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Fine scale morphological and structural analysis of the East Pacific Rise, 21°N (Rita project)

East Pacific Rise
Tectonics
Accreting plate boundary
Extension
Volcanism

Dorsale Est-Pacifique
Tectonique
Zone d'accrétion
Extension
Volcanisme

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ABSTRACT

Manned submersible observations on a transect from the axis of the East Pacific Rise (21°N) to the area of the Brunhes-Matuyama magnetic inversion were made during the Cyamex and Rise diving phases of the Rita project. In the northern part of the study area, axial, linear, 400 to 600 m-wide topographic highs are formed by relatively unfaulted fresh pillow-lava-flows (zone 1). Flanking the axis of recent volcanism is a 1,200 to 1,500 m-wide zone of highly fractured volcanic hilly terrain that represents the main region of extension as expressed on the surface (zone 2). In the southern part of the study area, the volcanic highs of zones 1 and 2 are flooded by fluid lava flows forming a gentle topography. In both areas, this central part of the Rise is bordered by outward-tilted flattish blocks that are mainly formed by fluid lavas. This zone, zone 3, could represent a former, large flooding episode of the sea floor at the axis of the Rise. Tectonic activity is particularly evident in zone 2, decreases rapidly across strike, and vanishes 12 km from the axis of the East Pacific Rise. The morphology of the East Pacific Rise is controlled by normal faulting, and by the relative abundance of fluid lavas and pillows-lavas which are emplaced at the axis of the Rise. The differing types of volcanism could reflect important variations in magma chamber size or depth or variations in the instantaneous accretion rates along the axis of the East Pacific Rise.

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RÉSUMÉ

Analyse morphologique et structurale détaillée de la dorsale Est-Pacifique, 21°N (projet Rita).

Des observations par submersible habité ont été réalisées durant les phases de plongée Cyamex et Rise du projet Rita, au long d'un transect allant de l'axe de la dorsale Est-Pacifique (21°N) à la zone d'inversion magnétique Brunhes-Matuyama. Dans la partie septentrionale du secteur étudié, les reliefs volcaniques axiaux, de 400 à 600 m de large, sont constitués de coulées de laves en coussins, fraîches et peu fracturées (zone 1). Cet axe volcanique récent est bordé de part et d'autre par une zone de 1 200 à 1 500 m de large, constituée de terrains volcaniques très fracturés. Cette zone (zone 2) représente la région à extension maximum exprimée en surface. Dans la partie méridionale du secteur étudié, les reliefs volcaniques des zones 1 et 2 sont ennoyés par des coulées de laves fluides à morphologie peu accusée. Dans ces deux secteurs d'étude, la partie centrale de la dorsale est bordée par des blocs à surface plane, formés principalement de laves fluides, et inclinés vers l'extérieur de cette dorsale.

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Cette zone (zone 3) pourrait représenter un ancien épisode d'ennoyage de la dorsale. L'activité tectonique est particulièrement marquée en zone 2, et décroît rapidement dans les zones plus externes pour venir mourir à 12 km de l'axe de la dorsale Est-Pacifique. La morphologie de la dorsale est contrôlée par des failles normales et par l'importance relative des laves fluides et des laves en coussins qui se sont mises en place à l'axe de la dorsale. Les différents types de volcanisme pourraient refléter d'importantes variations de la taille ou de la profondeur de la chambre magmatique, ou encore des variations du taux d'accrétion instantané au long de l'axe de la dorsale.

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INTRODUCTION

Oceanic ridges can be classified on the basis of their rate of accretion :

— slow spreading centers (V < 4 cm per year) such as the Mid-Atlantic Ridge (Arcyana, 1975 ; Ballard *et al.*, 1975 ; Ballard, Van Andel, 1977).

— moderately fast spreading centers such as the East Pacific Rise (EPR) at 21°North, and the Galapagos spreading center (Klitgord, Mudie, 1974 ; Van Andel, Ballard, 1979 ; Allmendiger, Riis, 1979).

— fast and superfast ridges, such as the East Pacific Rise between the Nazca and Pacific plates (Lonsdale, 1977 *a* and *b*).

Marked differences in the morphology of the various spreading centers exist (Anderson, Noltimier, 1973 ; Shih, 1979), for example between the moderately fast and superfast ridges. In this last category, the axial high is well developed. The deep axial valley, typical of the slow spreading centers is not encountered in the East Pacific Rise.

Morphological study of mid-ocean ridges has recently been made by side looking sonar (Gloria), multi-beam echosounders (Sea-Beam), as well as towed vehicles (Deep Tow and Angus). Information from these tools must be complemented by direct observations on the sea floor. These are best made using manned submersibles, as in project Famous (Heirtzler, Le Pichon, 1974). With the use of such tools, detailed and precise geological cross sections can be established. Sedimentary, volcanic and structural characteristics of the terrain traversed during the dives appear on such profiles. They can be used as a basis for comparison of ridges with differing spreading rates.

The EPR at 21°N is characterized by a relatively wide zone, where the crust is less than 100,000 years old (the axial zone), bordered by an area with less fractures, where faults have a relatively constant strike, and a larger vertical offset than in the axial zone.

Former studies of this ridge crest area (Larson, 1971 ; Normark, 1976) revealed that the axial zone, 5 km wide, formed by isolated topographic highs distributed over a 2 to 2.5 km wide band at the ridge axis, is flanked by a 1 to 1.5 km wide extensional tectonic zone.

In the framework of an international project (Rita), a total of 15 dives were conducted with the French diving saucer Cyana in March-april 1978, in the axial region of the EPR at 21°N (Fig. 1). The general results of this expedition (called « Cyamex ») are given in Cyamex Scientific Team (1980) and Francheteau *et al.* (1980). A companion expedition

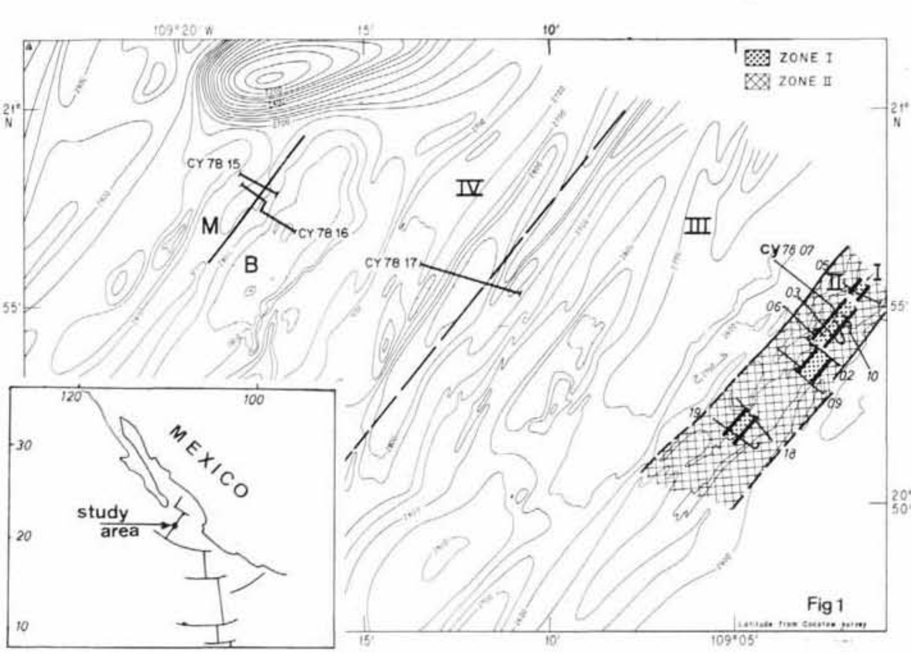


Figure 1
Location of Cyamex dives at EPR 21°N.
Localisation des plongées Cyamex-EPR 21°N.

