Nazca plate fragmentation off Peru : the Mendaña fracture zone*

Peru
Nazca Plate
Mendaña fracture zone
Magnetic anomalies
Fragmentation

Pérou
Plateau de Nazca
Zone de fracture de Mendaña
Anomalies magnétiques
Fragmentation

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ABSTRACT

The Mendaña Fracture Zone is a major intra-oceanic feature on the Nazca Plate off Peru. During the Seaperc cruise of R/V *Jean Charcot* in 1986, Seabeam bathymetric data, single channel seismic records, geomagnetic and gravity measurements and heat flow data were obtained over this area. In this paper, we show that the Mendaña Fracture zone is actively opening perpendicular to its trend, resulting in the formation of new oceanic crust since about 3.5 Ma. This new rift is propagating westward along the fracture zone at a velocity of about 17 cm.yr^{-1} with respect to the trench). The origin of the Mendaña spreading centre would be the extensional stress acting parallel to the Peru Trench in this area.

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RÉSUMÉ

Fragmentation de la plaque Nazca au large du Pérou : la zone de fracture de Mendaña

La zone de fracture de Mendana est une structure majeure de la plaque Nazca, au large du Pérou. En 1986, pendant la campagne Seaperc du N/O Jean Charcot, des données bathymétriques Seabeam, de la sismique monotrace, des mesures magnétiques, gravimétriques et de flux de chaleur ont été acquises sur l'extrémité orientale de la zone de fracture de mendana, à la jonction avec la fosse du Pérou. Dans ce travail, nous montrons que la zone de fracture est le siège d'une ouverture active, perpendiculaire à sa direction générale. Une nouvelle croûte océanique s'y fabrique depuis 3,5 Ma. Cette zone d'accrétion de croûte océanique, se propage vers l'Ouest à une vitesse de 17 cm/an (8,5 cm/an par rapport à la fosse). L'origine de la zone d'accrétion de Mendaña serait l'extension reconnue dans cette région et dont la direction est parallèle à la fosse, en réponse à la subduction.

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INTRODUCTION

The break-up of an oceanic plate into two new plates has been addressed by several authors (Hey, 1977; Hey *et al.*, 1977; Wortel and Cloetingh, 1981) using the Cocos-Nazca spreading ridge as a case example. The Cocos-Nazca spreading centre is thought to have originated from the Peru-Chile Trench 23 Ma ago and to have propagated westward at a rate of 7.1 cm. yr^{-1}, along a pre-existing Pacific-Farallon Fracture Zone inferred to be the Marquesas Fracture Zone (Hey, 1977). This process led to the fragmentation of the Farallon Plate and the birth of the Cocos and Nazca Plates.

The present interest in the Mendaña Fracture Zone (MFZ hereafter), located on the Nazca Plate off Peru, stems from the hypothesis of Hilde *et al.*, (1980) who postulated, on the basis of bathymetric and Gloria long-range side-scan sonar data, that the MFZ is the locus of an active spreading centre that propagates seaward. This propagating rift was assumed to have formed in response to subduction-induced extensional stresses in the Nazca Plate. Further support for this hypothesis is provided by finite element stress-models of the Nazca Plate (Richardson and Cox, 1984; Wortel and Cloetingh, 1985) which indicate that the Nazca Plate in the vicinity of the MFZ exhibits an extensional stress oriented parallel to the trench axis.

Another structure on the Nazca Plate off Peru is the Trujillo Trough (TT hereafter), which joins the Peru Trench to the Vera Fracture Zone (VFZ hereafter). Warsi *et al.* (1983), and Huchon and Bourgois (1990) situate, a westward-trusting ("tectonic front") along the eastern edge of the TT. The TT, being located about 200 km to the north of the MFZ, Huchon and Bourgois established a relationship between the MFZ where oceanic crust accretes and the TT where a possible intra-oceanic thrusting occurs.

In order to answer the question concerning the mechanism of fragmentation of oceanic plates, the Mendaña Fracture Zone (Fig. 1) was surveyed during the Seaperc cruise of R/V *Jean Charcot* in 1986 (Bourgois *et al.*, 1986; Pautot *et al.*, 1986; Bourgois *et al.*, 1987; Bourgois *et al.* 1988). During this cruise, we used a Seabeam system that provided a real-time contoured map of the sea floor on a scale of 1: 25,000 and with 20-metre contour intervals. Underway geophysical measurements (magnetics and gravity) as well as single-channel seismic records were also obtained. In addition, heat flow measurements and core samples were obtained along a transect perpendicular to the MFZ. The GPS was used in addition to standard satellite navigation, to obtain the ship's location, and provided an accurate and suitable resolution of about 100 metres.

The Mendaña "box" (Fig. 1) was surveyed to test the Hilde *et al.* (1980) hypothesis by means of a dense magnetic and bathymetric coverage of the MFZ near its junction with the Peru Trench.

