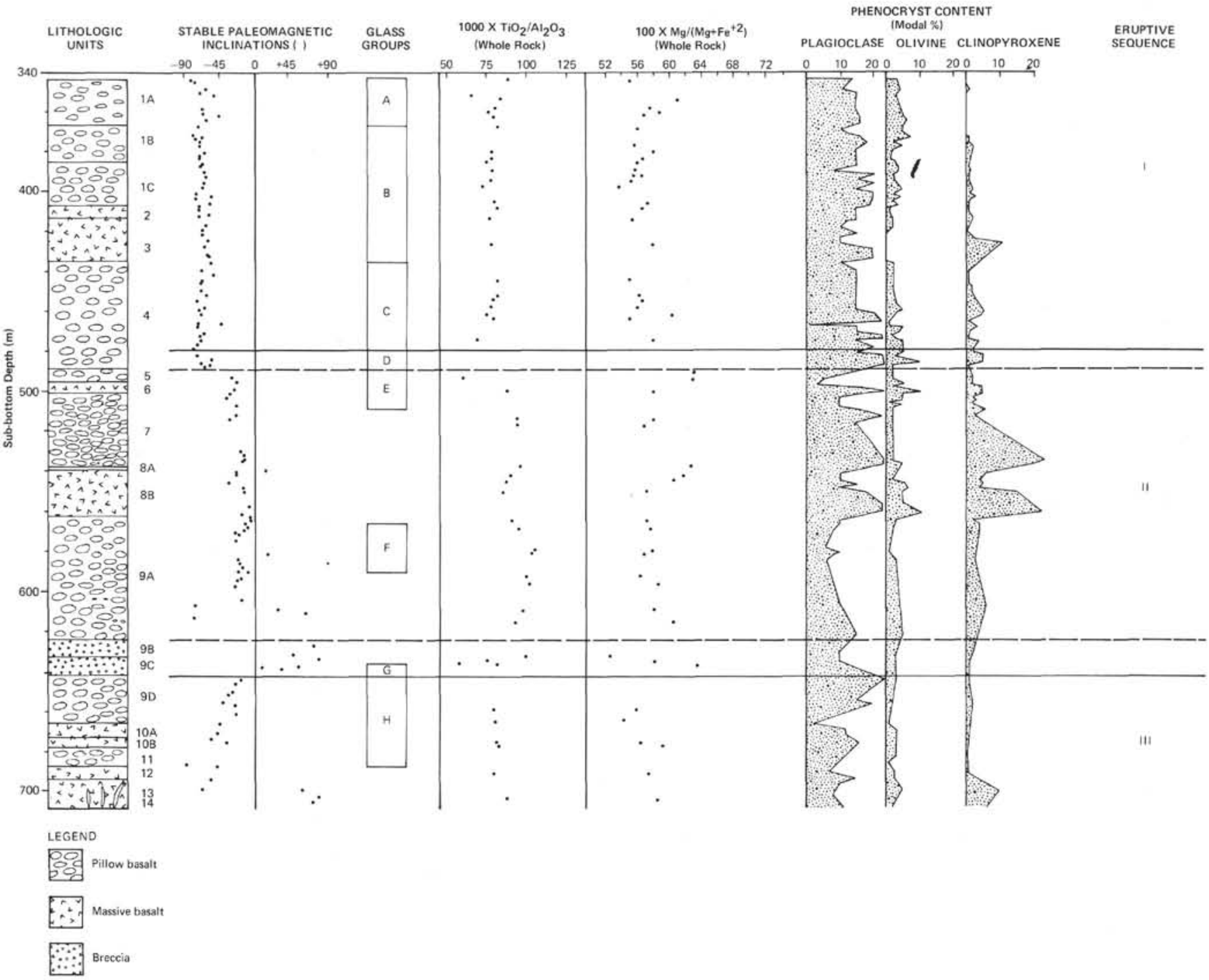

Figure 3. *Stratigraphic interpretation of the crustal section drilled in Hole 417D. Lithologic, mineralogic, and paleomagnetic data are from 417 Site Chapter and Levi et al. (Paleomagnetic compilation chapter, this volume). Glass data are from Byerly and Sinton (this volume) and whole-rock chemical data are from 417 Site Chapter and Flower et al. (both this volume). Solid horizontal lines mark major stratigraphic breaks in the section, dashed lines are subordinate stratigraphic discontinuities.*

lation in the lower 20 meters and possibly plagioclase accumulation in flow interiors. Modal data indicate clinopyroxene accumulation in the lower 10 meters. Most magnetic inclinations in the flows are steep, in contrast to those of sequence VII, and negative. The dikes have correspondingly steep, but positive inclinations, as does some of the adjacent country rock owing to reheating.

The massive flows were likely erupted in quick succession from a single source. Variations in the liquid fraction may have occurred during eruption, but there are insufficient glass data to document this effect adequately. The dikes are compositionally distinct from the host rock and have been related by least-squares modeling to glass group I higher in the succession (Flower and Robinson II, in preparation).

Eruptive Sequence V (786.5 to 695.5 m sub-bottom)

Sequence V is a 91-meter-thick succession of moderately to highly plagioclase–olivine–clinopyroxene–phyric basalt comprising Units 12 and 13 (Figure 4). The sequence is divided into Sub-units Va and Vb by a thin breccia zone at 710 meters sub-bottom. Another breccia zone at the base of the sequence separates these basalts from those of sequence VI.