(Rise) using the submersible Alvin, focused one year later on the southern extension of the region explored by Cyana (Rise project Group, 1980).

The purpose of this paper is to present the fine scale morphology and tectonics of crust accreted at a medium rate spreading center using field observations made from Cyana on the sea floor. The study leads to a model for the evolution of a moderately fast spreading center. It can be compared to similar studies conducted on either slow (Arcyana, 1975 ; Ballard, Van Andel, 1977) ; or moderately fast spreading ridges (Van Andel, Ballard, 1979).

The observations of the shallow tectonics and styles of volcanism provide necessary contrainsts for any model of the structure at depth underneath the ridge crest.

GEOLOGY OF THE ACTIVE TECTONIC ZONE

The active tectonic zone extends 12 km on either side of the axis of the ridge. The outer western limit of the active tectonic zone was observed during dive CY 78-17.

Within this zone where active faults are observed, a finer zonation was established using other criteria such as the relative abundance of sediments, the freshness and type of lavas, and purely morphological characteristics (Cyamex Scientific Team, 1980). We are thus able to distinguish an axial zone, with marked along strike variations, and an external zone characterized by a relatively homogeneous morphology.

Axial zone

The northern part of the diving area

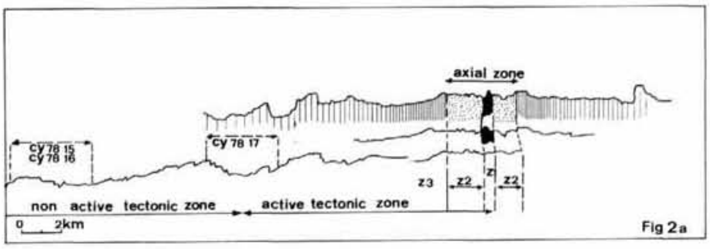
In the northern part of the diving area, the axial zone has been subdivided into an extrusion zone (zone 1), and an intensively fractured zone (zone 2) marked by its horst and graben morphotectonic style (Fig. 2 *b*).

The extrusion zone (zone 1) is limited to young volcanic highs, up to 1,300 m long, and 400 to 800 m wide.

The axial volcanic highs (*a*, *b*, *c* on Fig. 2), are not strictly aligned along a theoretical ridge axis. Volcanic high (*a*) was identified during dives CY 78-03, 04 and 05 (Fig. 3). Standing higher than adjacent topographic highs it forms a simple dome, with a constant width on dives CY 78-04 and 05, but much narrower toward the south on dive CY 78-03. This volcanic high disappears along strike around 20°-54′N, on the southern branch of dive CY 78-03. On the southern part of this dive (Fig. 2 B), the more recent volcanic high is offset to the SE.

This next axial high (*b*) offset with respect to (*a*), widens southward, but was only partially observed along dives CY 78-06 and 08. During this later dive, volcanic high (*b*) was followed along strike over a distance of 900 m. Fresh lava, flowing either to the west or the east, suggest a complex geometry for these axial volcanic highs, characterized by steep flow fronts. Further south along dive CY 78-06, volcanic high (*b*), is only 120 m wide. This anomalous width for the extrusion zone is interpreted as the southern closure of axial high (*b*), which reaches a maximum width of 450 m and a length of 1,300 m.

Dive CY 78-02 found two loci of fresh lava. Numerous flows with glassy buds were observed between 14 h 05 and 12 h 29 (Fig. 3), on the eastern part of the axial high. Fresh volcanic glass disappears rapidly to the west (14 h 07). Between 14 h 18 and 14 h 20 (Fig. 3) glassy buds preserved at the base of the pillow-lavas, and covered by a sediment dusting reappear. We interpret the presence of the two fresh lava areas on dive CY 78-02 as a relay zone between axial volcanic highs (*b*) and (*c*) (Fig. 2 *a*).



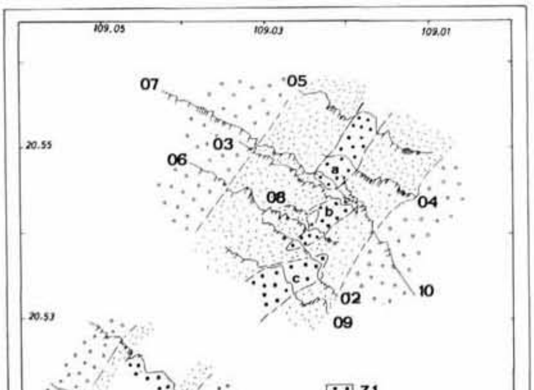


Figure 2

a : *Generalized Cross Section of EPR 21°N from Deep Tow profiles and selected Cyamex dives.*

b : *Cyamex dives topographic profiles — EPR axis 21°N. "En echelon" axial volcanic highs are labeled* a, b, c.

a : Coupe générale de EPR 21°N réalisée à partir de profils Deep-Tow et de quelques plongées Cyamex.

b : Profils topographiques des plongées Cyamex-EPR 21°N. Les lettres a, b, c correspondent aux reliefs volcaniques axiaux disposés en échelon.