GEODYNAMIC SETTING

The Nazca Plate (Fig. 1) is bounded by the Peru-Chile Trench to the east and by three active spreading ridges :

- to the north, the Cocos Ridge exhibits an E-W trend perpendicular to the Peru-Chile Trench;
- to the west, sea-floor spreading occurs at the East Pacific Rise at a total rate of about 16 $cm.yr^{-1}$. Spreading activity shifted 600 km to 850 km westward from the old Galapagos Rise, now in the centre of the Nazca Plate. Three large jumps occurred from 8.2 Ma to 5.7 Ma ago that led to the present time situation (Rea, 1981);
- to the south, the Nazca-Antarctica Plate boundary is along the Chile Rise that joins the Peru-Chile Trench at 45°S to the East Pacific Rise at 34°S. The Chile Rise is inherited from the old Galapagos Rise.

The present kinematics of the Nazca plate is mainly controlled by the East Pacific Rise spreading centre. The pole of relative motion between the Nazca and South America Plates is located near 95°W and 60°N, some 6 000 km north of the Nazca Plate. Consequently, the motion the Nazca-South America consuming boundary is convergent (azimuth N80°E) at a rate of about 8.5 $cm.yr^{-1}$ according to the RM2 model of Minster and Jordan (1978).

Studies on the past motion of the Nazca Plate with respect to South America shows that the convergence history can clearly be separated into a pre-anomaly 7 (28 Ma) period when the convergence occurred along a N45°E direction at an average rate of 9.5 $cm.yr^{-1}$ and a post-anomaly 7 period when the motion was faster (11 $cm.yr^{-1}$) along a N80°E direction (Pilger, 1983; Cande, 1984). This abrupt change during anomaly 7 time has been related to the break up of the Farallon Plate into the present Nazca and Cocos Plates (Pilger, 1981). This period also coincided with a major change in spreading velocity in the Atlantic Ocean and with the beginning of the uplift of the Andes (Burke and Wilson, 1972). More recently, at anomaly 3 time (4 Ma ago), there was a significant decrease in the convergence rate (from 11 to 9 $cm.yr^{-1}$).

The MFZ is an oceanic fracture located on the Nazca Plate off Peru (Fig. 1 and 2). It trends approximately N65°E and intersects the Peru trench between 9°40'S and 10°35'S. Bathymetry indicates that :

- the width of the MFZ increases eastward towards the trench, being 50 km wide approximately 400 km seaward of the trench and approximately 100 km at its junction with the trench;
- a series of parallel ridges and troughs trending N65°E occurs within the MFZ. The spacing between these ridges increases eastward toward the trench. Near, the trench axis these ridges are devoid of sediment cover. However, sediment is noted inside the troughs. The spreading fabric of the Nazca Plate to either side of the MFZ is observed to differ by 7 to 8° : it trends N145°E to N150°E to the north and N153°E to N158°E to the south (Fig. 2). The spreading fabric of the Nazca Plate is roughly perpendicular to that of the MFZ. The average depth of the Nazca Plate is about 5 000 metres south of MFZ and 4 500 metres to the north. Magnetic anomalies of the Nazca Plate on either side of

