4. DEEP-TOW OBSERVATIONS AT THE EAST PACIFIC RISE, 8°45′N, AND SOME INTERPRETATIONS

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ABSTRACT

A near-bottom survey of a 24-km length of the East Pacific Rise (EPR) crest near the Leg 54 drill sites has established that the axial ridge is a 12- to 15-km-wide lava plateau, bounded by steep 300-meter-high slopes that in places are large outward-facing fault scarps. The plateau is bisected asymmetrically by a 1- to 2-km-wide crestal rift zone, with summit grabens, pillow walls, and axial peaks, which is the locus of dike injection and fissure eruption. About 900 sets of bottom photos of this rift zone and adjacent parts of the plateau show that the upper oceanic crust is composed of several different types of pillow and sheet lava. Sheet lava is more abundant at this rise crest than on slow-spreading ridges or on some other fast-spreading rises. Beyond 2 km from the axis, most of the plateau has a patchy veneer of sediment, and its surface is increasingly broken by extensional faults and fissures. At the plateau's margins, secondary volcanism builds subcircular peaks and partly buries the fault scarps formed on the plateau and at its boundaries. Another deep-tow survey of a patch of young abyssal hills 20 to 30 km east of the spreading axis mapped a highly lineated terrain of inactive horsts and grabens. They were created by extension on inward- and outward-facing normal faults, in a zone 12 to 20 km from the axis. Sediments sampled on the rise crest and flanks are mixtures of calcareous ooze and metalliferous precipitates, and they have been redistributed by southerly currents with average velocities of 9 cm/s.

INTRODUCTION

North of the Siqueiros transform fault, the Pacific and Cocos plates are separating at a rate of about 115 mm/yr. This segment of the East Pacific Rise (EPR) has become a type area for geological and geophysical studies of a fast-spreading rise. A bathymetric reconnaissance was made for the IPOD site survey (Rosendahl, this volume), and prior to the Leg 54 drilling the axial ridge and young flanks of the rise were targets for rock dredging (Batiza et al., 1977; Batiza and Johnson, this volume) and subjects of detailed seismic reflection and refraction studies (Herron et al., 1978; Rosendahl et al., 1976; Orcutt et al., 1976).

In 1974 the deeply towed instrument package of the Marine Physical Laboratory (Spiess and Mudie, 1970; Spiess and Tyce, 1973) was used to examine an adjacent part of the Siqueiros fracture zone (Figure 1), and to make a single, near-bottom traverse of the rise crest (Crane, 1976). In 1977, several months after Leg 54 drilling, we made further observations with the same instrument, concentrating on transponder-navigated surveys at a 24-km length of the axial ridge between 8°37′N and 8°50′N, at a 100 km^2 patch of young abyssal hills 20 to 30 km east of the spreading axis, and at a cratered tholeiitic seamount 35 km east of the axis (Figure 1). In addition, a 75-km near-bottom traverse was made between this seamount (East Seamount) and its mirror image (West Seamount), which is equidistant from the spreading axis on the Pacific plate; this traverse was navigated mainly by satellite fixes at the towing ship. During these studies, sensors on the deep-tow vehicle included a high-resolution 125-kHz bathymetric profiler, a 4-kHz profiler for measuring sediment thickness, a pair of side-scan sonars for mapping rock outcrops, fault scarps, and fissures, a magnetometer, a thermometer, and a battery of deep-sea cameras (snapshot TV, black-and-white stereo, and color) which collected about 2000 sets of bottom photos. This package was towed 10 to 100 meters above the sea floor, at an average speed of 3 km/hr.

This work was sponsored by the National Science Foundation as part of the Manganese Nodule Project, its primary objective being to locate and map sites for geochemical experiments, rather than to complement the deep-sea drilling effort. However, just as we took advantage of the IPOD site survey for our site selection and to provide a regional context for our small-scale surveys, the deep-tow observations may assist in interpreting some of the drilling results. In this initial report we present a brief description of the fine structure on the axial ridge, as well as photographs of some of the

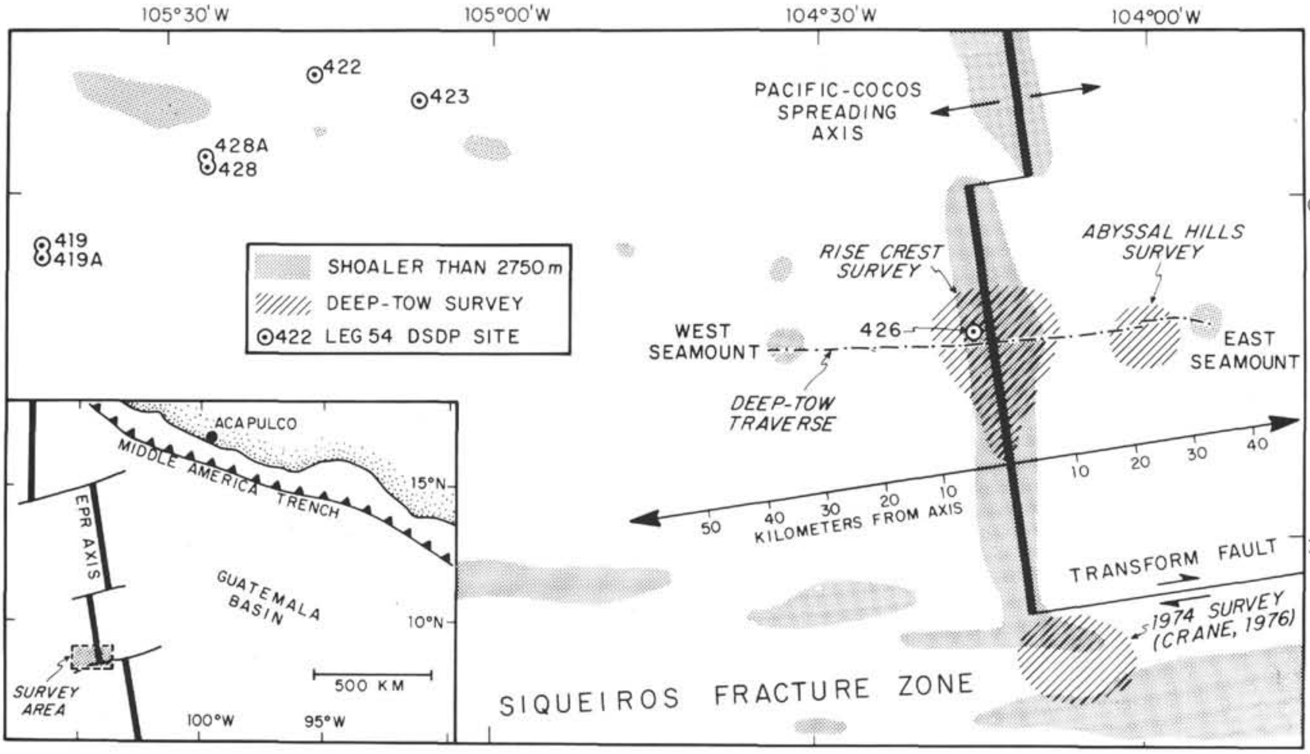

Figure 1. *Location map showing position of DSDP Leg 54 drill sites, and extent of deep-tow surveys. The 2750-meter contour demarcates the axial ridge of the East Pacific Rise, ridges along the Siqueiros fracture zone, and seamounts on the rise flanks.*

volcanic and tectonic phenomena displayed there. A more comprehensive analysis and comparison of this part of the EPR with other segments that have been closely examined is in preparation. A structural map of the patch of abyssal hills on a half-million-year-old part of the Cocos plate is included; its lineated structure is probably very similar to that at those "normal fabric" sites (Sites 419, 420, 421, and 429) drilled in somewhat older parts of the Pacific plate. The distribution of sediment, as observed along our traverse of the rise, is also discussed. Results of our seamount studies are reported in Lonsdale and Spiess (1979).

THE AXIAL RIDGE

Morphology

The axis of the greater part of the fast-spreading EPR is marked by a ridge which is commonly 10 km wide and 200 to 300 meters high, with concave side slopes that rise to a narrow summit, and with a very regular longitudinal gradient (Lonsdale, 1977c). The cross-sectional shape of the 75 km of rise crest between the Siqueiros transform fault and the short transform fault at 9°N is quite different. Even on low-resolution surface-ship profiles (e.g., Figure 2), it can be seen that the axial ridge has very steep sides and an almost flat top, giving it a rectangular cross section . A deep-tow survey of a typical section of rise crest (near 3°25'S) determined that the axial ridge there is primarily a volcanic construction (Lonsdale, 1977d). We wished to test the assumption (by Rosendahl et al., 1976) that the unusual axial ridge near 8°45 N is bounded by faults. We found that it is. For much of its surveyed length (Figures 3 and 4), the sides of the ridge are outward-facing normal faults with throws of over 100 meters. Along the strike, the large fault scarps are replaced by steep slopes with an irregular relief of volcanic peaks (e.g., Figure 4, profile 4, east); it is likely that faulting at these sections has been obscured by subsequent lava flows.

The top of the axial ridge is a 12 to 15-km-wide basalt plateau, with minor relief that rarely exceeds 50 meters, (except at the crestal rift zone) and a narrow band of intense faulting, fissuring, and constructional volcanism. The plateau flanks are gently inclined (average slope 2°) away from this rift zone, which occupies the shoalest part of the ridge except where recent subsidence has created summit grabens. The dimensions of these linear calderas vary along the strike. At 8°42'N (Figure 4, profile 8) the summit graben is 500 meters wide and 40 meters deep, comparable in size to the corresponding feature mapped at 3°25'S (Lonsdale, 1977d); at 8°46'N (profile 4) the graben is 2 km across and has one wall that is 90 meters high. Elsewhere, any collapse structures in the rift zone have been buried by later lava flows, which south of 8°40'N have built a 150-meter-tall peak precisely on the spreading axis.

