23. DRILLING DIFFICULTIES IN BASEMENT DURING DEEP SEA DRILLING PROJECT LEG 54

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ABSTRACT

The principal objective of Leg 54, to drill a deep multiple, re-entry hole in young, fast-spreading East Pacific Rise crust, was not achieved. Instead, eight shallow-penetration holes were drilled into basement on the East Pacific Rise, and five on the Galapagos Rift. The deepest penetration was 52.2 meters in Hole 428A. Most holes were abandoned at an early stage because of extreme torquing on the drill string and caving of rocks into the holes. The drilling difficulties were much more severe than experienced with crust of similar age in the North Atlantic. They were caused by a combination of factors, of which the most important are:

1) The basalts are highly fractured, possibly a result of dropping of fault blocks from the East Pacific Rise axial plateau;

2) the lavas consist of a large proportion of sheet flows rather than pillows, and therefore do not have the interlocking joint structure which would prevent them from dropping down holes and binding the bit during drilling; and

3) the rocks are very fresh and hard, with few if any fractures healed by alteration and cementation.

There appears to be a slight correlation between rock freshness, as measured by the abundance of combined water (H_2O^+), and the greater severity of drilling conditions on the East Pacific Rise compared with the Mid-Atlantic Ridge. There is a stronger correlation between iron enrichment in the basalts and drilling difficulty, probably because ferrobasalts on the East Pacific Rise tend to be sheet flows. We also speculate that ferrobasalts are denser and have fewer microfractures than olivine basalts, owing to their different mineralogy. Glassy ferrobasalt samples also contain a high proportion of linked (chain or network) polymers of silica tetrahedra, which may make them crystallize to harder rocks.

On the basis of Leg 54 drilling, no deep-penetration hole into fast-spreading crust appears feasible unless that crust is significantly altered. In all likelihood, this means that the crust will have to be old, or, if young, uniformly and thickly sedimented in an area of high sediment-accumulation rates and, probably, high heat flow. Such sites could be near a continental margin or beneath the thick belt of equatorial pelagic sediments in the eastern Pacific. Alternatively, some method must be devised to allow drilling on the unsedimented East Pacific Rise axial block where high upper crustal velocities imply that little fracturing has as yet occurred. The life expectancy (rotating hours) of bits currently in use, however, will be very low in such rocks. These considerations may be important for planning future geothermal exploration of rise or ridge axes by drilling.

INTRODUCTION

Leg 54 of the Deep Sea Drilling Project was designed to drill as deep a hole as possible into basement on the flank of the East Pacific Rise near 9°N, 106°W. It was thus a grave disappointment to all of us who were on Leg 54 that this objective was not achieved. The basement rocks were almost completely resistant to the drill string despite any strategy we devised (see East Pacific Rise Site Report, this volume). In this respect we confirmed the observations on Leg 34 , when similar low penetration and recovery were achieved on the Nazca Plate (Yeats, Hart, et al., 1976a). The experience of Leg 54 was contrary to all expectations based on earlier Mid-Atlantic Ridge drilling, but perhaps could have been anticipated from Leg 34 results.

Because of drilling difficulties near 9°N, the *Glomar Challenger* was diverted to the Galapagos Rift during Leg 54, for tests to determine the feasibility of drilling in very thin sediment cover (30 m) on very young crust (about 600,000 years), and still penetrate basement. An additional objective was to see if the *Challenger's* re-entry scanning system could identify small geological targets, namely mounds of hydrothermal sediments about 5 to 10 meters high and up to 20 meters wide, and, if so, to core these mounds.

A draft of this chapter was circulated to the JOIDES Ocean Crust Panel in July, 1977, and was a factor in planning several additional eastern Pacific Legs, including the very successful programs on the Galapagos and Costa Rica Rifts completed during Legs 69 and 70. Most of the recommendations of that document were borne out by the subsequent drilling, including the conclusion that further basement drilling would be very difficult in the mounds region but stood a good chance of success on older Costa Rica Rift crust (where Hole 504B was drilled to a depth of 561 into basement during Legs 69 and 70). Because it is still important for future planning, we here present a summary of the Leg 54 experience, and assess the prospects for drilling on young crust in the eastern Pacific. Much of the discussion is based on our personal experience examining dredge hauls, cored material, and bottom photographs, and discussions with many people in addition to participants on Leg 54. What we offer is informed opinion, not scientific proof. To that extent, we alone are responsible for the views expressed here.

SYNOPSIS OF THE PROBLEM

Leg 54 penetration and recovery data into basement are presented in Table 1. Seven sites (eight basement holes) were drilled on the East Pacific Rise flank near 9°N, and two sites (five basement holes) on the Galapagos Rift near 0°37′N, 86°06′W. At two other sites, no basement penetration was attempted. The holes can be divided into two types: (1) those where individual cooling units were typically (but not exclusively) 1 to 5 meters thick (Holes 422, 424, 425, 427, and 428); and (2) holes where cooling units were on the order of 10 to 20 cm thick to the extent this could be determined (Holes 420, 421, 423, 424A, 424B, 424C, and 429). Site locations are shown on Figures 1 and 2. Type 1 sites near 9°N were all in areas where the acoustic signature of basement was strong and flat. All were in structural depressions (such as Site 427 in the Siqueiros fracture zone). We thus infer that lavas in these holes have been ponded. All other sites near 9°N were on what we called "normal fabric," away from structural depressions on the normal fault block topography (abyssal hill topography) of the western East Pacific Rise flank. Basement acoustic signature here is fuzzy, because the typical dimensions of the fault blocks are less than the beam width of the air-gun sound pulses on the sea floor. More than 95 per cent of the East Pacific Rise flanks have this acoustic signature.