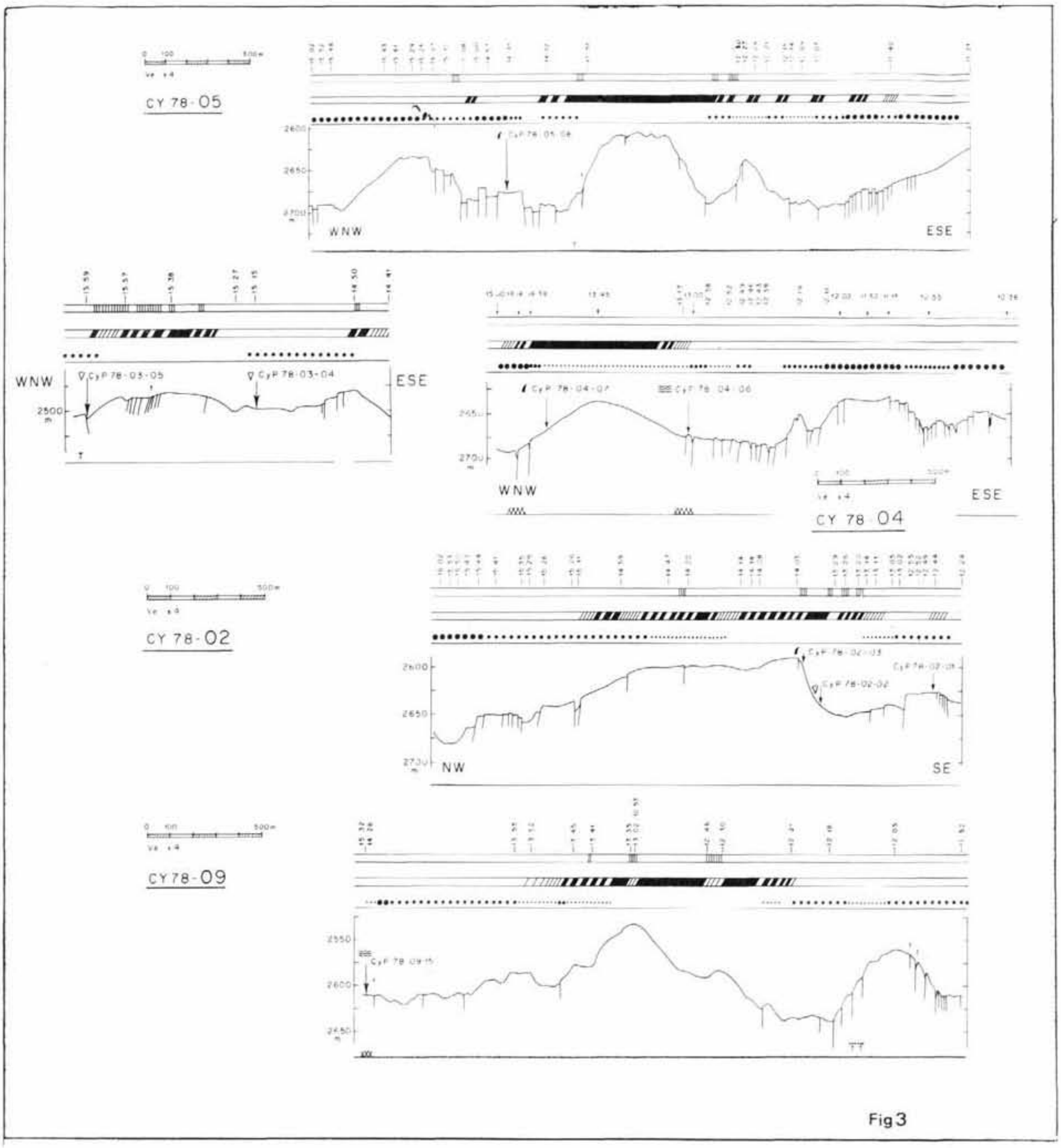


Figure 3

Geological sections at the axis of EPR 21°N (northern diving area). Vertical exaggeration = 4.

Crosses under each profile represent fluid lavas, T indicates talus and P collapsed lava lakes marked by pillars.

Above each profile, from top to bottom: 1) diving time; 2) presence of staining (vertical stripes); 3) freshness of volcanic glass (black stripes). Three stages of glass freshness were recognized: — continuous black stripes represent shiny glass and buds, — discontinuous black stripes represent areas with shiny glass and rare glassy buds preserved at the base of pillow-basalts, — oblique stripes indicate places where glass is altered but locally preserved on small surfaces; 4) relative importance of sediment cover, from dusting (small dots) to increasing thickness (large dots). Sediment-covered talus are represented by T topped by dots.

Coupes géologiques à l'axe de EPR 21°N (zone septentrionale de plongée). Exagération verticale = 4.

Les hachures sous chaque profil représentent les laves fluides, T indique les talus et P les lacs de lave effondrés soulignés par des piliers.

Au-dessus de chaque profil, et de haut en bas, sont figurés : 1) l'échelle de temps de la plongée ; 2) la présence de colorations hydrothermales (hachures verticales) ; 3) la fraîcheur du verre volcanique (banches noires). Trois stades de fraîcheur des verres ont été reconnus : — les bandes noires continues représentent le verre brillant et les excroissances vitreuses, — les bandes noires discontinues représentent les zones à verre brillant et à rares excroissances vitreuses préservées à la base des coussins de lave, — les hachures obliques indiquent les secteurs où le verre est altéré mais localement préservé sur de petites surfaces ; 4) importance relative de la couverture sédimentaire, depuis un saupoudrage (pointillé fin) à une épaisseur croissante (gros pointillé). Les sédiments recouvrant les talus sont représentés par des T surmontés d'un pointillé.

The volcanic highs are not faulted. Fractures are limited to fissures (dive CY 78-03 : Fig. 4). Faults transverse to the main direction (N.30) of the ridge are ubiquitous in the region of offset of the axial volcanic highs (CY 78-02 : Fig. 3), or at the foot of recent volcanic highs (CY 78-05 : Fig. 2 *b* and 3). It is not demonstrated whether the transverse faults represent the same tectonic regime as the faults parallel to the ridge.

The fractured extension zone (zone 2).

— Morphology and tectonics.

The axial volcanic highs are flanked by an intensively tectonized zone with open fissures and near vertical faults, resulting in a horst and graben terrain, and extending 1.2 to 1.5 km on either side of the axial volcanic highs. On dive CY 78-05, this zone exhibits a strong asymmetry in morphology. West of the axial high, the pillow-lava flows are cut by a series of faults, 30 to 100 m apart resulting in a horst-like morphology. The top of the faulted blocks are comprised of well-preserved trap door and pillow-type basalts. In contrast, east of the axial high, fracturing is denser, without any apparent vertical offset, and none of the primitive volcanic highs are well preserved. Similar observations were made on dives CY 78-03, 04, 06, 07 and 10 (Fig. 3 and 4).