The crestal rift zone does not occupy the geometric center of the ridge: the spreading axis is an average of 5.5 km from the western margin and 7.5 km from the eastern margin. The outer part of the extensive eastern

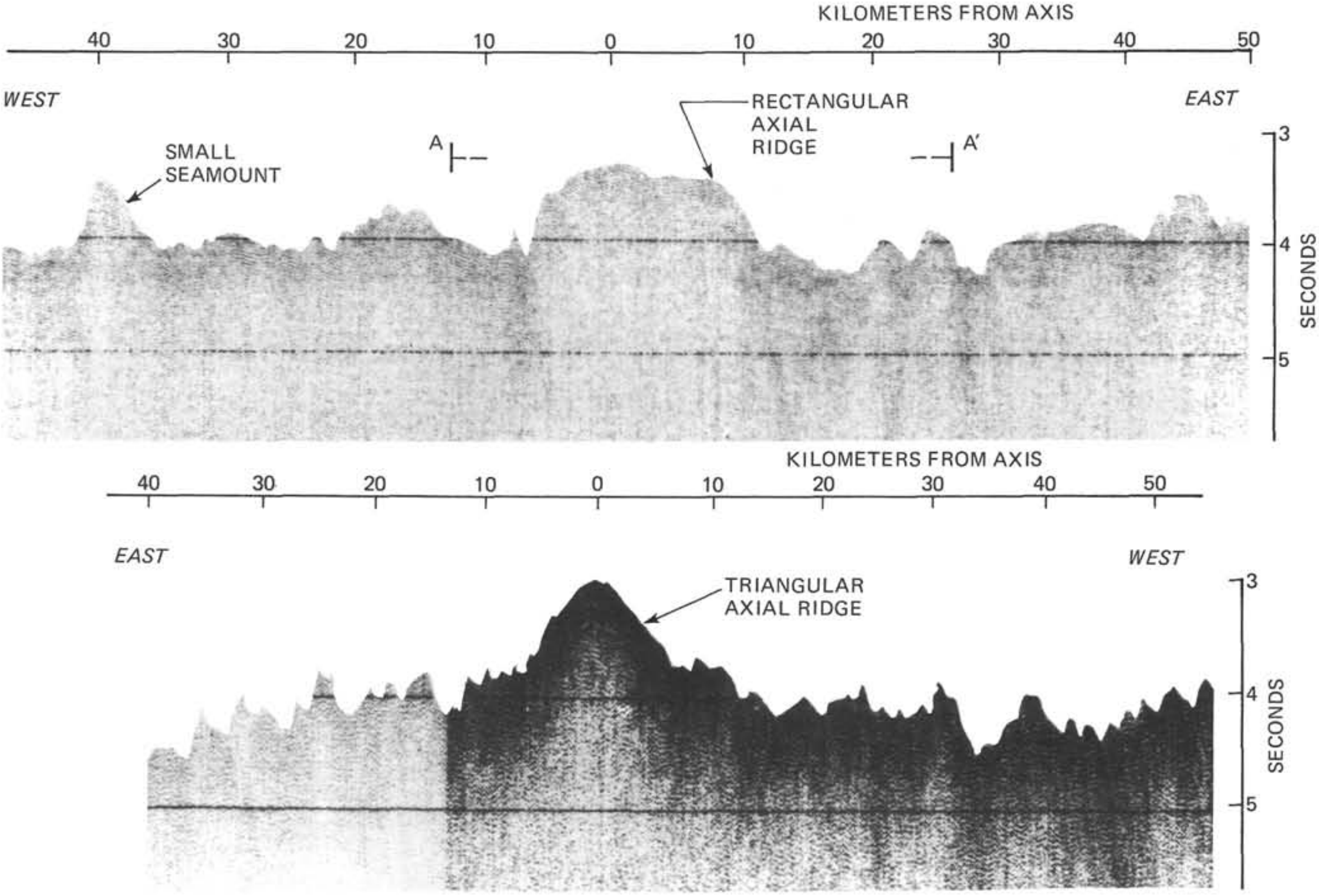

Figure 2. *Transverse shape of the East Pacific Rise, on Leg 54 reflection profiles. Upper profile is from near 8°45 'N (A–A' on Figure 3), showing the unusual rectangular cross section of the axial ridge there. Lower profile, from near 9°20 'N, shows a more common shape, although the axial ridge is still broader and shallower than along most of the rise.*

flank of the plateau has been regionally uplifted, with the maximum elevation centered 5 to 6 km east of the spreading axis. As a result, several profiles of the axial ridge show a double peak with an intervening plain. North of 8°45 'N the center of the flank uplift has collapsed to form a marginal graben. The intervening lava plain, though gently sloping and undeformed, is not a perfectly horizontal and smooth feature of the type found at some medium-spreading ridges, where they probably represent the solidified surfaces of lava lakes dammed between central highs and marginal horsts (Lonsdale, 1977a). Instead, it appears to have been built, just like a subaerial flood basalt plateau, by the successive accumulation of thin, mobile flows of fissure basalt. A possible frozen lava lake, with a smooth surface marred only by irregularly shaped 10-meter-deep collapse depressions, was discovered in the southern part of the survey area (profile 11), between the axial peak and a marginal volcanic ridge. Shallow collapse depressions and low volcanic peaks were mapped elsewhere on the plateau, but most of its relief is tectonic and highly lineated.

Types of Lava

The primary site of volcanism, judging from the lava's freshness and lack of sediment burial, is the crestal rift zone, where fissure eruptions occur as dikes reach the sea floor. Along-strike variation in timing and volume of eruption causes variation in the volcanic landforms and types of lava exposed in the rift zone. Voluminous eruptions fill the summit graben and, depending on the mobility of the lava (probably a function of the rate of discharge), they may either spill out across the plateau or build an axial peak similar to a "central high" on a slow-spreading ridge (e.g., Mount Venus in the FAMOUS Rift; Luyendyk and Macdonald, 1977). Local accumulation above a slowly erupting fissure builds narrow linear ridges called "pillow walls" (Fornari et al., 1978), and the intervening depressions are commonly flooded by very fluid lava which moves along the rift zone from centers of eruption.

Classic bulbous and elongate pillows of the type so common at steep volcanic slopes near the axis of the Mid-Atlantic Ridge (Ballard and Moore, 1977) and on

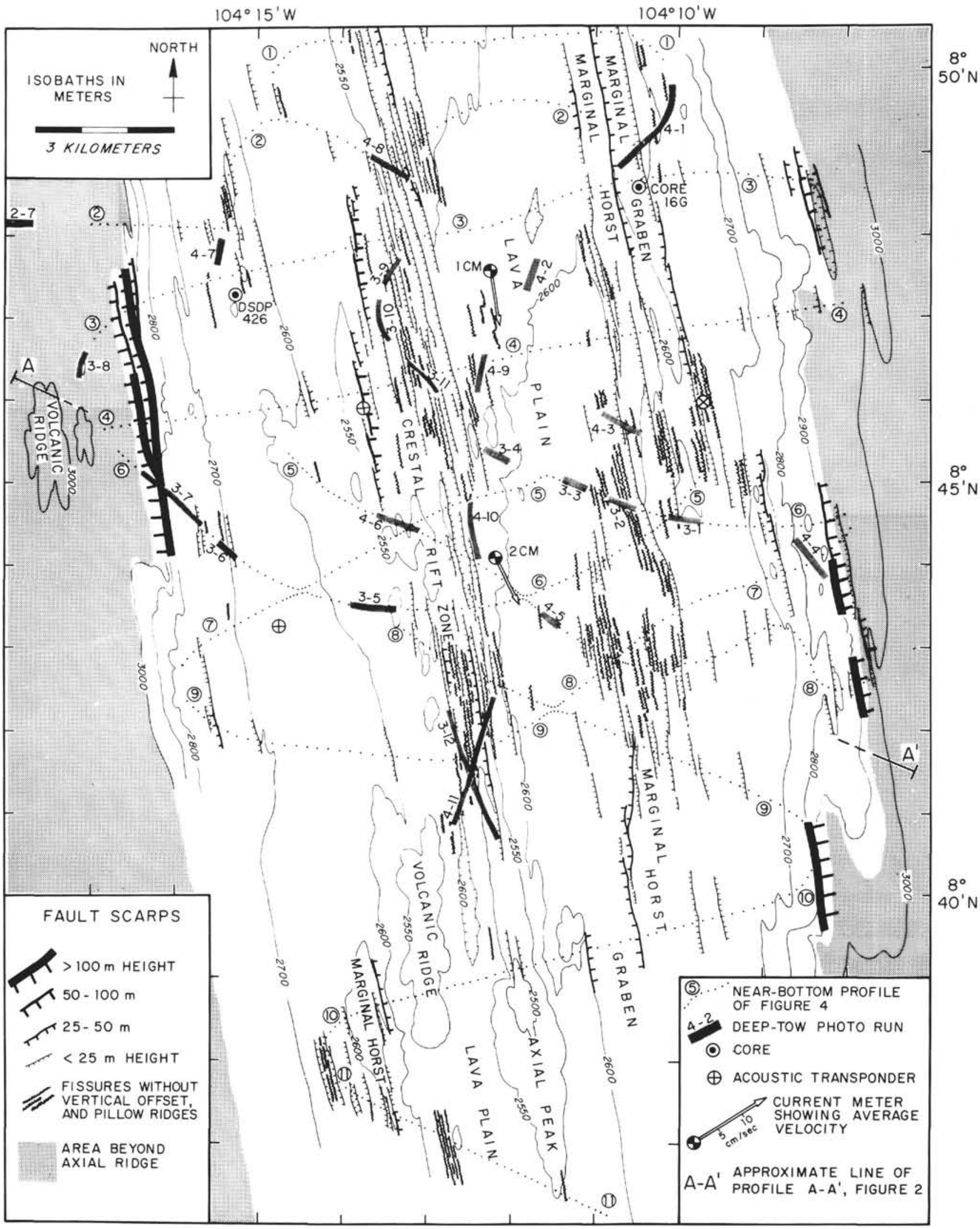

Figure 3. *Deep-tow survey of the axial ridge of the East Pacific Rise. Dotted lines show deep-tow tracks used to construct the profiles of Figure 4; many other deep-tow tracks (providing almost complete side-scan sonar coverage of this segment of the rise crest) are not shown.*

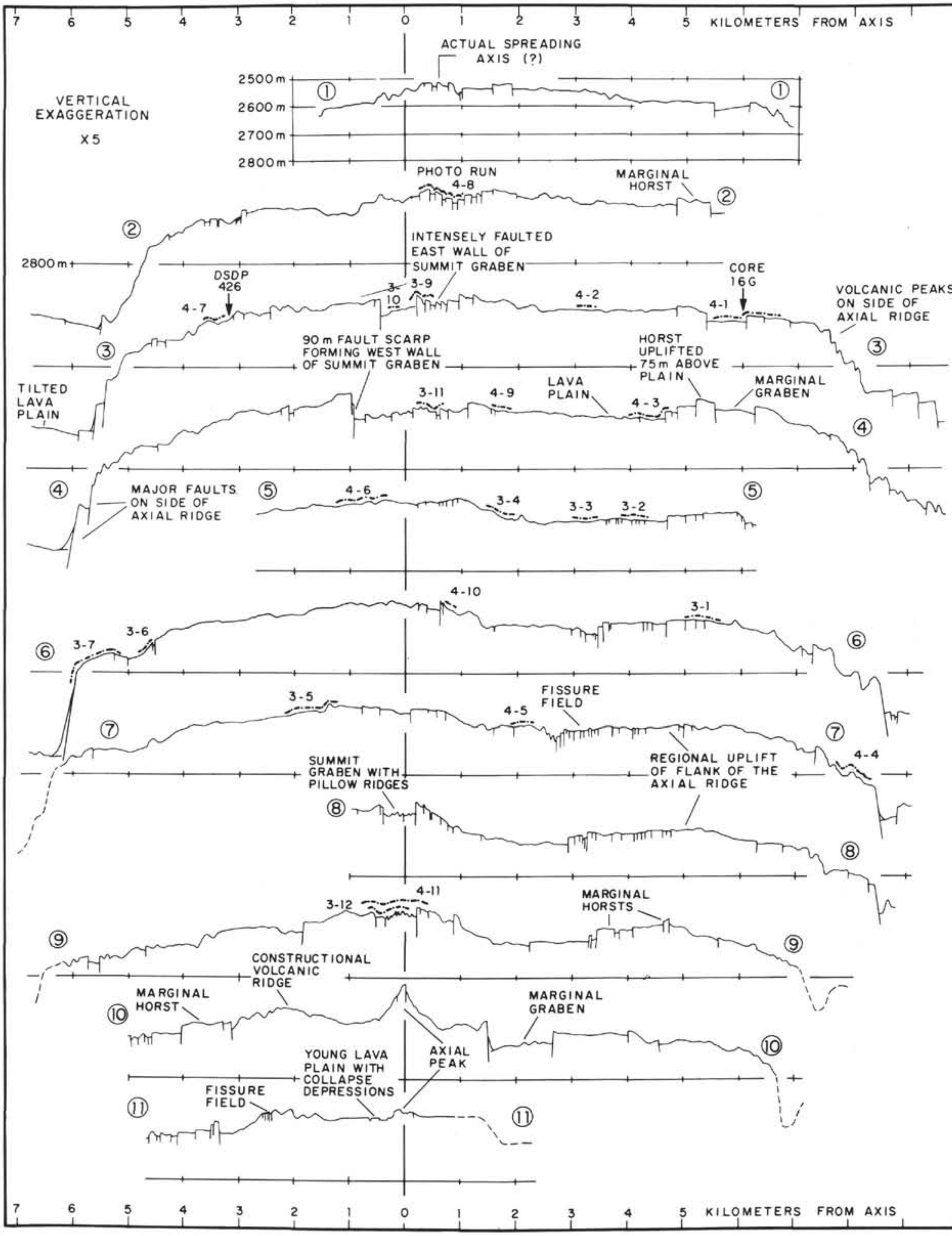

Figure 4. *Transverse profiles of the axial ridge, projected normal to its 350° strike. Based on data from the near-bottom echo-sounder and side-looking sonars (used to map fault scarps and fissures) along the tracks shown in Figure 3. All profiles have the 2800-meter level shown for reference. The chosen center of spreading ("0 km from axis") is the best-fitted 349° line through all the profiles; in the north the actual spreading axis may be a few hundred meters east of this line.*

