Morphology and evolution of hydrothermal deposits at the axis of the East Pacific Rise

Hydrothermalism
Submersible
Morphology
Evolution
EPR
Hydrothermalisme
Submersible
Morphologie
Évolution
Dorsale Pacifique Est

R. Hékinian[a], J. Francheteau[b], R. D. Ballard[c]
[a] Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Centre de Brest, B.P. n° 337, 29273 Brest Cedex, France.
[B] Institut de Physique du Globe, Université Paris VI, 4, place Jussieu, 75230 Paris Cedex 05, France.
[c] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA.

Received 6/7/84, in revised form 26/12/84, accepted 28/12/84.

ABSTRACT

Submersible studies of the East Pacific Rise (EPR) near 12°50'N and 11°30'N where accretion is fast (11 cm/year) reveal the existence of short segments, about 7 km in length, of intense hydrothermal activity in central depressions (< 50 m deep and < 600 m wide) running down the summit of the axial topographic ridges of the EPR. The hydrothermal edifices formed very rapidly (< 100 years) and have undergone four stages of evolution. The early stages are marked by low temperature deposits and by the development of luxuriant animal life communities. The last stage corresponds to the formation of massive sulfide associated with the waning stage of hydrothermal activity. The black smokers appear at an intermediate stage marking the climax of hot water venting. The heterogeneous internal structure of sulfide edifices is described.

Oceanol. Acta, 1985, **8**, 2, 147-155.

RÉSUMÉ

Dépôts hydrothermaux à l'axe de la dorsale du Pacifique Est : morphologie et évolution

Des études faites par submersible à 12°50'N et 11°30'N le long de la dorsale du Pacifique Est (avec un taux d'accrétion de 11 cm/an), ont montré que l'activité hydrothermale la plus intense était concentrée au niveau de segments restreints (environ 7 km de long), limitée aux dépressions tectoniques (grabens), et localisée à l'axe de la dorsale. Les édifices hydrothermaux sont créés rapidement (< 100 ans) et passent par quatre stades d'évolution. Les premiers stades de cette évolution sont marqués par la formation de dépôts à basse température (< 150°C), accompagnés par le développement d'une faune animale luxuriante. Le dernier stade de formation des édifices correspond à la mise en place de sulfures de nature « massive ». La formation des « fumeurs noirs » apparaît à un stade intermédiaire et correspond à un paroxisme de l'activité hydrothermale (250-330°C). L'hétérogénéité interne représentée par les édifices de sulfures est décrite.

Oceanol. Acta, 1985, **8**, 2, 147-155.

INTRODUCTION

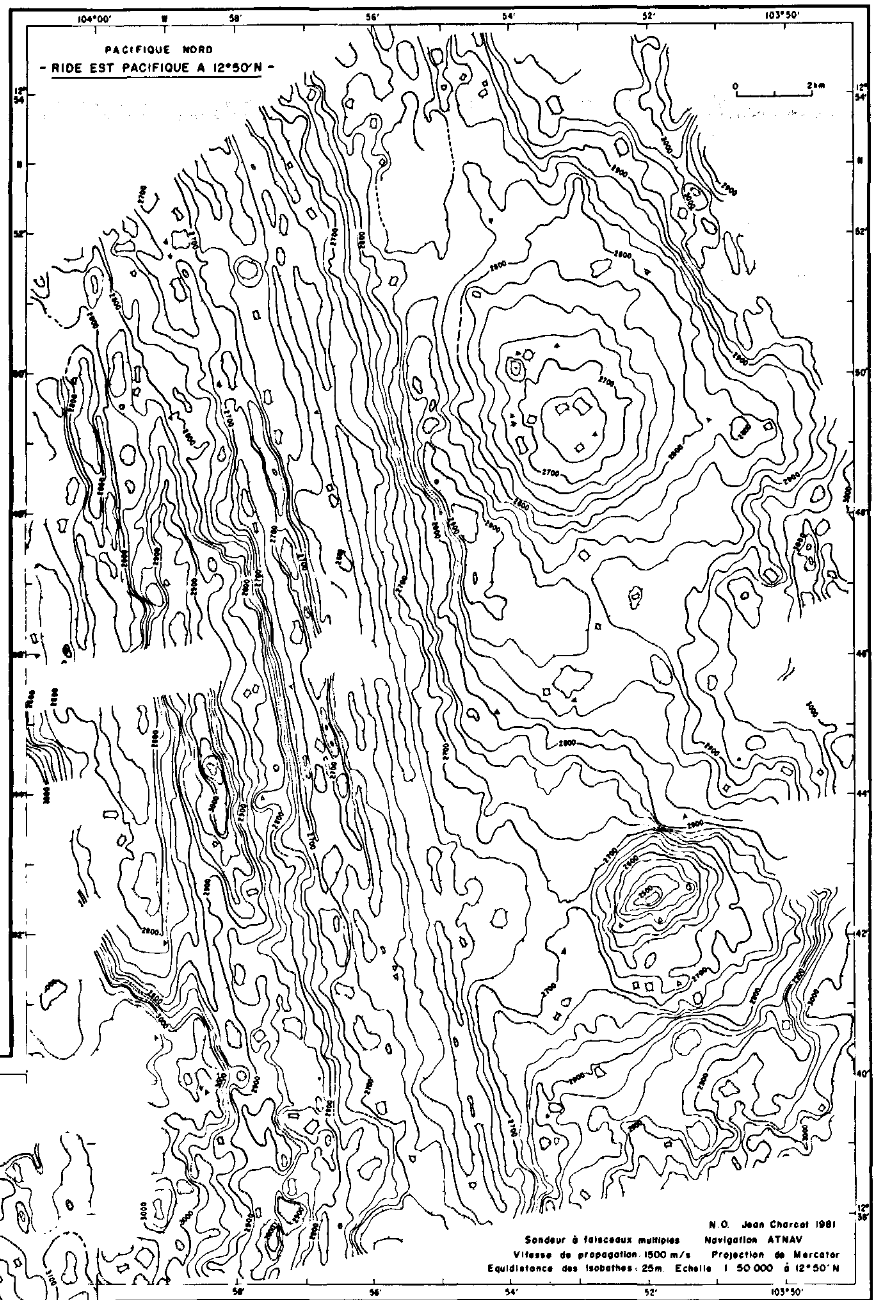
Since the discovery in 1978 of sulfide deposits on the East Pacific Rise (Cyamex, 1978; Francheteau *et al.*, 1979), using the submersible Cyana, three major oceanographic expeditions have been organized and sponsored by the Centre Océanologique de Bretagne (Centre National pour l'Exploitation des Océans, now Institut Français de Recherche pour l'Exploitation de la Mer) to study volcanic and hydrothermal processes in the Eastern Pacific. Initially, the Searise cruise (1980) carried out a large scale survey of the East Pacific Rise between 20°N and 20°S using swath bathymetric mapping (Seabeam) and deep-towed photography and temperature profiling (Raie), which recognized several indices of hydrothermal discharge zones along the strike

