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FIRST MANNED SUBMERSIBLE DIVES ON THE EAST PACIFIC RISE AT 21°N (PROJECT RITA): GENERAL RESULTS

CYAMEX SCIENTIFIC TEAM

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Abstract. A submersible study has been conducted in February – March 1978 at the axis of the East Pacific Rise near 21°N. The expedition CYAMEX, the first submersible program to be conducted on the East Pacific Rise, is part of the French-American-Mexican project RITA (Rivera – Tamayo), a 3-year study devoted to detailed geological and geophysical investigations of the East Pacific Rise Crest. On the basis of the 15 dives made by CYANA in the axial area of the Rise, a morphological and tectonic zonation can be established for this moderately-fast spreading center. A narrow, 0.6 to 1.2 km wide zone of extrusion (zone 1), dominated by young lava flows, is flanked by a highly fissured and faulted zone of extension (zone 2) with a width of 1 to 2 km. Further out, zone 3 is dominated by outward tilted blocks bounded by inward-facing fault scarps. Active or recent faults extend up to 12 km from the axis of extrusion of the East Pacific Rise. This represents the first determination from direct field evidence of the width of active tectonism associated with an accreting plate boundary. Massive sulfide deposits, made principally of zinc, copper and iron, were found close to the axis of the Rise. Other signs of the intense hydrothermal activity included the discovery of benthic fauna of giant size similar to that found at the axis of the Galapagos Rift. We emphasize the cyclic character of the volcanicity. The main characteristics of the geology of this segment of the East Pacific Rise can be explained by the thermal structure at depth below this moderately-fast spreading center. The geological observations are compatible with the existence of a shallow magma reservoir centered at the axis of the Rise with a half-width of the order of 10 km.

1. Introduction

During the past 6–7 years much interest has been shown in the detailed study of accreting plate boundaries and associated transform faults. The zones of accretion represent the locus of separation between lithospheric plates, and the interest is two fold. First, they are zones of intense tectonic and seismic activity and the oceanic crust is well exposed, allowing the details of crustal creation and mode of emplacement to be studied. This information is crucial, for example, in making realistic models of the magnetic pattern of ocean crust, which has played the key role in dating ocean basins. Second, welling-up of new material from the mantle at the axis of mid-ocean ridges provides a window into the mantle and enables geochemists to infer the nature of the solid mantle source, and of the differentiation processes which have been at play, from a study of the final eruptive products.

The world-encircling Mid-Oceanic Ridge system, although continuous in a tectonic sense (Heezen and Ewing, 1956), exhibits sharply different morphologies (Heezen and Menard, 1963). The frequency distribution of separation or opening rates at presently active mid-oceanic ridges (Lonsdale, 1977) suggests a division into slow (e.g. FAMOUS; < 4 cm/yr), moderately fast (e.g. this paper, Galapagos; 4–8 cm/yr), fast (e.g. East Pacific Rise, between Pacific and Nazca plates; > 12 cm/y). Ridge segments with rates of crustal growth of less than 4 cm/yr (slow ridges) are characterized by a 1.5 to 2 km deep axial rift valley (Heezen, 1959; Hill, 1960), including in the deepest part an inner floor, and flanked by rugged, subparallel topographic lineaments (ridges and valleys) that create an across-strike relief varying from several hundred to a thousand meters (Heezen *et al.*, 1959). In contrast, the crests of Ridge segments with rates of accretion greater than 4 cm/yr do not have a deep rift valley and can be described to a first approximation as broad swells disrupted by subparallel ridges and valleys representing depth differences of only several tens to a few hundreds of meters (Menard, 1960; Larson, 1971; Klitgord and Mudie, 1974). When they are examined in more detail, the more rapidly accreting ridge segments are found to include two fairly distinct styles of crestal terrain. The axial portions of ridge segments with rates of accretion between 4 cm/yr and 8 cm/yr (moderately fast ridges) are typically marked by a subtle but distinct axial inner floor that is flanked by inward-facing escarpments with heights of approximately 100 m. When rates of opening exceed 8 cm/yr (fast ridges), the morphotectonic expression of plate separation in the form of an axial inner floor is completely lost, and the ridge axis is characterized by a topographic high that rises approximately 100 to 200 m above the surrounding terrain (Anderson and Noltimier, 1973; Lonsdale, 1977). The basic morphotectonic fabric developed along the Mid-Oceanic Ridge axis is a temporally and spatially complex arrangement of constructional volcanic features and of fault-generated scarps. Changes in this fabric that accompany changes in spreading rate must reflect fundamental differences in the processes of accretion. The differences also probably reflect important differences in the deeper structure of the accreting plate boundary (for example thickness of the lithosphere at the axis, size and permanence of a magma chamber). Some of the inferences that can be made from detailed studies of the morphology of Ridge segments are the least ambiguous of the constraints that can be placed on the interpretation of volcanism and tectonics at accreting plate margins. It is therefore of critical interest to document rigorously the detailed structure of the Mid-Oceanic Ridge crest over a wide range of spreading rates.

2. Previous Work

The investigation of the morphology of the Mid-Oceanic Ridge has, over the years, evolved from reconnaissance studies carried out almost exclusively from surface ships equipped with wide-beam echo sounders and conventional geophysical instruments to more intensive and sophisticated studies focusing on relatively small areas of the sea floor. For this work, use has been made of high-resolution tools covering a wide range of scales and geared to different purposes, namely side-looking sonar systems, notably GLORIA (Rusby, 1970), multi-narrow beam echo-sounders (Glenn, 1970) of which the civilian version is SEABEAM, deep-towed vehicles such as DEEP-TOW (Spiess *et al.*, 1976) and ANGUS (Phillips *et al.*, 1979), and submersibles. The first major application of the high-resolution approach towards unravelling the complexities of tectonic and volcanic activity along the Mid-Oceanic Ridge was the integrated investigation of a slowly accreting plate boundary (French-American Mid-Ocean Undersea Study) that was launched in 1973–1974 (Heirtzler and Le Pichon, 1974). This project led to a detailed description of a small segment of the Mid-Atlantic Ridge South-west of the Azores (e.g. Needham and Francheteau, 1974; Bellaiche *et al.*, 1974; Arcyana, 1975; Ballard *et al.*, 1975; Ballard and Van Andel, 1977) and of an adjacent, slowly slipping transform fault (Detrick *et al.*, 1973; Arcyana, 1975; Choukroune *et al.*, 1978). Project RITA (RIVERA-TAMAYO) was conceived, in 1978–1979, as a detailed investigation of a crestal portion of the East Pacific Rise including a moderately fast-slipping transform fault. The selected area, at 21°N, was chosen partly for logistical reasons and partly because deep-tow studies had already laid the ground-work for a submersible study (Larson *et al.*, 1968; Normark, 1976). The Tamayo Transform, located at the mouth of the Gulf of California, and known to have a slip rate of 6 cm/yr, was selected as the site of the transform investigations (Figure 1).

The first phase of the RITA project involved new deep-tow studies of the East Pacific Rise crest at 21°N (Normark *et al.*, in prep.) and at two sites within the Tamayo Transform at 23°N (Macdonald *et al.*, 1979). These were followed in 1978 by the CYAMEX expedition, which conducted field studies from the submersible CYANA at 21°N and within the Tamayo Transform (CYAMEX 1978). Further dives in both these areas were made in 1979 during the RISE (RIVERA submersible experiments) expedition, and during a follow-up phase later in the same year. The purpose of this paper is to present the general results of the studies that were carried out at 21°N during the CYAMEX expedition. The results of the CYAMEX dives in the Tamayo Transform Fault and the details of the petrology of the basaltic rocks sampled by CYANA are reported elsewhere (CYAMEX and Pastouret, 1980; Juteau *et al.*, 1980).

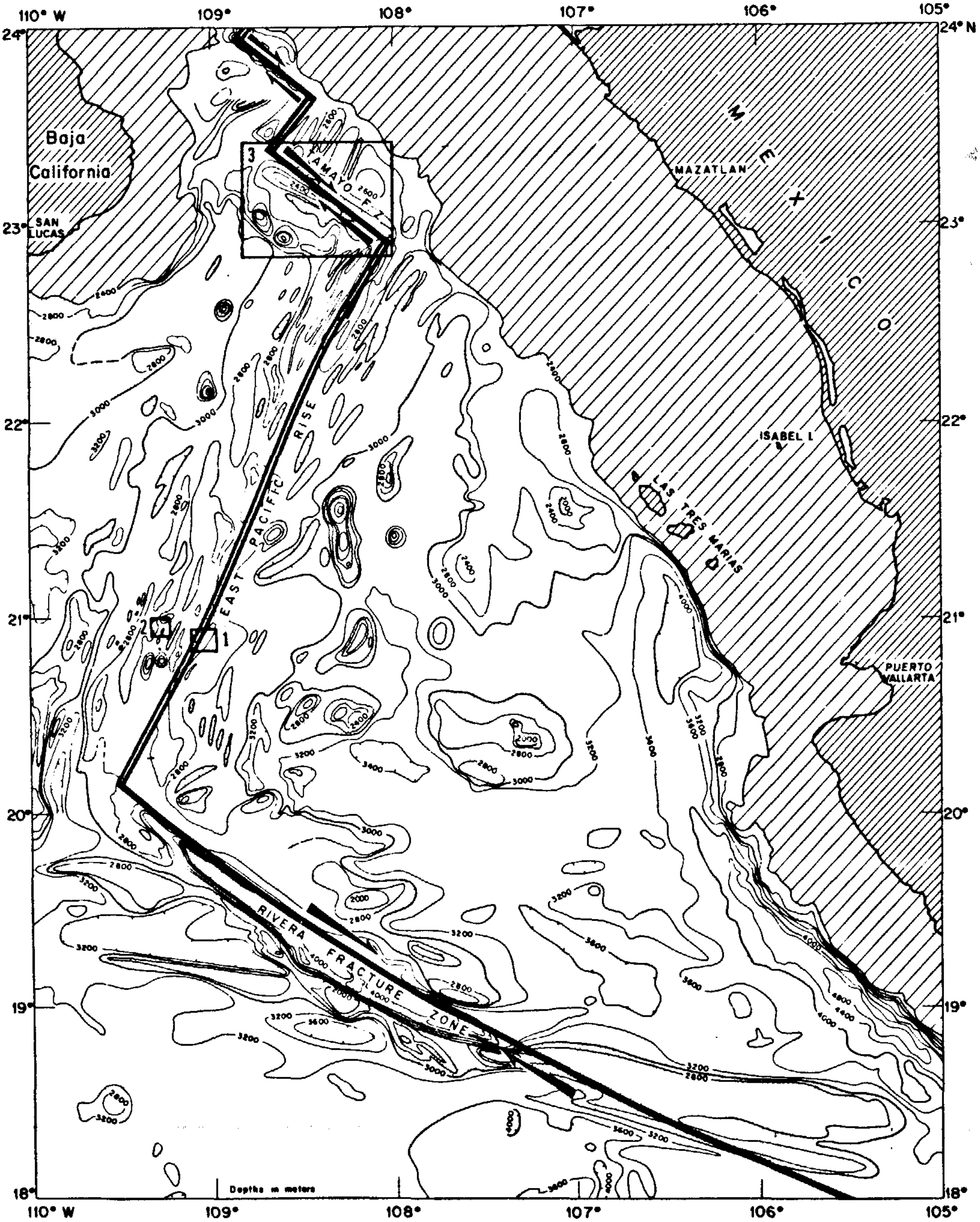

Fig. 1. Setting of the CYAMEX diving program in the axial region of the East Pacific Rise at 21°N. Bathymetric contours in meters.