the steep flanks of EPR's axial shield volcano near 3°25 'S (Lonsdale, 1977d) have a rather restricted distribution in the areas photographed. The freshest examples were near the northern end of the axial peak, which is so young as to be almost unfissured; it occupies the rift zone in the southern part of the survey area. The flows here (Figure 5A-D) have scarcely a trace of sediment cover to obscure the characteristic corrugations and spreading cracks formed during pillow growth (Moore, 1975). Narrower, smoother skinned elongate pillows, extending down even steeper slopes (Figure 5E), are found within the summit graben on pillow walls. These features are the fissural equivalents, and have an identical type of lava, to the "haystacks" or pillowed cones in the FAMOUS Rift, illustrated by Ballard and Moore (1977).

The mode of volcanism contributing most to crustal accretion at this section of the Pacific–Cocos plate boundary is effusive discharge from a few kilometers of a rapidly erupting axial fissure. Relatively mobile lava overflows the erupting length of the summit graben, spilling laterally along the rift zone and transversely across nearby parts of the plateau. A recent center of this style of eruption is near 8°44 'N (Figure 4, profiles, Figures 5-7), where the axis is occupied by a low ridge whose gentle slopes are continuous with the west flank of the plateau. Photographs from this region show some elongate pillows with corrugated crusts (e.g., Figures 6A, B), though many are covered with breadcrust cracks. More abundant, however, are knobby pillows (Figure 6C) and, especially, flattened pillows (Figure 7A); these are thought to be the faster growing equivalents of elongate and bulbous pillows, respectively (Ballard and Moore, 1977). Clearer evidence of highly mobile basalt are patches of sheet lava, forming islands of smooth, wrinkled, or ropy pahoehoe (Figure 6D, E) and lava rivers with lineations along the flow path (Figure 6F) on the predominantly pillowed slopes. Large areas of the formerly plastic skins of sheet lava, or of flattened pillows, have not been merely wrinkled, but have been shattered and jumbled. The resulting lava surface (e.g., Figure 7B-D) is so rough that it resembles aa, but its proper subaerial equivalent is slab pahoehoe (Macdonald, 1967).

Although this section of fast-spreading EPR differs from the previously studied 3°25 'S site in having sheet flows that extend beyond the crestal zone, it is similar in that the best examples of pahoehoe surfaces were found where lava had ponded within the summit graben, between pillow ridges (Figure 8). Some of the smooth and wrinkled lava here is very fresh and totally free of sediment (e.g., Figure 8A-C, from photo run 3-12). It probably represents the most mobile and far-traveled flow units of the lava recently erupted along the southern axial peak; other equally fluid units may have built the flat lava plain that was crossed on profile 11 (Figure 4), but not photographed, while contemporary slower moving flows constructed the pillowed ridge illustrated in Figure 5. The pahoehoe photographed in the northern summit graben (Figure 8D-F) is older, with a sediment veneer sufficient to cover its smooth surfaces.

With the local exceptions noted below, no fresh, sediment-free lava was photographed more than 1 km from the axial rift zone. Major fissure flows must originate close to the center of spreading and spill only a short distance across the axial ridge. Most of the basalt plateau has spread beyond the zone of frequent lava supply to a zone of sedimentation. The sediment blanket hampers attempts to use photographic observations for estimates of the relative importance of the several types of pillow and sheet lava at the top of the igneous crust, because their great variation in roughness causes them to be buried and obscured at different rates. For example, even within 2 km of the spreading axis (photo runs 3-4 and 4-9 on the west flank), knobby and bulbous pillows are partly submerged in sediment but are still clearly identifiable (Figure 9A, B), an area of flattened pillows is almost obscured by sediment except near a fissure (Figure 9D), and a patch of low-relief sheet lava is completely buried, with visible outcrops only in the wall of a fissure (Figure 9F). Elsewhere on the inner parts of the plateau, perhaps where bottom currents have impeded deposition, some sheet lava is rather well exposed (Figure 9C). On the outer, older, parts of the plateau (Figure 10) only prominent bulbous pillows are visible, because they alone project through the thickening sediment. Only where the sea floor is broken by faulting or fissuring is it possible to get an unbiased view of the lava type: of the 50 photographs of tectonic fractures on the plateau (outside of the axial rift zone) about 45 per cent expose a section of flattened pillows (e.g., Figure 11B), 40 per cent expose sheet lava (e.g., Figures 9E, 10E), and only 15 per cent expose bulbous or elongate pillows (e.g., Figure 11A). It would, of course, be rash to take these per centages as representative of the entire thickness of lava accreted at this plate boundary.

In addition to the axial fissure volcanism, secondary volcanism that discharges magma from off-axis pipes has built subcircular volcanic knobs, commonly 20 to 25 meters high, on the lava plateau. These small peaks have steep sides of elongate pillow lava (Figure 11F). They are particularly abundant and large at the margins of the axial ridge; volcanic eruption may be revived here as the deep fractures of the axial block's boundary faults tap parts of the shallow magma chamber. As to whether such boundary eruptions ever produce extensive flows, rather than merely building small peaks, our observational evidence is ambiguous. Near the brink of the boundary fault scarp on photo run 3-7 (profile 6) we photographed a patch of almost sediment-free sheet lava, spalling off in regular blocks 20 cm thick (Figure 11D), that may have been part of a young off-axis flow, though sediment deficiency might also be caused by strong bottom currents near the plateau's edge. At the foot of the boundary scarp in the northwest section of the survey area (profiles 2 and 3) there is an extensive lava plain, tilted at 2° toward the axial ridge. Its surface is so smooth and undeformed that an origin near the axial rift zone, and subsequent plate tectonic transport across the plateau and down the axial ridge's margins, seems implausible: the plain appears to have been formed recently and *in situ*, by flows extending outward

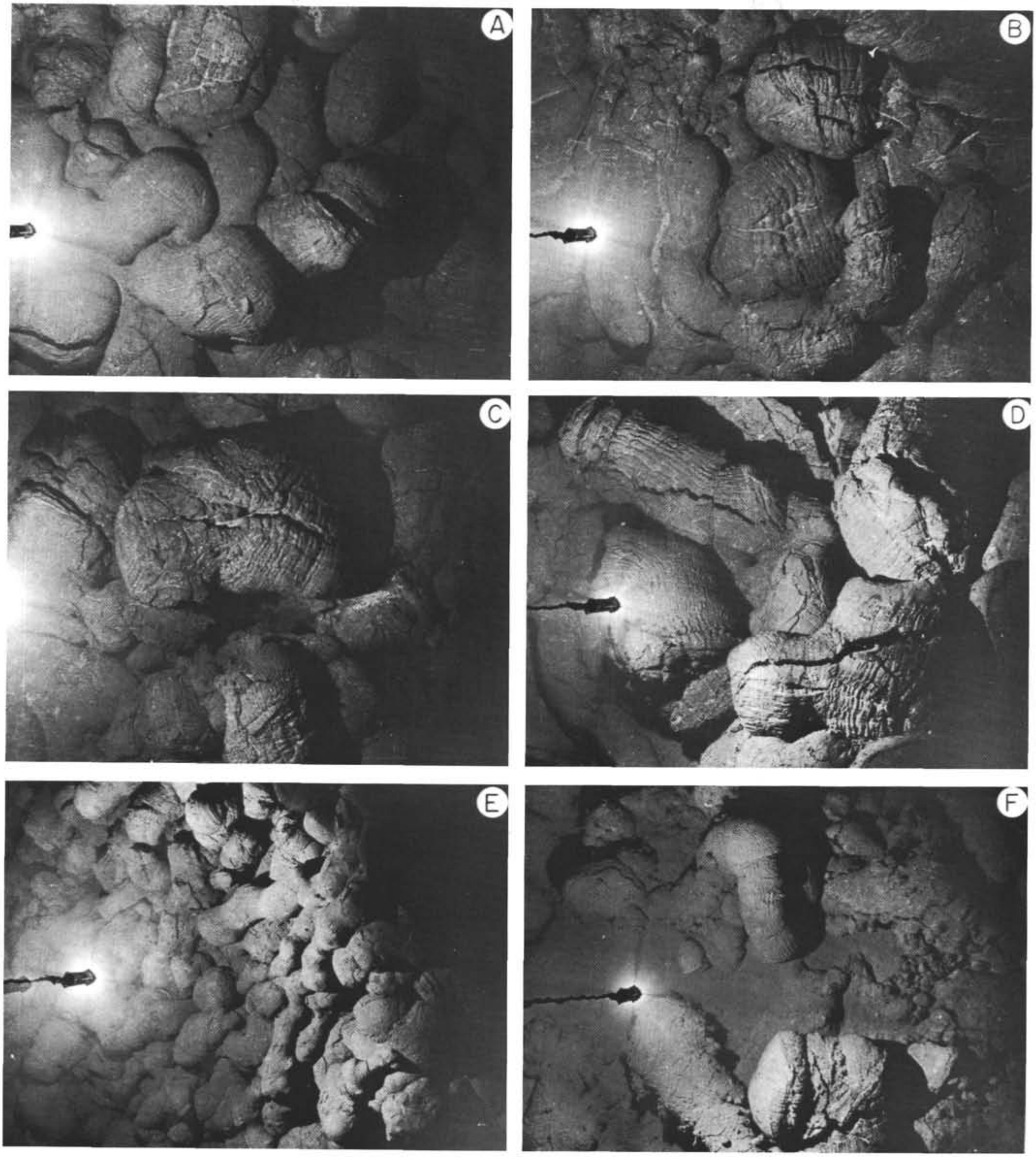

Figure 5. *Vertical incidence bottom photographs taken by the deep-tow instrument, on photo runs located on Figures 3 and 4. Area of frame is 4 × 5 meters (all photos on Figures 5 through 12 are at approximately the same scale). Frames 5A through D are of fresh, corrugated bulbous and elongate pillows on an axial peak (southern end of photo run 3-12). Frame 5E shows small-diameter elongate pillows on a steep wall crossed during the northern part of 3-12; 5F (3-9) shows elongate and knobby pillows, dusted with sediment, in the northern summit graben.*