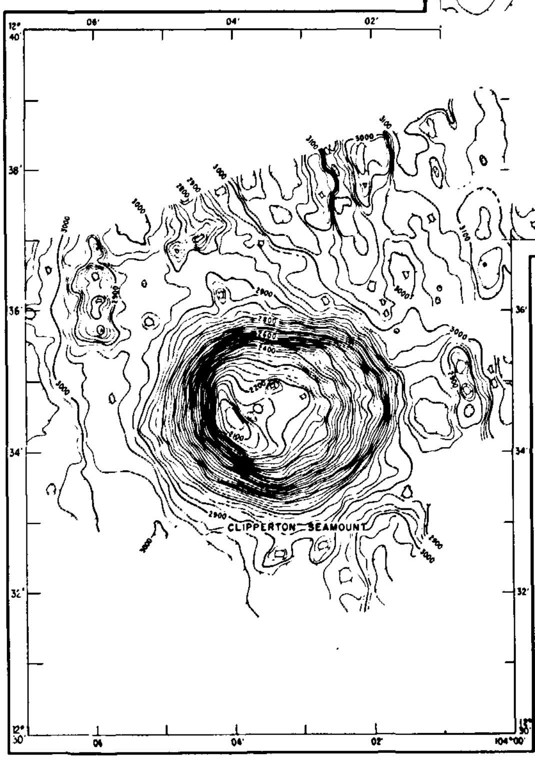
Contribution n° 0031 du Centre de Brest de l'IFREMER.

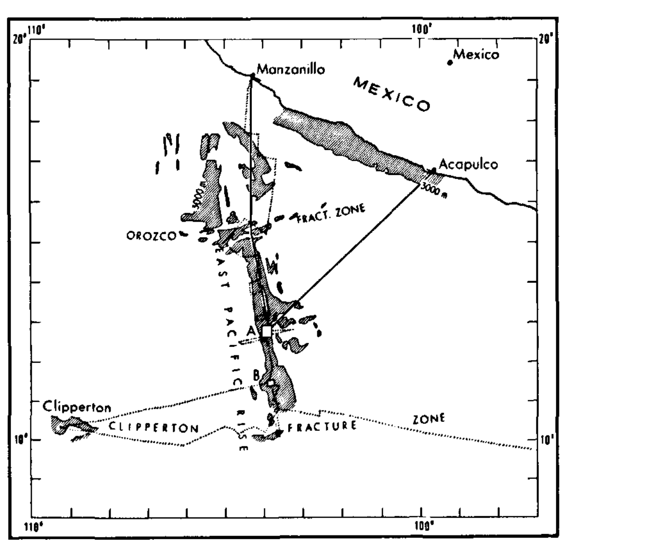
Figure 1

Detailed bathymetric map of the East Pacific Rise near 12°50'N (zone "A") made by the N.O. Jean Charcot in 1981 during the Clipperton cruise, using a hull-mounted Seabeam sonar mapping system and bottom moored transponder navigation network (ATNAV). Major off-axis seamounts are shown. The contour interval is 10 m. Generalized location map of the northern East Pacific Rise between the Orozco and the Clipperton fracture zones shows the two detailed zones ("A" and "B") studied during the 1981 Clipperton cruise and the 1982 Cyatherm cruise. The dotted lines indicate the tracks of the N.O. Jean Charcot (1981) and the continuous lines show the tracks of the N.O. Le Suroit (Cyatherm cruise, 1982).

Carte bathymétrique détaillée de la dorsale du Pacifique Est près de 12°50'N (zone « A ») dressée pendant la campagne Clipperton de 1981 du N.O. Jean Charcot. La localisation des zones étudiées en détail (« A » et « B ») est montrée en insertion sur une carte générale du Pacifique. Les lignes tiretées montrent le trajet suivi par le N.O. Jean Charcot (1981) tandis que les lignes continues montrent les trajets du N.O. Le Suroit (campagne Cyatherm 1982).







of the ridge (Francheteau, 1981; Francheteau, Ballard, 1983). The Clipperton cruise (1981) then conducted detailed studies of fast spreading segments (about 11 cm/yr-1 whole rate) on the EPR at 13°N and 11°N using the same techniques (Hékinian *et al.*, 1983). Additional studies on specific targets recognized during the previous cruises were carried out in 1982 (Cyatherm cruise) using the diving saucer Cyana (Hékinian *et al.*, 1983 *a*; Ballard *et al.*, 1984; Choukroune *et al.*, 1984). The reason for choosing these specific zones is that since they are the shallowest topographic features located between two fracture zones, they may be the location of a well developed magma reservoir including active hydrothermal circulation (Ballard, Francheteau, 1982; Francheteau, Ballard, 1983).

The portion of the East Pacific Rise situated at 13°N (zone A; average crestal depth of 2 600 m) occurs about 300 km south of the Orozco fracture zone and 100 km north of a small transform fault (STF) located at 11°49′N (Fig. 1). The other part of the Rise explored is located near 11°30′N (zone B; average crestal depth of 2 510 m) about 40 km south of the STF and 110 km north of the Clipperton fracture zone (Fig. 1). The East Pacific Rise in these two regions (zone "A" and "B") comprises an axial block of about 8 km in width and 300-400 m in height. The axial block of the rise bounded by marginal faults includes a shallow (less than 50 m in depth) central depression (graben; Fig. 2, 3 and 4). Both zones ("A" and "B") show asymmetrical structures due to the occurrence of linear depressions on the flank of their axial blocks and off-axial volcanoes (seamounts; Fig. 2 and 4).

In this article, we first summarize structural and morphological studies at the EPR axis near 13°N (zone "A": by Hékinian *et al.*, 1983 *a; b*; Choukroune *et al.*, 1984; and Ballard *et al.*, 1984). Second, we present the salient features of the East Pacific Rise axis near 11°30′N (zone "B") about 150 km to the south of the zone "A" (Fig. 1). Finally we propose an evolution for the hydrothermal edifices drawn from observations made at 21°N (Cyamex Scientific Team, 1981; Rise Project Group, 1980) and at 13°N-11°30′N on the East Pacific Rise.