3. Regional Setting

From the mouth of the Gulf of California at 23°N, where the East Pacific Rise is offset in a left-lateral sense by the Tamayo Transform Fault (Larson, 1972; Moore, 1973), although locally the strike can be N38°E, the Rise crest trends southwards with a strike of N25°E (Figure 1; Larson, 1972; Normark, 1976) and is uninterrupted by a major transform for approximately 300 km until at 20°N the Rise is offset in a left-lateral sense by the Rivera Transform Fault. The recent kinematic history of this portion of the East Pacific Rise has been quite simple. Analysis of the magnetic anomaly pattern indicates that for the last 4 million years the separation rate between the Pacific and Rivera plates has been relatively constant (6,2 cm/yr) and that spreading has been symmetric (Larson *et al.*, 1968; Moore and Buffington, 1968; Klitgord *et al.*, 1972).

The morphology of the East Pacific Rise, between the Tamayo and Rivera transform faults, is typical of the morphology expressed by intermediate-rate (4–8 cm/yr) spreading ridge segments. An axial inner floor is flanked by generally 100 m-high inward-facing escarpments. Abyssal hills with heights of a few hundred meters or less, linear and parallel with the Rise axis, dominate the morphologic character of the flanks of the Rise, although several large isolated seamounts have been mapped. Pelagic sediments thicken continuously with distance away from the Rise axis until proximal to the Baja peninsula and the Mexican continental margin, accumulations of turbidite sediments obscure the pelagic record and blanket the Rise flanks.

4. Review of Deep Tow Results

The CYAMEX study area at 21°N is centered on the axis of the East Pacific Rise (Figure 1) and has been the focus of several expeditions that utilized bottom-moored acoustic transponders and the instrument Deep-Tow, developed at Scripps Institution of Oceanography (Spiess *et al.*, 1976). In 1968, Larson (1971) conducted the first survey (TIPTOW), which extended from the Rise axis to the edge of the Brunhes normal magnetic polarity event of the west flank. A second survey (OCONOSTOTOW) extended this western profile and obtained deep-tow lines out to 125 km from the Rise axis on tracks normal to the axis (Larson and Spiess, 1969; Klitgord, 1976). These field studies defined the structure, sediment distribution and topography of the crestal zone and obtained near-bottom magnetic-field profiles necessary for improved modelling of magnetic anomaly data. Two additional deep-tow expeditions, COCOTOW – Leg IA in 1974 (Normark, 1976) and F. DRAKE – Leg VI in 1977, returned to the Rise axis at 21°N and delineated the structures developed along and within the axial extrusion zone and the flanking tectonic provinces. These new data, over 9,700 narrow-beam deeptow soundings, provided the constraints needed to compile the bathymetric map used during the CYAMEX expedition (Normark *et al.*, 1978; Figures 2 and 3).

The crestal area of the East Pacific Rise near 21°N is marked by a narrow, 5-km wide, axial block whose edges are elevated about 80 m above the adjacent sea-floor (Normark, 1976). Based upon an interpolation of the magnetic time scale, the rocks that comprise the axial block are less than approximately 100,000 yrs old. The axis of the block roughly coincides with an axis of symmetry in the bathymetry and in the thickness of accumulated sediment (Normark, 1976). The local bathymetric relief is much greater in the central part of the block (inner floor) than on the flanks for a distance of 5 km to either side. The margins of the inner floor are delineated by inward-facing escarpments having about 80 m of relief; these scarps form the inner margin of lips whose outer margins are sediment-covered and slope gently away from the inner floor.

Three distinct morphotectonic regions characterize the axial block of the Rise which is comprised of the inner floor and flanking terrain (Normark, 1976). An innermost region, 2 to 2.5 km wide, is typified by numerous isolated topographic highs that stand 20 to 90 m above the surrounding terrain. Many of these highs are elongate parallel to the regional trend of the Rise. These are few major scarps and most of the relief is a product of volcanic construction. Photographic data indicate that the area is dominated by volcanic extrusives, mostly pillow lavas, and that smaller patches of fluid pahoehoe-like flows and collapsed lava lakes lie between the pillow edifices. The volcanic constructional terrain is disrupted occasionally by fissures or small-throw faults. A zone of most recent volcanism, approximately one kilometer wide, is suggested by photographic data that show continuous outcrops of extrusive lavas devoid of sediment.

The central area, comprised of relatively undisrupted volcanic constructional features, is flanked by faulted and fissured terrain, 0.5 to 1 km wide, that creates horsts and graben. The relief on the faults of this second morphotectonic area varies from a few meters to a few tens of meters. With increasing distance from the axial volcanic zone, the number of faults decreases but the offset on a given fault increases, and faults may be traced for greater distances along strike. The size of talus accumulations at the base of faults and the thickness of pelagic sediment also increase continuously, and these observations serve to identify the third morphotectonic region as one marked by a small number of faults, each with hundreds of meters of displacement. The distinctive morphology of the flanking region clearly indicates that, with time, the volcanic constructional basement is disrupted by extensional tectonics (Normark, 1976).

During the COCOTOW survey the temperature of the seawater was monitored on traverses of the axial block. The elevation of the instrument package ranged between 30 and 60 m above the sea floor but the recognition of subtle temperature anomalies ($3-5\times10^{-2}$°C) suggested that hydrothermal vents or vent systems are active somewhere in this area (Crane and Normark, 1977). Later work, during F. DRAKE, with a CTD unit (measuring conductivity, temperature,

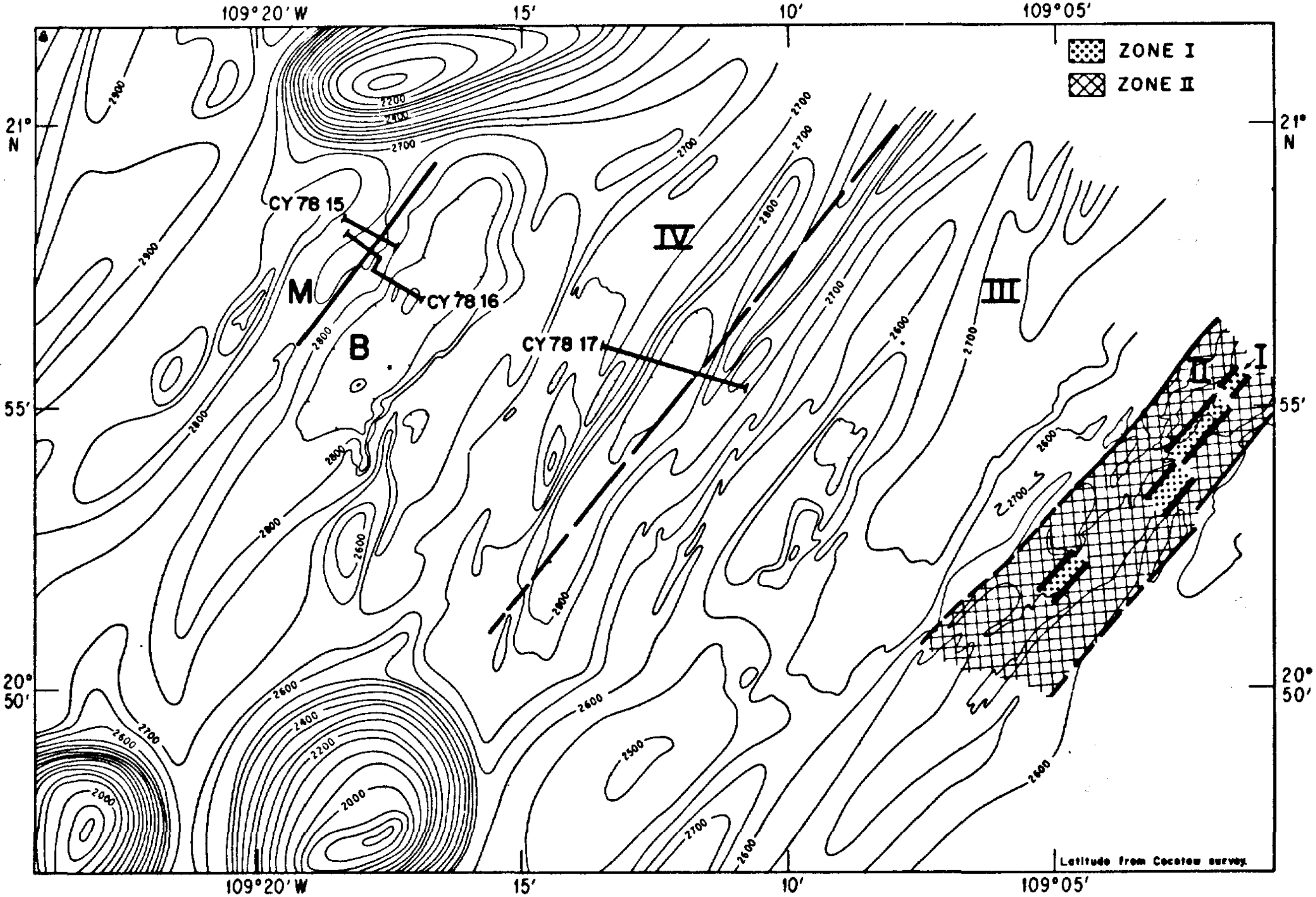

Fig. 2. Bathymetry of the western axial limb of the East Pacific Rise at 21°N incorporating the results of Larson (1970), Normark (1976), and MacDonald (personal communication). Contour interval 50 meters. The location of the 4 major tectonic zones identified from the dives is marked. The Figure also shows the location of dive CY 78–17 about 12 km from the axis and of dives CY 78–15 and 16 straddling the Brunhes (B)-Matuyama (M) boundary as inferred from deep-tow data by MacDonald (personal communication).