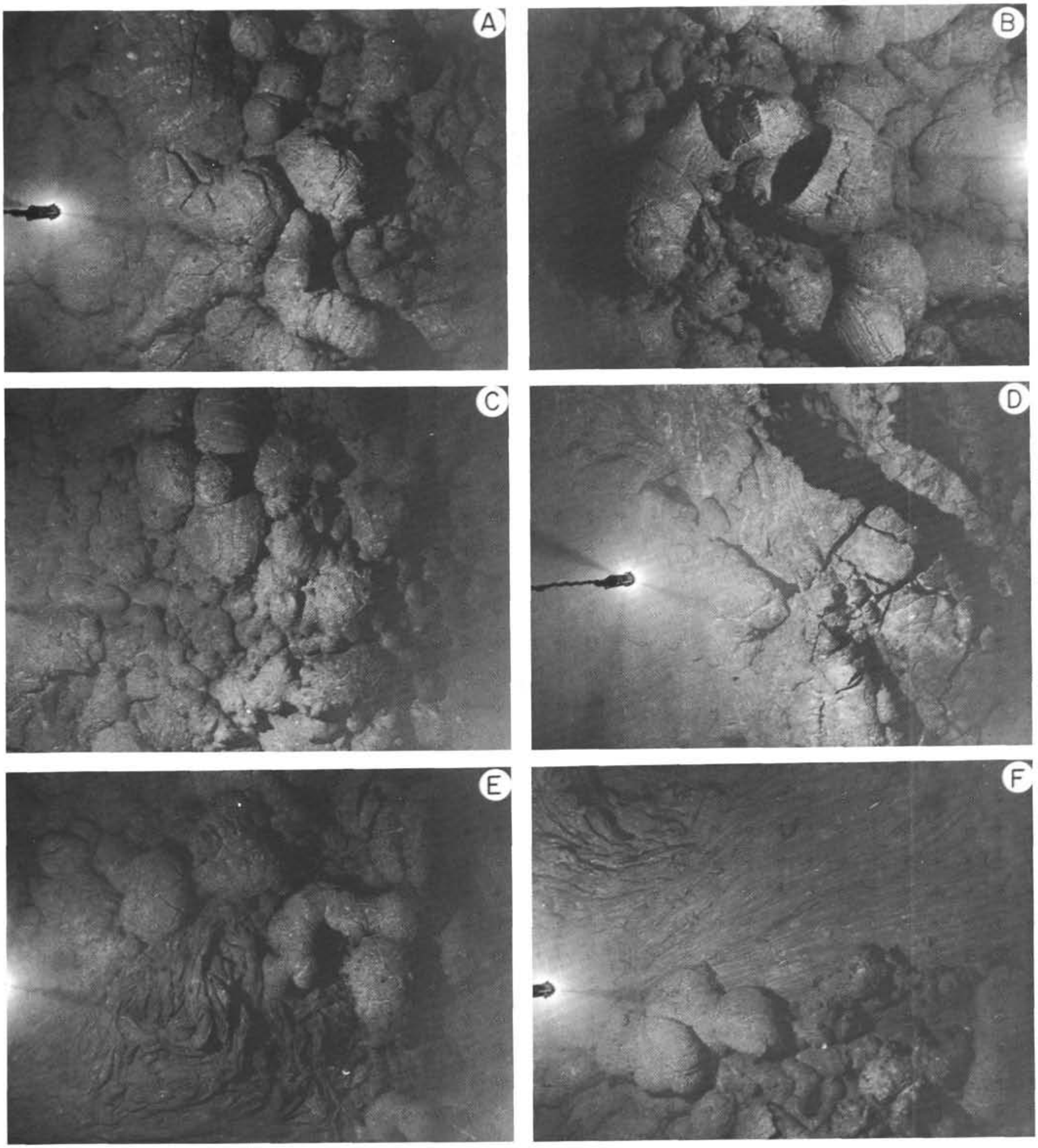

Figure 6. *Lava flows on the inner part of the basalt plateau, all from photo run 3-5. Frame B shows a trapdoor pillow, D a fractured tumulus, and E and F wrinkled pahoehoe and a frozen lava river among pillow basalts.*

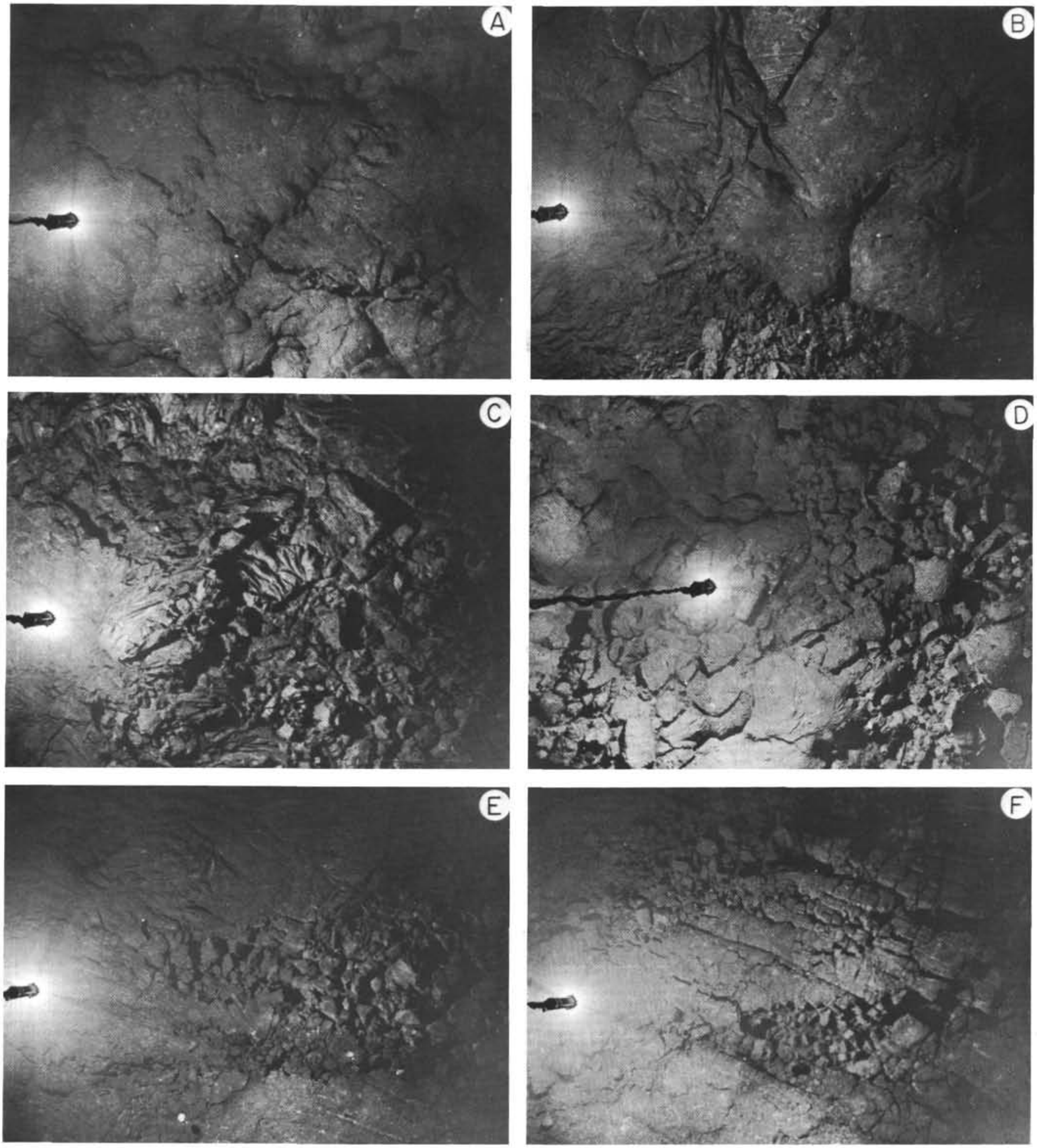

Figure 7. *Surfaces of young, gently sloping lava flows near the margins of the crestal rift zone. Frames A, B, and C (north end of photo run 3-12) show a transition from flattened pillows to slab pahoehoe. Frames E and F show sheet flows autobrecciating along rectangular contraction joints.*

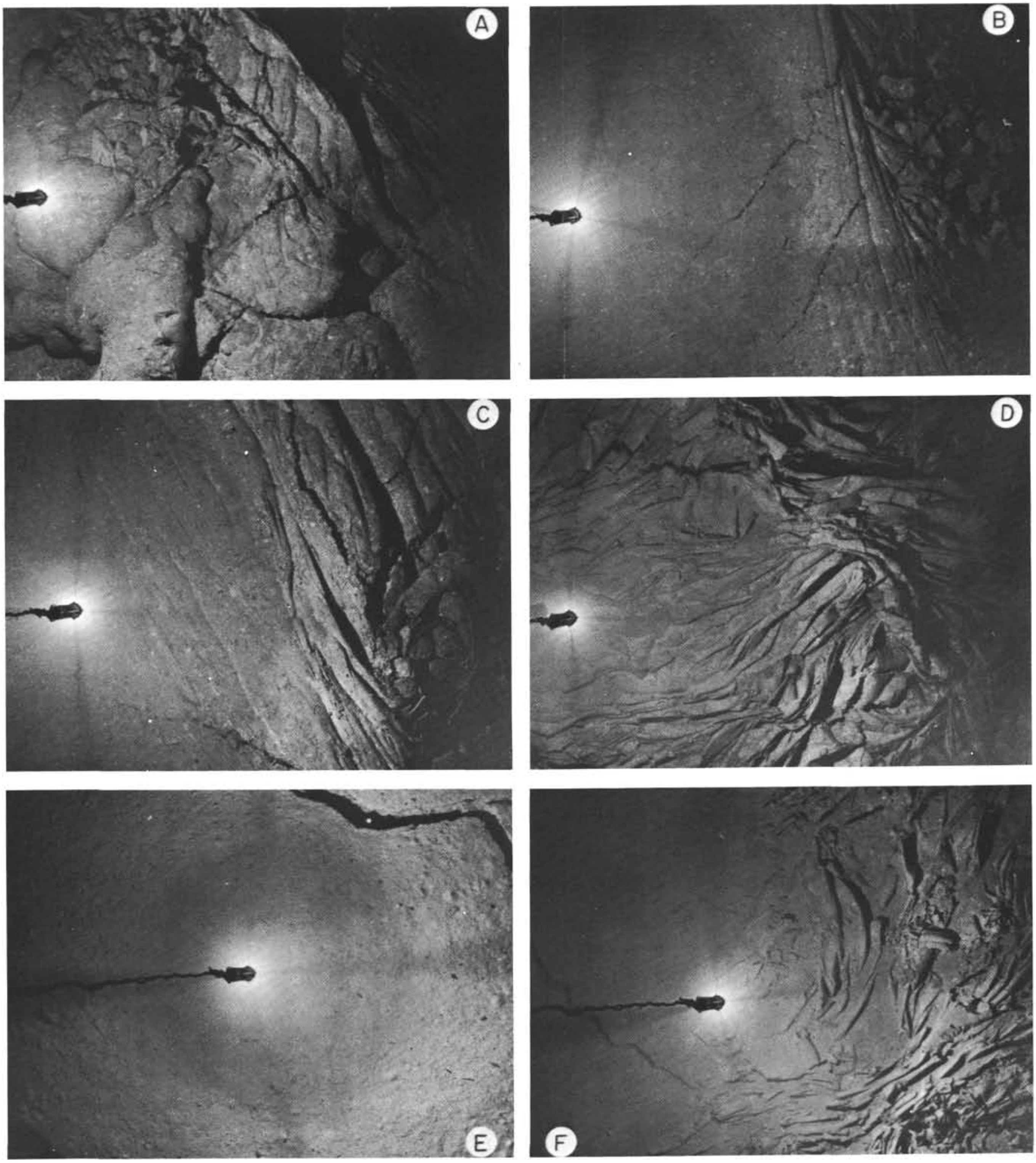

Figure 8. *Sheet lava (with transition to flat pillows in frame A), including smooth and wrinkled pahoehoe, from the floor of the summit graben. Frames A through C (photo run 3-12) show very fresh lava hardly dusted with sediment; note rudimentary lava coil (Lonsdale, 1977a) in 6C. Frames D (3-11) E, and F (3-10) show similar lava types from further north in the crestal rift zone, where they are veneered with sediment.*