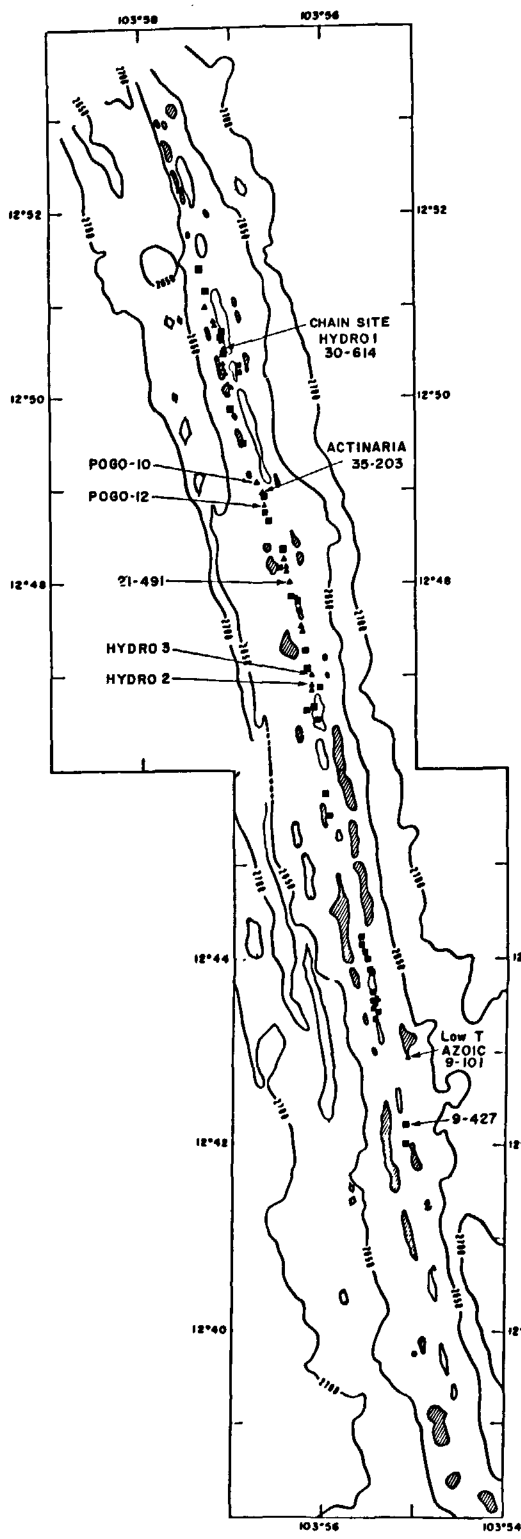


Figure 2

Distribution of active (black triangles) and inactive sites (black rectangles) observed by Cyana and deep-towed vehicles during the 1982 *Cyatherm cruise on the East Pacific Rise near* 12°50′*N. The* 2 650 *and* 2 700 *m contour lines were chosen to delineate the axial zone which includes the central graben and the two bordering rims. The dashed area represents the small highs on the rims of the graben. The sulfide deposits are lined up in the central graben. The rate of growth of a sulfide edifice was measured at the "chain site" (black smoker). The Pogo-*10 *and the Pogo-*12 *sites discovered during dives Cy* 82-10 *and Cy* 82-12 *consist of a luxuriant animal community made up essentially of pogonophorans and polychete worms. The "Actinaria" site consists also of abundant animal life as shown in Figure 5B. The numbers* (i.e. 9-427) *shown indicate the dive* (i.e. 9) *and the photograph number* (i.e. 427) *keyed to Figure* 5. *Three stations where hydrothermal fluid was sampled by Cyana (Hydro* 1, 2 *and* 3) *are also shown. The chemistry is described in Michard* et al., 1984.

La distribution des sites hydrothermaux actifs (en triangle noir) et inactifs (en carré noir) découverts pendant les plongées Cyana par un engin photographique remorqué (RAIE) le long de l'axe de dorsale du Pacifique Est à 12°50′N, est ici représentée. Les courbes de niveaux 2 650 et 2 700 m choisies permettent de délimiter le sommet de l'axe de la dorsale, entaillé d'un graben central bordé par des hauts marginaux (tireté). La plupart des dépôts de sulfure sont alignés le long de l'axe du graben. Le taux de croissance d'une cheminée hydrothermale active a été mesuré sur le site à « chaînette ». Les sites désignés par Pogo-10 et Pogo-12 et Actinaria montrent une vie animale très importante (fig. 5B). Le site appelé « Azoic » 9-101 situé en dehors du graben central sur un haut marginal est dépourvu de vie animale et construit par des sulfures plus massifs que ceux de l'axe. L'activité hydrothermale est de nature diffuse (<20°C). Les désignations : Hydro 01, 02 et 03 indiquent les sites d'échantillonnage de fluides hydrothermaux.