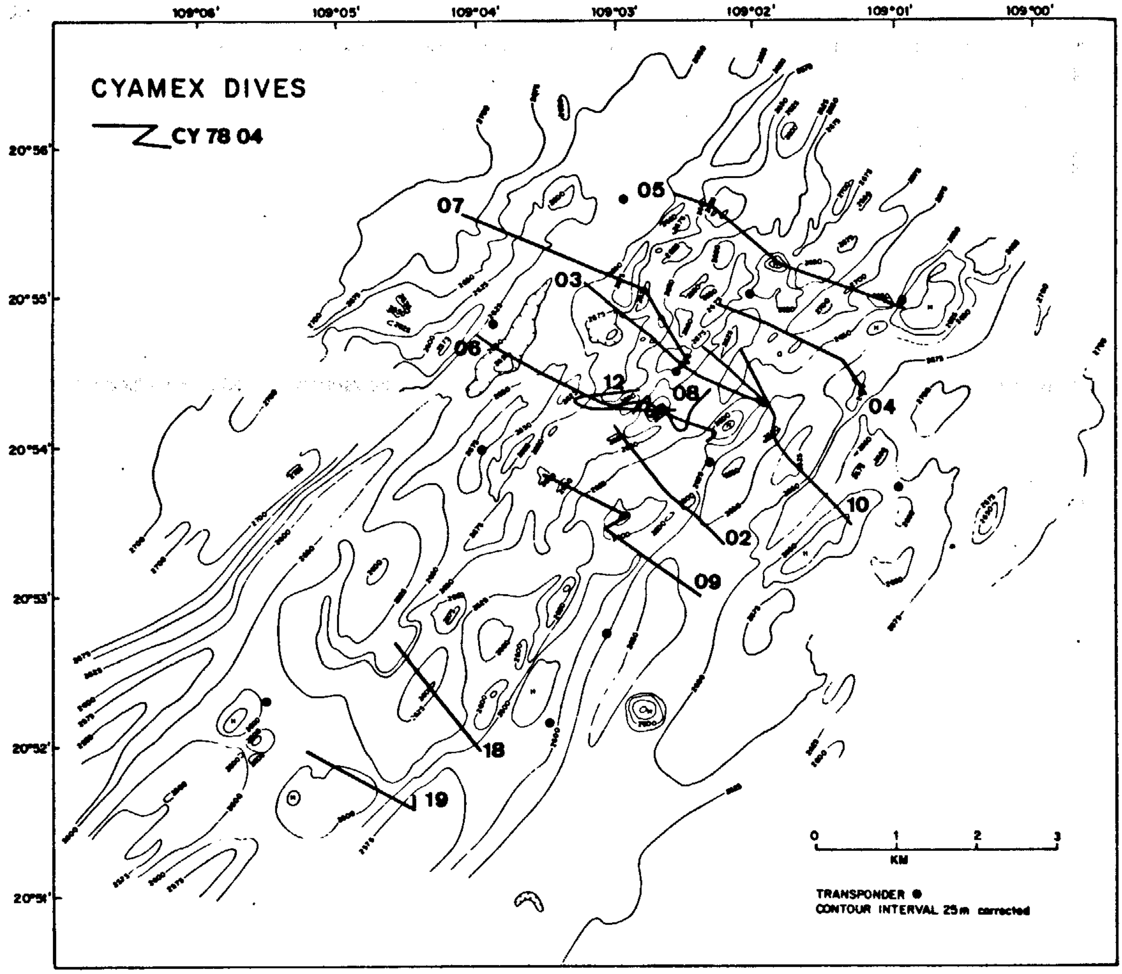

Fig. 3. Bathymetry of the axial zone of the RITA area (East Pacific Rise 21°N) from Normark *et al.* (1978). Contour interval 25 meters. The location of the 12 CYANA dives at the axis is shown.

depth) and a geochemical sampling system demonstrated that hydrothermal anomalies were confined to the axial volcanic region. Direct photographic evidence of hydrothermal venting (i.e., hydrothermal deposits, large benthic fauna; Corliss *et al.*, 1979), however, was not obtained on either of these surveys.

5. CYAMEX Diving Program

The CYAMEX program at 21°N took place in February and March of 1978. The dives were made with the French submersible CYANA, which can be positioned on the bottom with an accuracy, relative to the THOMSON-CSF transponder net used during the program, of a few meters. The dive traverses were linked to the deep-tow bathymetry by positioning the transponder net used by CYANA with respect to one of the transponders left from the F. DRAKE deep-tow survey. CYANA, operated from the mother ship NADIR, is an 8.5 ton diving saucer with a maximum working depth of 3 km. One pilot, one scientific observer, and one navigator occupy a 2 m outside-diameter sphere made of VASCO-JET 90 steel. The main scientific equipment includes a remote-control arm and a retractable sample basket, one external 35 mm Benthos camera with 30 m of color film, one electronic flash, one low-light-level television camera with continuous image and voice recording of the dive on videotapes, and one digital data logger with time, depth, altitude, heading, and water temperature. A stable clock provides time, a pressure gauge with a one decibar resolution provides depth, a digital high-resolution sonar gives altitude, a magnetometer gives heading, and a thermocouple gives temperature. The equipment also includes a panoramic sonar with images recorded on still photos from a CRT display, and a 16 mm Beaulieu movie camera used for subjects of special interest. The data recorded on the digital data logger is also displayed on both the 35 mm still color photos and on the television videotape.

A total of 15 dives were made in the area (Figures 2 and 3), resulting in a sea-floor coverage of 39 km during 69 hrs on the sea floor. Along the dive traverses, 37 stations were occupied and 48 samples were obtained. Twelve of the dives, ranging in length from 2 to 4 km, were positioned along a 9 km-long segment of the crestal portion of the East Pacific Rise. These dives were oriented to provide 8 geologic sections, 2 to 3 km long, across accretion-related structures, and to straddle the axis of the Rise. Three among these dives (dives 7, 3, 10; Figure 3) were positioned sufficiently close together so that they link to provide a composite 8 km-long traverse across the axis of the Rise. The goal of the latter dives was to establish the nature of the volcanic morphology created along the zone of accretion and the pattern of volcanism and tectonics in the axial region of the East Pacific Rise. Three other dives were located at some distance to the west of the axis of the Rise: One of these was positioned at a distance of 10 km and traversed 4 km in a northwesterly direction; the other two dives were located in close proximity to each other at a distance of roughly 20 km from the Rise crest and traversed across the Brunhes-Matuma reversal boundary for a distance of four kilometers. These three dives help establish how the morphotectonic fabric created and modified at the Rise axis evolves with increasing age. They also define the western boundary of the region affected by active faulting.

Based upon the observations made during the 15 CYANA dives, four zones may be defined that exhibit distinctive morphologic and structural properties. This classification supports, and refines and expands the morphotectonic zonation that was based on the deep-tow survey data as proposed by Normark (1976). The axial zone of extrusion, Zone 1, 0.5 to 1 km in width, is a product of recent volcanic processes and is essentially unmodified by extensional tectonics. Zone 2 is approximately 1 to 2 km wide and represents an interval within which the volcanic terrain experiences active and pervasive extension resulting in the production of horst and graben relief. A well-defined tectonic polarity characterizes Zone 3. In this province, linear ridges and troughs with the approximate dimensions of abyssal hills begin to develop and these are assymetric in profile, with steep active faults characterizing the inward-facing flanks. At a distance of 12 km or more from the ridge axis, no signs of active tectonism are recognized; this is the boundary of the tectonically quiescent Zone 4.

6. Axial Zone of Extrusion (Zone 1)

6.1. Morphology

Observations from CYANA enhanced and refined the morphologic zonation of the East Pacific Rise crest based on the deep-tow data. Most of the 50 to 80 m high, irregularly shaped ridges in the central zone are shown to be individual volcanic centers composed of sequences of pillow lavas. Down-slope elongated pillows predominate on the flanks of the ridges, but steep-fronted pillowed flows are much less common than in the FAMOUS area. Fault scarps within the central zone are observed across the northern edge of the work area only.

The width of Zone 1 is limited (by definition) to the central portion of the Rise crest without (surface) fissuring and faulting. The width ranges from 0.6 to 1.2 km, generally being wider to the south. The zone can be divided into two parts: the youngest extrusion area, recognized by glassy pillows, abundant glass buds and no sediment (1A), and the older terrain where pillows are less glassy, prominent buds have been broken or shed, and pillows are dusted with appreciable sediment (1B). The central zone was recognized on all dives across the axis, but the position of the zone changes along strike (Figure 4). It is approximately centered in the northern part of the area but is displaced to the east in the area of dives CY–78–02 and – 09. Further south, in the F. DRAKE extension of the survey area, the youngest zone is displaced to the west side (dives CY–78–18 and –19).

The central, or extrusion, zone as described above is substantially narrower than the extrusion zone described from the deep-tow data (0.6 to 1.2 km contrasted with 2 to 2.5 km). This difference results from our exclusion of faulted terrain from the central zone. The boundary based on the deep-tow observations, however, includes all terrain with an irregular, volcanic morphology of hills and ridges; only where the topography becomes linear and shows distinct horst and graben structures is it excluded from the central zone. The central, unfaulted zone is the same width or narrower than the discontinuous central high (Needham and Francheteau, 1974; Moore *et al.*, 1974) of