TABLE 1
Basement Coring and Recovery Data

Hole	Length Cored (m)	Length Recovered (m)	Recovery (%)	Type
East Pacific Rise				
420	31.5	1.39	4.4	1
421	30.0	1.60	5.3	1
423	11.5	0.87	7.6	1
429A	21.5	2.95	13.7	1
Total	94.5	6.81	7.2	
OCP Ridge "Moat"				
422	13.5	9.56	70.8	2
428	15.5	2.14	13.8	2
428A	52.5	16.37	31.2	2
Total	81.5	28.07	34.4	
Siqueiros Fracture Zone				
427	28.5	12.51	43.9	2
Grand Total (EPR)				
	204.5	47.39	23.2	
Galapagos Rift				
424	45.0	8.45	18.8	2?
424A	5.0	0.10	2.0	1
424B	14.5	2.35	16.2	1
424C	3.0	0.48	16.0	1
425	30.0	5.66	18.9	1
Total	97.5	17.04	17.5	

Note: Type 1 = fabric sites; type 2 = ponded basalts.

In the Galapagos area, the acoustic character of basement is less useful in differentiating ponded lavas from "normal fabric" lavas. The dimensions and relief of fault blocks are a bit larger than on the East Pacific Rise, and there is no axial block (Figure 2). We made no attempt there, however, to search for ponded lavas in structural depressions or fracture zones.

The lack of ponded lavas on the the East Pacific Rise appears to reflect crestal geomorphology. The rise crest is at the summit of a prominent axial block, between 10 and 20 km wide, rising about 200 meters above surrounding "abyssal hill" topography (Figure 3). In places this summit is very flat or plateau-like (e.g., Lonsdale and Spiess, this volume); elsewhere it is convex. Deep-tow observations of a similar convex structure near 3°25′S show it to have the cross-sectional geomorphology of a shield volcano, with a small graben at the precise crest similar to the graben above the central portion of the Kilauea east rift (Lonsdale, 1977a).

The Galapagos rift, however, has no axial block near our drill sites. The center of spreading is bounded within a few hundred meters by 20 to 50 meter fault blocks that rise above the rift zone. Most important to our discussion, these fault blocks constrain lava flows. Lonsdale (1977b) has described both pillow lavas and lava plains (ponded lavas with the features of pahoehoe) adjacent to the Galapagos Rift barely 20 km due north of Site 424. These lava plains are bounded by the fault blocks.

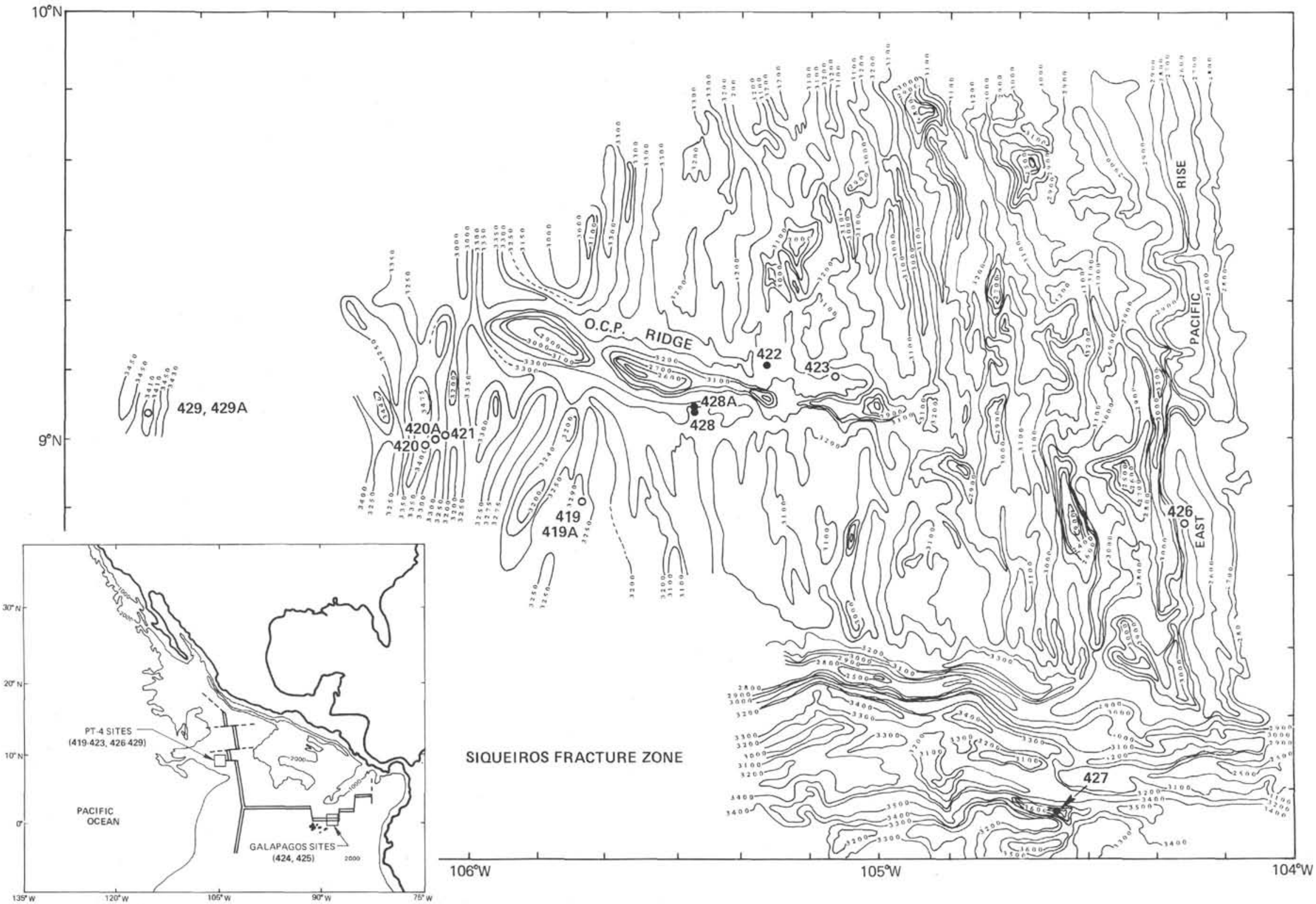


Figure 1. *Location of sites drilled during Leg 54 on the flanks of the East Pacific Rise near 9°N and in the Siqueiros fracture zone. Type 1 (fabric) sites are open circles. Type 2 (ponded) sites are dots. See text for explanation. Inset shows general locations of both East Pacific Rise and Galapagos Rift sites.*