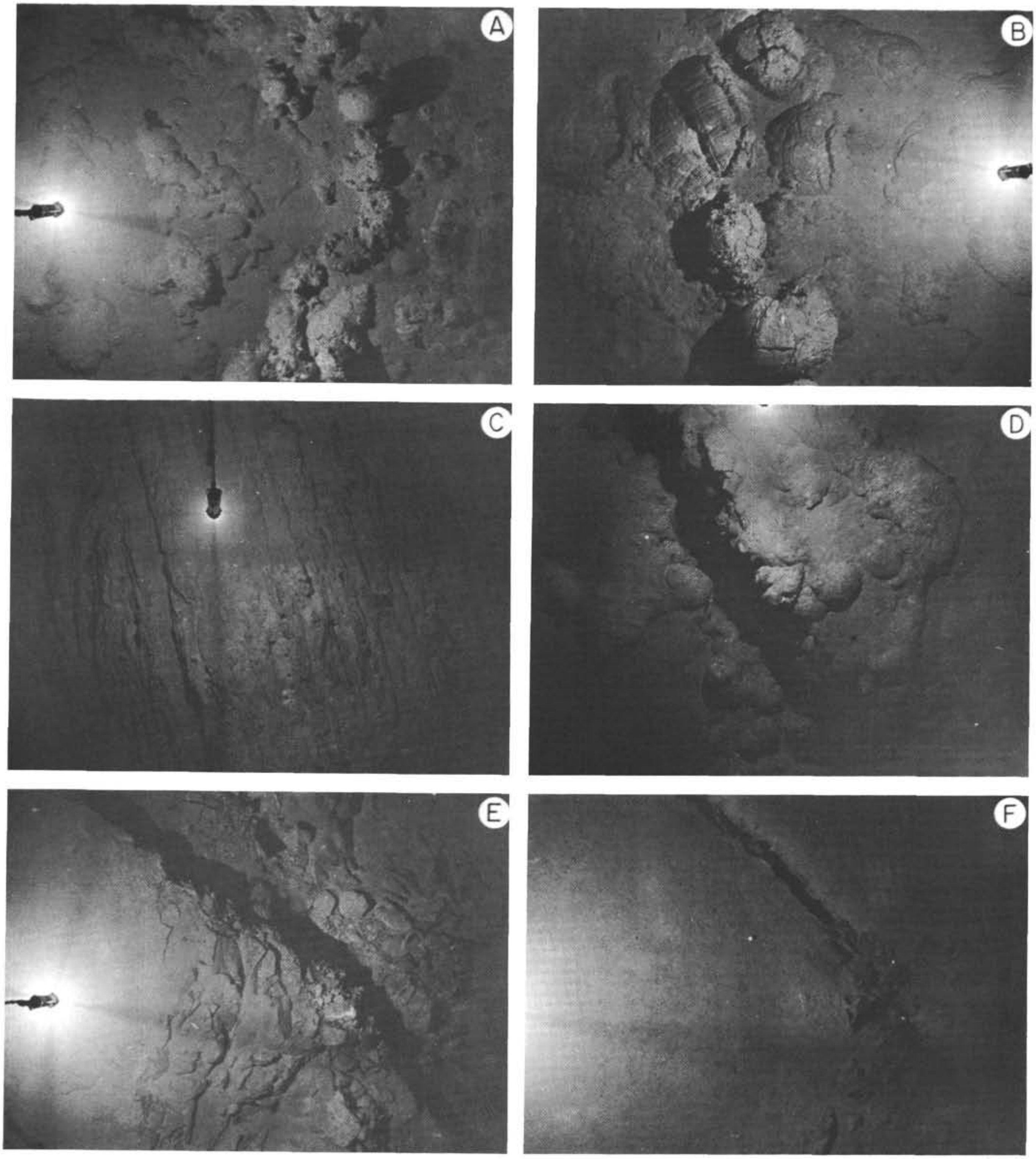

Figure 9. *Partly sedimented lava flows on the inner part of the basalt plateau. Frames A and B (photo run 3-4 1.7 km from spreading axis) show knobby and bulbous pillows, partly buried in sediment; frame C (4-2, 3.2 km from axis) shows a wrinkled pahoehoe surface. Frames D, E, and F (runs 4-9, 3-3, and 3-4) show narrow dilational fissures cutting a variety of lava types.*

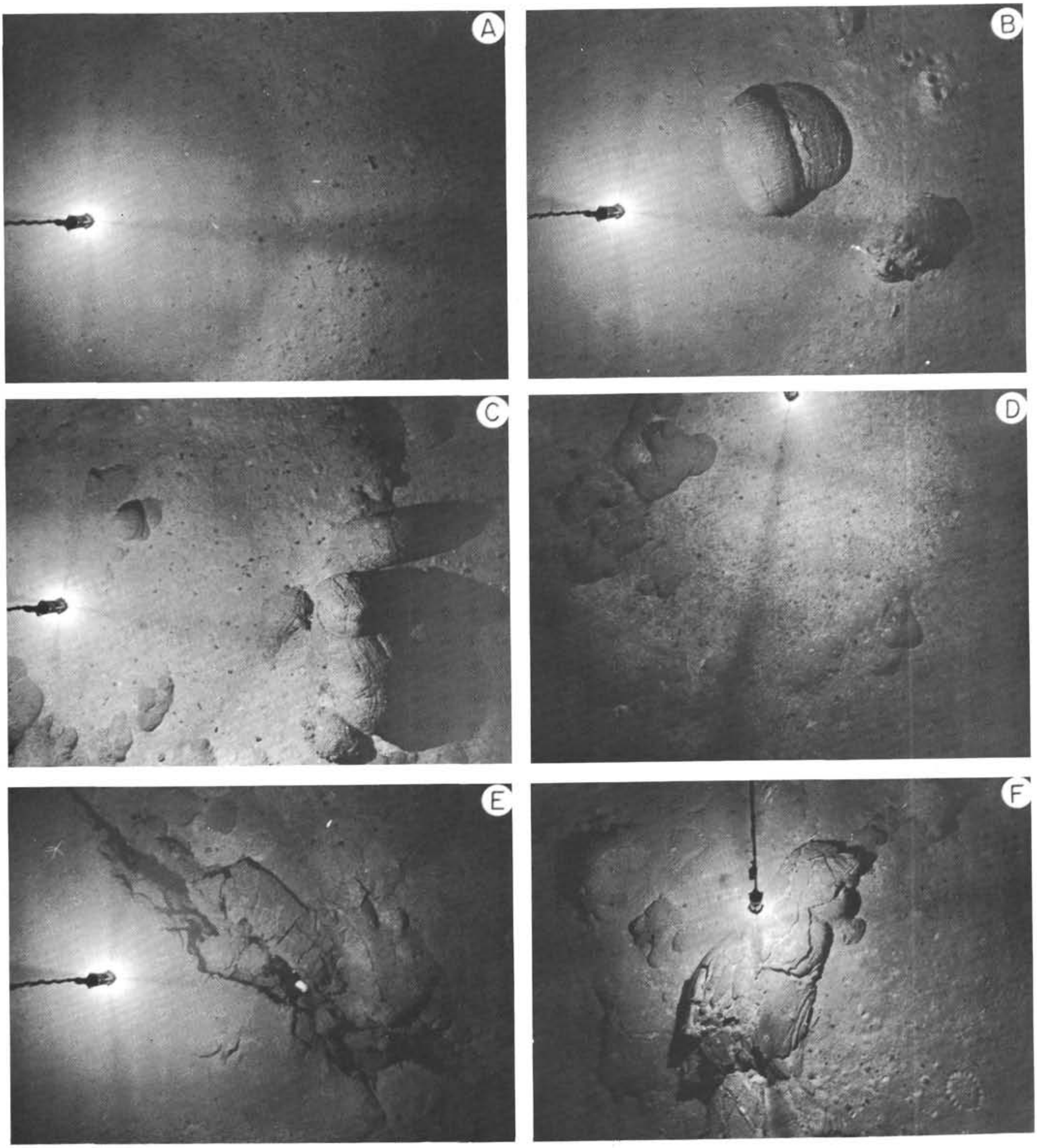

Figure 10. *Surfaces of older lava flows on the outer parts of the basalt plateau. Frames A and B (photo run 3-2, 4 km east of the axis) and C (3-7, 5.5 km west of axis) show almost complete sediment burial, except for prominent bulbous pillows. Note that sediment surface is strewn with small rock fragments or ferromanganese nodules; in frame D (4-3, 4.5 km east of axis) the entire sediment surface has a coarse, gravelly texture. Frame E (3-2) shows an outcrop of sheet lava in a fissure field, and F (4-1) shows the sedimented floor of the marginal graben 6 km east of the axis.*