Numerous talus piles, either bare or slightly sedimented are present at the foot of the walls. Near the ridge axis, fresh talus without sediment is common at the foot of both inward and outward facing scarps. Further away from the axis of extrusion, talus piles present at the base of outward-facing

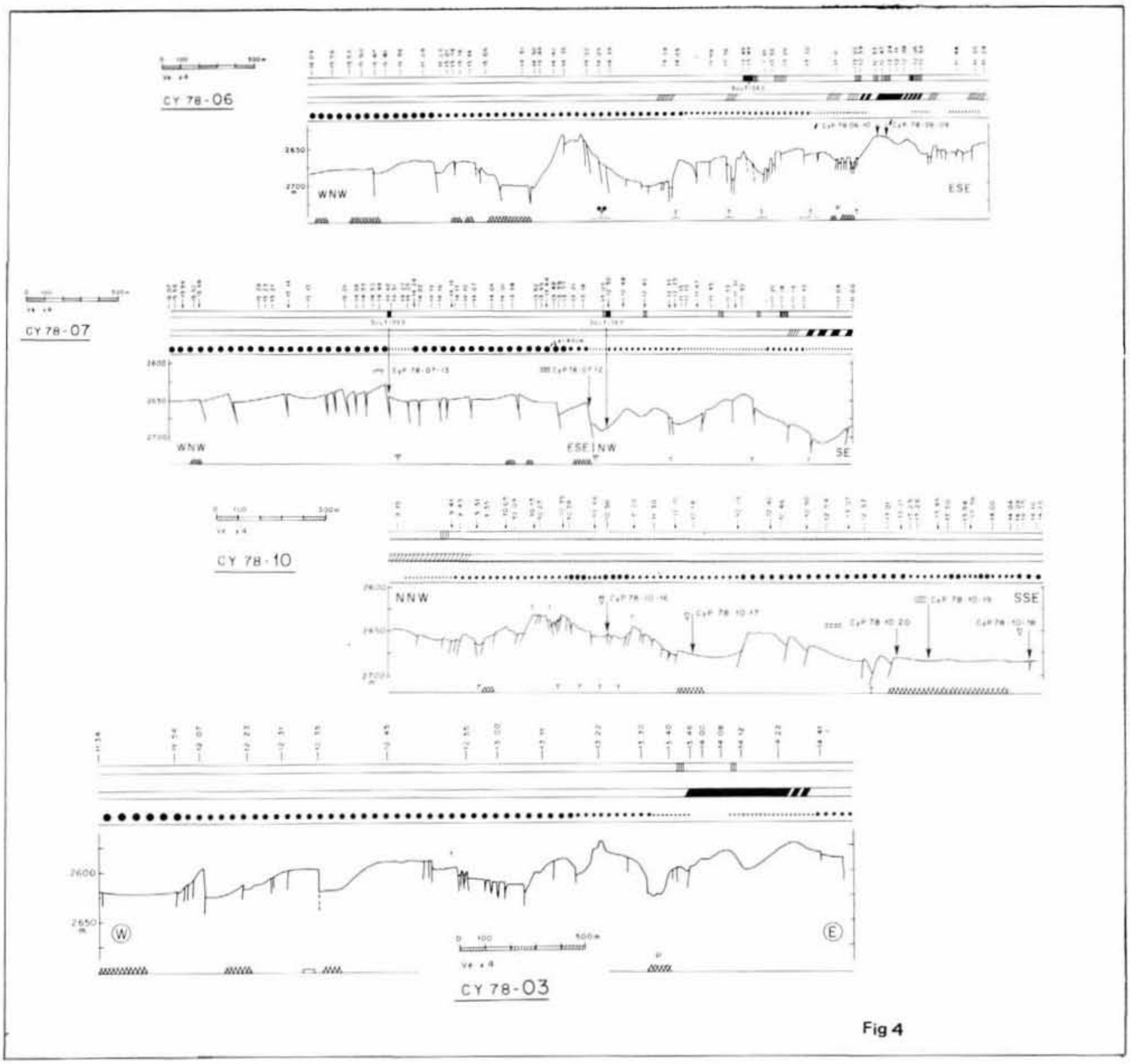


Figure 4

Complete geological sections through the Cyamex area, from zone 1 to zone 3. Same caption as Figure 3.

Coupes géologiques complètes à travers le secteur Cyamex de la zone 1 à la zone 3. Même légende que la Figure 3.

scarps are more and more sedimented, indicating a rapid decay in the tectonic activity of these faults. In contrast, talus associated with inward-facing scarps, often shows superposition of fresh talus on top of slightly sedimented talus, a clear indication for renewal of tectonic activity along the faults.

In a region starting 500 m away from the boundary between zone 1 and zone 2, talus piles are frequently separated from adjacent fault scarp by an open fissure. The presence here of fissures, is compatible with outward tilting of the blocks formed near the axis of the ridges.

Within zone 2, one can differentiate two sub-zones : A purely extensional domain, where offsets on outward and inward-facing faults are comparable in value (Fig. 5 *a*). This sub-zone, approximatively 500 m wide is well defined east of the axial volcanic highs. Further away from the axis, zone 2 is characterized by a domain, where the offset suddetly increases on inward-facing faults, and where fissures are developed between talus and feeder scarps.

In zone 2, the various topographic highs are deeper than the fresh axial volcanic highs of zone 1. The relative uplift of the faulted topographic highs of zone 2, due to inward-facing faults is cancelled by a differential subsidence of zone 2 with respect to zone 1 (compare in Fig. 3, dive CY 78-05, the topographic high at 15 h 30 with the axial high).

— Extension in zone 2.

In the Famous area, McDonald and Luyendyk (1977) proposed, on the basis of the Deep-Tow data, a value of 4 and 6 percent for the extension on either side of the axial zone. The extension reaches 18 percent on the inner walls of the axial valley. The manned submersible observations made by Ballard and Van Andel (1977), for the Mid-Atlantic Ridge, lead to a 2-3 percent value for extension due to the fissures in the axial valley. The Cyamex submersible observations show that the extension due to faults and fissures in zone 2 of the EPR is less than 10 percent. Using an average dip of 80 degrees for the fault scarps, the extension is 3.6 % for zone 2 East to the axial ridge, and 2.1 % West (Unterhner, 1979). The difference in extension may reflect the existence of younger crust in zone 2 west of the axial highs.

The pattern of extension in zone 2 can be estimated by calculating the average extension over arbitrary 200 m-wide intervals, normal to the ridge axis (Fig. 5 *b*). Between 500 and 900 m, one can observe a sudden increase in the extension ratio (5 %). Beyong 800 m, the ratio diminuishes steadily. Three stages of fracturing can be distinguished from crust with zero age to zone 2 : first, an inferred purely extensional regime (over 90 % of extension) in zone 1 (Fig. 5 *b*). Second, an extensional domain with low values (3 %) within the first 500 m of zone 2. Finally, an extensive zone with higher values (6 %) where extension is accompanied by an outward rotation of the blocks (tilting) (Fig. 5 *c*).