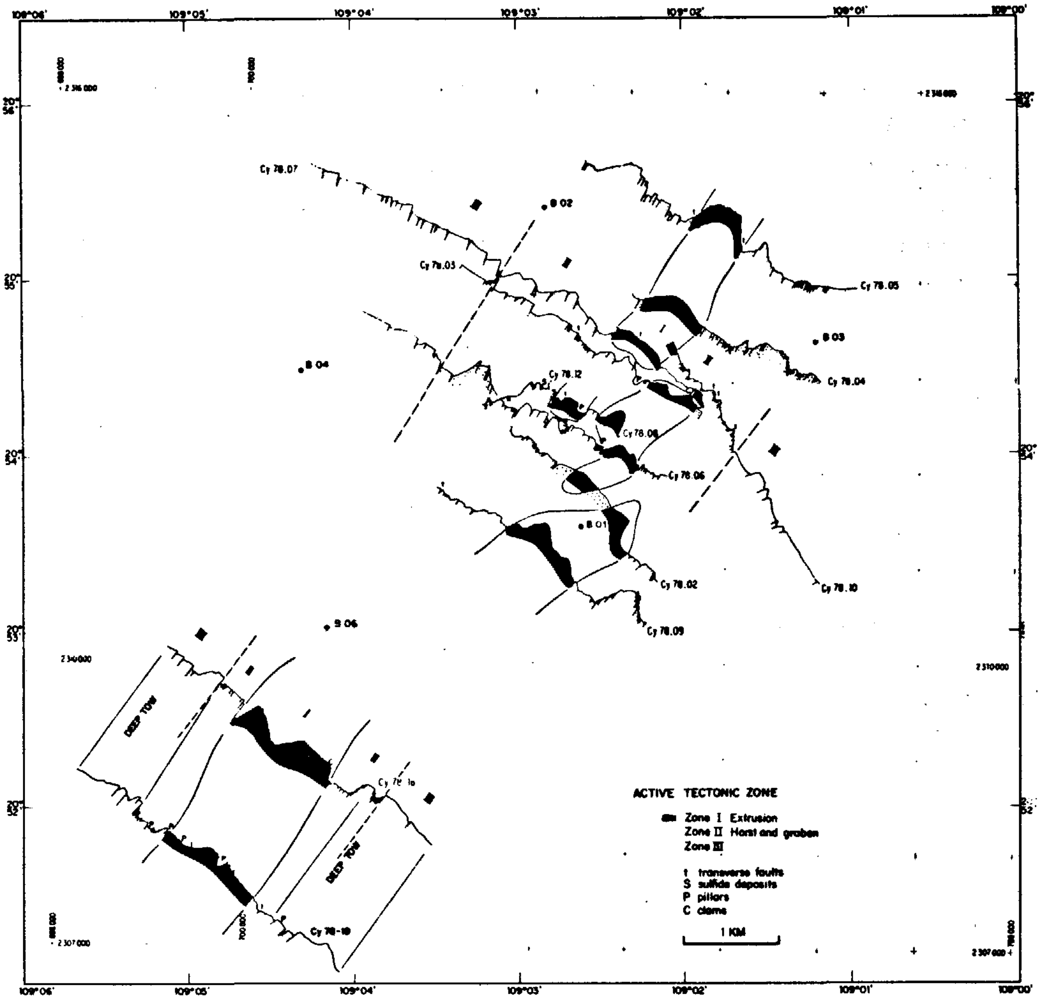

Fig. 4. CYANA dive bathymetric profiles with surface distribution of structural zones in the axial region of the East Pacific Rise. The location of faults transverse to the general ridge direction, of massive sulfide deposits, of lava pillars and of clam beds is identified in the figure.

the slower-spreading Mid-Atlantic Ridge in the FAMOUS area, even though the spreading rate of the East Pacific is three times that of the Mid-Atlantic Ridge.

Near the western boundary of the extrusion zone, a large lava 'lake' was studied on several dives (Francheteau *et al.*, 1979). Similar features have been observed in the Galapagos Rift (Ballard *et al.*, 1979). Over an area approximately 200 m long and 50 m across, a low-relief, lobate surface of pahoehoe-like lavas onlap elongate pillows on the slopes of adjacent volcanic ridges. Much of the center of the lave lake is occupied by a large pit with steep walls that are 6 m to 15 m high. Often near the edges, but also within the pits, tall (10 m), narrow (1/2 m or less) pillars of very irregular shape (see plate 2) are common, and some pillars form roof supports for sections of lobate-flow lavas that bridge across to the lava surface at the edge of the pit. The height of the pillar is similar to the depth of the pit or to the adjacent wall height.

6.2. Flow types

The lava flows take two different forms in the axial extrusion zone: pillow flows and sheet flows. The axial zone can be subdivided on the basis of the relative proportion of these forms and of associated morphological features.

Sub-zone 1A is the youngest and freshest extrusion area, devoid of any sediment dusting, and consisting of constructional volcanic hills (30 to 80 m high) entirely made up of pillow lava flows. On the flanks of the volcanic edifices, lava flows are made of elongate pillow-lavas ornamented with abundant glass buds and horns up to 30 cm long (Plate 1A). This is the only area where summital vertical glass buds are preserved. Brilliant glass cascades are common, draping the steepest flow-slopes (60° or more, Plate 1B). More gentle terrain is associated with sub-spherical bulbous pillows. Ornamentation typical of fresh pillow surfaces, such as striations, corrugations and breadcrust structures (Ballard and Moore, 1977) is widespread. Very little flow rubble has been seen at the foot of the slope. On the summits of the volcanic ridges, both bulbous and flattened pillows are widespread. Many of them are collapsed hollow pillows (Plate 1C) organized in linear groups along strike, indicating the location of the hidden feeder tubes (Ballard and Moore, 1977). Red-ochre to orange stainings appear frequently over broad areas at the base of the pillows, resulting in a less brilliant glass surface. On exposed fracture edges, amorphous silica develops white staining on scars (broken buds for instance). Based on the documented association of distinct bottom fauna with the venting of warm water along the Galapagos Rift, (Corliss *et al.*, 1979), clear evidence of recent hydrothermal activity in Zone 1 is given by the occurence of colonies of dead giant clams (family VESICOMYIDAE; dive CY 78–18; Plate 3A). The clam beds lie on a field of dark matt-finish pillows with a soot-like cover of hydrothermal deposits thought to be manganese. The narrow (1–2 m) clam beds are elongated parallel to the strike of the ridge (040°) over a distance of 10 to 50 m.

Sub-zone 1B, though quite devoid of faulting and fissuring, is made up of somewhat older lavas. Pillows are less brilliant, summital and prominent buds have been broken. The terrain is dusted with some sediments, and the first appearance of bottom organisms is observed. Glass cascades are still common on steep slopes. The area includes some sheet flows and fossil lava lakes. Sheet flow units consist of sequences of several thin individual sheet flows, several cm to 30 cm thick, commonly displaying a flat and glassy (brilliant) top surface that, to varying degrees, is folded, rippled, or whorly (Plate 2A) according to the classification of Ballard and Moore (1977).

Areas of low-relief with thick sheet-flow lavas, with lobate surfaces and collapse holes and interpreted as fossil lava lakes, have been discovered in several locations near the transition between Zones 1 and 2. The lakes always occur in topographic lows, and cover small surfaces of several km^2. As they collapsed after emptying and formed pits, their internal structure was exposed.

Their total thickness ranges between 10 and 15 m. The lateral walls and the floor of the lakes are entirely made of pre-existing pillow lavas. Tens (hundreds?) of more or less cylindrical pillars, 10–15 m high and 1–5 m wide, stand up among abundant angular and coarse rubble, forming a spectacular 'ruiniform' landscape (Plate 2B). Both the pillars and pit walls exhibit a very regular layering, with alternating black (glassy) and grey (basaltic) layers (Plate 2C) a few centimetres thick. The examination of broken pillar samples have shown that this is a pseudo-layering, restricted to the outer surface of the pillars. The layering may record successive chilling episodes of the lava lake surface during emptying of the lake, indicating that the pillars were formed before emptying of the lake. Observation of pillars, including one pillar broken by CYANA, reveals that at least some of them are hollow, and are made up of a fine grained and massive basalt. The internal margin seems to be glassy. When entirely preserved, the pillars are shaped like a wrinkled funnel at the top (Plate 2C). In many places, especially near the margins of the lake, the roof of the lava lake has been preserved, bridging several pillars (Plate 2B). It is 30–40 cm thick, with a black and brilliant glassy top surface, wrinkled or typically lobate. The lateral contact of the lava lake against the pillows was observed during dives 8 and 12.

During dive 8, the contact of the top surface of the lava lake onlapped a steep volcanic constructional slope of pillow flows. During dive 19, the lateral contact of the lava lake is defined by a chilled margin on a near-vertical normal fault scarp exhibiting truncated pillow lavas (Plate 2D). After emptying and collapse of the lava lake roof, the chilled margin, made of fine grained, massive basalt, remained as a vertical layer, 30–50 cm thick. The margin also displays a pseudo-layering on its internal face, identical to that of the pillars. The layer is separated from the pillowed fault surface by a void of 10–20 cm, probably as a result of pulling away after cooling. Ochre-orange stainings are widespread along pillar surfaces.

6.3. Structure

The axial extrusion zone is defined by the degree of freshness of the lavas and the almost total absence of sediment. The major structural characteristic is the presence of open fissures or gjas up to 3–4 m wide without any vertical relative displacement (Plate 1D). Commonly, the open fissures are parallel to the strike of the East Pacific Rise (about 040°) but transverse fissures have been observed.

In the north, the axial extrusion zone is very narrow (400 m; dive CY–78–05; Figure 4), and is bounded by outward-facing, near-vertical normal faults. Further south (dive CY–78–06), the faults that border the axial volcanic ridge are part of small graben that have been filled by fossil lava lakes (Figure 5). Finally, in the southernmost region explored by CYANA (CY–78–18 and – 19), the extrusion zone can include an axially located lava lake (CY–78–19) or be bordered by an inward-facing normal fault of Zone 2 (western portion of CY–78–18; Figure 4).

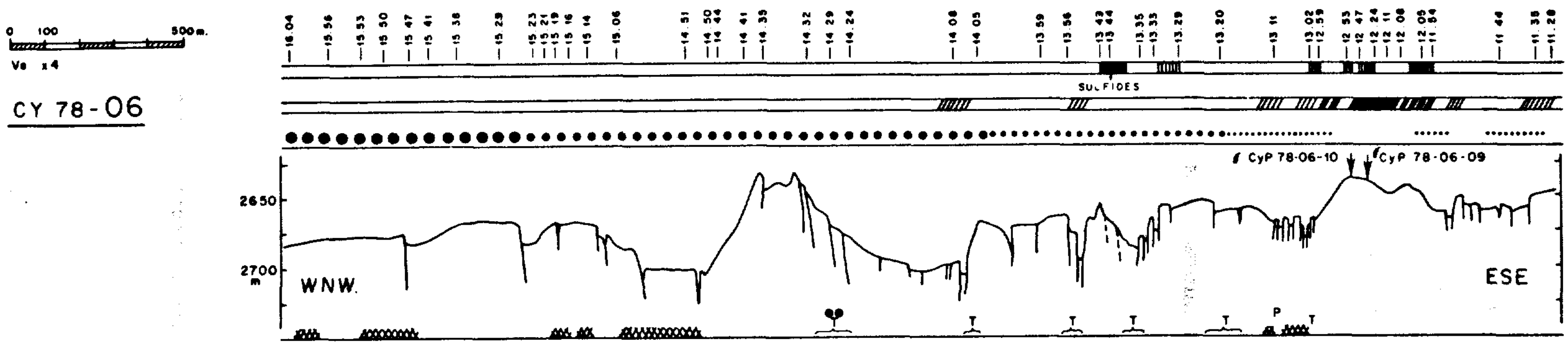

Fig. 5. Geologic profile along dive track CY 78–06 (see Figure 3 for location) derived from dive data and observations. Vertical exaggeration ×4. The top line gives time. The second line portrays the existence of signs of hydrothermal activity (vertical stripes) including sulfide deposits (black). The third line notes the presence of fresh glass and buds in the most recent extrusive area (black) and the more altered glass (inclined stripes) in outer zones. The line with dots above the profile represents the increasing thickness of the sediments with age. The symbols underneath the profile represent talus (T), pillars (P) and sheet flows (crossed area). The sample numbers and their location is drawn on the profile.