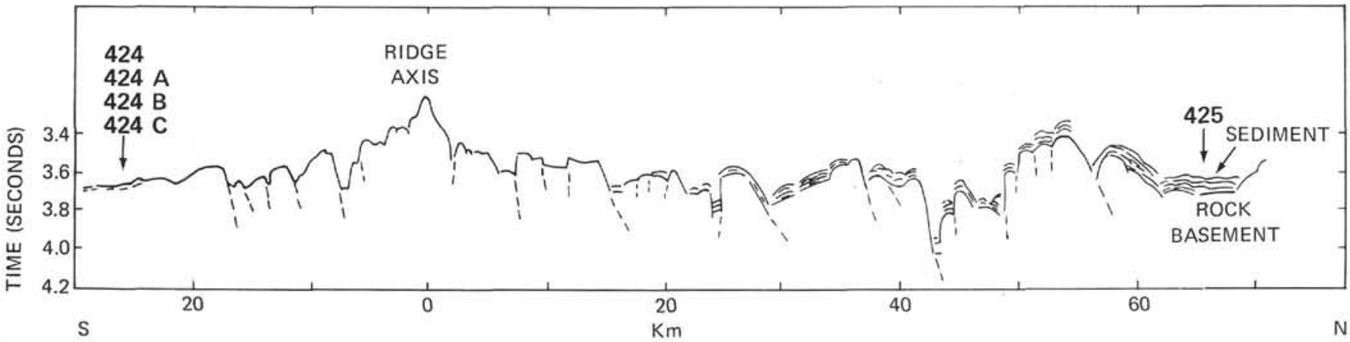


Figure 2. *Line drawing of* Glomar Challenger *air-gun profile between Sites 424 and 425, showing fault-block structure and sediment distribution on either side of the Galapagos Rift axis. Locations of Sites 424 and 425 are also indicated. Dashed lines are extrapolated faults into basement based on surface topography. Note absence of deep axial rift or pronounced axial block.*

It is apparent then, that lavas erupting at the axial rift of the Galapagos Spreading Center at 86°W will tend to be ponded against proximal fault blocks. So, too, will they tend to be ponded on the deeply rifted Mid-Atlantic Ridge. No such fault blocks occur near the East Pacific Rise summit. Lavas there will tend to flow over the smooth summit and not be ponded except in isolated small depressions.

The Leg 54 problem in a nutshell was that it was possible to penetrate neither "normal" East Pacific Rise fabric wherever we drilled it, nor non-ponded Galapagos lavas. Yet where we found ponded lavas, in both areas they were so fresh and hard that bit life was too short for penetration into basement beyond about 50 meters. Ponded lavas did not produce the great torquing and sticking problems of the other sites, but rarely were more than one or two lava types sampled in the ponded targets. In addition, ponded lavas almost certainly overlie non-ponded lavas in both areas. At Site 422, we succeeded in drilling completely through several thick cooling units into "normal" fabric, whence our torquing difficulties commenced again.

OPINIONS OF THE DRILLERS AND OPERATIONS MANAGER

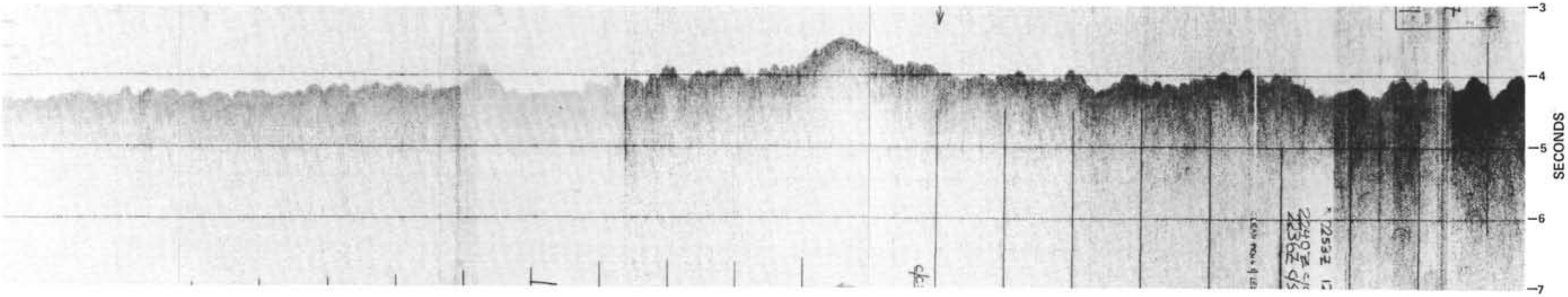
The Leg 54 drill crew was substantially the same as on Legs 45 and 49, the most recent prior Atlantic Legs on young oceanic crust. Our operations manager had been on Leg 46. On many occasions during Leg 54, these gentlemen told the chief scientists that drilling was much more difficult than anything experienced on the Mid-Atlantic Ridge. Overall drilling performance improved as the cruise went on, and as the drillers made every effort to treat the holes with care (see operations summary, East Pacific Rise Site Report, this volume). Mud was spotted after every core where torquing or sticking occurred. A gel was used to cement up Hole 428, to no particular advantage. The typical problem on normal East Pacific Rise fabric was inability to get back down to the depth left after taking the previous core. Torquing was most pronounced while the holes were being cleared, and it increased with depth. Penetration was limited to the depth at which frictional binding overcame rotation of the drill string or resulted in destruction of the bit—a depth of about 30 meters for drill holes on normal fabric. At Site 420, all four cones, the core guides, and all stabilizer pads were worn from the bit within nine hours of rotation. This was our most successful hole on normal EPR fabric.