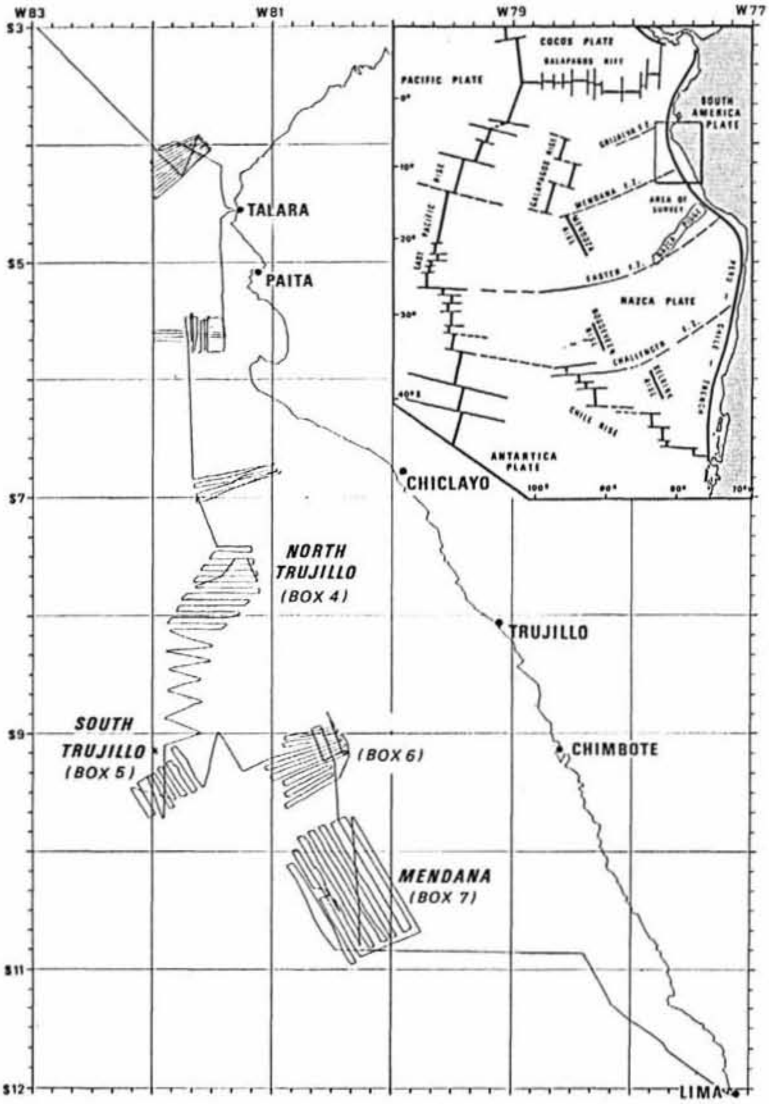

Figure 1

Geodynamic setting of the survey area and track lines during the SEAPERC cruise off Peru.

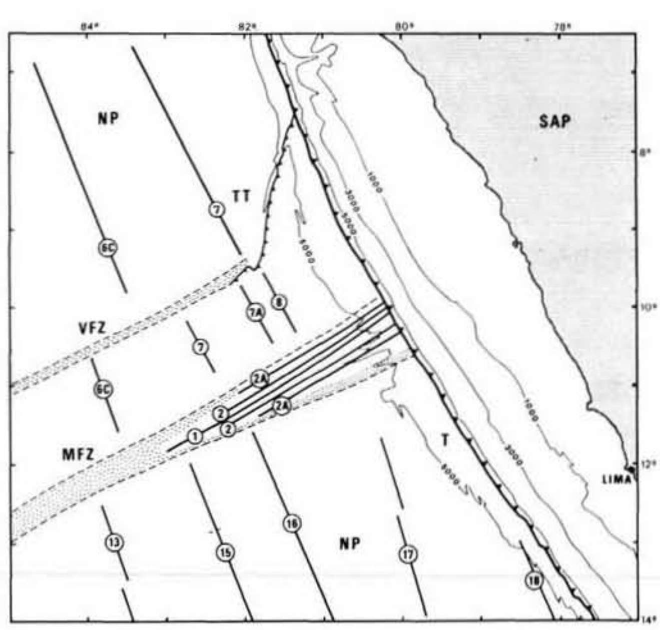

Figure 2

Simplified structural map of the mendana – Trujillo area. Main magnetic anomalies are identified. MFZ : Mendana Fracture Zone, NP : Nazca Plate, SAP : South America Plate, T : Peru Trench, TT : Trujillo Trough, VFZ : Vera Fracture Zone.