Plate 1. Crestal area

1A. Pillow-lavas of Zone 1 (extrusion zone) on the steep slopes of axial constructional volcanic hills (30–80 m high). Lava flows are comprised of elongate, black and brilliant pillow-lavas ornamented with abundant glass buds. Notice the lack of sediments and the existence of secondary pillow flows escaping downslope from fissured primary pillow flows (dive –07, 12 h 49 mn 20 s.).

1B. Pillow-lavas of Zone 1 (extrusion zone). Brilliant glass fall, ornamented with abundant glass buds, draping one of the steepest natural front slopes on the flank of an axial volcanic hill. White area is a scar stained by a thin layer of amorphous silica (dive –09, 12 h 53 mn).

1C. Pillow-lavas of Zone 1 (extrusion zone). Sediment-free summit of an axial volcanic hill, showing a typical bulbous and collapsed hollow pillow. Notice the white silica staining on the scar (dive –10, 9 h 38 mn 10 s.).

1D. Open fissures or 'gja' of Zone 2 (horst and graben zone), developed in a sheet flow unit, parallel to the EPR axis (dive –18, 12 h 19 mn 50 s.).

Plate 2. Crestal area

2A. Sediment-free sheet flow of Zone 1, with a strongly folded surface ('pencil' folds) (dive –09, 15 h 01 mn).

2B. Near the margin of the lake remnants of the roof bridging the pillar summit are visible. In foreground, an isolated pseudo-stratified pillar. The lobate and collapsed aspect of the glassy lava lake surface is visible (upper left) (dive –06, 13 h 25 mn 30 s.).

2C. Collapsed lava lakes and associated pillars (Zone 1). Detail of a pillar summit, showing the very regular rhythmic layering, with alternating dark (glassy) salient layers, and ochre staining basaltic pseudo-layers. Notice the funnel shape of the pillar top (dive –19, 13 h 33 mn).

2D. Collapsed lava lakes and associated pillars (Zone 1). Lateral chilled contact margin of a lava lake against faulted pillow lava flows. This vertical wall, 30–50 cm thick, is separated from the pillowed fault surface by a void of 10–20 cm. The wall displays, on its internal face, a pseudo-layering identical to that of the pillars. Some ochre staining is visible on the truncated pillows (dive –19, 13 h 01 mn 10 s.).

Plate 3. Crestal area

3A. Hydrothermal activity observed in the outer edge of the southern portion of Zone 1. Fossil colonies of dead giant clams collected around fossil hot springs. Notice the advanced stage of dissolution of the shells (dive –18, 13 h 11 mn 30 s).

3B. Hydrothermal activity in Zone 2. Pronounced ochre-orange staining at the base of pillow lavas (Fe oxides/hydroxides) (dive –06, 12 h 36 mn 30 sec.).

3C. Hydrothermal activity in Zone 2. Ochre-orange staining (Fe oxides/hydroxides) on the scarp of a normal fault that exposes truncated pillow-lavas (dive –19, 13 h 14 mn 10 s.).

3D. Hydrothermal activity in Zone 2. Sulfide deposits. Extremely irregular vertical and porous edifices several meters high, made of travertine-like incrustations that consist mainly of polymetallic sulfides. The edifices are aligned on fractures parallel to the EPR axis (dive 08, 12 h 21 mn 30 s.).

7. Active Extension: Horst and Graben Terrain (Zone 2)

7.1. Morphology and Structure

With increasing distance from the axis of recent volcanism the volcanic constructional terrain is subjected to increasingly more apparent extension that dismembers the constructional features and creates fault-bounded ridges and troughs(horsts and graben). In this region, called zone 2, we observed numerous near-vertical faults that face both inward and outward with respect to the Rise axis, have relief of a few tens of meters, and that strike, in general, parallel with the regional trend of the Rise. The width of Zone 2 varies markedly along its length, from 2 km at the northern end of the survey area to approximately 300 m at its southern end. The tectonic style of Zone 2 also varies significantly along its length, and, although the characteristic features of Zone 2 flank the axial Zone 1 along the entire length of the survey area, these features are not symmetrical with respect to the axial zone. For example, at the northern end of the survey area, it is apparent (CYANA traverses CY 78–04, –05, and –10; Figures 4, 7 and 10) that the density of faulting and the throw on some faults on the east flank of the Rise axis is very large, and that these faults obliterate the volcanic, constructional features. In contrast, examination of CYANA profiles CY 78–03, located on the opposite side of the Rise axis (Figures 4, 6 and 10), indicates that Zone 2 here is not severely tectonized: volcanic constructional edifices are still intact, the number of faults is fewer and the throw of these faults is less. On neither side of the Rise axis anywhere in the survey area, however, can the faults of Zone 2 be traced along strike for more than a few hundred meters.

Within Zone 2, processes other than extensional tectonics are operating to modify the character of the volcanic constructional basement, and the effects of these processes are progressive and cumulative with increasing distance from the Rise axis. The thickness of pelagic sediment increases from a few millimeters to a few decimeters at distances of 2 km from the axis of the central volcanic zone. An increasing density of benthic life accompanies this increase in thickness of sediment. At the distal margins of Zone 2, pillow lavas are still readily apparent, and the diverse range of pillow lava morphologies recognized within the extrusive axial zone (i.e., elongate, bulbous, flattened) still characterizes the volcanic edifices. The exteriors of the pillow lavas, however progressively lose their delicate ornamentation. The brilliance of the glassy pillows decays in time, and glass rinds spall off to create hyaloclastic accumulations in the interstices between pillows; palagonite appears with the low temperature alteration of the glass, and manganese incrustations envelope exposed rocks. The near-horizontal surfaces of the lava lakes become quickly covered by the pelagic rain and the distinctive surface morphology of the lava flows (whorly structures) is rapidly lost. Talus ramps develop and grow rapidly larger with distance from the axis; the continued addition of material to the ramps throughout Zone 2 is

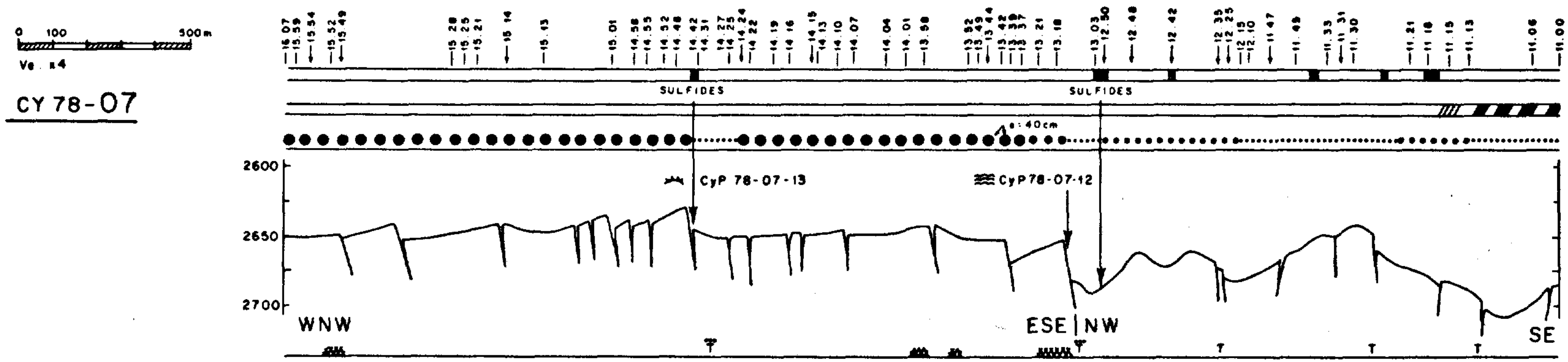

Fig. 6. Geologic profile along dive track CY 78–07 (see Figure 3 for location) derived from dive data and observations. VE × 4. Symbols same as in figure 5.

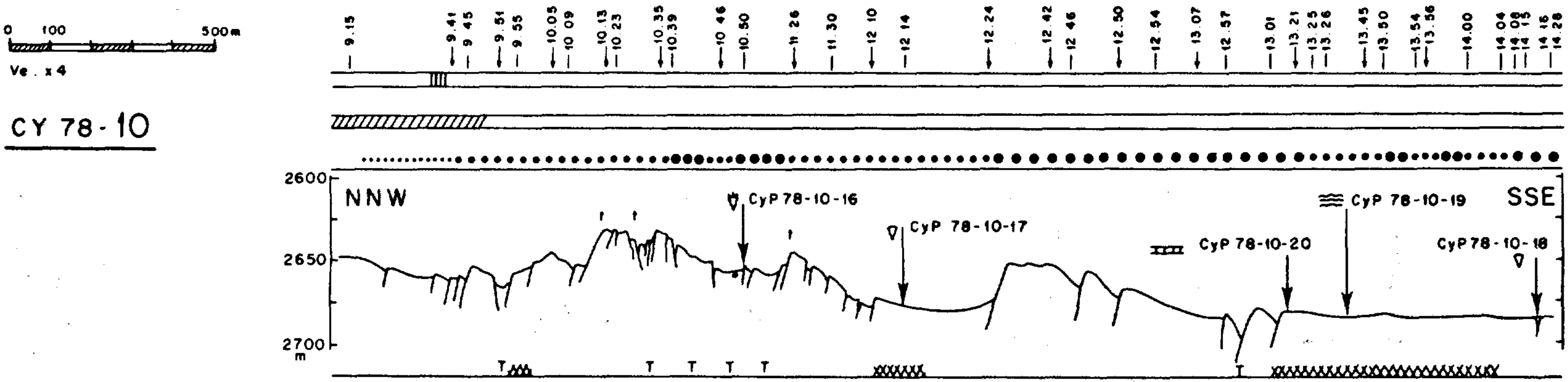

Fig. 7. Geologic profile along dive track CY 78–10 (see Figure 3 for location) derived from dive data and observations. VE × 4. Symbols same as in figure 5.

indicated by the angularity of the fragments and the relative paucity of sediment on the ramps. The recurrence of tectonic activity in this zone is demonstrated by the separation of some talus ramps from the adjacent fault scarps.