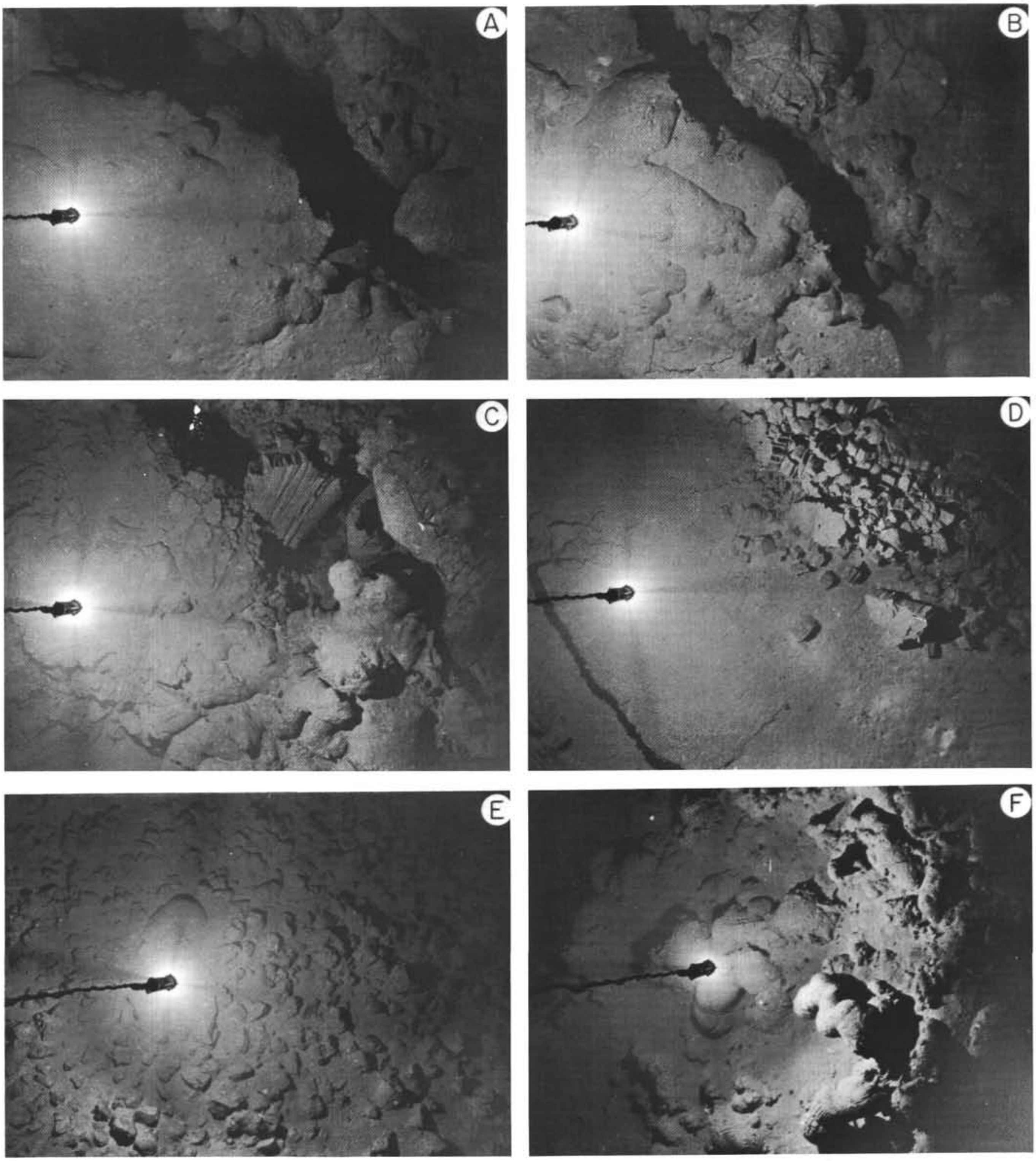

Figure 11. *Photographs from near the boundaries of the axial ridge. Frame A (photo run 3-6) shows a fault of small offset that has evolved from dilational fissures of the type shown in frames B and C (3-7). Frame D (3-7) shows unusually fresh sheet lava, broken into cubes, 5.6 km west of the axis. Sediment-dusted breccia (frame E) is from the 30° side slope of the axial ridge (3-7); young elongate pillow basalt that has flowed down a steep constructional slope (frame F) is from a volcanic knob on a ridge 7 km west of the axis (run 3-8, Figure 3).*

from the boundary scarps. However, it has a fairly complete sediment veneer, with only occasional outcrops (of sheet lava) visible on our photographs (photo run 2-7).

Rock Fracturing

Basalt accreted at the spreading axis is fractured as soon as magma freezes to form a brittle rock. Intense tectonic activity at the plate boundary zone ensures that before the upper crust spreads away from the axial ridge it has several scales of pervasive fracturing.

Repeated rifting of brittle pillow crusts by the pressure of still-molten lava is essential to pillow growth (Moore, 1975) and is responsible for such superficial phenomena as spreading cracks with fault slivers (e.g., Figure 5A,D), breadcrust cracks (e.g., Figure 6A), and trapdoor pillows (Figure 6B). Pahoehoe surfaces generally have a few cracks that probably formed by thermal contraction (e.g., Figure 12B), and rapid cooling of thin sheet flows may shatter them with closely spaced contraction joints (Figures 7F, 11). As on thin subaerial flows (Macdonald, 1967, p. 40) vertical joints "show a tendency toward regular arrangement in polygonal patterns, the most common being an almost square rectangle, and the joint blocks tend to be more or less cubic." Contortion (Figure 6E) and fracturing (Figure 7C) of the plastic and brittle skins of sheet flows have been caused by motion of underlying fluid lava. Movement of flow units has also created low elongate tumuli in some sheet and flat pillow lavas, generally with a crack along their crests (Figure 6D) which may be partly filled with a squeeze-up (Figure 12F).

Nontectonic fracturing, producing talus of pillow joint blocks, also occurs by rockfall from steep flow fronts. Models of pillow flow progradation based on observations at the Mid-Atlantic Ridge (e.g., Ballard and Moore, 1977) assume that flow foot rubble created while the flow is active is a volumetrically important component. This type of talus is rarely seen in our photographs from the East Pacific Rise. Extensive rubble may have been produced, and then overridden and burried by pillows, but our preferred interpretation of the apparent absence is that the more mobile flows of this fast-spreading rise advance on low fronts with little talus formation. The near-vertical pillow walls within the summit graben have local talus at their feet (Figure 12E, but most of the talus in the crestal rift zone and elsewhere on the lava plateau has accumulated below fault scarps and within fissures. Even at these sites the volume of talus cones is small: most of the relatively small faults maintain a near-vertical scarp with little evidence for significant degradation. Much greater volumes of talus have accumulated at the margins of the axial ridge, by rockfall from the large outward-facing normal fault scarps. The extensive talus cones photographed there (e.g., Figure 11E) are comparable to the talus ramps at the walls of the Mid-Atlantic Ridge's axial rift valley (Ballard and van Andel, 1977).

Tectonic fracturing on the axial ridge is caused by dike injection at the spreading axis (and presumably, by lesser off-axis intrusions), repeated collapse of the summit graben, extensional fissuring and faulting on the plateau surface, and step-faulting as the crust descends the sides of the axial ridge. Subsequently, further extensional faulting creates abyssal hills.

In the crestal rift zone, a few open dilational fissures that cut pahoehoe on the floor of the summit graben (e.g., Figure 12D) probably represent sites of dike injection where the magma froze before reaching the sea floor. Along-strike, these "noneruptive" fissures are replaced by pillow walls, marking sites where small volumes of lava did erupt. Most of the fissures near the spreading axis, however, are replaced along-strike by boundary step-faults of the summit grabens.

On the plateau surface a few kilometers from the axis of spreading, extension of the young, thin lithosphere creates gaping fissures, commonly 0.5 to 2 meters wide (e.g., Figure 9D-F). They are concentrated in fields 0.5 to 1 km wide, where side-looking sonar records show densities of 5 to 8 km/100 m, and each individual cannot be shown on the scale of Figure 3. Although in detail they are sinuous and, occasionally, they branch, the fissures are impressively parallel to each other and to the 350° strike of the spreading axis. Differential vertical motion across some of these fissures converts their walls to low vertical fault scarps (Figure 11A), and continued growth on a few master faults creates the marginal horsts and grabens on the older parts of the basalt plateau.

Tensional faults on the top of the axial ridge may be shallow structures affecting only a thin, brittle outer layer of the oceanic crust, but fracturing along the shear faults that mark its boundaries must be deep seated. In some places the descent from the lava plateau to the adjacent plain seems to be accomplished by a single 300-meter-high, talus-covered fault scarp (Figure 4, profile 6), but more often there are step-faults with intervening back-tilted blocks.

THE RISE FLANKS

Abyssal Hills

The patch of young abyssal hills surveyed (Figure 13) has a relief of about 300 meters, almost all of it attributable to faulting except for scattered volcanic knobs, 20 to 50 meters high. The incomplete sediment cover has a maximum thickness of 8 meters, and most bedrock structures are well displayed on our mosaic of overlapping side-looking sonar records, although some fissures have probably been obscured by sediment burial. Rock crops out at the volcanic knobs and along fault scarps; the larger scarps have extensive talus ramps at their feet. Our few bottom photos of outcropping basalt show pillow lava, but many of the sediment-covered lava flows are quite smooth, and could well be sheet lava.

The crust has been broken by normal faulting into the linear fault slices common to all rise flanks (e.g., Klitgord and Mudie, 1974; and Whitmarsh and Laughton, 1976). As on other sections of the fast-spreading EPR (Lonsdale, 1977d), both inward- and outward-facing faults occur (with a slight and perhaps not signifi-

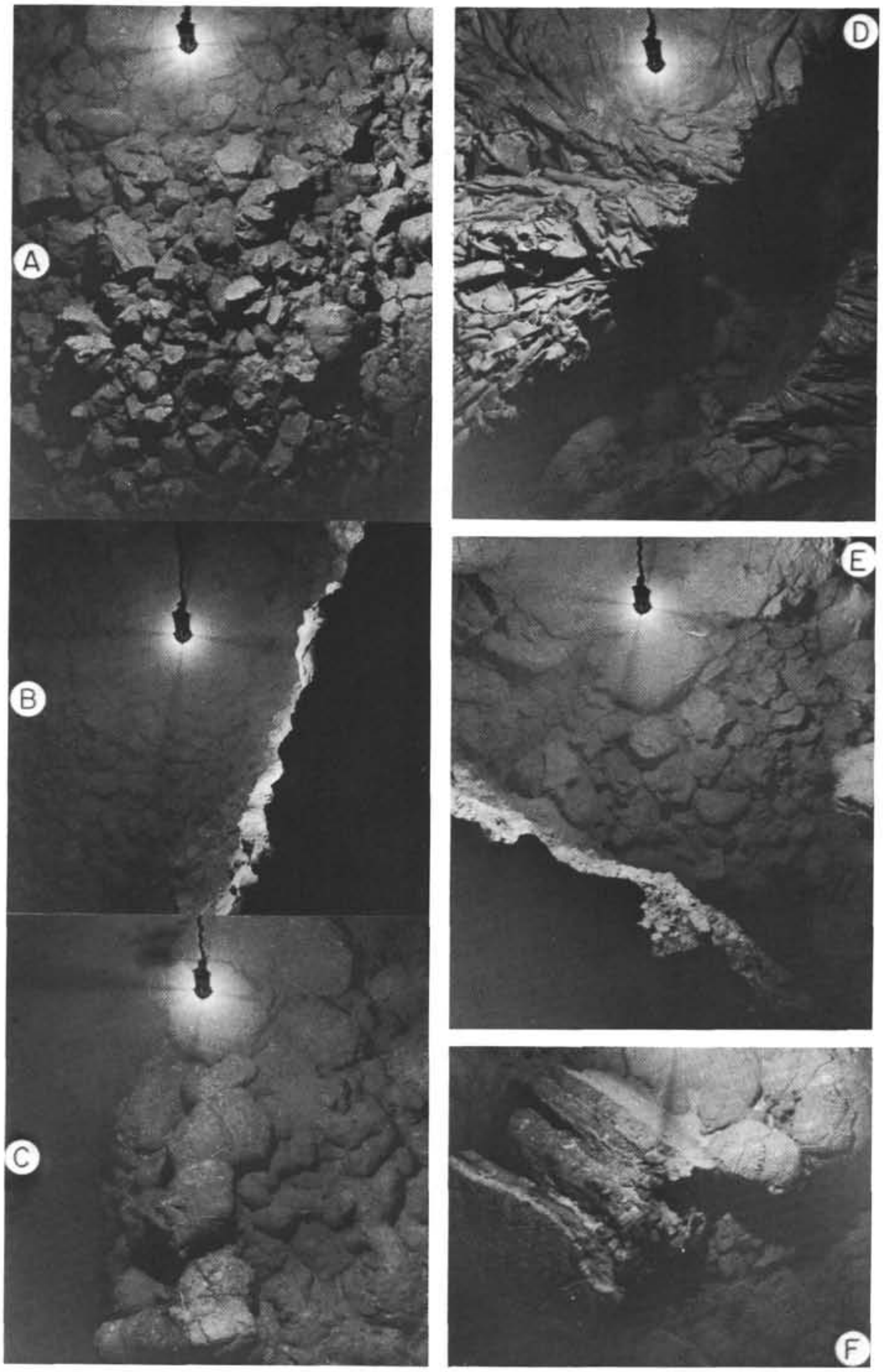

Figure 12. *Tectonic and pseudotectonic features in the axial rift zone. Frames A through C are a series showing the oblique crossing of a boundary scarp of the summit graben, from the pillow joint block talus at its foot, to alongside the vertical scarp (bright line in B), to the pillow lava at its crest. Frame D (3-11) shows a non-eruptive 2-meter-wide axial fissure, cutting wrinkled pahoehoe on the axial floor; and shows a steep cliff (brightly illuminated band) thought to be the steep side of a pillow wall; and F shows a squeeze-up of pillow basalt through a small tumulus in sheet lava.*