COMPOSITION DIFFERENCES BETWEEN EASTERN PACIFIC AND MID-ATLANTIC RIDGE BASALTS

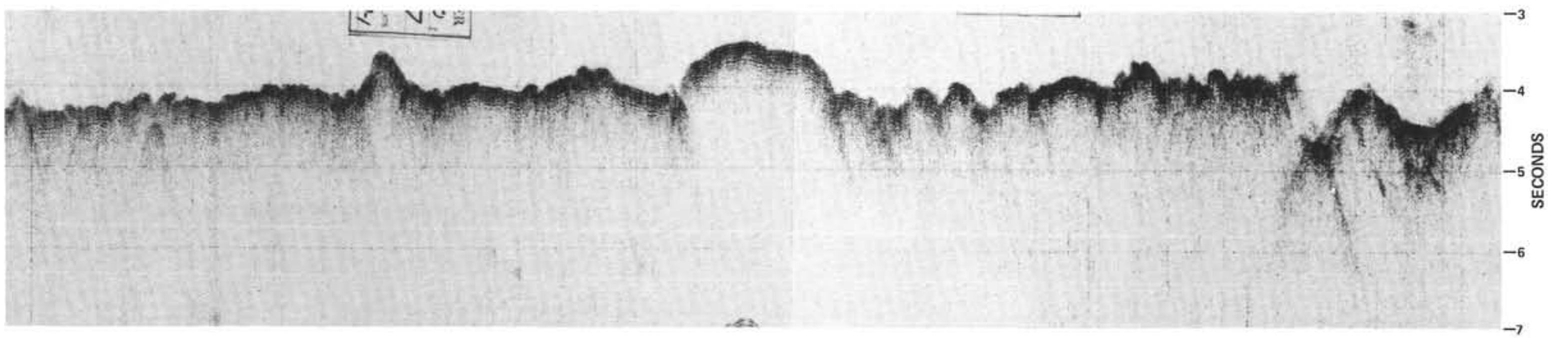
One possibility explaining the differences in drilling characteristics between the East Pacific Rise (or Galapagos Rift) and the Mid-Atlantic Ridge is that the rocks are chemically distinct, and that this chemical difference dictates a difference in the physical state of the rocks.

East Pacific Rise and Galapagos basalts are mainly aphyric clinopyroxene-plagioclase basalts; few contain olivine. Most Mid-Atlantic Ridge basalts have at least a few per cent phenocrysts, usually including olivine (e.g., Blanchard et al., 1976; Dungan et al., 1978; Natland, 1978a); many have 15 to 20 per cent phenocrysts. Not so for the basalts of the eastern Pacific. The scarcity of phenocrysts in East Pacific Rise basalts is probably their most striking contrast to Mid-Atlantic Ridge basalts. They are also markedly more iron-rich (Figure 4), with scarcely 10 per cent overlap in Mg/(Mg + Fe). Because they are more iron-rich, East Pacific Rise rocks also have a higher density than Mid-Atlantic Ridge basalts (~ 2.9 versus ~ 2.7 g/cm^3; Warren and Rosendahl, this volume). Vesicles are too sparse (1–2%) to affect density much.

Leg 54 basalts are on the average fresher than even Leg 34 basalts (Figure 5), and significantly fresher than Leg 46 basalts from 22°N on the Mid-Atlantic Ridge where a moderately deep (>250 m) hole was drilled. The deepest hole drilled into basement, Hole 332B at 37°N on the Mid-Atlantic Ridge, includes many more altered basalts, especially with depth, where H_2O^+ values between 1.0 and 3.4 per cent predominate. However, basalts recovered in the pilot Hole 332A are apparently as "fresh" as anything on the East Pacific Rise (Figure 5B).



East-west Profile near 9°N



East-west Profile near 8°30′N

Figure 3. Glomar Challenger *air-gun profiles across the crest of the East Pacific Rise during Leg 54. The upper profile shows a triangular crestal geomorphology, with adjacent fault-block topography subsiding and becoming covered with sediments away from the rise crest. The lower profile shows a plateau-like axial block; this is the crestal geomorphology between about 9°N and the Siqueiros fracture zone at about 8°N. Compare with Figure 2.*

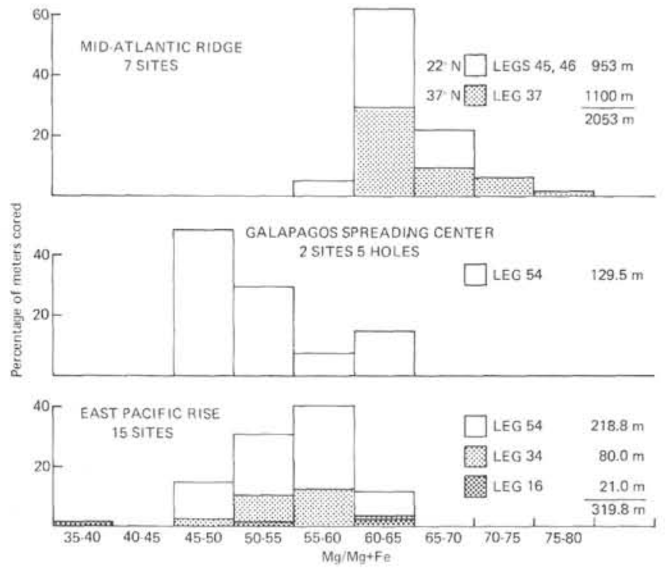


Figure 4. *Histogram of Mg/(Mg + Fe) versus percentage of meters drilled for DSDP basalts from the Mid-Atlantic Ridge compared with data from the East Pacific Rise. Histogram is constructed by weighting according to the thickness of clearly identified chemical units. Figure from Natland (1978b), where data sources are given.*

There thus appears to be a good correlation between the Mg/(Mg - Fe) ratio and ability to penetrate young oceanic crust. A weaker but still evident correlation exists between alteration (expressed by H_2O^+) and ability to drill young crust. There is no correlation between age of crust and ability to drill, since holes in crust as old as 21 m.y. have been drilled on the East Pacific Rise with a minimal penetration (Site 321, 15 m), yet the deepest hole on the Mid-Atlantic Ridge, Hole 332B, is on crust barely 3 m.y. old.