Glass compositions (group J) in the lower part of the sequence indicate a uniform, relatively high TiO_2 liquid composition. Glass group K, represented by only one analysis from the basal breccia zone, is probably related to group J glasses but has not been modeled quantitatively. Whole-rock compositions in sequence Vb have compara-

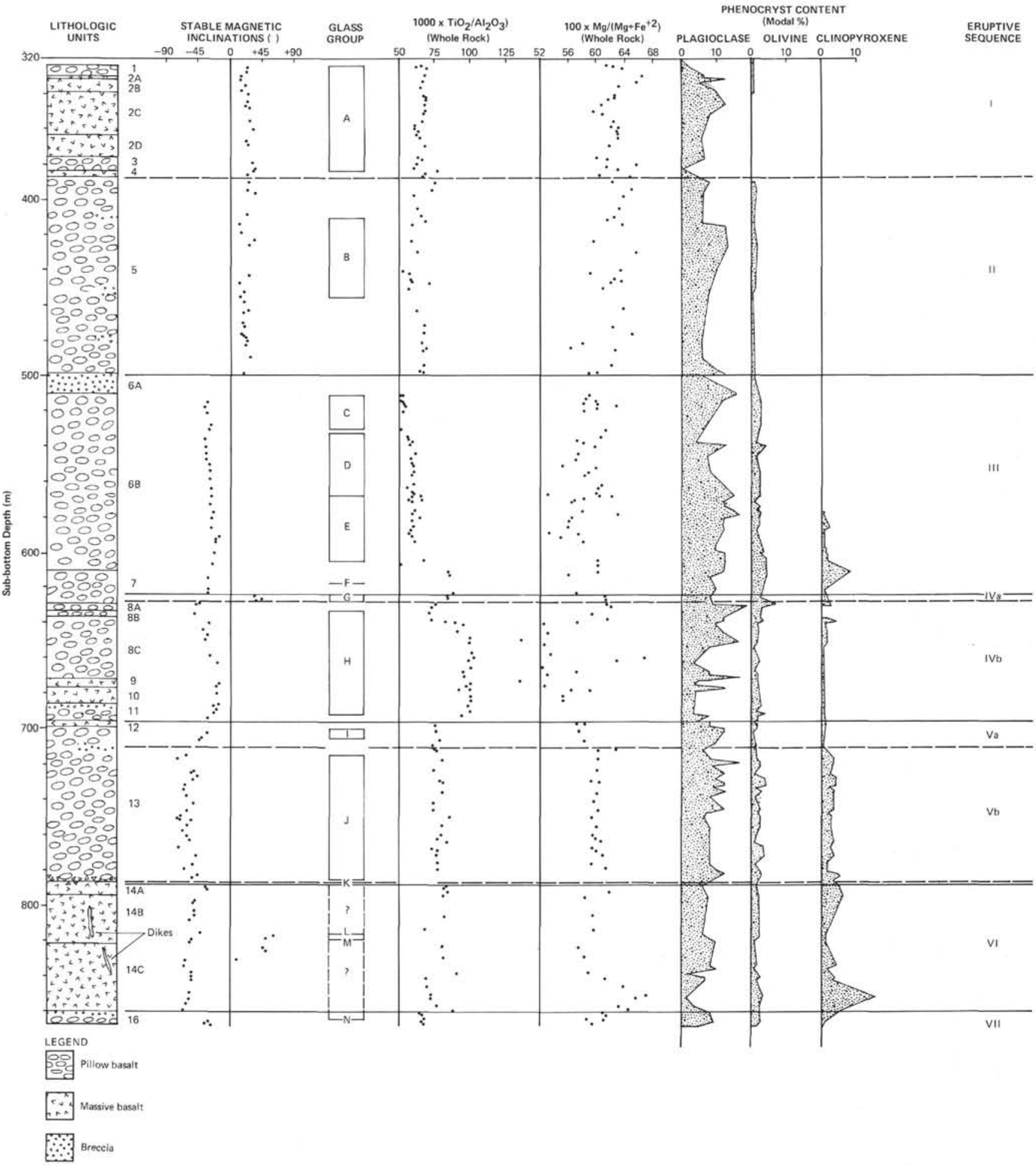

Figure 4. *Stratigraphic interpretation of the crustal section drilled in Hole 418A. Lithologic, mineralogic, and paleomagnetic data are from Site 418 Chapter and Levi et al. (Paleomagnetic compilation chapter, this volume). Glass data are from Byerly and Sinton (this volume) and whole-rock chemical data are from Site 418 Chapter and Flower et al. (both this volume). All else is the same as in Figure 3.*

tively uniform TiO_2/Al_2O_3 and $Mg/(Mg + Fe^{+2})$ ratios and show only moderate degrees of plagioclase accumulation. However, clinopyroxene and olivine are visibly enriched in this interval compared to sequence Va. Stable magnetic inclinations are negative, and mostly steep, averaging about −60 degrees.

Sequence V(a) is about 15 meters thick and has an average stable magnetic inclination of about −36 degrees. The two sequences, V(b) and V(a), are here interpreted as parts of a single eruptive sequence mainly because the glasses of group I appear from quantitative modeling (Flower and Robinson II, in preparation) to be parental to the underlying basalt represented by glass group J. Sequence V(a) probably reflects two to three sporadic late-stage eruptions from the same magma reservoir that produced the V(b) eruptions. The sharp change in magnetic inclinations may reflect a tilting episode between the eruptions, although other interpretations are possible.