The fine scale zonation would be better defined if the

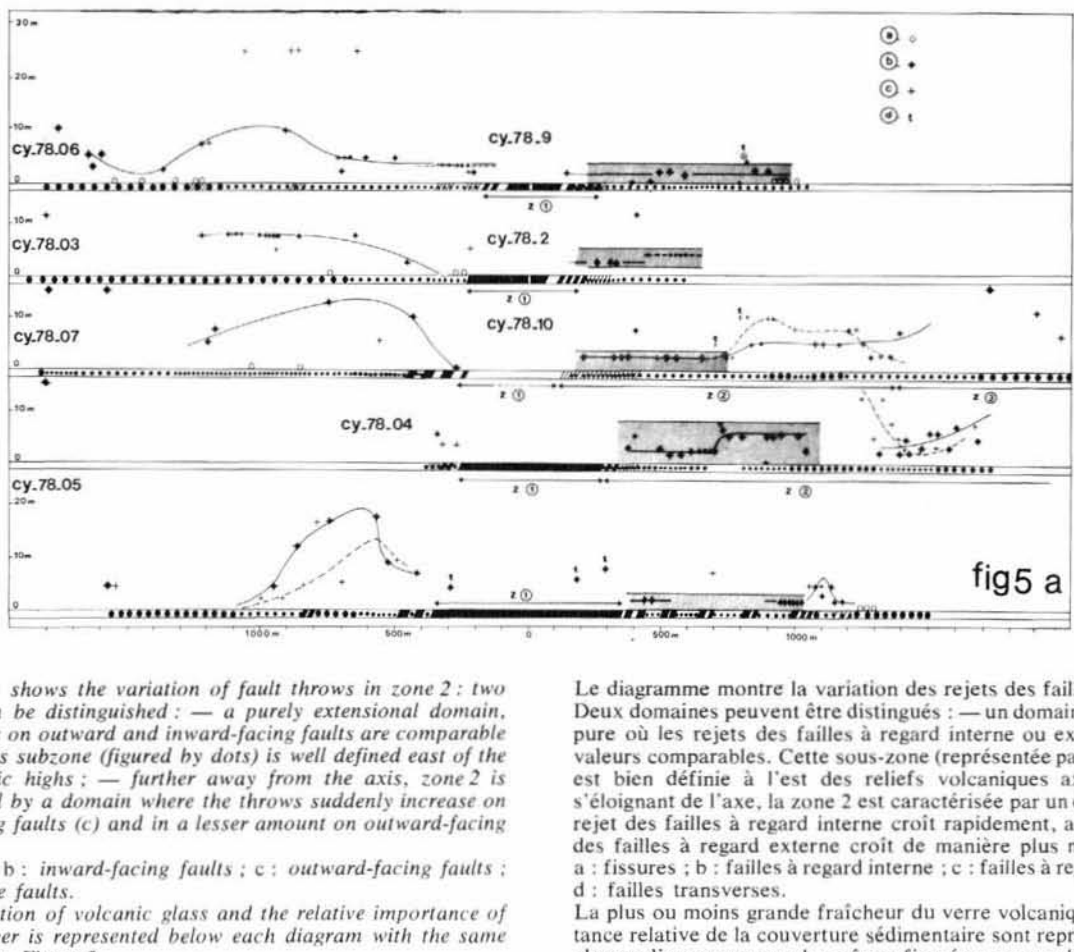


Figure 5 *a*

The diagram shows the variation of fault throws in zone 2 : two domains can be distinguished : — a purely extensional domain, where throws on outward and inward-facing faults are comparable in value. This subzone (figured by dots) is well defined east of the axial volcanic highs ; — further away from the axis, zone 2 is characterized by a domain where the throws suddenly increase on inward-facing faults (c) and in a lesser amount on outward-facing faults (d).

a : *fissures* ; b : *inward-facing faults* ; c : *outward-facing faults* ; d : *transverse faults.*

The preservation of volcanic glass and the relative importance of sediment cover is represented below each diagram with the same patterns as in Figure 3.

Le diagramme montre la variation des rejets des failles en zone 2. Deux domaines peuvent être distingués : — un domaine à extension pure où les rejets des failles à regard interne ou externe ont des valeurs comparables. Cette sous-zone (représentée par un pointillé) est bien définie à l'est des reliefs volcaniques axiaux ; — en s'éloignant de l'axe, la zone 2 est caractérisée par un domaine où le rejet des failles à regard interne croît rapidement, alors que celui des failles à regard externe croît de manière plus modeste.

a : fissures ; b : failles à regard interne ; c : failles à regard externe ; d : failles transverses.

La plus ou moins grande fraîcheur du verre volcanique et l'importance relative de la couverture sédimentaire sont représentées sous chaque diagramme avec les mêmes figurés que ceux de la Figure 3.

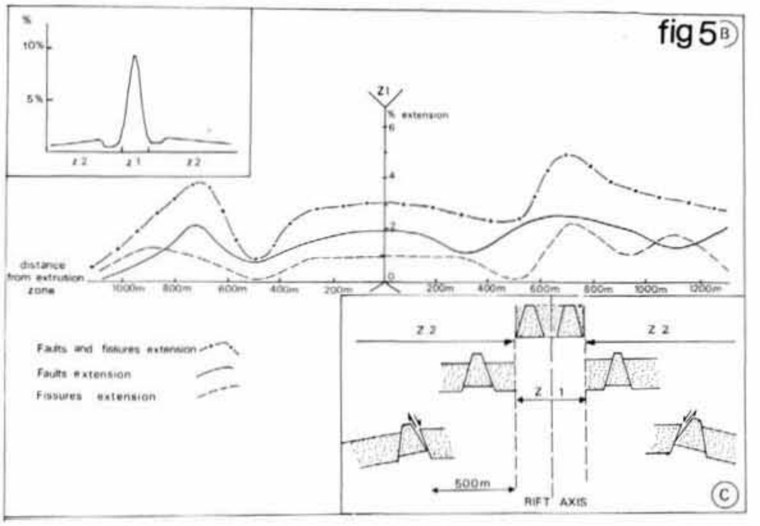


Figure 5 *b*

Diagrams showing the variation of extension in zone 2. The extension associated with normal faults is computed assuming an 80° dip.

Diagramme montrant la variation de l'extension en zone 2. L'extension associée aux failles normales est calculée pour une inclinaison de 80° du miroir de ces failles.

Figure 5 *c*

Lower right inset : schematic representation of tectonic processes in axial zone. Pure extension is replaced in outermost areas by tilting.

Encart inférieur droit : représentation schématique des processus tectoniques dans la zone axiale. L'extension pure est prise en relais dans les secteurs plus externes par un basculement.

extrusion were in a steady state (permanent axis of extrusion) ; but good preservation of old volcanic highs west of the extrusion zone, demonstrate the non-steady state nature of the extrusion process. This fine scale zonation is also locally blurred in zone 2, by sheet flows and old lava pools emplaced in zone 2. An explanation for the origin of the lava pools has been proposed by Ballard *et al.* (1979) and Francheteau *et al.* (1979).