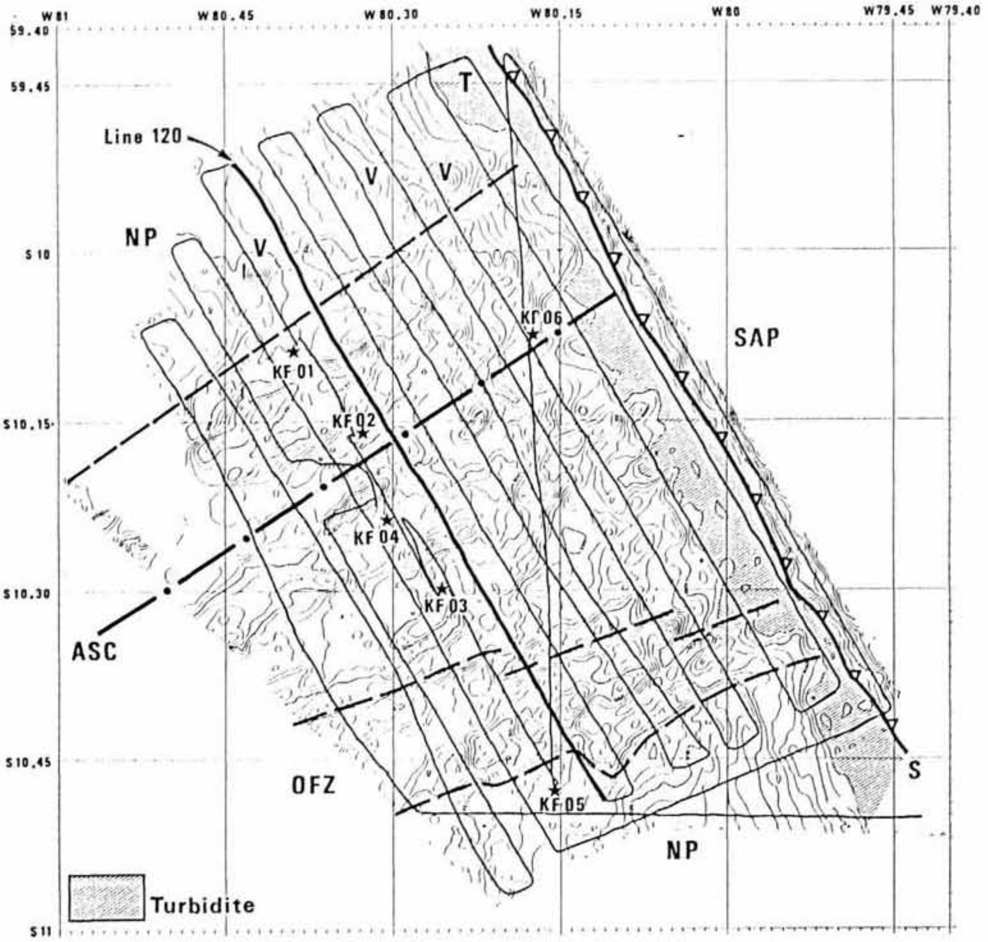

Figure 3

Seabeam bathymetric map of the Mendana area. Solid lines : tracks. Hachured pattern : trench floor. ASC : active spreading centre, NP : Nazca Plate, OFZ : Old Fracture Zone, S : Subduction front, SAP : South America Plate, T : Peru Trench, V : Volcano. KF01 to KF06, heat flow measurements. Location of line 120 (Fig. 6) is shown as a thick line.

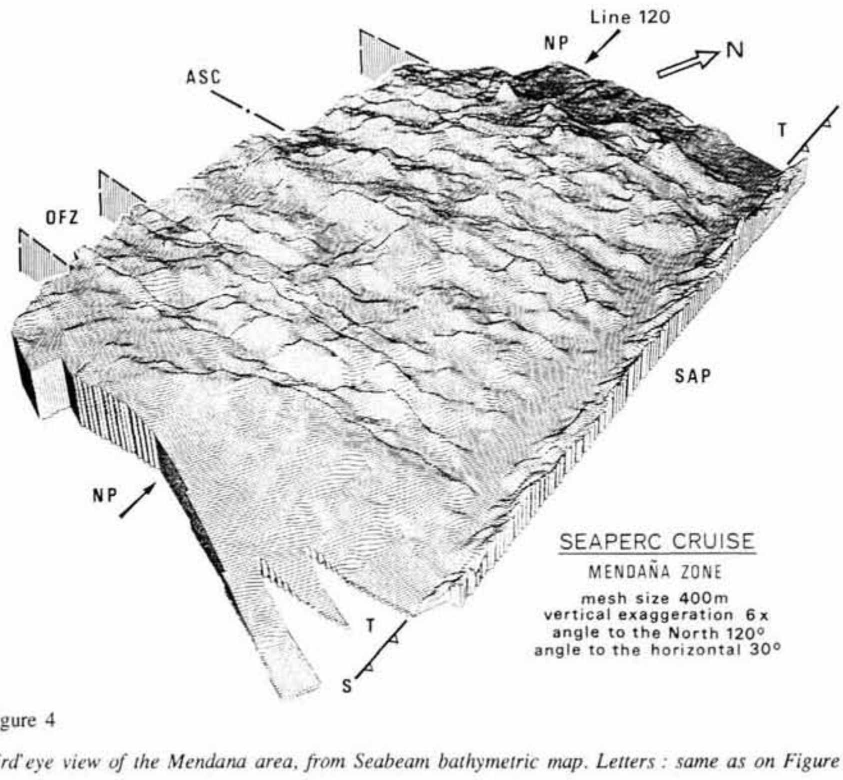

Figure 4

Bird'eye view of the Mendana area, from Seabeam bathymetric map. Letters : same as on Figure 3.

the MFZ exhibit differences in age of approximately 10 Ma across the MFZ (older to the south);

• the old fracture zone (OFZ in Fig. 3 and 4) is characterized by a rough topography. The depth of this area decreases from north to south in a series of steps outlined by large faults trending N65°E. These normal faults are cross-cut by strike-slip faults trending N40°E to N50°E with an inferred dextral displacement;

• the Nazca Plate (NP in Fig. 3 and 4) south of the MFZ represents the fourth domain. Gentle normal faults trending N160°E parallel the magnetic anomalies and the original pattern of the oceanic plate.

Within the trench, a thick (0.8 s twtt) turbiditic infill almost completely masks the ridge and trough morphology of the fracture zone. Finally, we note that the MFZ does not produce any important deformation of the landward slope, indicating a weak coupling between the Nazca and South America Plates (Bourgois *et al.*, 1987 and 1988).