Eruptive Sequence IV (695.5 to 625 m sub-bottom)

This sequence is distinguished from subjacent basalts (sequence V) by a small change in magnetic inclination and by the appearance of the high TiO_2 glasses of group H; the boundary between sequences IV and V is marked by a zone of weak alteration and a 2-meter-thick breccia (Figure 4). Sequence IV consists of pillow lavas, with minor massive basalt and breccia, comprising Units 7 (lower part) through 11. Most rocks contain sparse to moderate amounts of plagioclase; and olivine phenocrysts and minor clinopyroxene phenocrysts, the latter two increasing slightly upward. The upper basalts contain abundant phenocrysts of plagioclase, clinopyroxene, and olivine. Glass compositions decrease in TiO_2 and increase in $Mg/(Mg + Fe^{+2})$ ratios in the upper third of the sequence, whereas whole-rock compositions show an upward decrease in TiO_2/Al_2O_3 ratios. $Mg/(M + Fe^{+2})$ ratios are variable and suggest irregular fractionation and accumulation of olivine and clinopyroxene. Magnetic inclinations are negative but show a systematic upward variation from about -45 degrees at the base of the sequence through about -15 degrees in the middle and back to -45 degrees at the top. These variations may be within the expected secular range; however, it is possible that the data reflect rapid emplacement associated with oscillatory tilting. The variability of magnetic inclinations and the high phenocryst content of the younger rocks suggest that individual eruptions were sporadic and that the magmas underwent a longer period of cooling and crystallization than those forming the earlier flows.

We have subdivided sequence IV in view of magnetic evidence of a polarity reversal between the main part of the sequence (IV[b]) and the overlying products of a single eruption that is probably cogenetic (IV[a]). The transition to sequence IV(a) occurs across a 5-meter-thick pillowed sequence and is marked by a magnetic polarity reversal and a break in glass and whole-rock compositions. However, the succeeding two (?) flows, characterized by having group G glass composition, are probably related to the same fractionation system as the IV(b) flows rather than to those in the next younger unit. Glasses of group G have intermediate TiO_2 contents of about 1.4 wt.%. Least-squares modeling suggests that these compositions are parental to the liquids represented by the underlying glasses of group H (Flower and Robinson II, in preparation). Magnetic inclinations in sequence IV(a) are positive and average about 40 degrees.

We interpret the flows of sequences IV(a) and IV(b) as having been derived from the same magma reservoir, but the magnetic reversal between the two sequences suggests a rather lengthy period between eruptions. This is supported by the more extreme alteration at the top of the IV(b) lavas.

Eruptive Sequence III (625 to 498.5 m sub-bottom)

A 126.5-meter-thick interval of pillow basalt and breccia, including Units 6 and (the upper part of) 7, make up this sequence. The basalt is plagioclase-olivine-phyric. Abundant clinopyroxene phenocrysts are present in the lowest part of the sequence but do not occur in basalt above about 580 meters sub-bottom. Spinel crystals are common throughout but never exceed 1 per cent by volume. Four glass types (F, E, D, and C) reflect changing liquid compositions through this sequence. Type F, represented by only one analysis, is distinctly different from the overlying groups but appears to be related to them, rather than to underlying glasses, by fractionation processes (Flower and Robinson II, in preparation). Glass compositions thus show a variation from most fractionated at the base to least fractionated at the top of the sequence. The uppermost glasses are the most mafic encountered at either Site 417 or 418. Whole-rock TiO_2/Al_2O_3 ratios exhibit a regular decrease in upward direction, but $Mg/(Mg + Fe^{+2})$ ratios are variable. Magnetic inclinations are shallow negative. The 12-meter-thick breccia at the top of the sequence is tentatively included in this sequence since the rocks are mineralogically similar to the underlying pillow basalts.

This eruptive sequence represents the simplest of several sequences interpreted as having developed from an evolving magma rservoir system. Relatively rapid eruption of this sequence is suggested by the narrow scatter of magnetic inclinations. The uniformity of inclinations is also interpreted as reflecting increasing stability of the crust, with thickening of the basalt pile. Following these eruptions, a long hiatus apparently occurred as indicated by the prominent discontinuity between sequences III and II, marked by a reversal in magnetic polarity, an abrupt change in glass and whole-rock compositions and phenocryst abundances, and strong alteration at the top of sequence III.

Eruptive Sequence II (498.5 to 387 m sub-bottom)

Sequence II is a 111.5-meter-thick succession of plagioclase-phyric pillow basalt and breccia, some of which also contains sparse olivine phenocrysts (Figure 4). Glass compositions (group B) are similar to those of sequence I (group A) but are consistently higher in TiO_2. However, data on group B glasses are sparse, with only a few analyses from the central part of the sequence. Whole-rock compositions show wide ranges of TiO_2/Al_2O_3 and $Mg/(Mg + Fe^{+2})$ ratios, reflecting changes in both liquid composition and phenocryst content. Magnetic inclinations are normal and increase slightly upwards. They are similar to those of sequence I basalts, suggesting a relatively short time of accumulation for both sequences and overall crustal stability.