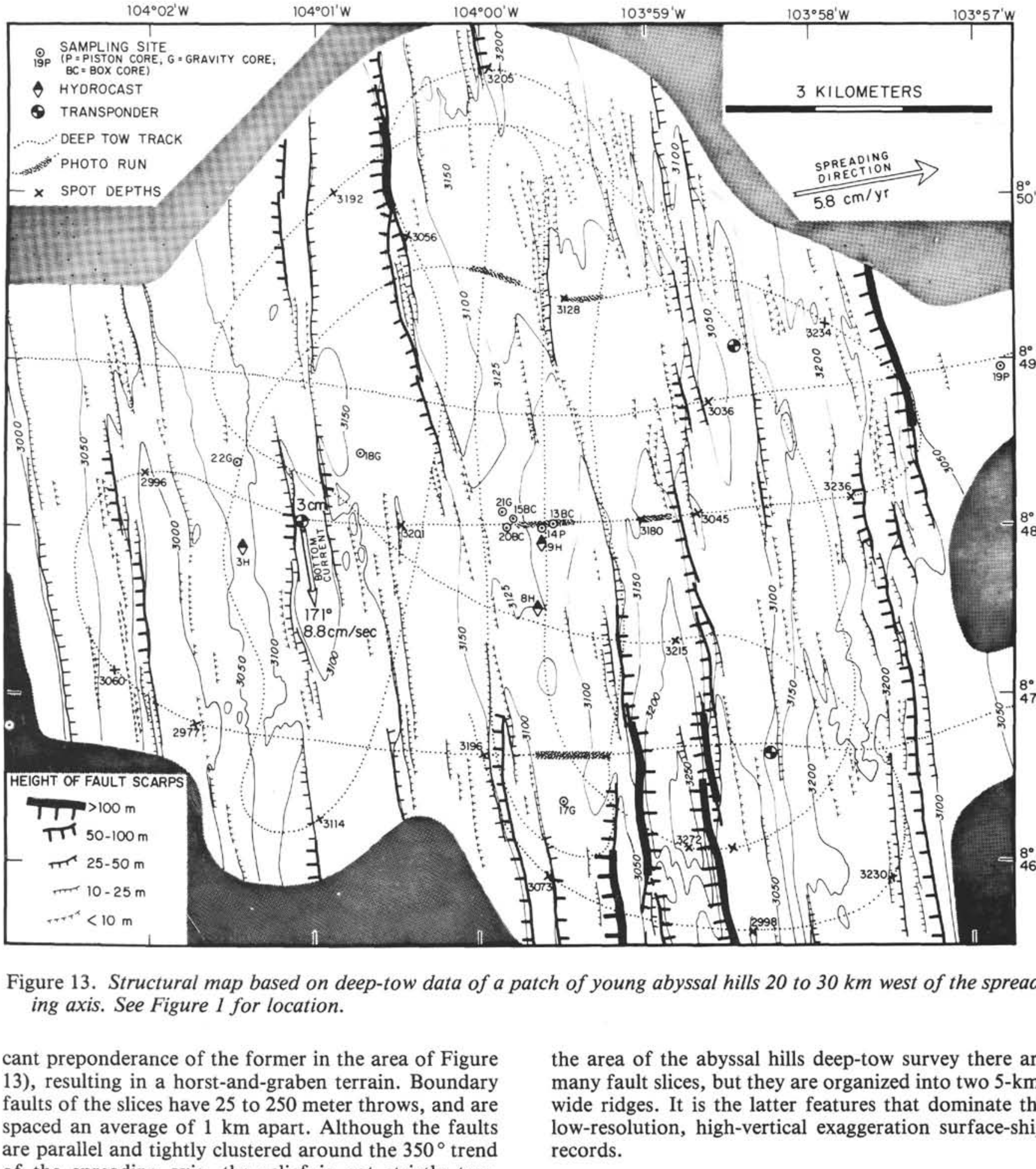

Figure 13. *Structural map based on deep-tow data of a patch of young abyssal hills 20 to 30 km west of the spreading axis. See Figure 1 for location.*

cant preponderance of the former in the area of Figure 13), resulting in a horst-and-graben terrain. Boundary faults of the slices have 25 to 250 meter throws, and are spaced an average of 1 km apart. Although the faults are parallel and tightly clustered around the 350° trend of the spreading axis, the relief is not strictly two-dimensional: most of the faults have *en-echelon* traces and limited lateral continuity.

Rosendahl (this volume) has used surface-ship echograms to map the rise flank "plate fabric" as linear ridges and troughs, with a wavelength of several kilometers, which are continuous for tens of kilometers. These landforms are not individual horsts and grabens, but are aggregates of several fault slices. On the transverse profile of the rise (Figure 14), it can be seen that in the area of the abyssal hills deep-tow survey there are many fault slices, but they are organized into two 5-km-wide ridges. It is the latter features that dominate the low-resolution, high-vertical exaggeration surface-ship records.

Seamounts

The rise flanks in the vicinity of our surveys have several seamounts and volcanic edifices that rise above the fault-block terrain. They include Ocean Crust Panel (OCP) Ridge, where lavas transitional between tholeiites and alkalic basalt are exposed (Batiza and Johnson, this volume), and a chain of seamounts extending from that ridge to the spreading axis near 8°39'N, where there is an axial peak (Figure 4, profile 10). At least one

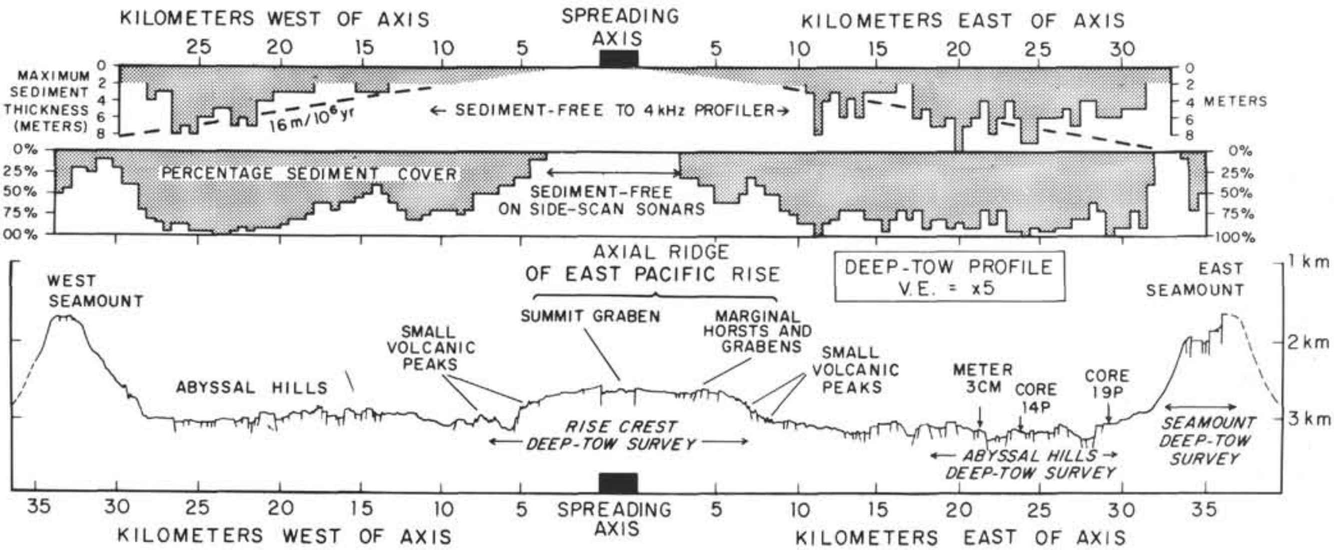

Figure 14. *Transverse profile of the East Pacific Rise near 8°45′N, based on near-bottom acoustic data. See Figure 1 for location. The upper panel shows the maximum sediment thickness on each 500 meters of the traverse, as recorded by the 4-kHz profiler; as used in this traverse, it could not resolve sediment less than 2 meters thick. The percentage of sea floor covered with sediment is estimated from side-scan sonar records.*

of these seamounts, which we refer to as West Seamount, is paired with a very similar volcano (East Seamount) equidistant from the spreading axis on the Cocos plate. We describe this pair of seamounts (Figure 14), and samples of hyaloclastite and "mid-ocean ridge" tholeiite dredged from the crest of East Seamount, in detail in Lonsdale and Spiess (1979). Our conclusions are that the volcanoes were born at a site of excess volcanism (a hot spot) on the spreading axis, and that they had a period of rapid growth after they had spread apart and were 10 to 20 km from the axis. After undergoing summit collapse to form caldera and pit craters, they have become dormant or extinct.

GEOLOGIC HISTORY OF YOUNG OCEANIC CRUST

Volcanism

The eruptive history of a typical section of oceanic crust near 8°45′N begins with discharge from an axial fissure and may continue for several hundred thousand years if it receives lava flows issuing from the foot of the boundary scarps of the axial ridge, or from seamounts. Deeper layers of the crust may be accreted over an even longer period.

Even disregarding the possibility of extensive lava accretion beyond the axial ridge, it is clear that a section of crust transported from the spreading center and delivered by sea-floor spreading to a potential deep-sea drilling site on the EPR's flank may have a rather complex volcanic stratigraphy. Within the 1- to 2-km-wide crestal rift zone its history may include repeatedly alternating accumulation of flattened pillows, axial peak or pillow wall elongate pillows, and summit graben pahoehoe (which may pond to form thick, local, cooling units). But as the crust spreads away from the rift zone, it experiences further frequent burial with many thin flows of flattened pillows and sheet lava; as it nears the margins of the axial ridge, it may be decorated with steep-sided knobs of elongate pillows.