The axial zone in the southern study area

Along dive traverses CY 78-18 and 19,60 % of the fresh lava flows are found in lava pits (Fig. 6). Along dive traverse CY 78-19, the 1,200 m wide extrusion zone is marked by intact lava pools (12 h 13 and 11 h 20) which can be detected by their roofs of lobate pillows. Along dive profile CY 78-18, the smooth nearly horizontal surface of the axial high (between 13 h 00 and 13 h 35) comprised of lobate pillows, could represent a large intact lava pool. In the northern area studied by Cyamex, lava pools were only rarely present in zone 2, close to the axial volcanic highs (CY 78-06, 08 and 12). In contrast, in the southern area, lava pools and sheeted lavas are widespread, and the flows have invaded both zones 1 and 2. The dives conducted during the Rise Program, south of the Cyamex area (Rise Project Group, 1980), have confirmed the large southward development of fluid lavas in the shallower southern axial zone. We believe that the increasing fluid-lava to pillow flow ratio as one goes south along the axis reveals a fundamental change along strike in the magmatic regime.

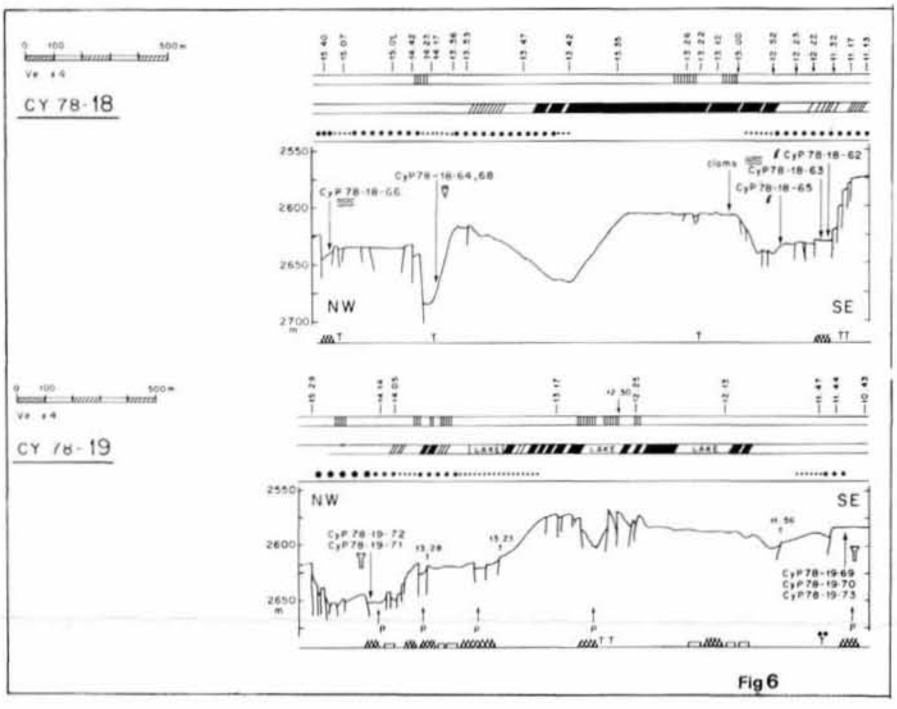


Figure 6

Geological cross sections in the southern diving area. Same caption as in Figure 3.

Coupes géologiques dans le secteur méridional de plongée. Même légende que celle de la Figure 3.

The external zone (zone 3)

The axial zone if flanked on both sides by outward tilted blocks, with wide flattish surfaces. This area of monotonous topography was observed over a width of 2 km on either side of the ridge.

Dives CY 78-07 and 10 (Fig. 4) focused on the transition between zones 2 and 3. Dives CY 78-03 and 06, reached the inward-facing fault scarps at the boundary between the two zones, where the offset is among the largest observed in the Cyamex area. The inward-facing fault scarps are arranged symetrically on either side of the axial zone, and show pillow basalts alternating with sheeted lavas along the scarp.

The top surface of the flat and smooth tilted blocks is mainly formed by slightly sedimented lobate pillows. Along dive traverse CY 78-07, 200 m west of the boundary between zones 2 and 3, sediments are 40 cm thick, and lobate pillows disappear progressively beneath the sediment cover.

Topographic highs comprised of pillow flows similar to those present in zone 2, were not seen in zone 3. The thin sediment cover in this area cannot account for the flattish morphology present in zone 3. The steady increase in sediment cover towards the external zone of the ridge, allows us to reject the hypothesis of off-axis volcanism. The tabular morphology and the large amount of lobate pillows, suggest a magmatic regime dominated by fluid lavas.

The numerous fresh talus piles present at the base of the fault scarps, suggest a continuous tectonic activity in this zone. In contrast, outward-facing faults are scarce, and open fissures are frequently present between inward-facing faults scarps and talus piles. Near the boundary of zones 2 and 3, the faults are spaced 200 m apart in a direction normal to the axis. Farther out, the frequency of faulting is decreasing progressively. The extensional process, seems to be concentrated along a few faults in the outwardmost area of zone 3.

GEOLOGY OF THE OUTER INACTIVE ZONE

A Deep Tow profile (K. McDonald, pers. comm.) across the East Pacific Rise at 21°N, from the axis to the Brunhes-Matuyama reversal area (Fig. 2 *a*) reveals two large outer topographic highs, bounded by inward-facing fault scarps.

Dive CY 78-17 was made in the area between these two topographic highs (Fig. 2 *a* and 7 *a*). Moderately sedimented talus was observed at the foot of the main faults scarps and in the depression between the two highs (12 h 47 : CY 78-17, Fig. 7 *a*). The presence of exposed talus in this area where sediment cover is important (a few meters), demonstrates very recent tectonic activity along these faults at a distance of 12 km from the ridge axis. The large offset along the faults (up to 50 m), indicates a prolonged faulting history for this fragment of oceanic crust.

In the Brunhes-Matuyama reversal area (dive traverses CY 78-15 and 16), the predominant inward-facing scarps are free of any talus (Fig. 7 *b*). In this area every fault is inactive. We conclude that tectonic activity extends at least 12 km from the ridge axis, in the region of dive CY 78-17, but is clearly absent 20 km from the axis in the reversal area.

DISCUSSION

Several observations made during the Cyana dives are worth pointing out :

a) the East Pacific Rise at 21°N can be subdivided into an active tectonic zone from the ridge axis to a distance of 12 km away from the axis, and an inactive tectonic zone beyond ;

b) the active tectonic zone is characterized by two principal styles of morphology, modified laterally by tectonic processes : rough terrain formed by volcanic highs with steep pillow basalt flow-fronts, dominating in the northern Cyamex area and smooth terrain formed by fluid lavas and partially collapsed lava pools, as in the southern axial zone and in zone 3 ;

c) the extension due to faulting is small (less than 10 %) in zone 2, but shows important variations from place to place