Eruptive Sequence I (387 to 324 m sub-bottom)

Sequence I includes Units 4 through 1, a series of mostly massive flows with some interlayered pillows (Figure 4). The basalt is plagioclase-phyric, and some samples contain a few per cent of olivine phenocrysts. Glass compositions are uniform (group A), with relatively low TiO_2. Whole-rock compositions show cyclic variation probably related to olivine and plagioclase fractionation or accumulation. Stable inclinations are positive and shallow, with the range of inclination attributable to secular variation in the magnetic field. The basalt is distinctly more mafic than most others at Sites 417 and 418 but shows no regular variation through the sequence.

Sequence I basalts are magnetically similar to those of sequence II, but chemically distinct. The glass compositions of the two sequences cannot be related by any simple scheme of low-pressure fractional crystallization (Byerly and Sinton, this volume; Flower and Robinson II, in preparation), but could possibly be related by a higher-pressure fractionation scheme involving clinopyroxene. These sequences could reflect either eruption from two adjacent but separate magma reservoirs unrelated at depth or sequential eruptions from a single reservoir after a period of deep-seated fractionation.

SUMMARY AND CONCLUSIONS

The sampled part of basement at Sites 417 and 418 consists largely of pillow basalt with interlayered massive basalt, breccia, and minor sedimentary rock. Dikes occur near the base of Holes 417D and 418A and are interpreted as feeders to flows higher in the succession. Pillow basalt is recognized largely by curved glass selvages, quench textures, and cooling-unit thicknesses between 10 and 150 cm, as sampled by drilling. Each massive basalt is interpreted as a flow because of contact relationships, textures, and chemical and magnetic similarities to enclosing pillow basalts. Cross-cutting dikes can be clearly distinguished from the intruded massive flows by their steep chilled margins, holocrystalline textures, and chemical differences from the host rock. Two major types of breccia are recognized: glassy pillow breccia formed during eruption, and lithic breccia representing possible talus accumulation among flow fronts or fault scarps. Interlayered sedimentary rocks make up less than 1 per cent of the drilled section, much less than inferred at younger Atlantic drill sites. The sedimentary rocks are mostly mixtures of recrystallized limestone and chert, sometimes containing altered glass fragments.

The downhole variation of lithologic, chemical, and magnetic parameters at Sites 417 and 418 defines numerous eruptive units and reflects episodic construction of the upper crust (Flower et al., this volume). The close coincidence of chemical and magnetic boundaries indicates that the eruptive units reflect individual eruptions or several related eruptions. We suggest that changes in magnetic inclination between eruptive units reflect either secular variation of the magnetic field or tilting of blocks between eruptions. It is also possible that later faulting associated with lateral translation of the basaltic pile can account for some of the variation in magnetic inclinations.

In addition to units produced during single or closely spaced eruptions, large-scale eruptive sequences can be recognized, particularly from the chemical data. These consist of basalts whose compositions appear to be related to one another by simple fractionation and which are bounded by major chemical, magnetic, or lithologic discontinuities. Internal variation of magnetic inclinations in certain sequences is possible evidence for syn-eruptive rotation or deformation (cf., Hall and Ryall, 1977). Lengthy periods of quiescence following each eruptive sequence are indicated by major changes in composition and magnetic character (polarity or inclination) between the sequences and by increased alteration at the top of most such sequences.

The amount of tilting or rotation of crustal blocks inferred from the paleomagnetic data is much greater than that observed directly from submersibles or recognized in ophiolite sequences. If tilting is coeval with crustal construction the lower, more tilted, blocks may be buried by younger, less disturbed flows. Ophiolite sequences may not represent typical segments of oceanic crust formed at mid-ocean spreading centers and, hence, lack evidence for this type of deformation. Nevertheless, the absence of observable segments of oceanic crust exhibiting widespread tilting is puzzling, suggesting an incomplete understanding of the paleomagnetic data.

We recognize three eruptive sequences in the 350-meter-thick section drilled in Hole 417D and seven in the 550-meter-thick section in Hole 418A. This may be compared with the section drilled in Hole 322B, in which nine magnetic "superunits" averaging 41 meters in thickness were identified (Hall and Ryall, 1977). If the basaltic crust is between 1 and 2 km thick and if the active zone of extrusion is 2 to 4 km wide with a half spreading rate of 1 to 2 cm/y, construction of any given vertical section of crust would take from 100,000 to 200,000 years. Major eruptions would occur on the average of about every 10,000 years. This estimate is similar to that for the FAMOUS inner rift valley (Bryan and Moore, 1977) and to that inferred from the magnetostratigraphy of eastern Iceland (16,000 years) by Watkins and Walker (1977).

Each major eruptive sequence appears to reflect the tapping of a single zoned magma reservoir and may comprise a single volcanic edifice in the median rift, such as Mount Venus or Mount Pluto in the FAMOUS area (Ballard and van Andel, 1977). The earliest eruptions often produce the most differentiated glass, with liquid compositions becoming more mafic in later eruptions. Both whole-rock compositions and phenocryst contents indicate that the uppermost basalt in a given cycle underwent significant crystal accumulation. Such a change from fractionated to more mafic basalt has also been observed in the most recent flows of the FAMOUS segment of the Mid-Atlantic Ridge (Bryan, personal communication). Glass compositions from separate sequences cannot be related by shallow-level fractionation processes, suggesting the presence of a number of isolated subrift magma reservoirs, different magma batches reflecting different melting conditions, or more complex magma fractionation processes than envisaged here.