Tectonism

As the crust spreads through the different structural provinces bordering the spreading axis it is broken by new faults, has old fractures infilled or obscured by new lava flows and probably by hydrothermal activity, and experiences rejuvenation of old fault trends. It is possible to trace this evolution by equating the spatial succession away from the spreading axis, as shown by the near-bottom traverse (Figure 14), with the temporal history of any section of crust. The alternative to this steady-state assumption is that there have been alternations in the structural style of the axial ridge, or perhaps major variations in the rate of eruption, during the 0.5 million years that the crust takes to spread out of the plate boundary zone.

The closely spaced vertical fissures and mainly inward-facing vertical faults produced by dike injection and summit collapse in the crestal rift zone are buried with lava flows on the inner part of the basalt plateau. As the crust ages, it is broken by new tensional fissures and faults. These do not seem to be rejuvenated summit graben faults, for they have a different pattern of organization into fields, and include both inward- and outward-facing scarps. The apparent decrease in density of these features near the margins of the axial ridge is probably caused by masking with secondary volcanism.

The large outward-facing step-faults observed or inferred at the boundaries of the axial ridge are the normal response of a brittle crust, under tension, descending a steep slope. An analogous situation is the formation of step faults on the oceanic slope of an active trench (e.g., Ludwig et al., 1966). More surprising than the presence of active outward-facing scarps on the steep sides of the ridge is the apparent absence of inactive examples on immediately older crust. One explanation could be that fault slices collapse off the axial ridge and subside to a uniform level on the flank. In this hypothesis, outward-dipping fractures initiated as normal faults become inactive, and then experience reverse faulting; it is similar to Harrison's (1974) explanation for formation and disappearance of the rift valley walls on a slow-spreading ridge. Alternatively, outward-dipping scarps may be buried with new lava erupted at the sides of the axial ridge; as noted above, such flows seem the most plausible way to account for the near absence of fault scarps in bands 8 to 12 km from the axis (Figure 14). In either case, the crust must be deeply sheared as it subsides 300 to 400 meters at the sides of the axial ridge, perhaps in slices only a few hundred meters wide.

Judging from the spatial pattern on the traverse (Figure 14), renewed faulting of the crust to create abyssal hills does not occur until it is about 12 km from the axis. There, new faults, or more probably rejuvenated faults that were initiated on the top of sides of the axial ridge, undergo rapid increase in throw to produce the 200- to 300-meter abyssal hill relief. They must soon become inactive, for the scale of fault-block relief does not increase beyond 20 km from the axis.

This inferred tectonic history is more complicated than on normal fast-spreading rises, which lack an axial ridge of rectangular cross section. In those cases (e.g., Lonsdale, 1977d), there is a direct evolution from the small-scale horsts and grabens formed 1 to 2 km from the spreading axis to abyssal hills of the rise flank, without an episode of deep faulting and renewed volcanism at the sides of the axial ridge. The rectangular cross section may not be a stable configuration even at 8°45′N; it is possible that it recently formed by uplift and inflation of the axial ridge, accompanied by volcanic eruption at its boundaries, in response to episodic enlargement of the shallow crustal magma chamber.

Sedimentation

Most of the axial ridge beyond the crestal rift zone has a patchy cover of sediment which is obvious in bottom photographs, but was too thin and discontinuous to be resolved by our near-bottom 4-kHz profiler and side-scan sonars. Even on the floor of the summit graben, right at the center of spreading, some local patches of pahoehoe have been completely covered with sediment (e.g., Figure 8E). Although these lava flows are very smooth, and would be covered readily by a few millimeters of sediment, this burial is still anomalous in view of the frequency of lava eruptions at the axis of a fast-spreading rise, and the slow rate of pelagic deposition there. On our color photographs the sediment appears brownish, and we suggest that it may be metalliferous sediment precipitated from local hydrothermal emanations and accumulated, perhaps very rapidly, on the summit graben floor. A core from a marginal graben 6 km east of the axis (Core 6G; Figure 4, profile 3) recovered 10 cm of chocolate-colored oxidized metalliferous mud that contained a few foraminifers and overlaid fragments of basaltic glass chipped from the bedrock by the core catcher. (At least this short gravity core recovered more sample than was obtained at Site 426, about 3 km west of the axis.)

If most of the sediment of the axial ridge is a precipitate formed at hydrothermal vents, then its relative thickness may not be a good guide to the relative ages of lava flows, especially if the discharge is concentrated at large springs along the spreading axis, as it seems to be at some other spreading centers (Weiss et al., 1977). Although several local temperature anomalies (of 0.02 to 0.03 °C) were measured in bottom water over the crestal rift zone in the study area, further analysis is required to establish whether these were *bona-fide* hydrothermal plumes. We photographed none of the clusters of filter-feeding animals that have proved to be diagnostic of warm-water discharge elsewhere in the ocean (Lonsdale, 1977b).

Another factor complicating sediment distribution patterns on the axial ridge, and possibly hampering identification of hydrothermal plumes there, is a geologically effective bottom current. At Sites 1CM and 2CM, just east of the crestal rift zone (Figure 3) instruments moored 90 meters above the sea floor for 13 days recorded average current velocities of 9.1 cm/s, flowing south along the rise crest with top speeds of 20 cm/s. These currents are certainly fast enough to entrain fine-grained metalliferous and pelagic particles, to impede their deposition, and to cause differential deposition at lava surfaces of different hydrodynamic roughness.

On the rise flanks the increase in sediment thickness with distance from the axis is highly irregular (Figure 14), presumably because of the effects of off-axis volcanism, variable slope inclinations, and bottom-current redistribution. At about 10 km from the axis more than half of the lava is covered with sediment, and further down the flanks outcrops are restricted to fault scarps, and the steep sides of volcanic knobs and seamounts. Near-bottom 4-kHz profiles show much evidence of local current effects (e.g., impeded deposition near the feet and crests of scarps), and some photographs from the abyssal hill survey area show semiconsolidated sediments apparently exposed by erosion. A nearby instrument moored 90 meters above a horst 22 km east of the axis (Figure 13), recorded a 10-day average current velocity of 8.8 cm/s, flowing south parallel to the structural grain.

Two piston cores (Cores 14P and 19P) were collected from within the abyssal hill survey area, and one of them (5.5 m long) sampled the entire sedimentary section and a few chips of basalt glass. Preliminary analysis shows that most of the section is a greenish calcareous clay (with a 10-cm-thick, dark brown oxidized zone), overlying a 150-cm basal layer of yellow-brown, orange, and dark brown metalliferous mud.

UNUSUAL FEATURES OF THE 8°45′N EAST PACIFIC RISE

Structure and Petrology

It may be rash to discuss what is aberrant about this section of spreading center, when there is so little information about the characteristics of a "normal" fast-spreading rise. However, it is clear from surface-ship records (e.g., Figure 2) and a comparison of the near-bottom observations with those from the 3°25′S EPR (Lonsdale, 1977d), that the segment of axial ridge north of the Siqueiros transform fault has an atypical morphology and structure, and that its margins may be sites of unusually extensive off-axis eruptions. The rise is shallower than normal, and a chain of seamounts has grown close to the axis. Lonsdale and Spiess (1979) suggest that these phenomena may be explained by a development of Vogt's (1976) hypothesis: that the region is the site of a "ridge-centered hot spot," one of the deep mantle plumes supplying the elongate crustal magma chamber beneath the axial ridge. Effects of being above a direct mantle source for magma may include enlargement of the crustal magma chamber, with consequent broadening and shoaling of the axial ridge, and more voluminous volcanism, including off-axis volcanism.

The abundance of sheet lava, and other forms characteristic of relatively low-viscosity lava flows (flattened and knobby pillows), may result from unusually large fissure eruptions associated with an enlarged magma chamber. Sheet lavas are known at other fast and medium spreading ridges, but there extensive pahoehoe surfaces seem to form only on lakes of ponded lava, where convective heating by underlying molten lava could allow a glassy skin to remain plastic enough to be deformed into the observed rippled and coiled surfaces. Because of the small scale of fault-block relief that might form lava dams, there is little potential for lava ponding near the axis of a fast-spreading rise, except in the summit graben. The inferred high mobility of the thin sheet flows photographed on the gently inclined plateau surface seems best explained by postulating very high effusion rates (the principal factor influencing the length and mobility of subaerial lava flows; Walker, 1973).

As for unusual petrologic characteristics, there is no evidence that the fractionated tholeiites dredged and drilled in this region are significantly different from those sampled elsewhere on the EPR. The occurrences of alkalic and transitional basalts so close to the spreading axis (Batiza et al., 1977; Batiza and Johnson, this volume) are anomalous, and, on the basis of Schilling's (1973) hypothesis of magma sources for crustal accretion, they could be used to support the concept of a mantle plume centered on the rise crest just north of the Siqueiros transform fault.

The spreading axis of 8°45′N is within 1000 km of the Mexican coast, and the continental influence is felt in a shallower calcium carbonate compensation depth (Berger and Winterer, 1974) and a thinner layer of oxidized surface sediment (Lynn and Bonatti, 1965) than at most rise crests. The accumulation rate estimated from seismic profiler data on our near-bottom traverse is 16 m/m.y.; this is less than the 23 m/m.y. average rate at the Leg 54 Sites (Scientific Staff, 1977), which were preferentially at sites of maximum accumulation, and less than at most of the equatorial EPR, where there is rapid accumulation of calcareous ooze. Whether or not the unexpectedly fast longitudinal currents are typical of most of the EPR can only be established by further current meter work (similar velocities were measured at 3°25′S; Lonsdale, 1977d).

Implications for Deep-Sea Drilling

If the present unusual structure of the rise crest near 8°45′N has persisted for 1.5 to 3.5 million years, then the structure and stratigraphy of the young rise flank drilled on Leg 54 is not typical of a normal fast-spreading rise. Unfortunately, most of the important differences seem likely to increase the difficulty of bedrock coring. For example, the abundance of thin sheet flows, accumulating as stacked panes of volcanic glass (many of which have already been shattered into cubes by natural forces), and the pervasive fracturing of the rock and creation of extensive talus layers during collapse down the steep sides of the axial ridge, probably make the crust more difficult to core than on a rise of normal cross section, where an outer crust made mainly of pillow basalt subsides gradually as it spreads from the axis. The apparent abundance of off-axis volcanism near 9°N may make the volcanic and magnetic stratigraphy more complex, but it does provide an opportunity for late accumulation of relatively unfractured cooling units in local ponds, such as the massive basalt flows of Sites 422, 427, and 428.

CONCLUSIONS

The crest of the EPR between the Siqueiros transform fault and 9°N has fine-scale structures (e.g., a crestal rift zone, marginal horst-and-graben terrain) similar to other fast-spreading rises, but has a rather different overall structure. The top of the axial block is a 12- to 15-km-wide basalt plateau, and its steep sides include large outward-facing fault scarps. Plate-boundary volcanism, though concentrated as usual in axial fissure eruptions, also has some unusual features: there is a high ratio of sheet flows to pillow flows, probably because of high effusion rates, and some evidence for frequent and extensive off-axis eruption that includes seamount volcanism. Sediment accumulation on the axial ridge is limited to a thin veneer of predominantly metalliferous sediments; a bottom current may hamper pelagic deposition.

Abyssal hills on the young rise flanks are lineated horsts or groups of several fault blocks formed by extensional faulting in a zone about 15 to 20 km from the spreading axis. They are being buried in a blanket of calcareous clay.

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