MAGNETIC DATA

The total force of the geomatic field was measured using a proton magneto-meter towed about 200 metres behind the ship and recorded every 30 seconds. magnetic anomalies were obtained by subtracting theoretical values computed using the IGRP 80 reference field from the measured values. Magnetic anomaly data were filtered for anomalous values and corrected for the effect of diurnal variation, which was digitized from analog magnetograms of the Huancayo Observatory (Latitude 12°5'S, longitude 75°10'W, alt. 3300 m). The amplitude of the diurnal variation was found to be about 100 nT peak to peak, a value which appears to be high compared with measured values ranging from – 270 nT to 120 nT. This is because the survey area and the observatory are close to the magnetic dip equator, located at 5°S for longitude 80°W (see for example Handschumacher, 1976). The correction has removed almost all track effects, reducing the average track crossing error from 56 to 13 nT. Corrected magnetic data were plotted along ship tracks (Fig. 5) and gridded in order to produce a contour map (not shown).

The northwestern part of the survey area does not show clear magnetic lineations. The morphological and structural data indicate that this part is outside the fracture zone. Further south, N60°E trending magnetic lineations parallel the MFZ. These anomalies have been identified to be anomalies 1, 2, and 2A (see below). The Jaramillo event is not discernable due to the slow spreading rate. The first negative peak of the triplet 2A is associated with the broad deep trough noted to greatly perturb the free air gravity. South of this trough, two large negative anomalies are located on the remnant fracture zone identified on the bathymetric map. The orientation of the magnetic dipole is consistent with the vertical offset of the fracture zone but its amplitude is much higher near the trench than in the southwestern part of the map. The explanation will be given later.

In order to identify the magnetic anomalies, we performed a 2-D analysis profile by profile, neglecting the effect of the bathymetric relief, which is very small compared with

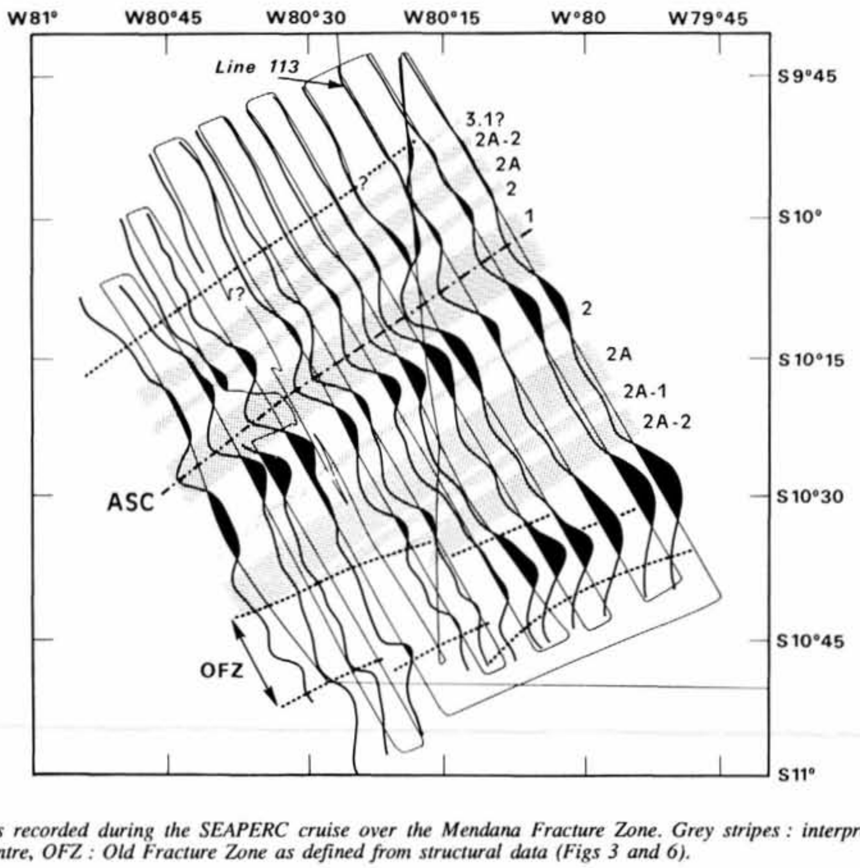

Figure 5

Magnetic anomaly profiles recorded during the SEAPERC cruise over the Mendana Fracture Zone. Grey stripes : interpreted from magnetization. ASC : active spreading centre, OFZ : Old Fracture Zone as defined from structural data (Figs 3 and 6).