With the available data we cannot prove the hypothesis for rotation or tilting during or between eruptive sequences at Sites 417 and 418. However, the upper eruptive sequences in both Holes 417D and 418A have the most uniform magnetic inclinations — a relationship observed in other deep holes in the Atlantic (Aumento, Melson, et al., 1977; Dmitriev, Heirtzler, et al., 1978). This suggests that progressively deeper units are more deformed during crustal construction — a situation that would prevail if deformation and eruption were coeval.

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PLATE 1
Pillow Basalts and Massive Flows

Figure 1 Interval 417D-54-5, 0-20 cm. Lateral pillow margin in basalt showing: convex glassy selvage mostly altered to smectite, with carbonate veins and possibly a narrow palagonite rim; two sets of joints, one radial and formed during cooling, the other concentric and probably related to formation and alteration of the glassy selvage, both now filled with alteration products; fine-grained to variolitic pillow groundmass grading into a 5-mm-thick glass selvage.

Figure 2 Interval 417A-24-2, 60-90 cm. Pillow fragments with hyaloclastic margins. Glassy selvages along the pillow margins spall off and are incorporated in interpillow hyaloclastic breccia. Note the "perlitic" structure of the altered glass which is now a mixture of smectite, carbonate, and zeolite.

Figure 3 Interval 418A-46-1, 23-66 cm. Complete single pillow, with top and bottom glassy selvages and a nearly continuous, lateral glassy selvage. Lateral margin indicates that the pillow has been molded about a preexisting pillow with a convex margin. A minor amount of fine-grained pillow breccia in an altered glass matrix is attached to the pillow margin.

Figure 4 Interval 418A-77-2, 51-78 cm. Medium-grained, aphyric massive basalt with abundant vesicles.

PLATE 1

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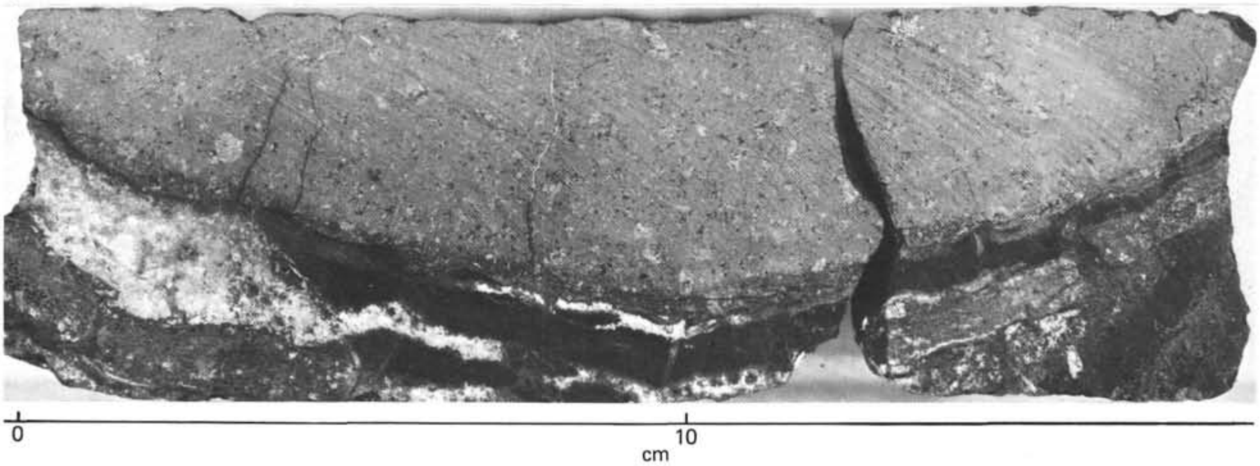

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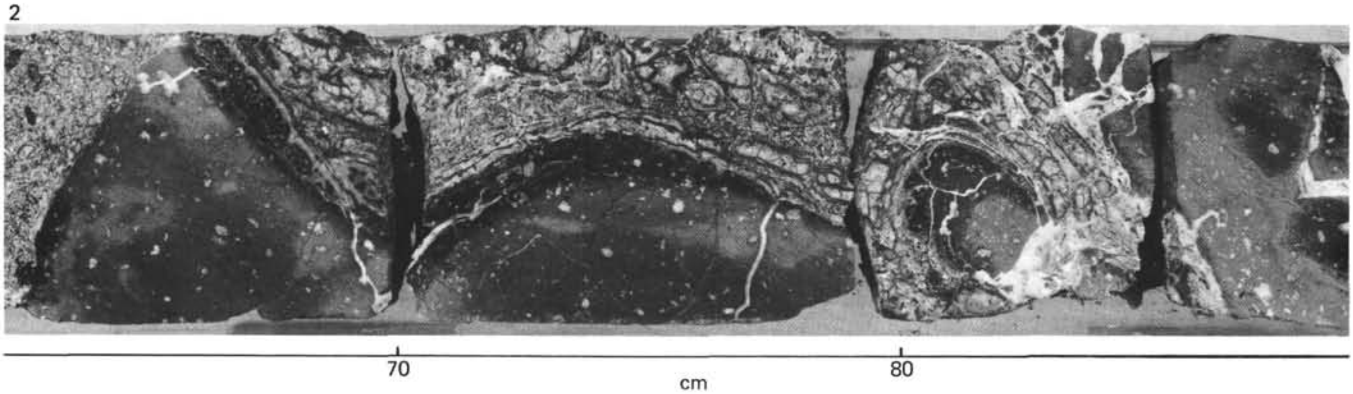