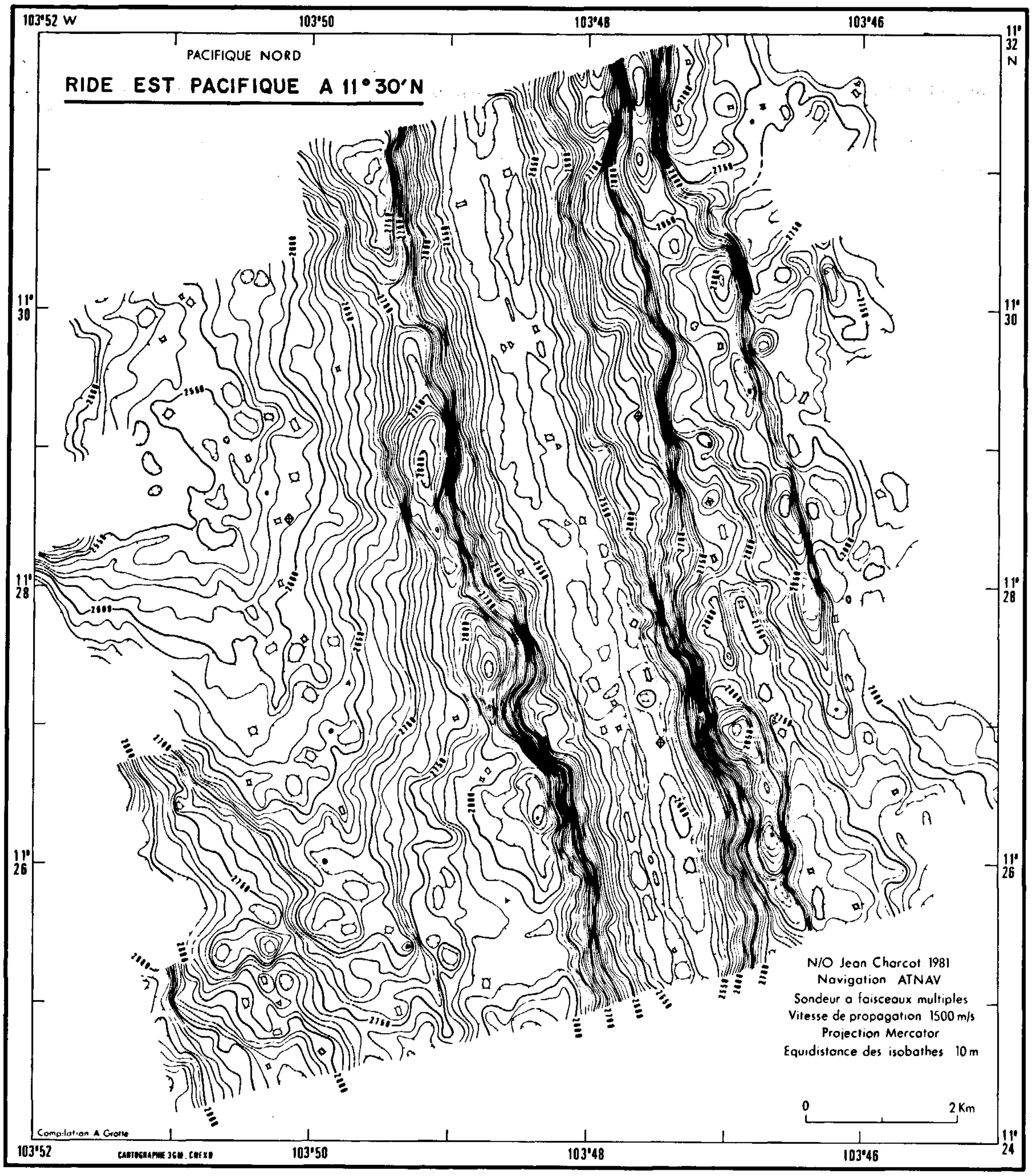


Figure 3

Detailed bathymetric map (Seabeam) of the East Pacific Rise near 11°304*N (zone "B" of the* 1981 *cruise of the N.O. Jean Charcot). The contour interval is* 10 *m. The limits of a seamount are partially seen on the north western corner of the map. The main structural features are schematized in Figure* 4.

Carte bathymétrique détaillée de la dorsale du Pacifique Est à 11°30'N (zone « B ») relevée pendant la campagne Clipperton de 1981 du N.O. Jean Charcot. Les contours sont tous les 10 m et un schéma des structures essentielles est montré en figure 4.

Figure 4

Schematic representation of the main structural and morphological features observed on the EPR near 11°30'*N (zone "B"). The segments of the active extrusive zone consisting of a depressed area (graben) and small highs (continuous lines with horizontal black triangles) are shown. The fissural domain is indicated by the darked area. The active high temperature hydrothermal fields (>*200°*C black smoker types) are shown by black triangles. The empty triangles are low temperature vents (<*30°*C "Galapagos type") with their characteristic animal communities (Fig.* 5*). The squares indicate the occurrence of sulfide (camera, stations RAIE). The data reported in the axial zone is the result of one extended deep towed station (RAIE) and two Cyana dives (Cy* 82-07 *and Cy* 82-08*). The hatched area indicates the occurrence of lobated flows. Isolated lava ponds are indicated by the letter "L". The shadowed area indicates ancient depressions (grabens) bounded with normal faults.*

Représentation schématique des principaux traits structuraux et morphologiques observés sur la dorsale du Pacifique Est à 11°30'N. La zone Ouest est caractérisée par la présence d'un seamount. Le graben central situé au sommet de la dorsale est représenté par des lignes parallèles continues avec des triangles horizontaux. Le domaine fissural du graben est indiqué par une zone foncée. Les coulées de laves lobées sont représentées par des tirets en diagonales, tandis que les laves types « à coussin » sont indiquées par des lignes horizontales. « L » est une désignation pour les lacs de laves isolées. Les régions hachurées représentent des anciennes dépressions (grabens).

MORPHOLOGY AND STRUCTURE ALONG THE RISE AXIS

The most detailed work was carried out in the area near 13°N. Eleven deep-towed camera stations, thirty two geological dives, dredging, sediment sampling, hydrocast stations, sediment trap stations, and biological sampling were performed and some of the data has been recently published elsewhere (Hékinian *et al.*, 1983*a*; *b*; Francheteau, Ballard, 1983; Michard *et al.*, 1983; Desbruyères *et al.*, 1982; Choukroune *et al.*, 1984). Zone "B", located near 11°30'N, was explored in less detail with only two dives and one deep towed camera lowering which covered three successive north-south runs along the strike of the rise axis between 11°26'N and 11°30'N (Fig. 3 and 4).

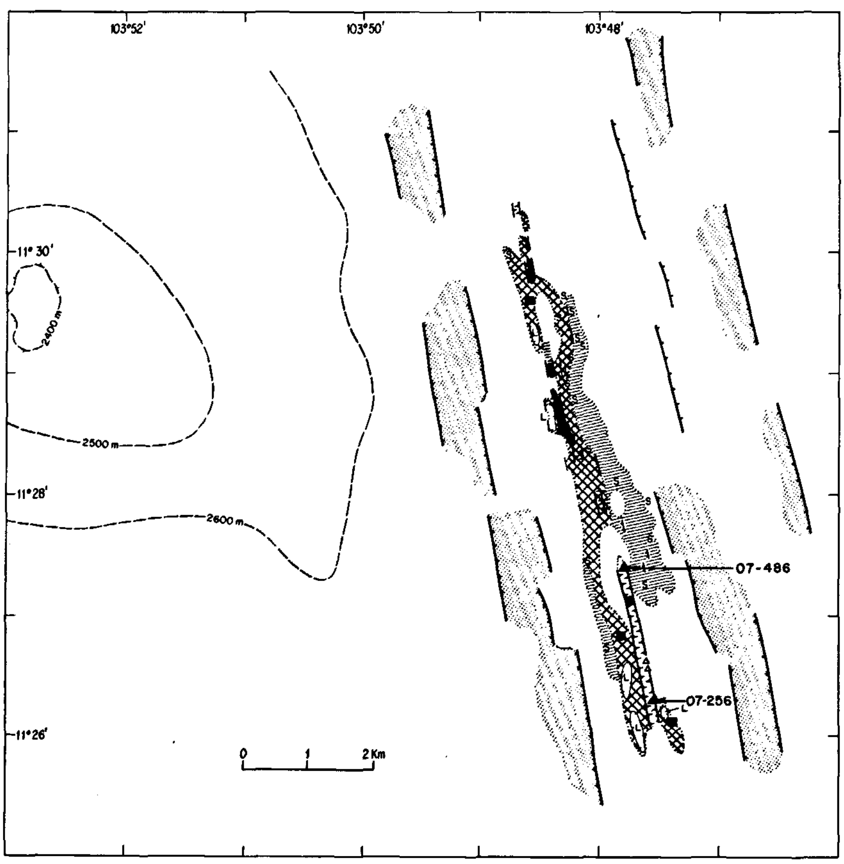
The "en échelon" segments (< 10 km in length) forming the central graben and where most of the recent hydrothermal activity occurs are divided into two major structural and morphological domains:

The "lava-pond" domain

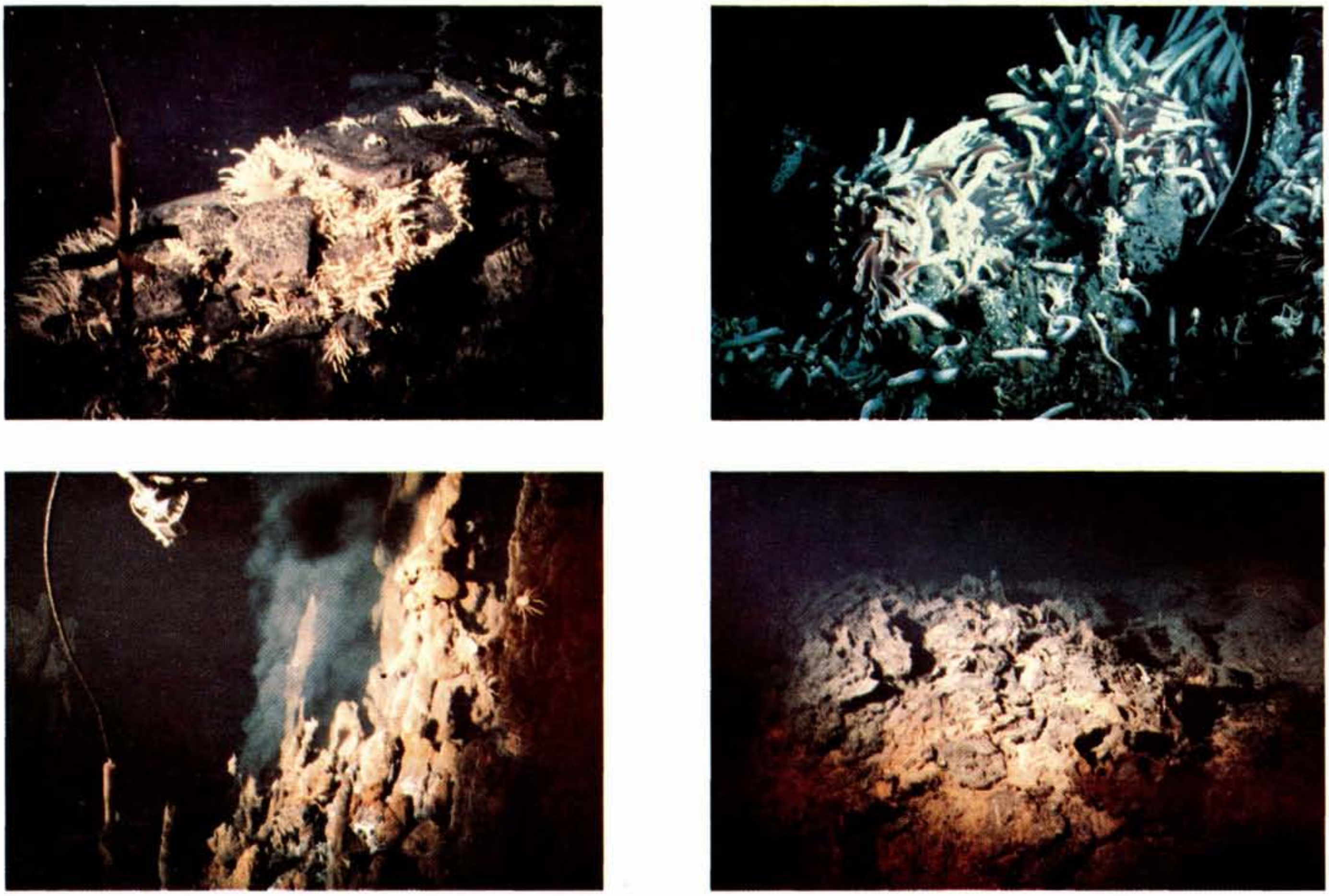
It is the most prominent terrain found at zero age along the strike of the central graben and consists of elongated collapse structures (less than 50 m in length) with "pillar" formations similar to those previously described by Francheteau *et al.* (1979) from the EPR, near 21°N and Ballard *et al.* (1979) at the Galapagos spreading center. The "lava-pond" domain includes the sites where the freshest volcanic flows occur in association with intensely active hydrothermal fields. The hydrothermal sites are discontinuously distributed in the "lava-pond" domain, and occur systematically on top of lobated flow units or inside the collapsed structures. It is also noticed that hydrothermal activity is not uniform within a single axial "en échelon" segment. High temperature vents which have formed large sulfide edifices and have very little animal life are found in association with dead vents and also with diffuse low temperature (< 30°C) vents at the same hydrothermal site or at separate sites. A hydrothermal site was previously defined (Hékinian *et al.*, 1983*b*) as being a limited area (< 50 m in diameter) comprising several large edifices topped or associated with active and inactive small chimneys (or vents). In zone "B" (near 11°30'N) both high temperature "black smoker" types of vents and low temperature (< 30°C) hydrothermal sites with abundant animal life comparable to the Galapagos type vents described by Ballard *et al.* (1982) were discovered along the same "en échelon" segments (Fig. 5A).

The fissural domain

Its is represented in the "en échelon" segments located between the "lava-pond" domains at 12°42'N and 12°46'N in zone "A" and north of latitude 11°29'N in zone "B" (Fig. 1, 3 and 4). This structural domain is characterized by tightly spaced cracks (fissures) cutting through pillows and massive flow units. The fissures are quasilinear and parallel to the main direction of the Rise axis (N 365°). They are relatively small (< 1 km in length and about 0.3-20 m in width) and are abundant across the central graben. The sporadic occurrences of



A B



C D

Figure 5

Bottom photographs taken during the Cyatherm cruise (1982) *by Cyana on the East Pacific Rise at* 12°50′*N (zone "A"; photos B and D) and at* 11°30′*N (zone "B"; photos A and C):*

A) *Active low temperature (Galapagos type) hydrothermal site (first stage of hydrothermal activity) with an abundant animal community made up of tube worms* (Pogonophora vestimentifera), *galathea, crabs and fish found on top of a lava pond wall associated with glassy basaltic slabs (Cy* 82-07, 2 525 *m depth; Fig.* 4).

B) *Luxuriant animal communities associated with small sulfide edifice representing the second stage of hydrothermal activity* (see *text for explanation). The animal life consists of pogonophorans worms associated with crabs, eel-like fishes and mussels. Dive Cy* 82-35, *photo* 203 *taken at a depth of* 2 623 *m in the axial graben near* 12°50′*N (Fig.* 2).

C) *Active high* (>200°*C) hydrothermal site ("black smoker" type) and concentration of thin and elongated chimneys at the margin of a fissure found near* 11°27′*N in the axial graben (Cy* 82-07, *photo* 486, 2 530 *m depth; Fig.* 4). *This type of activity represents the third stage of evolution of a sulfide deposit.*

D) *Degraded and oxidized hydrothermal deposit forming (fourth stage of hydrothermal activity) a mound-like edifice with relics of sulfides. Dive Cy* 82-30, *photo* 614 *taken at a depth of* 2 590 *m in the central graben (zone "A"; Fig.* 2).

Photographies sous-marines prises pendant la campagne Cyatherm de 1982 par la soucoupe plongeante Cyana sur la dorsale du Pacifique Est à 12°50′N (zone « A »; photos B et D) et à 11°30′N (zone « B »; photos A et C). Les différents types de dépôts hydrothermaux sont ici représentés :

A) Source hydrothermale active à basse température (<60°C) du type Galapagos. Exemple d'un premier stade d'activité.

B) Source hydrothermale active avec une abondante communauté animale (<150°C). Exemple d'un deuxième stade d'activité.

C) Source hydrothermale du type « fumeur noir » (>200°C) située dans une fissure du graben axial. Exemple d'un troisième stade d'activité.