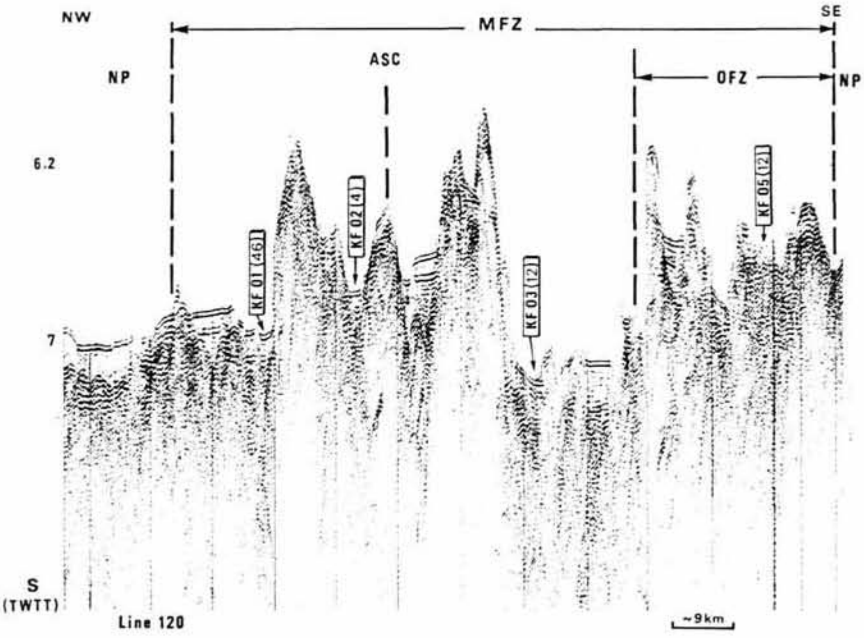

Figure 6

Single channel seismic record : line 120. Letters : same as on figure 3. Location and values (in brackets, unit : mW/m²) of heat flow measurements are indicated (see also Fig. 3).

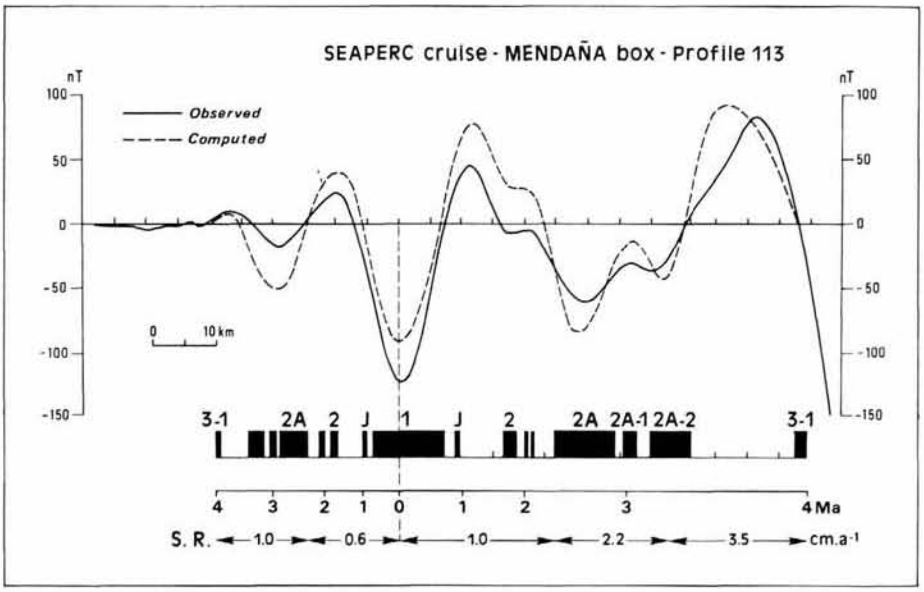

Figure 7

Interpretation of magnetic profile 113 (location on Fig. 6) Solid line : observed profile, Dashed line : computed profile, Upper curve : bathymetry. Bottom : magnetic block model, ages and spreading rates. Theoretical profile is shown up to anomaly 3.1. Note however that this part of the profile belongs to the Old Fracture Zone as defined from structural data.

Table 1
Heat flow measurements (location of sites on Fig. 3)

N°	Latitude S	Longitude W	Depth m	Pen m	N	GradT mK.m^{-1}	K W.m^{-1}.K	H.F. mW.m^{-2}	Age Ma
KF01	10°08.176	80°38.770	5030	3.6	6	64	0.717	46	2.5
KF02	10°16.323	80°33.730	5015	3.6	6	5	0.703	4	0.5
KF03	10°30.637	80°25.661	5101	4.2	7	17	0.694	12	2.5
KF04	10°23.762	80°29.432	4716	4.2	7	19	0.706	13	1.0
KF05	10°47.682	80°15.699	4730	4.2	7	17	0.708	12	(FZ)
KF06	10°07.012	80°17.462	5850	4.2	7	15	0.675	10	0.5

GradT : thermal gradient, K : thermal conductivity, N : number of active thermistors in mud, Pen : estimated penetration of the lowermost active thermistor.