PHYSICAL STATE OF THE ROCKS

On Leg 54, a recurrent suggestion for our difficulties was "talus." This seems to be a common phenomenon at the base of the large scarps on the Mid-Atlantic Ridge, but in our opinion it is scarcely plausible for the East Pacific Rise of Galapagos Rift. Hundreds of deep-tow photographs in both eastern Pacific areas have failed to turn up any significant evidence for talus (Lonsdale and Spiess, this volume). Fault scarps exist, to be sure, but the typical offset is 10 to 50 meters. In the absence of mechanisms for erosion, these can scarcely produce much talus.

Bottom photographs (Lonsdale, 1977b) and submersible observations (Ballard et al., 1979) of the Galapagos Rift typically show smooth lavas, including pahoehoe, which probably represent ponded lavas, thin sheet flows, or pillow lavas. The rise-crest, deep-tow survey at 3°25'S (Lonsdale, 1977a) failed to find lava plains (ponded lavas), and instead bottom photos usually showed types of flattened pillows and sheet flows. This is consistent with our argument that lavas are usually not ponded on East Pacific Rise normal fabric. The deep-tow survey at 9°N (Lonsdale and Spiess, this volume) detected ponded lavas near the rise crest. From bottom photos a rough estimate of the proportion of the lava types on the axial plateau was made by Lonsdale and Spiess, as follows: 45 per cent flattened pillows, 40 per cent sheet flows, and 15 per cent bulbous or elongate pillows. Some lava surfaces were shattered and jumbly, resembling aa, but probably these are more equivalent to subaerial slab pahoehoe.

Dredges from the East Pacific Rise usually include the tabular type of lava, usually with glassy edges (Figure 6). The (inferred) upper surfaces are flat with about 1 cm of glassy or near-glassy material. Joints are nearly perpendicular to the glass, and the pieces are 5 to 15 cm thick. Sometimes the "bottoms" have cast structures suggesting that the molten material filled in joints on surfaces below.

These are not true pillows in the sense of being tube-shaped and having radial or keystone joints (e.g., Figure 7). An experiment on such tabular pieces from a dredge haul at 3°25'S (J. Hall and J. Natland, unpublished data) verifies that the flat glassy surfaces were almost certainly horizontal, since the magnetic inclinations of over two dozen such pieces are consistent with near-equatorial shallow inclinations assuming horizontality of the glassy edges.

A similar experiment was conducted on Leg 54 on pieces with the same type of flat, glassy tops (Figure 8). Here again, inclinations had the dip expected from the paleomagnetic latitude and polarities of the sites (see East Pacific Rise Site Report, this volume).

An interesting feature of the Leg 54 East Pacific Rise basalts is that they have wide (1-3 cm) alteration rinds tending to parallel the coring direction and be perpendicular to glassy edges (Figure 8). Alteration rinds of this type were rare and very thin on Leg 45 Mid-Atlantic Ridge basalts (Melson, Rabinowitz, et al., 1978) and are not described from Leg 37 basalts (Aumento, Melson, et al., 1977). Yet they are also prominent on Leg 34 basalts from the Nazca Plate (J. Natland, personal observation). Those appear to define joint directions (althoughly crudely) and again suggest joints perpendicular to flat, glassy edges. Distances between joints inferred from recovered specimens must have ranged from 2 cm to a maximum of 10 cm—averaging less than the diameter of the cores.

One other aspect of the basalts we cored on the flanks of the East Pacific Rise and at Site 424 on the Galapagos Rift is that they are probably "harder" or "tougher" than basalts that are not so iron-enriched. We speculate that this has primarily to do with composition, in that it determines the degree of polymerization of silica tetrahedra in glassy samples and the abundance of plagioclase (a network silicate) and clinopyroxene (a chain silicate) in crystalline samples. Olivine-bearing basaltic magmas have few linked and more isolated silica tetrahedra in polymer form than those that are more fractionated, and therefore quench or crystallize to rocks that are not as hard. Olivine is also more readily altered than the other silicates (Humphris et al., this volume),