7.2. Hydrothermal deposits

Many manifestations of hydrothermal activity were seen in Zone 2, including fields of pillow lavas with pronounced ochre-orange staining at the base of pillows (Plates 3B and 3C), coloured deposits on scarps created by normal faulting and fissuring and, for the first time along the axis of a mid-oceanic ridge segment, massive sulphide deposits (CYAMEX *et al.*, 1978, 1979). Three dives (CY 78–06, –08 and –12) crossed two sites of sulphide mineralization, both of which lie on the lightly sediment-covered flanks of a graben that is about 20–30 m deep, 20–30 m wide, and located about 600 m west of the axis of the extrusion zone (Figure 4). The sulphide deposits occur as columnar edifices up to 10 m high and 5 m wide (Plate 3D). At one site, explored in detail during dive CY 78–08, the vertical edifices are spaced 4 to 5 m apart on the outward-facing escarpment of the graben, and are aligned over a distance of roughly 50 m in a direction nearly parallel with that of the Rise. The second site of sulphide mineralization, explored during dive CY 78–12, is located 200 to 300 m to the northeast of the first site and is positioned on the inward-facing escarpment of the graben.

The sulphide edifices are colour-variegated, predominantly in the colours ochre, red, yellow, brown, white and black, and are built on pillow lava terrain that is covered with a light dusting of sediment. Analysis of samples taken from the edifices indicates that they are comprised of an assemblage of minerals of two major groups; the first is a suite of dark-coloured sulphide minerals including sphalerite, marcasite, pyrite and chalcopyrite embedded in amorphous white silica; the second is a suite of fragile, ochre-coloured, amorphous iron oxides that represent oxidation products (gossan) of the sulphides. Pure native sulphur is found dispersed throughout many of the samples. A labyrinth of small channels and tubes penetrates the edifices, and their tops are characterized by open vents; the structures appear to have served as passageways through which hot, metal-laden solutions, percolating upward from depth in the crust, have circulated.

Three other modes of mineralization are found in association with the edifices. First, flattish incrustations composed of amorphous silica and sulphides, coat volcanic slopes proximal to the edifices. Secondly, bright yellow or orange, 10 to 20 cm – wide conelets with small holes at their tops are built on sediment and positioned around the large sulphide accumulations; visual similarity between the native sulphur found in samples of the edifices and the distinctively coloured conelets suggests that these conelets may represent accumulations rich in native sulphur. Thirdly, yellow and red-brown travertine-like deposits drape the near-vertical scarps that link the edifices. Bottom-water temperature anomalies were not observed during CYANA's exploration of the edifices and other mineralized sites, suggesting that hydrothermal waters were not fluxing through the vents at the time of our dives.

Active Extension: Outward Tilted Blocks (Zone 3)

Zone 2 is recognized as an interval over which extensional tectonics dominate over volcanic processes, and create a series of fault-bounded discontinuous ridges and troughs that distrupt the volcanic constructional terrain of the Rise axis (Zone 1). With increasing distance from the axis the morphologic elements indicate that extensional tectonics continue to dominate in the creation of the sea-floor physiography, but the tectonic style changes. At the outer margins of Zone 2, topographic lineaments become increasingly better defined; a smaller number of faults with larger displacements produce escarpments with a relief of several tens of meters and, more importantly, the relief on the faults exhibits a clear polarity with motion concentrated on inward-facing escarpments. The topography produced by this change in tectonic style is a series of asymmetric, tilted blocks. The interval over which terrain with these characteristics develops and becomes clearly defined is called the "outward-tilted block province" or Zone 3. The boundary between Zones 2 and 3 is generally signified by the evolution of large, inward-facing fault scarps. CYANA dives CY 78–10 (Figure 7, east flank of Rise), and CY 78–06 (Figure 5) and 07 (Figure 6, west flank of Rise) showed that initially, in Zone 3 the motion along faults is concentrated on closely-spaced, inward-facing escarpments separating a series of heavily sediment-covered blocks a few hundred meters wide that slope gently (a few degrees) away from the Rise axis. This tectonic style creates topographic lineaments or ridges that are asymmetric in cross-section (Figure 4). As the terrain of Zone 3 ages with increasing distance from the Rise axis the differential motion between blocks is concentrated on fewer, and more widely spaced, inward-facing escarpments and, consequently, the ridges become more clearly defined. The relief on the steep, inward-facing scarps increases to 50 to 70 m, the width of the ridges increases to approximately a kilometer, and the crests of individual ridges trend parallel with the axis of the Rise to create a distinctive terrain typical of abyssal hill topography.

The steep inward-facing fault scarps expose a complexly layered assemblage of truncated pillow lavas and sheet flows of variable thickness. The exposed rocks are covered by a veneer of manganese incrustations and pelagic sediment. Lapping up against the bases of fault scarps are well-developed talus ramps comprised of pelagic sediment and of blocks of rock spalled from the adjoining escarpments. At the base of some scarps, the coating of manganese is absent and the scarp-talus contact is disrupted, suggesting recent tectonic activity.

The outward-facing slopes of the ridge are, in general, very gentle and are covered by a thick (up to 1 meter) blanket of undisturbed pelagic sediment that obscures the volcanic constructional terrain and inactive faults, and that fills inactive fissures. In places the outward-facing slopes are quite steep (i.e., CY 78–18, west flank, Figure 4; CY 78–17, Figure 8) but these slopes represent the flanks of undisrupted volcanic constructional highs.

9. Inactive Tectonic Domain (Zone 4)

About 12 km west of the East Pacific Rise axis (CYANA traverse CY 78–17) there is a transition to a zone characterized morphologically by the large, near-vertical and inward-facing escarpments typical of Zone 3, but distinguished from it by an apparently complete lack of recent tectonism. Termed the "inactive tectonic domain", or Zone 4, this region contains inward-facing fault escarpments with a relief of up to 70 m, and a small number of outward-facing fault escarpments with very small relief; rare mini-graben, with widths and depths of a few meters to a few tens of meters, are produced by pairs of inward and outward-facing escarpments. The inward-facing faults, or groups of inward-facing faults, are spaced at intervals of 600 to 800 m, and generally strike parallel with the regional trend of the Rise. All of the faults observed are inactive: the broken pillows that outcrop on the escarpments are sediment covered and manganese-incrusted, and no talus breccia was observed at the bases of the escarpments, which are heavily covered by sediment.

The low-relief areas between the escarpments are covered with pelagic sediment, which has been oxidized to a brown colour at the surface and exhibits strong evidence of bioturbation. Large, undisrupted pillow outcrops stick through the sediment at intervals in the low-relief areas. On dive CY 78–15 (Figure 9) a series of volcanic constructional ridges was observed, and their steep slopes expose elongate, downslope-trending pillow flows. The escarpments generally expose pillow basalt; on one of the larger fault scarps explored by CYANA, however, massive lavas with prismatic vertical jointing were observed to be intercalated with the pillow flows. The massive lava unit ranges in thickness from 3 to 4 meters (12 h 58 in dive CY 78–16; Figure 9) to 35 meters (14 h 32 in dive CY 78–15; Figure 9). Sheet flows were observed on small outcrops exposed on dive CY 78–16 (13 h 33 and 13 h 48; Figure 9. A half-dome with roughly 15 m of relief, and with downslope-trending pillow flows radiating from its apex, was observed perched at the top of one 50 m high fault scarp (CY 78–16, 11 h 38; Figure 9).

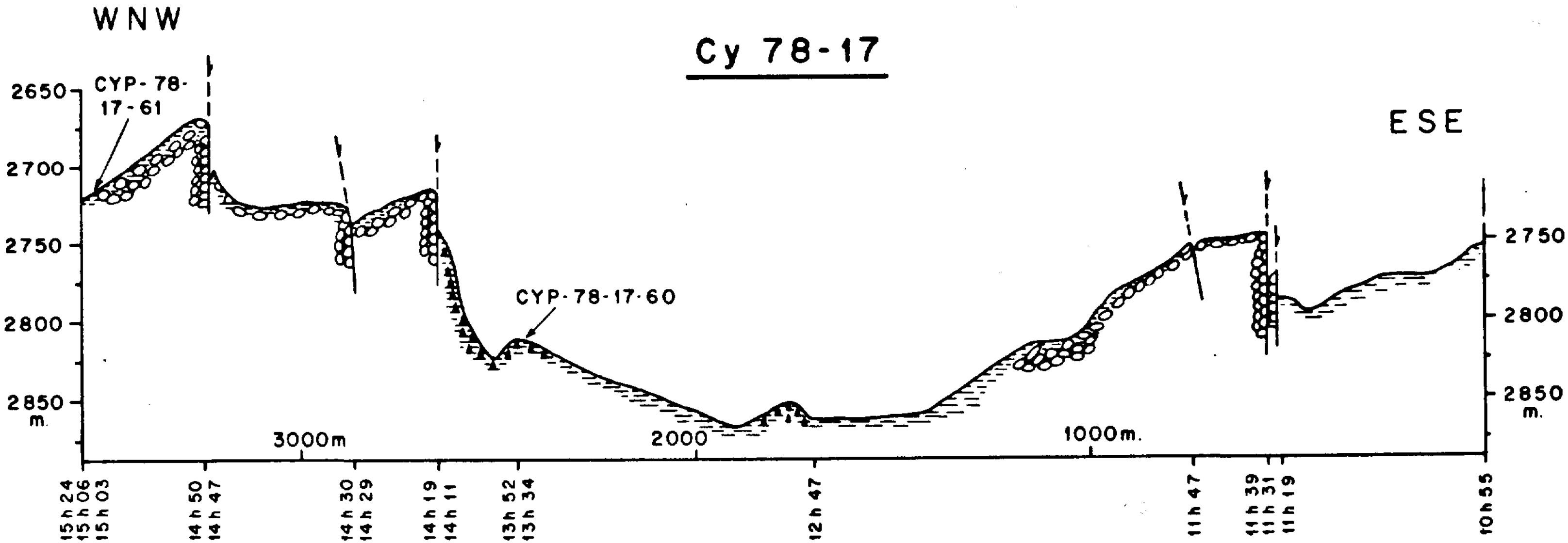

Fig. 8. Geologic profile along dive track CY 78–17 (see Figure 2 for location) derived from dive data and observations. VE × 4. The round structures are pillows, the black triangles are talus piles and the dotted horizontal lines mark the dediment.