the average depth (over 5 000 m). Synthetic magnetic profiles were computed using the geomagnetic time-table of Lowrie and Alvarez (1981). The computer programme used is based on a fast Fourier transform algorithm which allows a large number of trials. The thickness of the magnetic layer (layer 2) and the magnetization were classically taken as 0.5 km and 0.01 emu/cm respectively. Instead of a standard block model with sharp vertical boundaries between blocks of opposite magnetization, we have used a model assumes that crust material is emplaced at the spreading ridge with a normal (*i.e.* Gaussian) distribution of standard deviation σ. This parameter σ is related to the width of the transition zone between opposite magnetized blocks. An increasing σ thus attenuates the amplitude of short reversals. For the Shikoku basin of moderate spreading rates (2 to 4 $cm.yr^{-1}$), Watts *et al.*, (1977) have estimated that a σ value of 2 to 3 km is required. However, a value of 1 to 2 km seems to be more appropriate in our survey area. By ajusting a synthetic profile to each recorded profile, we are able to obtain the distribution of magnetization and thus of the age of the newly accreted crust. An example of magnetic anomaly identification is given in Figure 7. On this profile, anomalies 1 to 2A-2 are clearly identified. The misfit between the computed profile and the recorded profile can be attributed to several causes : off-ridge volcanism, as imaged by the Seabeam bathymetric map (Fig. 3 and 4), irregular bottom topography (Fig. 6) since the model assumes a planar surface and variations in magnetization.

A special mention should be made of the magnetic anomalies over the old fracture zone (OFZ in Fig. 3, 4 and 6), because the large positive anomaly can also be explained by oceanic crust emplaced between the triplet 2A and anomaly 3.1 (Fig. 5 and 7). An important observation is the trenchward increasing amplitude of these anomalies, whereas the plate deepens and the vertical offset of the fracture zone remains the same. Comparing the magnetic anomaly map (Fig. 5) with the Seabeam bathymetry map (Fig. 3), it clearly appears that the decrease in amplitude of the magnetic anomalies away from the trench closely follows the boundary between the remnant MFZ and the newly accreted crust : anomalies 2A-2 and 2A-1 clearly abut againt this boundary. This V-shapped pattern is less obvious in the northwestern part of the map (Fig. 5). However, its seems a symmetric, althrough much smaller, positive anomaly may exist on the northern rim of the newly accreted ridge. Consequently, the new rift could have began as early as 3.9 to 4 Ma ago, the age of anomaly 3.1.

The observed magnetic anomaly pattern in the area of new accreted crust is clearly asymmetric (Figs 5 and 7). South of anomaly 1, roughly 45 km of new crust has been accreted during the last 3.5 Ma (anomaly 2A-2) while only 25 km has been accreted north of anomaly 1. These values correspond to average half spreading rates of 1.3 $cm.yr^{-1}$ to the southeast and 0.7 $cm.yr^{-1}$ to the northwest. The 70 km of new crust accreted during the last 3.5 Ma fully accounts for the observed increase in width of the MFZ as it approaches the trench.

FREE AIR GRAVITY ANOMALY DATA

The contours of the free air gravity anomalies parallel the trend of the trench with minimum values of –180 mgals located over the trench axis as typical over trench areas. However, the ridges and troughs of the MFZ as well as scattered seamounts located on the Nazca Plate to the north perturb the contours. Positive relative anomalies of + 10 mgals are associated with the two ridges bordering the axis of the new accreted zone.

HEAT FLOW DATA

Thermal gradient was measured at six stations across the MFZ (Fig. 3 and 6) using thermistors attached to a Kullenberg-type corer. Conductivity was measured on board on the collected samples. Heat flow values recorded during the SEAPERC cruise are shown in Table 1. Together with those previously published (Yamano and Uyeda, in press; Hussong *et al.*, 1984) around the MFZ, heat flow values are typically about 40 $mW.m^{-2}$ on the lower landward slope of the trench and are from 10 to 35 $mW.m^{-2}$ along the trench axis. The Nazca Plate south of MFZ exhibits heat flow values between 47 and 107 $mW.m^{-2}$. Little can be said about the heat flow of the Nazca Plate north of the MFZ in the vicinity of the Mendana Box. Here, only three values have been reported, two of which lie near the trench; the other lies close to the TT and may therefore not be representative of the Nazca Plate in this area. The values within the MFZ (both previous and the present measurements) show low but variable heat flow, ranging from 4 to 46 $mW.m^{-2}$ the last one was obtained near a small seamount. Heat flow values obtained by Yamano and Uyeda (in press) within the intersection of the MFZ and the Peru Trench were computed using a thermal conductivity of 0.86 $W.m^{-1}.K$ which was not measured directly at the stations. Our stations consistently show thermal conductivity values of about 0.700 $W.m^{-1}.K$ (standard deviation 0.013 $W.m^{-1}.K$. Using this thermal conductivity value, Yamano and Uyeda's values of 18,36 and 7 $mW.^{-2}$ become 15,29 and 6 $mW.m^{-2}$ respectively, closer to our values.