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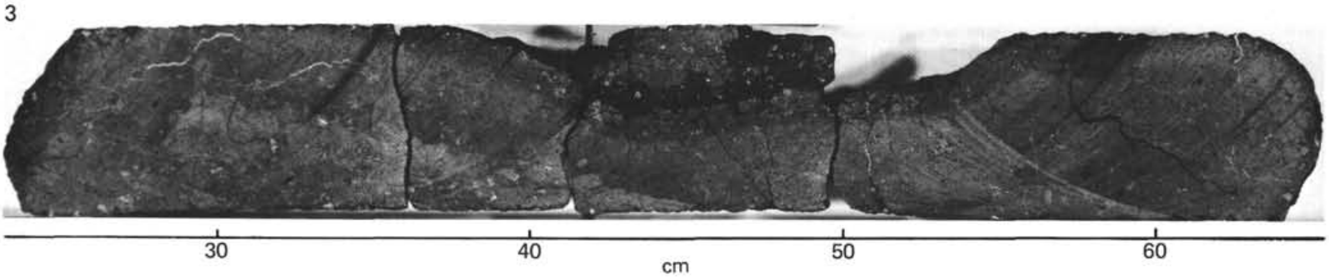

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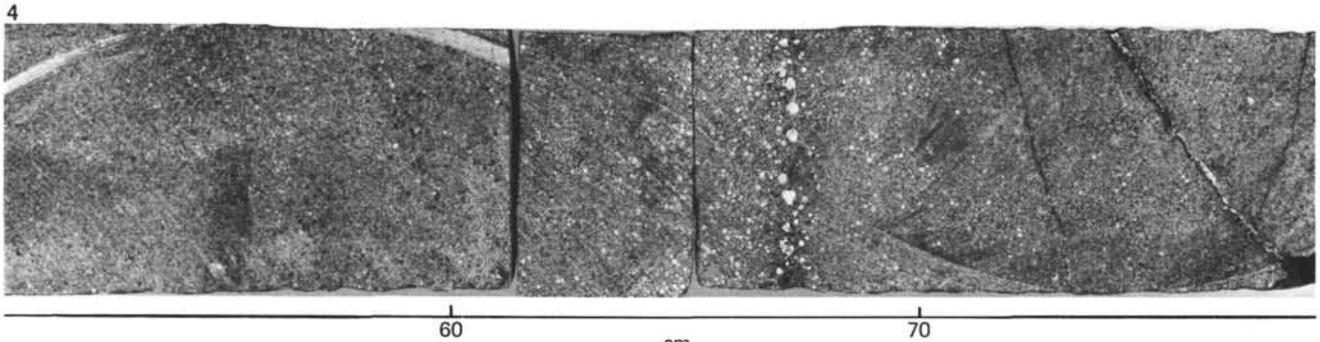

PLATE 2
Dikes and Segregation Veins

Figure 1	Interval 417D-48-7, 50-56 cm. Fine-grained aphyric segregation vein cutting massive basalt of Unit 8A. Note gradation of vein material into fine-grained, interstitial material of host rock.
Figure 2	Interval 417D-48-7, 53-56 cm. Photomicrograph of segregation vein shown in Figure 1. Vein is about 2 cm wide. Groundmass of host rock is similar to texture of aphyric vein.
Figure 3	Interval 418A-79-4, 58-81 cm. Dike cutting massive basalt near base of Hole 418A. Dike (right) is composed of fine-grained basalt with a glassy margin along contact. Host rock is medium-grained, aphyric, massive basalt of Unit 14B. Light colored material along contact is carbonate.
Figure 4	Interval 418A-79-4, 67-97 cm. Downward continuation of dike in Figure 3. This dike continues into Section 3 and is present over a 135-cm-long interval.

PLATE 2

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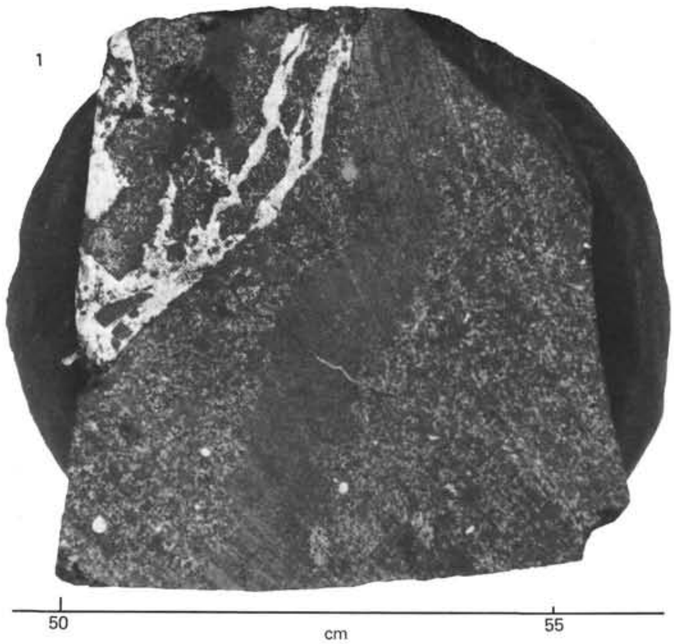