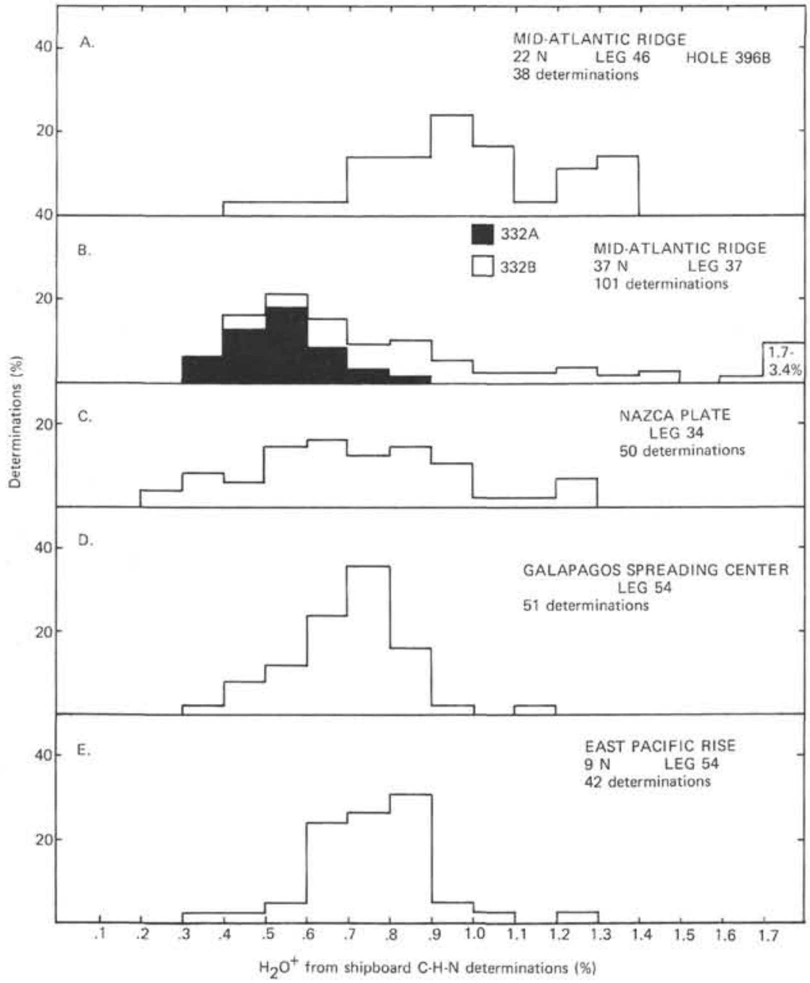


Figure 5. *Histogram of H_2O^+ versus percentage of analyses for Mid-Atlantic Ridge and East Pacific Rise basalts drilled on young oceanic crust. Data based on shipboard determinations using a Hewlett-Packard CHN analyzer. Leg 34 data from Yeats, Hart, et al. (1976b). Leg 37 data from Aumento, Melson, et al. (1977). Leg 46 data from Dmitriev, Heirtzler, et al. (1978). Leg 54 data obtained by Craig Hallman, Susan Humphris, and James Natland.*

and its inability to crystallize in Fe-rich basalts may have the result that they are less susceptible overall to alteration. Even their glasses may be more stable. We suggest that the abundance of microfractures in iron-rich basalts is less than in more olivine-rich varieties, because network and chain silicate structures and polymers are more abundant, and hold the rock together better. One physical manifestation of this toughness may be that iron enrichment produces anomalously low measured velocities at densities above about 2.90 g/cm^3 (Warren and Rosendahl, this volume). In any case, the apparent toughness of the rocks may have had a considerable effect on drilling and in producing the extreme torquing we experienced, especially if such hard pieces dropped down the sides of the holes and bound the bit. No amount of torque that could be applied was sufficient to break them up.

In summary, we appear to have cored thin, platy flows (sheet flows), or tabular lobes on the normal East Pacific Rise. The reasons for this may relate to rock composition or to lack of relief on the East Pacific Rise axial block. One can speculate that iron-enriched basalt lavas are more fluid (less viscous) than olivine-bearing lavas, but the rate of eruptive discharge and gentleness of slopes may be more critical in formation of sheet flows than anything else (e.g., Ballard et al., 1979). The reason for better drilling results in pillows may be that the interlocking keystone joint pattern of pillows plus their intercalated glass breccias tend to hold the basalts together better as they are drilled than the sheet flows or tabular lobes of the East Pacific Rise.

GEOPHYSICAL ASPECTS OF THE PROBLEM

The ocean-bottom seismometer data from survey area PT-4, where the *Challenger* drilled the East Pacific Rise on Leg 54, suggest that the axial block is significantly less fractured than the surrounding crust. Near-surface Layer 2 velocities are about 5.5 km/s on the ax-