D) Ancien dépôt hydrothermal altéré avec des reliquats d'édifices sulfurés.

inactive and altered sulfide fields and the presence of more altered balsaltic flows indicate that these highly fissured areas represent terrains older than the domain of lava ponds.

Ancient volcanic terrain occurs on the topographic highs (rims) which border each side of the central graben at an average depth of about 2 500 m (Fig. 3 and 4). The rims on each side of the graben consist of pillow lava having abundant interstitial and interconnected sediment networks and corresponding to the relative age groups of 1.7-2.0 defined by Ballard *et al.* (1982). Remnants of ancient "lava-ponds" among the pillow flows are scattered on the rims (Fig. 4).

FORMATION AND GROWTH OF HYDROTHERMAL EDIFICES

The hydrothermal edifices have a great variety of shapes, including massive, tubular or columnar, mound-like, conical, or irregular agglomerates of scoria-like material. As these edifices grow due to sulfide precipitation they acquire a complex structure and it is difficult to assign to them a particular geometrical shape. Previous studies on the formation of sulfide deposits have shown that the chimneys grow vertically by an early precipitation of anhydrite and Zn-Fe sulfides around a discharging column of hot fluid (Haymon, Kastner, 1981; Février, 1981; Haymon, 1983; Oudin, 1983). Mineralogical and textural observations have revealed a zonal distribution of various mineral phases related to existing temperature gradients across the walls of the individual chimneys (Le Bel, Oudin, 1982). Most of the active chimneys show a general zonation sequence from the outer wall inward of Fe-sulfide, anhydrite and Cu-sulfide. Some others consists of a pyrite, Zn-sulfide and Cu-sulfide, pyrrhotite, and silica sequence (Hékinian, Fouquet, in press). The dendritic nature of the outermost precipitates (nearest to seawater) suggests a rapid quenching condition during the chimney's building stage.

The growth of one sulfide chimney was witnessed and measured using a marker during several submersibles dives (Cy 82-25, 30, 37) which took place on an active site (Hydro 1) located near 13°50′N (zone "A", Fig. 2). When the site was revisited five days later (Cy 82-30), it was seen that a cylindrical tube about 40 cm in height, 7 cm in thickness and 10 cm in external diameter had been rebuilt above the marker, yielding an average short-term growth of 8 cm per day. It was calculated that a cylindrical shaped sulfide chimney (with average density of 2.9 g/cm^2) will increase its mass by about 1.6 kg/day. Fluid sampling (Hydro 1) carried out (Fig. 2) on the chimney whose growth was monitored showed that the metal ions dissolved in the hot fluid (mainly Fe, Mn and Zn) comprised about 0.10-0.13 $g\ l^{-1}$. The total mass of metallic products exiting from a single chimney was measured to be about 86-112 kg/day (when assuming an average flow rate of about 10 l/s; Hékinian *et al.*, 1983*b*). Thus, most of the discharged hydrothermal products (98%) are dispersed and deposited elsewhere and only a small portion precipitates *in situ* and contributes to the formation of a chimney.

Extending the growth rate of a single chimney, an entire sulfide edifice (6 m in height, 3 m in base diameter and weighing about 41 t) built by the coalescence of several chimneys would be formed in less than 100 years (Hékinian *et al.*, 1983). The young age for the sulfide edifice formations is also corroborated by recent age dating (< 70 years) using the $^{210}Pb/Pb$ methods on the hydrothermal deposits from 21°N and 12°50′N of the EPR (Lalou, Brichet, 1981; Lalou *et al.*, 1985).

We now present a model for the evolution of a sulfide field.

The early stage of hydrothermal activity is marked by inter-pillow low temperature (< 30°C) fluid discharge seen as shimmering clear water. The rocks at the venting area are stained orange, red and white by the iron, aluminium and magnesium hydroxide precipitates which are similar to those found at 21°N (Cyamex Scientific Team, 1979; Rise Project Group, 1980). Animal communities made up of short tube worms (pogonophorans), crabs and mussels start to develop along the cracks of the lava flows from which warm fluid is exiting (Fig. 5A, B).

The second stage is reached with an increase in hydrothermal activity leading to an outpouring of mainly diffuse white colored fluid. The high pH (> 5)