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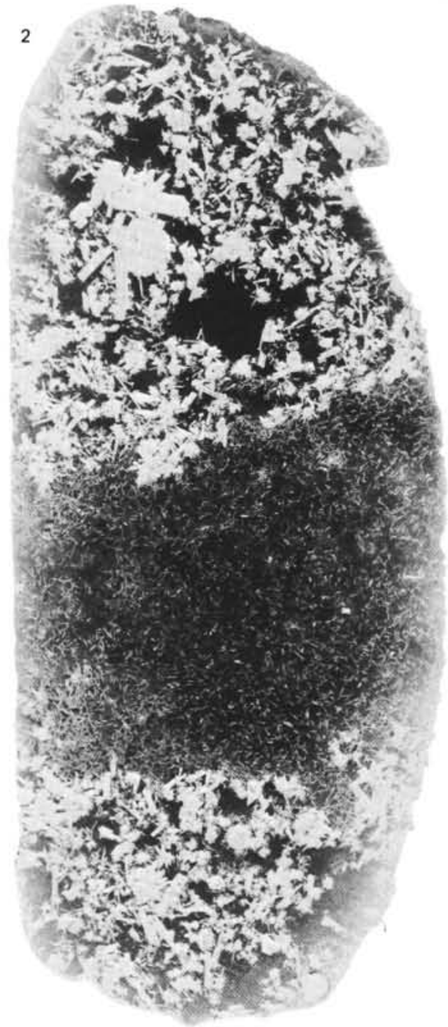

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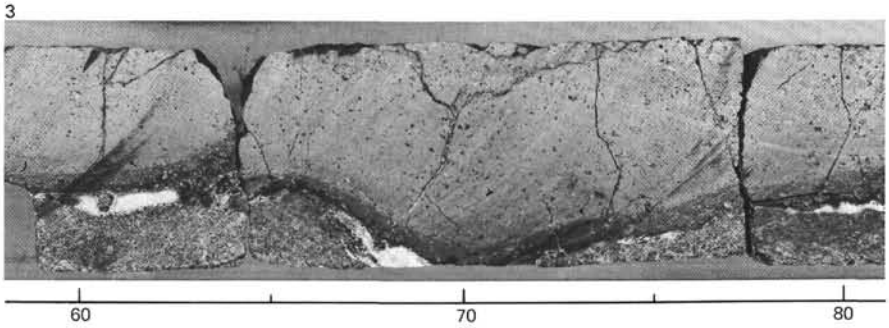

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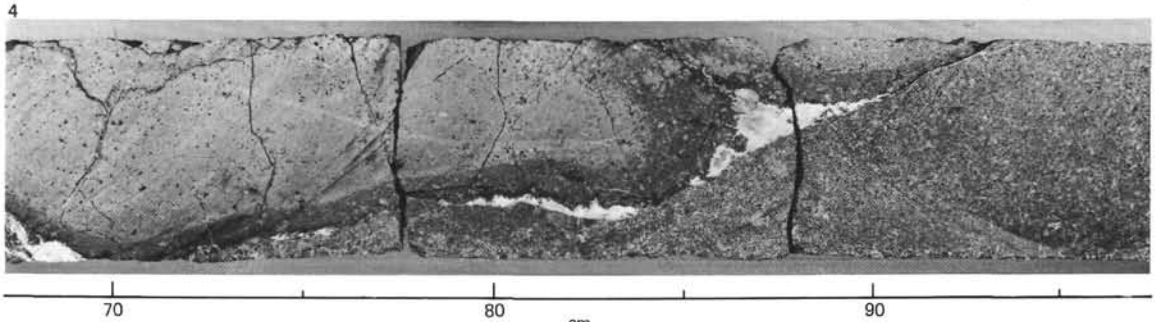

PLATE 3
Photomicrographs of Basalts

Figure 1 Sample 417D-49-3, 20-22 cm. Photomicrograph of highly phyric massive basalt showing gradation to much coarser grain size of phenocrysts and matrix in Figures 2 and 3. In this section plagioclase phenocrysts are commonly intergrown with clinopyroxene, forming subophitic clots ranging in size to about 3 mm. Very dark zones are pseudomorphs of smectite, carbonate, and iron oxide after olivine. Groundmass is mostly magnetite and granular clinopyroxene, but in many places is devitrified glass.

Figure 2 Sample 417D-50-2, 88-90 cm. Photomicrograph of porphyritic basalt similar to that in Figure 1. As grain size increases within this unit, the distinction between groundmass and phenocrysts becomes arbitrary. Olivine phenocrysts (replaced by smectite) are less than 1 mm in size. Subophitic clots of plagioclase and clinopyroxene range in size to 3 mm and form 30 per cent of the rock. Single phenocrysts of plagioclase range up to about 5 mm and are seriate in size distribution. Devitrified glass is 5 to 10 per cent of rock.

Figure 3 Sample 417D-52-2, 41-43 cm. Photomicrograph of porphyritic basalt similar to that in Figures 1 and 2. This section, from lower part of lithologic Unit 8B, shows subophitic clots of plagioclase and clinopyroxene up to 5 mm in diameter, which form about 50 per cent of rock. These are set in glassy or very finely crystalline groundmass producing typical "ophimottled" texture. Single plagioclase laths up to 7 mm in size form about 5 per cent of the rock, and smectite pseudomorphs after olivine form about 5 per cent. Plagioclase and clinopyroxene are seriate in size distribution, olivine is about 3 mm across. Devitrified glass (altered to smectite) forms up to 10 per cent of the rock.