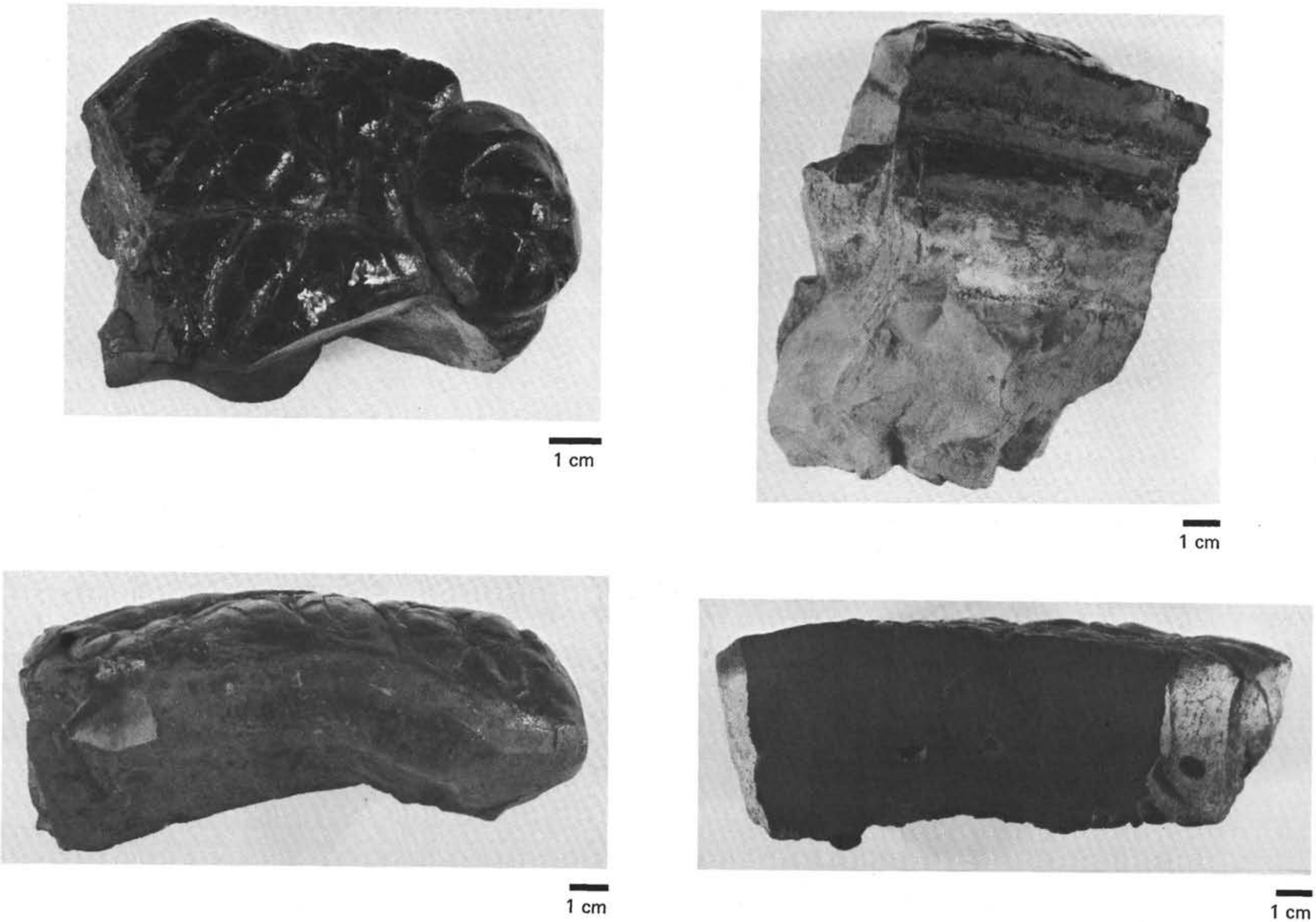


Figure 6. *Examples of dredged, tabular basalts with parallel chilled rinds representing either portions of sheet flows or tabular pillows. Dredge is Pleiades D-1, from the crest of the East Pacific Rise at 3°25′ S (Lonsdale, 1977a). Glass edges are all at top of pieces. Note alteration on polished piece. Basalts are ferrobasalts.*

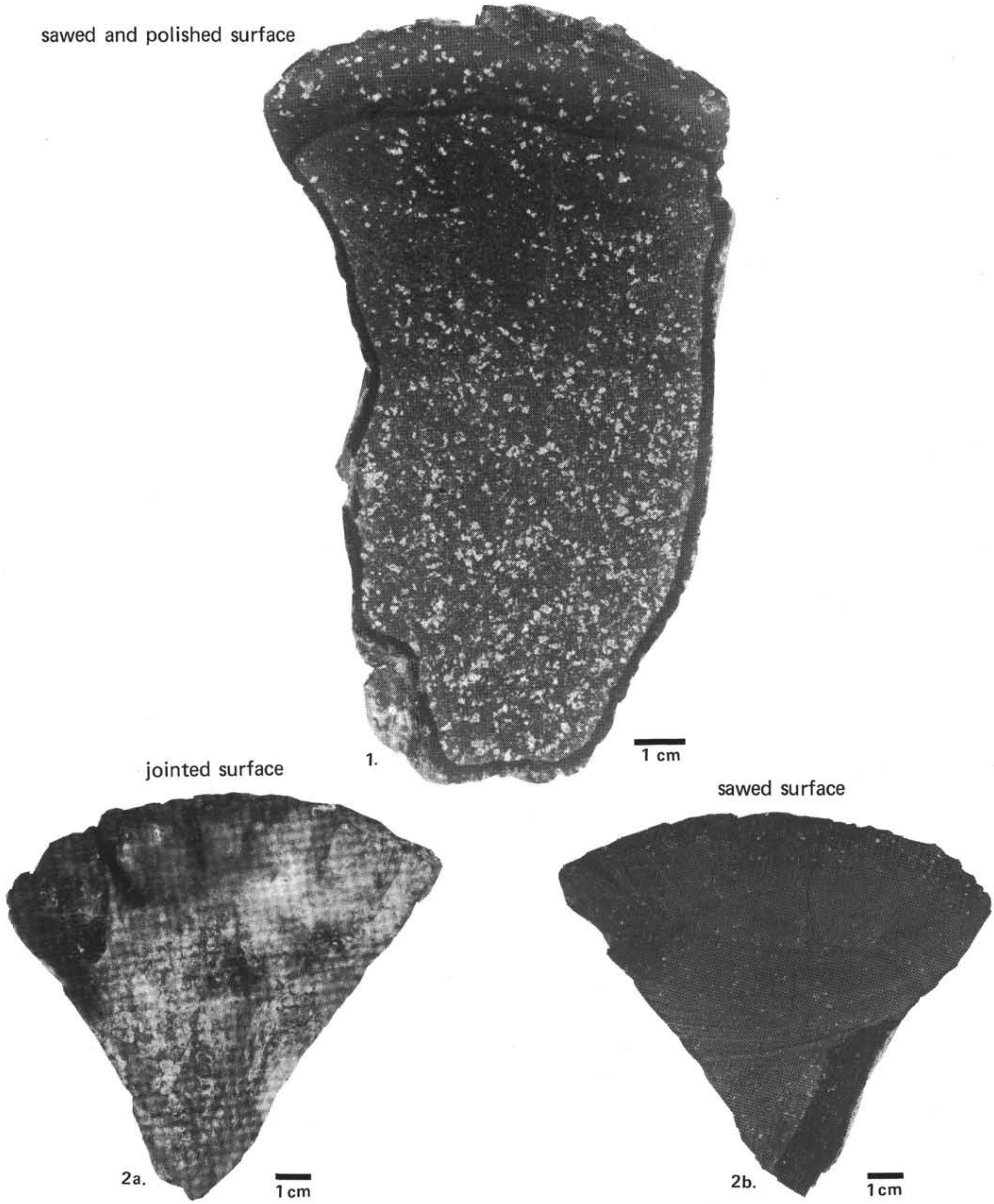


Figure 7. *Keystone-shaped pillow fragments of olivine-rich tholeiites from the Siqueiros fracture zone, dredge SD-7 (Schrader et al., this volume; Natland, this volume). Compare radial joint pattern with basalts of Figure 6. Surface of 1 is polished. 2a and 2b are opposite sides of the same piece.*