A

B

C

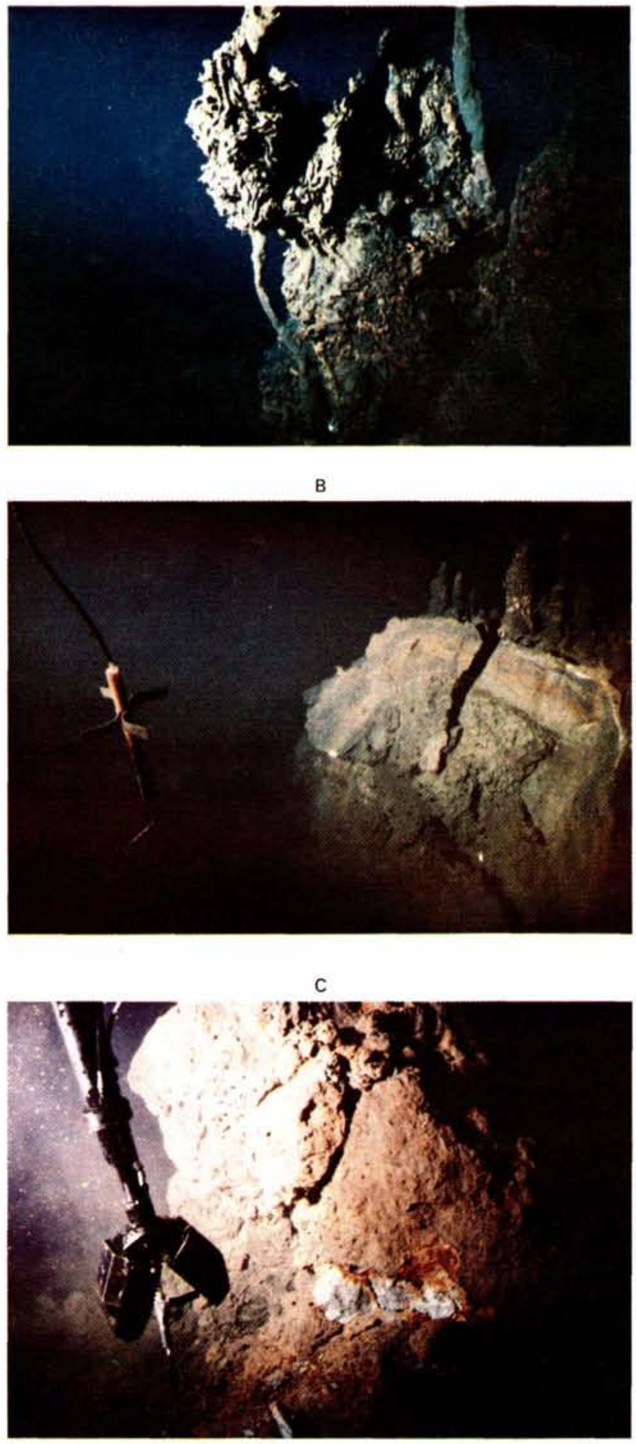


Figure 6

Inactive sulfide edifices representing the fourth stage of evolution of a hydrothermal deposit:
A) *Sulfide edifice (Cy* 82-09, *photo* 427) *showing the internal structure of an edifice with an hydrothermal conduct (left hand side of the edifice) and empty tubes of polychete worms seen at a depth of* 2 631 *m. For location* see *Figure* 2.
B) *Cross section (about* 2 *m across) of a sulfide edifice split by a fissure (Cy* 82-21, *photo* 491, 2 622 *m). Cyana is sitting on the other collapsed half of the edifice. The interior of the edifice consists of tubular structures and the margin is made up of layered massive sulfides. Dead chimneys are overlaying the edifice (Fig.* 2).
C) *Massive sulfide deposit made up essentially of Fe-sulfide and minor amounts of Cu precipitates found on the Eastern rim of the graben at* 2 596 *m depth (dive Cy* 82-09, *photo* 101, *azoic site Figure* 2).

Édifice de sulfures inaltérés représentant un 4ᵉ stade d'évolution de dépôts hydrothermaux :
A) Édifice sulfuré montrant une structure interne de conduit.
B) Section à travers un édifice de sulfure fissuré.
C) Sulfure massif fait essentiellement de pyrite avec des concentrations mineures en Cu (< 3 %).

of the white colored fluid suggests that mixing of hydrothermal fluid with ambient seawater takes place prior to venting throughout the porous edifices. Prior to mixing, precipitation of sulfides will give rise to small (< 1 m in height) edifices having an oval shape similar to "snowball" edifices and first observed at 21°N (Rise Project Group, 1980). These small edifices contain orifices similar to "honey-combs" which are filled with small polychete worms called "Alvinella" by Desbruyères and Laubier (1979). It is at this stage of low temperature sulfide precipitation that luxuriant animal communities made up of long tube worms (Pogonophorans) reaching up to 1.5 m in length and associated with crabs, eel-like fish, and mussels are observed to have colonized the site. While the temperature within the edifice is around 100°-200°C, the animal community surrounding the edifice lives in a lower temperature (< 50°C) environment.

During the third stage, when the intensity of hydrothermal discharge reaches a climax, small (< 1 m high) cylindrical, or irregular shaped chimneys are formed around the hot column (200°-350°C) of dark colored fluid (Fig. 5C). These types of chimneys consist essentially of chalcopyrite and Zn-sulfides, the dark colored and high-temperature fluid with a pH of less than 5 being enriched in Ca, Si, Rb, Mn, K and Cl and depleted in Mg and SiO_4 with respect to seawater (Michard *et al.*, 1984; Edmond *et al.*, 1982). At this stage, the luxuriant animal community has declined considerably because of the high temperature environment and the high rate of sulfide deposition which buries the organisms. Both the extensive growth of new chimneys and the burial of the sessile animals (mainly worms) contribute to the formation of large edifices. Growth continues as long as there is a fissure in the basement rocks and open pathways in the edifices.

The fourth and waning stage is reached when the individual chimneys and their orifices are clogged by hot sulfide deposition and when only diffuse intermediate to low temperature (< 250°C) venting takes place (Hékinian and Fouquet, in press). This stage produces a more massive texture on the edifices because the voids are filled by late low temperature precipitates. Evidence for this process is seen on the outer massive layer (about 15 cm thick) of an edifice split by a fissure cutting through and exposing its internal structure (Fig. 6B). The outer layer (about 15 cm thick) of the edifice consists of zoned massive sulfide (Fig. 6B). The central portion of the edifice is made up of cavities and pore spaces consisting of interconnecting tubes having a scoriaceous aspect due to the presence of voids (Fig. 6B). Some of the tubes which are short and contorted are probably the remnants of polychete tubes (Alvinella) which colonized the edifice during its early stage of growth. The internal structure of the edifices is shown by the skeleton of an old chimney remnant which shows the imbricate plumbing system of an edifice (Fig. 6A, B). This is also revealed by fissures which have cut through an entire edifice (Fig. 6B). Koski *et al.* (1984) discovered on the Juan de Fuca Ridge massive structures made up of low temperature Zn-rich sulfides and Fe-sulfides which they thought represented late stage precipitates which have grown outward coating a hydrothermal edifice. Massive deposits made up of iron (and minor copper) sulfide have been observed and sampled on the eastern rim of the graben (azoic site, *see* Fig. 2, 6C) and also on the flank of the large southeastern seamount. When the hydrothermal activity has completely ceased, the edifices tend to degrade (Cyamex Scientific Team, 1978) because of the highly oxygenated environment of seawater which reacts with the metallic sulfides and forms oxides and hydroxides of iron (limonite), goethite and hydrated copper chlorite such as atacamite (Février, 1981; Fig. 4D). These older deposits are associated with manganese and iron rich compounds and resemble the oxidized capping zone (gossan) of ancient sulfide rich deposits.

SUMMARY AND CONCLUSIONS

Fast spreading segments of the East Pacific Rise near 12°50′N (zone "A") and 11°30′N (zone "B") show similar geological settings. The axial graben which is found in both zones, although less well developed in part of zone B, is comprised of "en échelon" segments dominated by either lava pond terrain with fresh flows and active hydrothermal sites or fissured terrain with older volcanic flows and fossil sulfide deposits. On evidence drawn from 13°N with support from 21°N, the evolution of hydrothermal activity can be described to occur in four main stages. The first stage corresponds to venting of clear warm water (< 30°C). The second stage is marked by the appearance of luxuriant life around "snowball" type edifices which diffuse hot water (< 250°C) and yield small sulfide deposits. The third stage which produces large porous sulfide edifices is marked by the climax of hot water venting (200-350°C) out of black smokers and a near extinction of life. The fourth and waning stage is that of massive sulfide formation with void filling through continuing diffuse low temperature venting. The Galapagos spreading center sites (Corliss *et al.*, 1979) are in the first stage, the sites in the Rise region, near 21°N (Rise Project Group, 1980) are in the second stage; and most of the sites at 13°N in zone "A" are in the third stage. The off-axis sites near 12°43′N on the eastern rim and on the southeastern seamount are in the fourth stage of formation during which intermediate to low temperature (< 200°C) Fe-rich sulfide phases have precipitated.

Acknowledgements

This study was made possible thanks to the Centre National pour l'Exploitation des Océans (CNEXO) now IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer) which supported the program for the study of ocean floor hydrothermalism. The authors wish to thank Captains G. Paquet of the N.O. Jean Charcot during the Clipperton cruise (1981) and J. Keranflec'h of the N.O. Le Suroit during the Cyatherm cruise (1982). We are also grateful to J. Roux and the Cyana's diving and navigation teams for their skillful handling of the submersible during the various legs. D. Desbruyères was helpful in discussing the biology of the sites. R. D. Ballard wishes to thank the National Science Foundation (OCE 80-20425) for supporting his participation in the Cyatherm cruise. J. Francheteau thanks the PIROCEAN (CNRS) for its support.