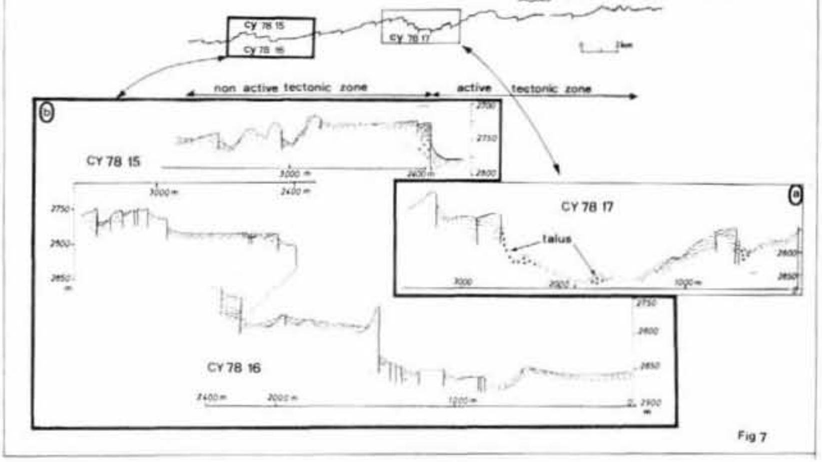


Figure 7

Geological cross sections in the outer zone. a : *Section located 12 km from the axis of EPR. Slightly sedimented talus suggest tectonic activity just ceased.* b : *Sections in the Brunhes-Matuyama magnetic reversal area.*

Coupes géologiques dans la zone externe. *a* : Coupe située à 12 km de l'axe de EPR. Les talus légèrement sédimentés suggèrent que l'arrêt de l'activité tectonique est récent. *b* : Coupes dans le secteur d'inversion magnétique Brunhes-Matuyama.

in this zone (3 to 6 %). The increase in the extension outward in zone 2, could be related to outward tilting.

Continuous and discontinuous regimes are ruling the geodynamic processes at the ridge axis.

— Continuous processes are illustrated by variation in the extension through zones 2 and 3, the general subsidence of the external zone, and the progressive decrease in the tectonic activity with distance from the axis.

— Discontinuous processes are illustrated in the en echelon disposition of the axial pillow lava highs and the lack of symmetry of zone 2 ; but they are also marked by the different types of volcanism (fluid lavas and pillow basalts), that can coexist at the same time along the strike of the East Pacific Rise.

The ratio of fluid lavas to pillow basalts increases southward from the Cyamex area to the Rise area. In the northern part of the Cyamex area, the limited amount of fluid lavas emplaced on the sea floor is unable to flood the major part of the horst and graben structures generated in zone 2. That is not the case in the south where such structures disappear below large volumes of fluid lavas delivered on the sea floor. The large percentage of lobate pillows and fluid lavas in zone 3, could represent a former large flooding episode at the axis of the East Pacific Rise.

The two types of volcanic flow have the same composition (Juteau *et al.*, 1980), and only their mode of emplacement can explain the differences between the two types of lavas.

The amount of fluid lavas necessary for a near complete flooding of structures in zone 2, has been estimated (Fig. 8 *a*). The thickness of fluid lavas showed here is compatible with the 15 m high basaltic pillars found in zone 2 (Francheteau *et al.*, 1980), and the few tens of meters of massive flows overlying pillow basalts, found in drill sites further north on the East Pacific Rise (Leg 65, DSDP, 1979). A 10 to 20 m thickness of fluid lavas is sufficient to transform the rough topography of zone 2 into the smooth morphology of zone 3.

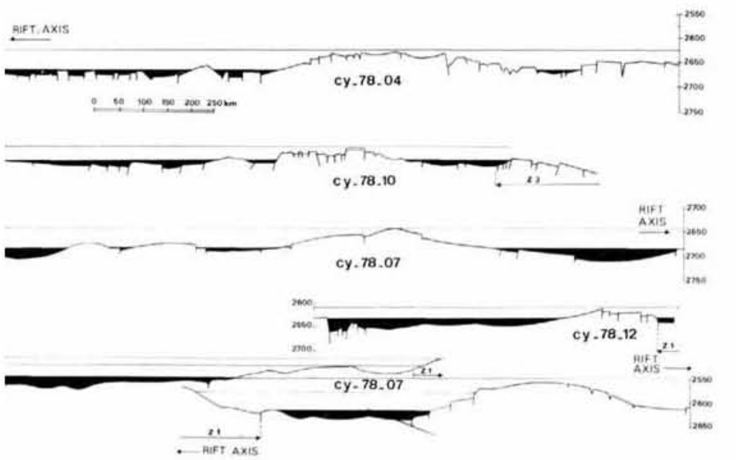


Figure 8 *a*

Flooding processes in zone 2 : the amount of hypothetical lava for smoothing the horst and graben structures is represented in black on top of observed topographic profiles (no vertical exaggeration).

Processus d'ennoyage en zone 2. La quantité hypothétique de laves nécessaire au nivellement des structures horst et graben est représentée en noir sur des profils topographiques observés (pas d'exagération verticale).

EVOLUTION MODEL, AND CONCLUSIONS

Two main cycles of volcanism alternate along the axis of the EPR (Fig. 8 *b*). We arbitrarily consider on Figure 9, that the axial zone is flooded by fluid lavas, during the first period represented in section A.

On the basis of the data collected during this diving program, the following model for the evolution of the East Pacific Rise at 21°N is proposed.

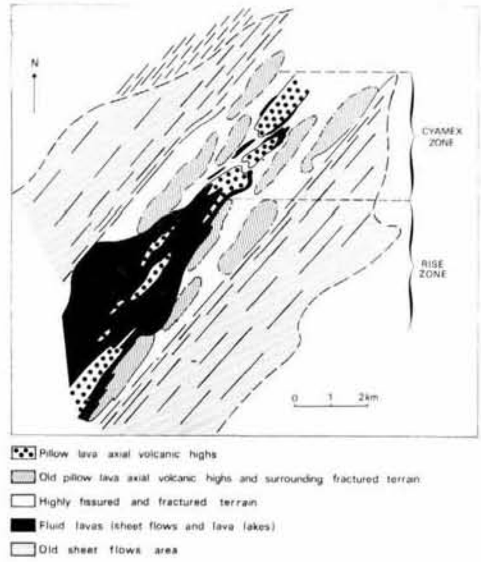


Figure 8 *b*

Schematic representation of the present distribution of fluid and pillow-lavas at 21°N based on dives conducted from Cyana (Cyamex zone) and Alvin (Rise zone).

Représentation schématique de la répartition actuelle des laves fluides et des laves en coussins à 21°N, basée sur les plongées de Cyana (secteur Cyamex) et d'Alvin (secteur Rise).

— After flooding (Fig. 9 B), a new pillow basalt cycle is initiated. Topographic highs with steep flow fronts and made up of pillow lavas, are built upon the subhorizontal sheet flows ;

— during a third stage (Fig. 9 C), axial volcanic high 1, immediately flanked by an intensively fractured zone, jups laterally in position 2. Figure 9 C represents in schematic form, a cross section of the present morphology of the East Pacific Rise across the Cyamex area ;

— after a second jump of the axial volcanic high from position 2 to 3 (Fig. 9 D), the axial zone is flooded again by a new batch of fluid lavas arriving on the seafloor.