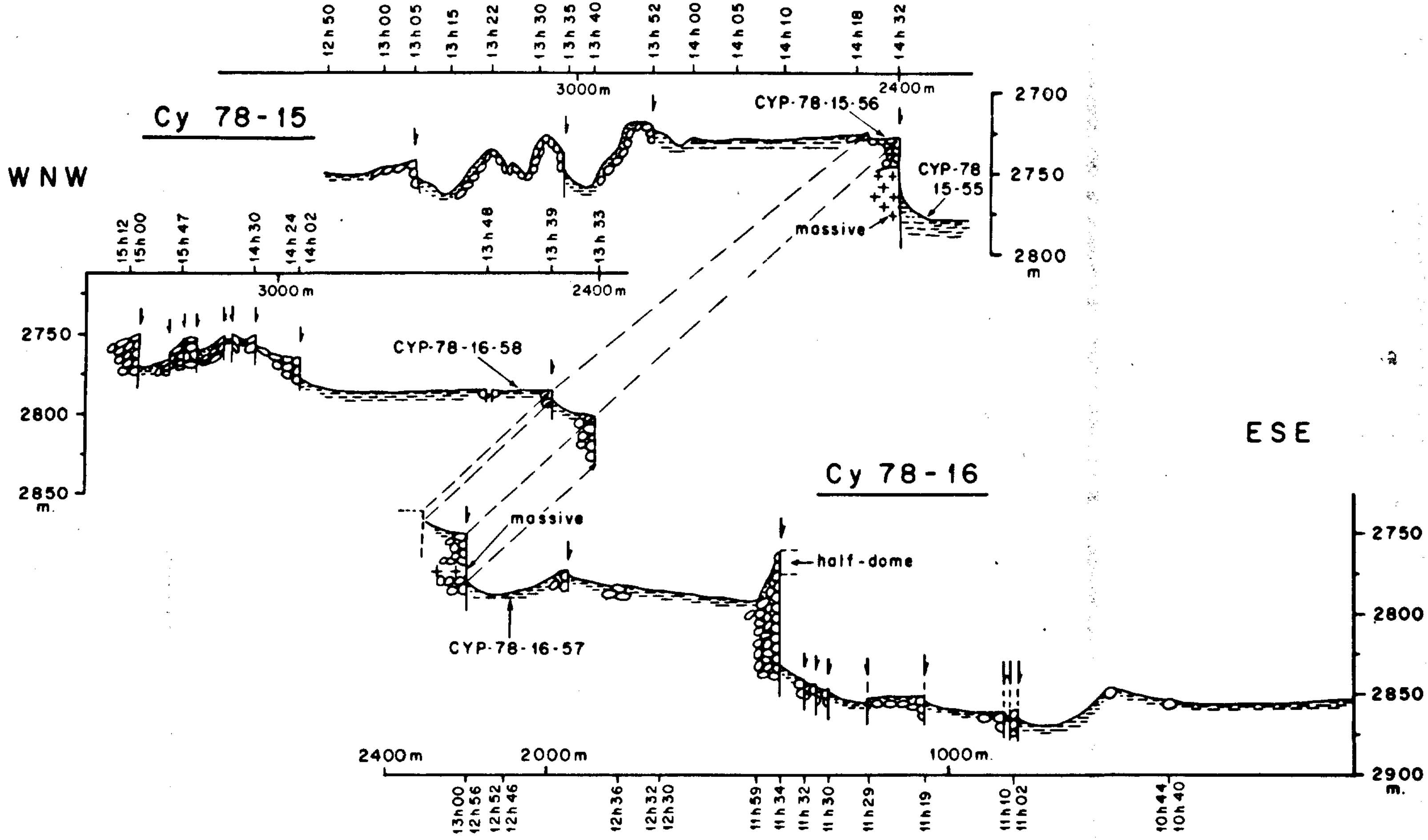

Fig. 9. Geologic profiles along dive tracks CY 78–15 and 16 (see Figure 2 for location) derived from dive data and observations. VE × 4. Symbols same as in Figure 8 with crosses marking massive lava.

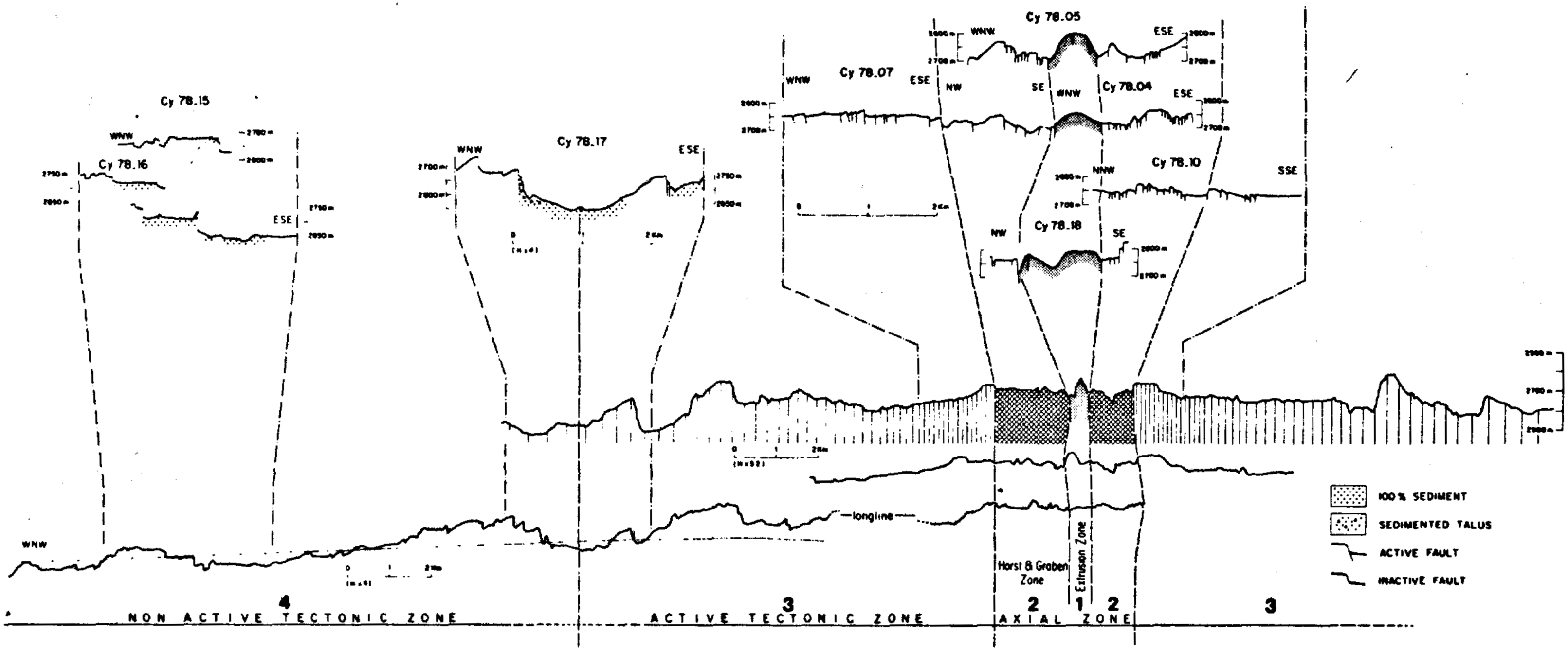

Fig. 10. Synthetic geologic observations in the axial region of the EPR at 21°N. Representative geologic profiles have been drawn from dive data at the axis, at a distance of 12 km from the axis and at the Brunhes-Matuyama reversal boundary. The deep-tow profiles show the 4-5 km wide raised axial block and the rough topography initiated at a distance of 8 km from the axis on both sides. The morpho-structural zonation revealed by the CYANA dives are shown at the bottom of the Figure.

10. Rock Samples

A total of 47 rock samples were collected during the CYAMEX program. Forty-one samples were recovered from the axial region at 31 stations (Zones 1 and 2), two samples were collected from the region marking the limit of the active tectonic zones at 2 stations (Zone 3 – Zone 4 transition), and four samples were recovered from the magnetic reversal area at 4 stations (Zone 4). Fresh glass margins characterize all samples collected in the extrusion zone (Zone 1) and in the inner part of the horst and graben zone (Zone 2). Samples collected elsewhere show palagonitization of the glass and/or manganese coating of rock surfaces. All but two of the samples are aphyric to subaphyric basalts. The pillow lavas are generally more phyric than either the sheet flows or pillars, with plagioclase and subordinate olivine phenocrysts. Clinopyroxene is apparently absent as a phenocryst phase. Major and trace element contents indicate that these basalts, which exhibit a composition that is characteristic of oceanic tholeiitic basalts, are chemically strikingly homogeneous. The two samples collected during dive CY 78–16 in the magnetic reversal area are rounded, manganese-covered fragments of volcanic pumice; similar rocks were dedged about 5 km west of the axis of the East Pacific Rise by Larson (1970).

11. Discussion

11.1. Volcanism and tectonics

The observations made during the 12 dives of CYANA on the East Pacific Rise document that the morphology of the sea floor in the survey area is generated by the variably mixed effects of two processes: the emplacement of lavas onto the sea floor and extensional tectonics. Volcanism controls the basic morphologic features of the East Pacific Rise crestal zone, both along and across strike. The volcanic processes produce two distinctive types of terrain. Pillow lavas emanating from elongate fissures or from point-source conduits create steep-sided constructional edifices (linear ridges or conical mounds) with relief of a few tens to several tens of meters. The rapid debouching of large volumes of lava into topographic lows creates sheet flows of varying thickness. A sheet flow can cover an area of several thousand square meters, and the flows tend to smooth the rough topography created by the pillow lavas. The relative proportions of the two types of volcanic products vary spatially and temporally along the axis of the Rise. The width of the extrusion zone is also controlled by the lava types. At the northern end of the survey area the axial extrusion zone (Zone 1) is very narrow (≈ 600 m) and is comprised almost solely of long volcanic ridges made up of pillow lavas. In contrast, at the southern end of the survey area, the width of the extrusive zone increases to more than 1 km, and the pillow lavas and sheet flows occur in almost equal abundance. Observations made during across-strike traverses at the northern end of the dive area (CY 78–06, –07) indicate that a significant proportion of the terrain of Zone 3 is characterized by the smooth topography created by sheet flows; these observations suggest that when this portion of the sea floor was created, sheet lows were an important component of the volcanic terrain, as they are today in the southern portion of the survey area. Thus, there is no need to invoke off-axis volcanism to explain the flattish areas of zone 3. The two contrasting styles of volcanic emanation – pillow lavas and sheet flows – reflect cycles of volcanic activity that vary spatially, along the axis of the Rise at any given time, and leave a record of the temporal changes along any given crustal flow-line. Moreover, the escarpments created by large-throw, dip-slip faults (for example, on dives CY 78–07, – 16; Figure 6 and 9) expose a multi-layered assemblage of pillow lavas and sheet flows of variable thickness, indicating that the oceanic crust at shallow levels is as heterogeneous vertically as it is laterally.