REFERENCES

Arcyana, 1977. Rocks collected by bathyscaphe and diving saucer in the Famous area of the Mid-Atlantic rift valley: petrological diversity and structural setting, *Deep-Sea Res.*, **24**, 565-589.

Ballard R. D., Francheteau J., 1982. The relationship between active sulfide deposition and the axial processes of the mid-ocean ridge, *Mar. Technol. Soc. J.*, **16**, 2, 8-22.

Ballard R. D., Holcomb R. T., Van Andel T. H., 1979. The Galapagos rift at 86°W: sheet flows collapsed pits and lava lakes of the rift valley, *J. Geophys. Res.*, **84**, 5407-5422.

Ballard R. D., Van Andel T. H., Holcomb R. T., 1982. The Galapagos rift at 86°W: variations in volcanism, structure and hydrothermal activity along a 300 km segment of the rift valley, *J. Geophys. Res.*, **87**, B2, 1149-1161.

Ballard R. D., Hékinian R., Francheteau J., 1984. Project Cyatherm: detailed investigation of hydrothermal activity at 12°50'N on the East Pacific Rise, *Earth. Planetary Sci. Lett.*, **69**, 176-186.

Choukroune P., Francheteau J., Hékinian R., 1984. Tectonics of the East Pacific Rise near 13°N from field observations, *Earth. Planetary Sci. Lett.*, **68**, 115-127.

Corliss J. B., Dymond J., Gordon L. I., Edmond J. M., Van Herzen R. P., Ballard R. D., Green K., Williams D., Bainbridge A., Crane K., Van Andel T. H., 1979. Submarine thermal springs on the Galapagos rift, *Science*, **203**, 4385, 1073-1082.

Cyamex Scientific Team, 1978. Découverte par submersible de sulfures polymétalliques massifs sur la dorsale du Pacifique oriental par 21°N (projet Rita), *C. R. Acad. Sci. Paris, Ser. D*, **287**, 1365-1368.

Cyamex Scientific Team, 1979. First manned submersible dives on the East Pacific Rise at 21°N (project Rita): general results, *Mar. Geophys. Res.*, **4**, 345-379.

Cyamex Scientific Team, 1981. Massive deep-sea sulfide ore deposits discovered on the East Pacific Rise, *Nature*, **277**, 5601, 523-528.

Desbruyères D., Laubier L., 1979. *Alvinella pompeijena* gen., Ampharetеidae aberrant des sources hydrothermales de la ride du Pacifique Est, *Oceanol. Acta*, **3**, 3, 267-271.

Desbruyères D., Crassous P., Grassle J., Khripounoff A., Reyss D., Rio M., Van Praet M., 1982. Données écologiques sur un nouveau site d'hydrothermalisme actif de la ride du Pacifique oriental, *C. R. Acad. Sci. Paris*, **295**, 3, 289-294.

Edmond J. M., Van Damn K. L., Mc Duff R. E., Measures C. I., 1982. Chemistry of hot springs on the East Pacific Rise and their affluent dispersal, *Nature*, **297**, 187-191.

Février M., 1981. Hydrothermalisme et minéralisation sur la dorsale est-pacifique à 21°N, *Thèse 3e cycle, Univ. Bretagne Occidentale et Centre Océanologique de Bretagne*, 270 p.

Francheteau J., 1981. Characteristics of the axial region of the East Pacific Rise (abstract), AGU Chapman confer.

Francheteau J., Ballard R. D., 1983. The East Pacific Rise near 21°N, 13°N and 20°S: inferences for along-strike variability of axial processes of the mid-ocean ridge, *Earth. Planetary Sci. Lett.*, **64**, 93-113.

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

Haymon R. M., 1983. The growth history of hydrothermal "black smoker" chimneys, *Nature*, **301**, 5902, 695-698.

Haymon R. M., Kastner M., 1981. Hot spring deposits on the East Pacific Rise at 21°N: preliminary description of mineralogy and genesis, *Earth Planetary Sci. Lett.*, **53**, 363-381.

Hékinian R., Fouquet Y., 1984. Volcanism and metallogenesis of axial and off-axial structures on the East Pacific Rise near 13°N, *Econ. Geol.* (in press).

Hékinian R., Février M., Bishoff J. L., Picot P., Shanks W. C., 1980. Sulfide deposits from the East Pacific Rise near 21°N, *Science*, **207**, 1433-1444.

Hékinian R., Février M., Avedik F., Cambon P., Charlou J. L., Needham H. D., Raillard J., Boulègue J., Merlivat L., Moinet A., Manganini S., Lange J., 1983 *a*. East Pacific Rise near 13°N: geology of new hydrothermal fields, *Science*, **219**, 1321-1324.

Hékinian R., Francheteau J., Renard V., Ballard R. D., Choukroune P., Cheminée J.-L., Albarède F., Minster J.-F., Charlou J.-L., Marty J.-C., Boulègues J., 1983 *b*. Intense hydrothermal activity at the axis of the East Pacific Rise near 13°N: submersible witnesses the growth of sulfide chimney, *Mar. Geol. Res.*, **6**, 1-14.

Koski R. A., Clague D. A., Oudin E., 1984. Mineralogy and chemistry of massive sulfide deposits from Juan de Fuca Ridge, *Geol. Soc. Am. Bull.*, **95**, 930-945.

Lalou C., Brichet É., 1981. Possibilités de datation des dépôts de sulfures métalliques hydrothermaux sous-marins par les descendants à vie courte de l'uranium et du thorium, *C. R. Acad. Sci. Paris*, **293**, 2, 821-826.

Lalou C., Brichet É., Hékinian R., 1985. Age dating of sulfide deposits from axial and off-axial structures on the East Pacific Rise near 12°50'N, submitted to *Earth. Planetary Sci. Lett.*

Le Bel L., Oudin E., 1982. Fluid inclusion studies of deep-sea hydrothermal sulfide deposits on the East Pacific Rise near 21°N, *Chem. Geol.*, **37**, 129-136.

Michard A., Albarède F., Michard G., Minster J.-F., Charlou J.-L., 1983. Rare-earth elements and uranium in high-temperature solutions from the East Pacific Rise hydrothermal vent field (13°N), *Nature*, **303**, 795-797.

Michard G., Albarède F., Michard A., Minster J.-F., Charlou J.-L., Tan M., 1984. Chemistry of solution from 13°N North East Pacific Rise hydrothermal site, *Earth Planetary Sci. Lett.*, **67**, 297-307.

Oudin E., 1983. Minéralogie de gisements et indices liés à des zones d'accrétion océaniques actuelles (ride est-pacifique et Mer Rouge) et fossile (Chypre), *Chron. Rech. Min. BRGM*, **470**, 43-56.

Rise Project Group, 1980. East Pacific Rise: hot spring and geophysical experiments, *Science*, **207**, 4438, 1421-1433.