Figure 4 Sample 417D-60-6, 35-36 cm. Photomicrograph of pillow breccia with fresh glass fragments down to 0.01 mm in size (medium-gray fragments in photo). Breccia has carbonate cement and large proportion of clastic material, consisting of basalt, plagioclase, and fresh and altered glass.

PLATE 3

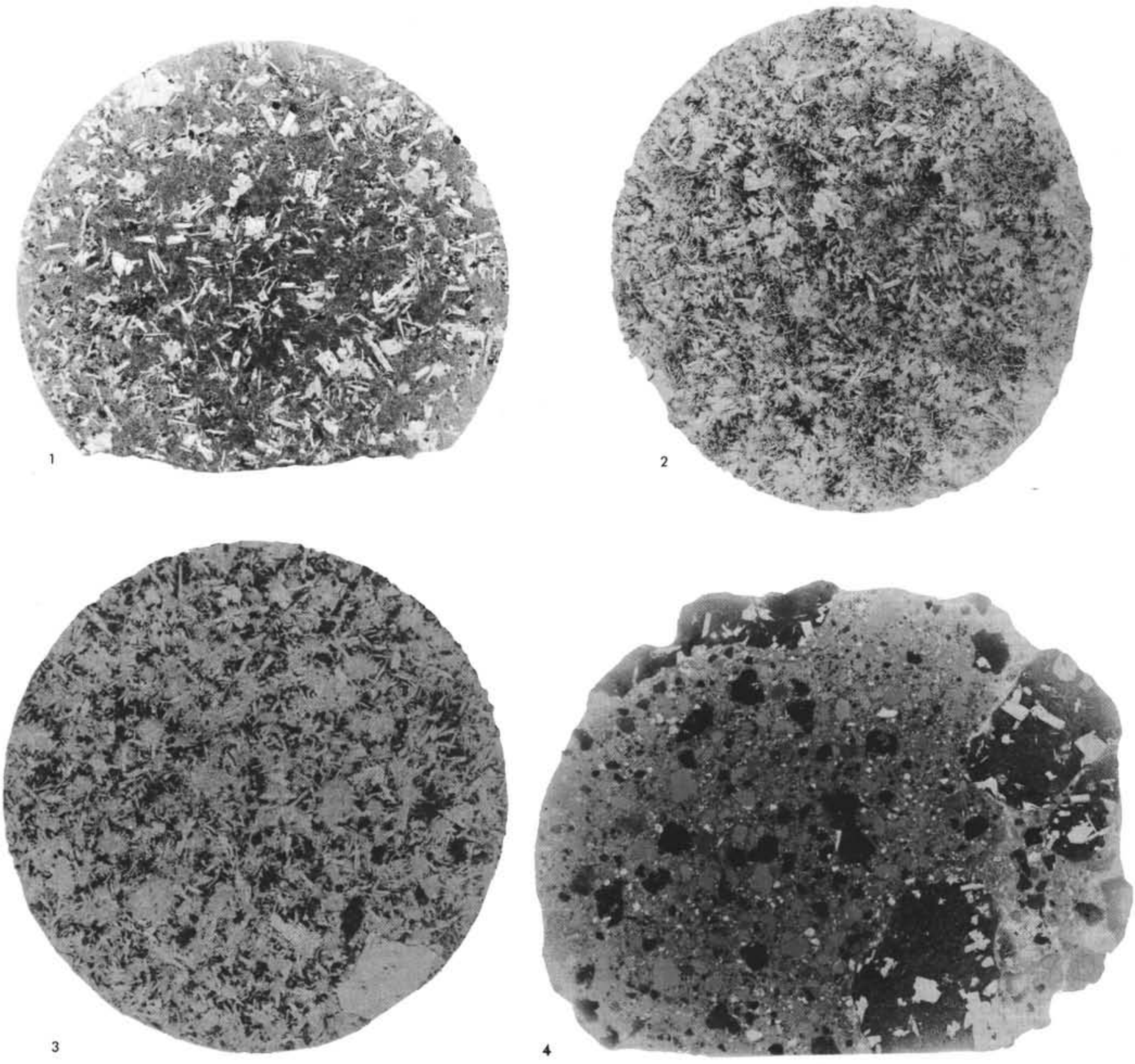

PLATE 4
Breccias

Figure 1	Interval 417D-58-2, 28-40 cm. Broken-pillow breccia. Large angular piece has altered glassy margin at upper right. Smaller clasts are of similar lithology as large pillow fragment and float in a matrix of altered glassy debris, now mostly smectite.
Figure 2	Interval 417D-59-1, 102-118 cm. Broken-pillow breccia. Angular fragments of basalt showing varying grain size. Matrix composed of glass debris altered to smectite.
Figure 3	Interval 417D-60-5, 120-130 cm. Possibly broken-pillow breccia. Sand-size clasts of basalt, plagioclase, and glass are common. Altered glass matrix is minor portion of rock. Recognizable pillow rinds are absent, but black fragments are fresh glass.
Figure 4	Interval 417D-49-2, 124-144 cm. Brecciation and net veining in basalt. Close "fit" of angular fragments indicates brecciation occurred *in situ* and is incipient, possibly related to compaction of the volcanic pile. Veining composed of smectite and minor carbonate.

PLATE 4