The two types of volcanic flows emplaced at different rates, may reflect a variable instantaneous spreading rate along the East Pacific Rise. The average spreading rate calculated from the magnetic anomalies may not be representative of the geodynamic processes occurring at the axis of a moderately fast spreading ridge ; there is evidence that this is also true for slow spreading ridges. In contrast, fast and super-fast ridges may be characterized by a more continuous volcanic and tectonic regime and the spreading rate averaged over a million years may be more representative of the instantaneous behavior.

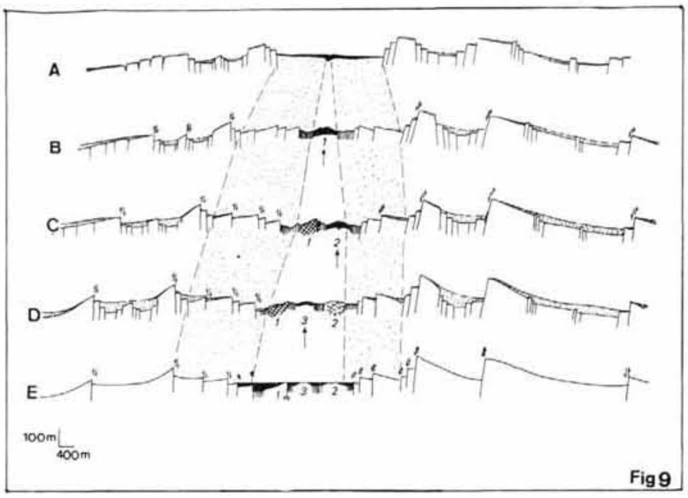


Figure 9

Evolution of the East Pacific Rise at 21°N. A : *Flooding of the axial zone by fluid lavas.* B-C-D : *Building up of fissural volcanoes jumping from positions 1 to 3 during new cycle of pillow-lava emplacement.* E : *Partial flooding of the pillowed topographic highs in the axial zone during a new cycle of fluid-lava production. On cross-sections A-D, we have illustrated the progressive burial and smoothing of outer areas under a cover of pelagic sediments by fine dots.*

Évolution de la dorsale Est Pacifique à 21°N. *A* : Ennoyage de la zone axiale par des laves fluides. *B-C-D* : Construction de volcans fissuraux sautant des positions 1 à 3 durant la mise en place d'un nouveau cycle de production de laves en coussins. *E* : Ennoyage partiel des reliefs topographiques formés de laves en coussins, dans la zone axiale, durant un nouveau cycle de production de laves fluides. Sur les coupes A à D, l'enfouissement progressif et le nivellement des zones externes sous une couverture de sédiments pélagiques sont représentés par un pointillé fin.

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REFERENCES

Allmendinger R. W., Riis F., 1979. The Galapagos Rift at 86°W. 1. Regional morphological and structure analysis, *J. Geophys. Res.*, **84,** 5379-5389.

Anderson R. N., Noltimier H. C., 1973. A model for the horst and graben structure of mid ocean ridges crests based upon spreading velocity and basalt delivery to the oceanic crust, *Geophys. J. R. Astron. Soc.*, **34,** 137-147.

Arcyana, 1975. Transform fault and rift valley from bathyscaphe and diving saucer, *Science*, **190,** 108-117.

Ballard R. D., Van Andel T. H., 1977. Morphology and tectonics of the inner Rift Valley at latitude 36°50'N on the Mid-Atlantic ridge, *Geol. Soc. Am. Bull.*, **88,** 507-530.

Ballard R. D., Holcomb R., Van Andel T. H., 1979. The Galapagos Rift at 86°W, sheet flows, collapse pits and lava lakes on the Rift Valley, *J. Geophys. Res.*, **84,** 5407-5422.

Ballard R. D., Bryan W. B., Heirtzler J. R., Keller G., Moore J. G., Van Andel T. J. H., 1975. Manned submersible observations in the Famous area Mid-Atlantic ridge, *Science*, **190,** 103-108.

Cyamex Scientific Team, 1980. First manned submersible dives on the East Pacific Rise 21°N (Project Rita). General results, *Mar. Geophys. Res.*, in press.

Francheteau J., Juteau T., Rangin C., 1979. Basaltic pillar in collapsed lava-pools on the deep ocean floor, *Nature*, **281,** 209-211.

Francheteau J., Juteau T., Needham H. D., Rangin C., 1980. *Naissance d'un océan*, CNEXO, 88 p.

Heirtzler J. R., Le Pichon X., 1974. Famous : a plate tectonics study of the genesis of the lithosphere, *Geology*, **2,** 273-274.

Juteau T., Eissen J. P., Francheteau J., Needham D., Choukroune P., Rangin C., Séguret M., Ballard R. D., Fox P. S., Normark W. R., Carranza A., Cordoba D., Guerrero J., 1980. Homogeneous basalts from the East Pacific Rise at 21°N. Steady state magma reservoirs at moderately fast spreading centers, *Oceanol. Acta*, **3,** 4, 487-503.

Klitgord K. D., Mudie J. D., 1974. The Galapagos spreading center : a near bottom geophysical survey, *Geophys. J. R. Astron. Soc.*, **38,** 563-586.

Larson R. L., 1971. Near bottom geophysical studies of the East Pacific Rise crest, *Geol. Soc. Am. Bull.*, **82,** 823-842.

Leg 65-Deep Sea Drilling Project, 1979. Drills into young ocean crust, *Geotimes*, 16-18.

Lonsdale P., 1977 *a*. Structural geomorphology of a fast spreading rise crest : the East Pacific Rise near 3°25'S, *Mar. Geophys. Res.*, **3,** 251-293.

Lonsdale P., 1977 *b*. Regional shape and tectonics of the equatorial East Pacific Rise, *Mar. Geophys. Res.*, **3,** 295-315.

MacDonald K. C., Luyendyk B. P., 1977. Deep tow studies of the structure of the Mid-Atlantic ridge crest near 37°N (Famous), *Geol. Soc. Am. Bull.*, **88,** 621-636.

Normark W. R., 1976. Delineation of the main extrusion zone of the East Pacific Rise at latitude 21°N, *Geology*, **4,** 681-685.

Rise Project Group, 1980. Hot springs and geophysical experiments on the East Pacific Rise crest, *Science*, **207,** 1421-1433.

Unternher P., 1979. La dorsale du Pacifique Est à 21°N (expédition Cyamex : projet Rita). Analyse structurale et valeurs de l'extension, *Mém. D.E.A., Univ. Bretagne Occidentale*, Brest, France.

Shih J., 1979. A study of sea-floor relief formation at spreading centers of different spreading rates using deep tow bathymetric data, *Ph. D. Thesis, Massachussetts Institute of Technology.*

Van Andel T. H., Ballard R. D., 1979. The Galapagos Rift at 86°W. 2. Volcanism, structure and evolution of the Rift Valley, *J. Geophys. Res.*, **84,** 5390-5406.