The reason for these two contrasting styles of volcanism is not readily apparent. The chemistries of the rocks comprising the sheet flows and pillow lavas are essentially the same (Juteau *et al.*, 1980) and therefore the different eruptive styles are not generated as a function of the chemical properties of the lavas. The contrasting styles of volcanism probably reflect differences in the volume of lava extruded at the time of the eruption. The extrusion of large volumes of lava on the sea floor could be initiated by the rapid replenishment from the athenosphere of a shallow level magma reservoir (perhaps at a depth of about 2 km; Reid *et al.*, 1977). Rapid swelling of the magma reservoir would create high instantaneous rates of extension in the overlying brittle volcanic lid, allowing for the rapid passage of large volumes of lava up through the lid and onto the sea floor. Between periods of magma replenishment and high instantaneous rates of opening, the volume of magma within the reservoir available for extrusion would diminish, and mean opening rates, averaged over a time scale of 10^4 to 10^6 yrs, would govern crustal extension. These intervals would be characterized by volcanic episodes favoring the emanation of pillow lavas.

The observations made during the dives establish that extensional tectonics modify to varying degrees the volcanic morphology created along the axis of recent volcanism. A small number of fissures and small-throw, dip-slip faults occur in Zone 1 but most are concealed by flows, and it is in the terrain adjacent to the axial volcanic zone that the surficial expression of extensional tectonics becomes clearly defined. A narrow interval, Zone 2, ranging in width from a few hundred meters to 2 km, flanks the axis of recent volcanism and is characterized by the development of inward and outward-facing, near vertical faults that create horsts and graben with relief of a few tens of meters, which disrupt and dismember the volcanic forms. The faults are subparallel with the axis of recent volcanism and cannot be traced along strike for more than a few hundred meters; a small number of faults that are oriented transverse to the general strike of the East Pacific Rise have been found in Zones 1 and 2. In Zone 3 tectonic activity becomes concentrated on inward-facing faults, the active faults become more widely spaced, and the continuity of faults along strike becomes clearly defined. At a distance of approximately 12 km from the ridge axis the evidence of active tectonism is no longer observed.

Seismic refraction studies at 21°N along the East Pacific Rise define a low velocity zone, interpreted to represent a magma reservoir that is centered beneath the axis of the Rise and can extend out to either side for a distance up to 10 km (i.e., Reid *et al.*, 1977.) The half-width of the active zone of tectonism is 12 km. Surely some of the tectonic activity exhibited at the sea floor must be linked to processes operating within the shallow-level magma body. The transverse faults that strike at an angle to the trend of the Rise may represent discontinuities between blocks opening at different instantaneous rates and may imply fine-scale, non-rigid behavior of newly-formed oceanic crust.

In plan view (Figure 4) the zone of most recent extrusion is not continuous along strike and appears to define an *en échelon* pattern. Presently it is not clear what significance this pattern may have but it is tempting to entertain some possibilities. Intuitively, it is unlikely that the spatial arrangement of the zone of most recent volcanism is fixed. We suggest that the locus of most recent volcanism changes in time within a relatively narrow region in which the properties (thickness of crust above underlying magma chamber, thermal structure, rheology) of the shallow intrusive and extrusive crust are approximately the same. The combined width of Zones 1 and 2 may bound the interval over which an extrusive event can occur. Immediately following an extrusive and intrusive episode along a portion of the ridge axis, the pre-existing crust through which the most recent lavas passed might be healed to some degree relative to the surrounding crust, because that portion of the lava that never reaches the surface would crystallize at depth in cracks and fissures created by extensional tectonics. Although the youngest volcanic terrain would experience extension over the years intervening before the next volcanic episode, and although the crust of the recent volcanic zone would be relatively hotter than the flanking crust, the basement rocks of the flanking zone will be the preferred site for the next volcanic episode because of the more fractured nature of the crust. The most recent volcanic emanation would also load the underlying volcanic layer that must to some degree be rendered buoyant by a shallow level magma body from which the lavas are derived. A response to loading may initiate crustal failure at the edges of the youngest volcanic terrain, thereby creating another possible preferred site of volcanism.

11.2. Hydrothermal deposits

Observations made in Zones 1 and 2 suggest that hydrothermal activity, the fluxing of heated seawater along permeable pathways within the volcanic basement, is an important process operating at, or proximal to, the axis of crustal accretion. In Zone 1, hydrothermal activity is indicated by the presence of staining along pillow interfaces, by deposits of white amorphous silica on fractures within pillows and by fields of dead clams. In Zone 2, we observed colorful stainings on normal fault scarps and on fields of broken pillow rubble, deposits of massive sulphides occuring only as tall edifices (CYAMEX *et al.*, 1978, 1979). Concentrations of yellowish sulphur (?), deposits occur locally. No evidence of recent hydrothermal activity was observed in terrain older than Zone 2.

11.3. COMPARISON WITH SLOW RIDGES

The CYAMEX investigation of the crest of the East Pacific Rise at 21°N has defined the volcanic and structural properties of a small portion of a moderately fast accreting plate boundary, and has provided constraints needed to compare some of the properties of the fabric of a moderately fast ridge with that developed along the axis of a slow ridge. Although the axial relief of slowly accreting ridges is much greater (a factor of ten or more), similar volcanic and structural processes characterize both environments. However, the processes do not necessarily operate in the same way temporally or spatially.

The axis of most recent volcanism in the CYAMEX area is made up of edifices, up to 50 m high, comprised of pillow lavas and sheet flows. Both of these morphologies are important and, when time-averaged, neither volcanic morphology appears to dominate over the other. Submersible investigations of the floor of the rift valley of the Mid-Atlantic Ridge conducted during the FAMOUS investigations (e.g. Bellaiche *et al.*, 1974; Arcyana, 1975; Ballard *et al.*, 1975; Ballard and Van Andel, 1977) indicate that constructional edifices of pillows lavas, up to 250 m high, are the most dominant volcanic product and that sheet flows comprise only a small percentage of the recently extruded lavas. Geophysical studies of the crest of the Mid-Atlantic Ridge in the FAMOUS area (e.g. Fowler, 1976) indicate that if a shallow level magma reservoir exists beneath the ridge axis it must be small, roughly 2 km or less in width (Nisbet and Fowler, 1978). The chemistries of basalts sampled at the ridge axis during FAMOUS are more heterogeneous (Arcyana, 1977; Hekinian *et al*, 1976; Bryan and Moore, 1977) than the chemistries of basalts erupted at 21°N (Juteau *et al.*, 1980). The FAMOUS data have been interpreted to suggest that the shallow-level magma chamber beneath the ridge axis must be small (<2 km), and that this shallow reservoir is infrequently replenished, thereby allowing magma batches to fractionate, and evolve chemically. If, as we suggested in the preceding discussion, the extrusion of sheet flows is linked to the replenishment of a shallow-level magma reservoir and to the creation of high instantaneous rates of extension in the overlying crust, then it is understandable that sheet flows should become progressively more numerous with respect to pillow lavas as the accretion rate increases. One might therefore predict that sheet flows will be found to be the dominant volcanic product at the axis of very fast accreting plate-boundaries.

Along the axis of the East Pacific Rise at 21°N, extensional tectonism is most intensely developed in Zone 2; in Zone 1, volcanism (edifices up to 50 m high and sheet flows) creates the morphology, but gja-type fissures and small, dip-slip faults disrupt the volcanic basement in some areas; in Zone 2 extensional tectonics proceed in the absence of volcanism, creating inward and outward facing, near-vertical faults, and horst-graben terrain. The width of these two zones varies little along strike, ranging between 2 and 3 km. In the FAMOUS region, most of the concentrated extensional tectonism is recognized along the inner floor of the rift, and is manifested as fissures, horsts and graben and, indirectly as young volcanic highs. The width of the inner floor, defined as the distance between the deepest opposed, inward-facing faults varies along strike, ranging between < 500 m and about 3 km.

For both slow and faster ridges the motion on faults becomes polarized at the outer edge of the horst and graben interval. Along slow ridges the motion on inward-facing faults adds up to create the 1000 m or more of relief that characterizes the walls of rift valleys. Along the moderately-fast ridges, the relief created by motion on inward-facing escarpments is of the order of several tens of meters to 250 m. Polarized tectonism is manifest along the axes of both slow and moderately fast ridges at about the same distance from the axis (a few to several kilometers) and appears to be independent of magma-chamber size. The reason for this polarity is not clear but it probably reflects the direction in which matter can be most easily transported in this tectonic situation, where the lithosphere is thickening rapidly away from a thinned axial region. At the axis, in a region characterized by a thin crustal cap of nearly uniform thickness, the near-vertical faults, which lack any polarity, probably represent true tensional fractures.

The major difference between the geology of slow ridges such as FAMOUS and that of the moderately-fast ridges, such as the RITA or Galapagos spreading centers is the intense hydrothermal activity associated with accretion along the moderately fast ridges. The large fields of stained basalts, the clam beds and the deposits of polymetallic sulfides are all absent in the FAMOUS rift valley, although small deposits of iron and manganese were found in a transform fault (Arcyana, 1975). The major difference in magma chamber size, depth and permanence between slow and faster ridges may explain the differences in surface manifestations of hydrothermal activity. The proximity of well-developed, permanent magma-reservoirs under moderately fast ridges provides an efficient energy source for driving the hydrothermal system.

11. Conclusions

The morphotectonic zonation in the axial region of the East Pacific Rise at 21°N involves an innermost zone of extrusion (Zone 1), flanked by a fissured and faulted extensional zone with a horst and graben topography (zone 2) that is, in turn, bounded by a back-tilted fault-block terrain exhibiting a clear fault-polarity (Zone 3). The width of the zone of extrusion varies along strike from 0.6 to 1.2 km. The zone shows an *en échelon* spatial arrangement associated with transverse faults. It is not centrally located in the inner tectonic zone. The width of the zone of active tectonics associated with the Mid-Oceanic Ridge has been established for the first time from direct field evidence. Active or recently active faults extend up to 12 km west of the axis of extrusion of the East Pacific Rise. The morphotectonic zonation does not represent a steady-state system from a morphological standpoint, because a rough inner zone is replaced by smoother zones further outwards; it points to the existence of volcanic cycles in the behaviour of the ridge and reflects the flooding by fluid lavas of pre-existing pillow-volcanic terrain.

The hydrothermal activity of the East Pacific Rise at 21°N is intense. It is concentrated in the extrusion zone and the inner extension zone and is clearly associated with structures produced by rifting. Dramatic new evidence of hydrothermal activity on the deep sea floor includes the presence of massive sulfides and the discovery of benthic fauna of giant size similar to that found at the axis of the Galapagos Rift.

The major differences in the morphology, lava types, chemistry and hydrothermal activity of slow ridges, such as the Mid-Atlantic Ridge in the FAMOUS area and faster ridges, such as in the RITA or Galapagos areas, may reflect profound differences in deep thermal structure.

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