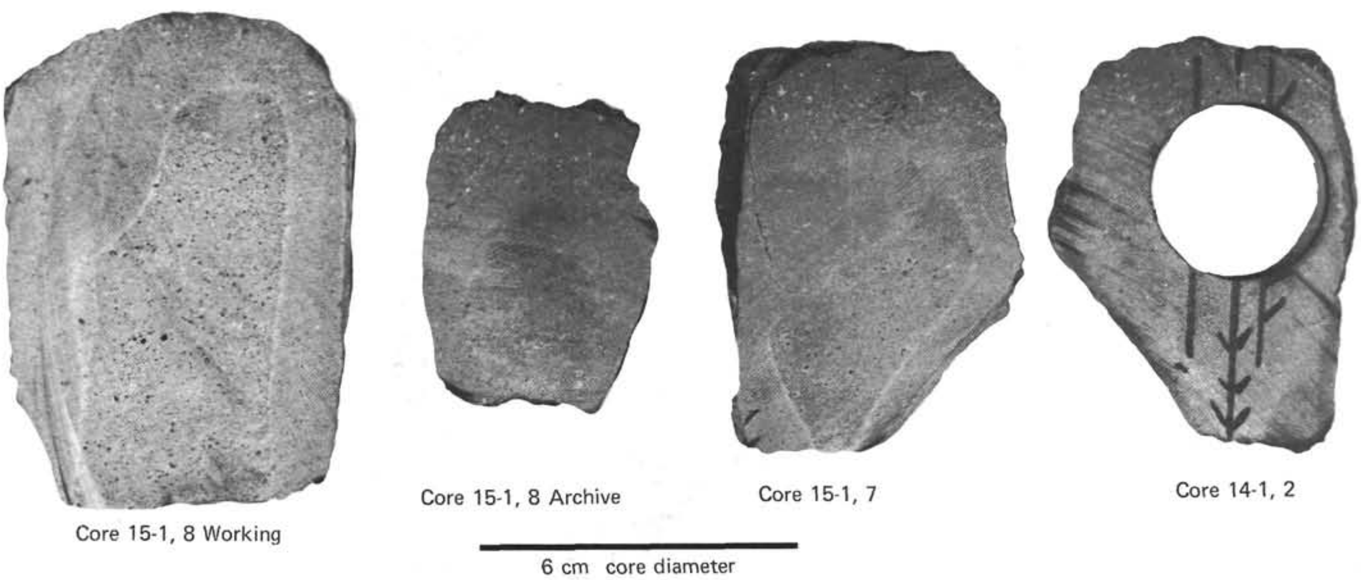


Figure 8. *Basalt pieces drilled at Site 420, showing flat glassy rinds and alteration zones paralleling glass and the vertical direction of the core. The hole drilled in Sample 420-15-1, #8 working is a mini-core used for paleomagnetic measurement which gave a stable inclination consistent with site paleolatitude and presumption of original horizontality of the upper glass rind shown. Arrows indicate piece was originally inverted.*

ial block, whereas they are only 3.5 km/s away from the block (Figure 9). Since the "abyssal hill" topography is formed by small fault blocks dropping off the axial block (Lonsdale and Spiess, this volume), it is possible that the velocity difference reflects a real difference in how broken up the surface rocks become, although it is difficult to relate this directly to the scale of the core bit. It also suggests that this difference occurs during the transition from axial block morphology to "normal" crustal morphology, and that it may be easier to drill on the axial block if means can be found to support the drill string during spud-in.

Formation of fault blocks as slivers of new crust spall off the edges of the axial block must itself contribute to the overall fragmentation of East Pacific Rise sea floor as sensed at the scale of the drill. At the very least, such a process will lead to further mechanical disruption of the jointing patterns in sheet flows, and we draw an analogy to the shear fracturing of a pile of intact but shattered plate glass sheets, to describe this process.

PROSPECT FOR DRILLING OCEAN CRUST IN THE EASTERN PACIFIC

On the basis of Leg 54 drilling, no deep penetration hole into fast-spreading crust appears feasible unless that crust is significantly altered. In all likelihood, this means that the crust will have to be old, or, if young, uniformly and thickly sedimented in an area of high sediment accumulation rates, and probably high heat flow. Such sites could be near a continental margin or beneath the thick belt of equatorial pelagic sediments in the eastern Pacific (e.g., Hole 504B on the Costa Rica Rift). Alternatively, some method must be devised to allow drilling on the unsedimented East Pacific Rise axial block, where high upper crustal velocities imply little fracturing has as yet occurred. The life expectancy (rotating hours) of bits currently in use, however, will be very low in such rocks. These considerations may be important

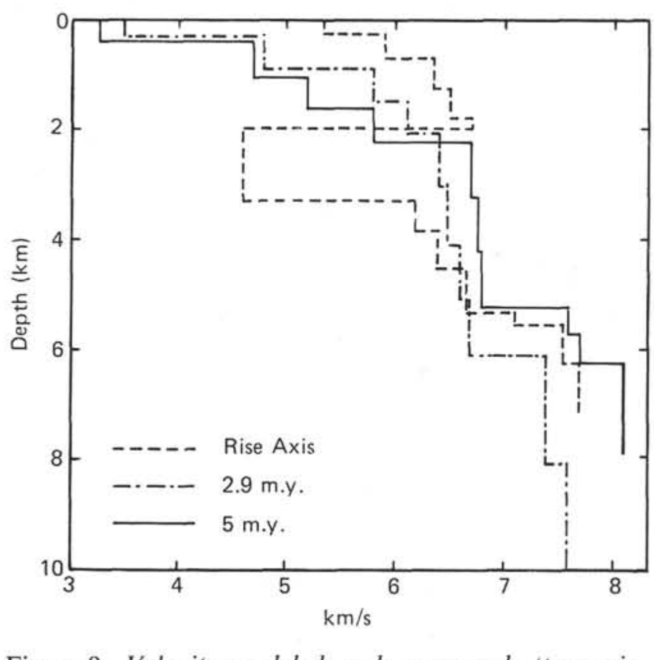


Figure 9. *Velocity models based on ocean-bottom seismometer data for three north-south profiles along the crest and flanks of the East Pacific Rise near 9°N from Orcutt et al. (1976) with permission. The depth origin is taken at the sea floor. Note velocity drop in shallowest rocks between the rise crest and rise flank profiles.*

for planning future geothermal exploration or rise or ridge axes by drilling.

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