The MFZ appears to be colder than the surrounding Nazca Plate whereas it should be warmer since it is a new spreading centre. However, the heat flow values are systematically low but show a wide variation. The three adjacent stations in the trenche have values ranging from 6 to 29 $mW.m^{-2}$ and the three adjacent stations on the northern side of MFZ range from 4 to 46 $mW.m^{-2}$. We attribute these variations to hydrothermal activity and rapid sedimentation. High heat flow values have not been sampled probably because discharge occurs preferably over the unsedimented areas.

CONCLUSIONS

The MFZ near its intersection with the Peru Trench clearly appears, both from a structural and from a magnetic point of view, to be formed by two domains : the old fracture zone responsible for the offset of the magnetic anomalies of the Nazca Plate, and a new rift which produces magnetic anomalies perpendicular to the old ones.

The newly accreted zone was produced asymmetrically since at least anomaly 2A-2 and possibly anomaly 3.1. It presents some atypical characteristics for a rift system :

- it is located on a former transform fault of the Nazca Plate, probably acting as a weakness zone;
- it quickly disappears eastward in the subduction zone;
- it trends perpendicular to the subduction zone and roughly parallels the general motion of the Nazca Plate;
- the depth of the rift axis is similar to the depth of the surrounding Nazca Plate. The bulge of this rift zone is reduced but clearly identified (Fig. 6);
- it displays very low heat flow values;
- although the rift zone itself is triangular, the magnetic lineations are not fan shaped, but the oldest anomalies are the shortest. This geometry is typical of a propagating rift. However, no transform zone connects the Mendana Rift to a failing rift, and no lithospheric transfer occurs. Thus, it does not conform the propagating rift model of Hey (1977). These anomalous characteristics can be explained by lithospheric divergence along an important weakness zone affecting all the lithosphere. The origin of the divergence would be, as suggested by the stress model of Wortel and Cloetingh (1985), the extensional stresses acting parallel to the Peru Trench in this area.

One can estimate the velocity of the propagation since the present tip of the propagating rift is about 350 km away from the trench (Fig. 2) while the oldest magnetic anomaly near the trench is anomaly 3.1, 4 Ma old (Fig. 5). The velocity with respect to the trench is thus about 8.5 $cm.yr^{-1}$. Adding the relative convergence rate of 8.5 $cm.yr^{-1}$, the total rate of propagation with respect to the Nazca Plate is thus about 17 $cm.yr^{-1}$.

Since the Mendana Rift does not propagate at the expense of another (failing) rift, it requires some compressive deformation within the Nazca Plate, as was described less than 200 km northward along the TT by Huchon and Bourgois (1990).

In order to explain the compressional features identified in the TT area, they invoked (Fig. 8) the proximity of the MFZ. As stated above, the mechanism of rift propagation in the Mendana Rift differs from the model defined for the Galapagos spreading centre (Hey *et al.*, 1986), since no features such as the dying and failing rifts, or transform fault are observed. It is probably similar to the rift which propagated along a fracture zone on the Farallon Plate, leading to the formation of the Cocos and Nazca Plates 23 Ma ago. The question which arises is : does this particular type of propagating rift require the amount of opening to be compensated by the equivalent amount of shortening ? Since the break-up is probably due to forces resulting from the shape of the subducting Nazca Plate and from the boundary conditions (Wortel and Cloetingh, 1985), the answer is not obvious. However, compression

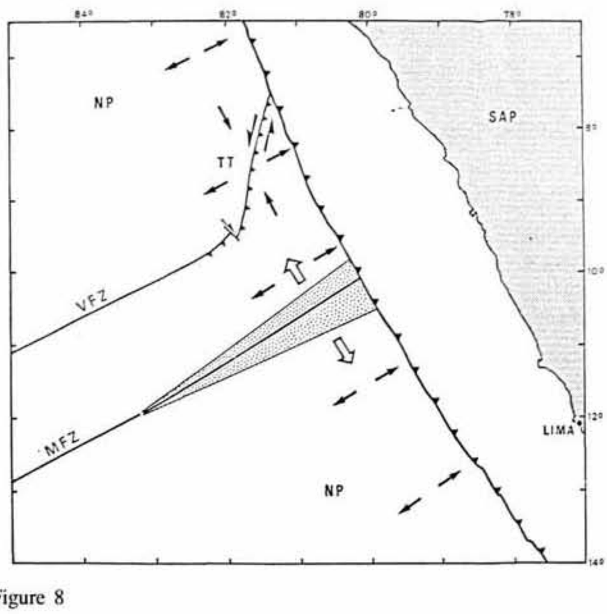

Figure 8

The Mendana Rift – Trujillo trough system : Sketch of the proposed tectonic model for the subduction-induced fragmentation of the Nazca Plate off Peru (after Huchon and Bourgois, in press).

north of the Mendana Rift, in the TT area was evidenced. Looking again at the stress model developped by Wortel and Cloetingh (1985), it is readily noticed that the trench-parallel extension rapidly decreases northward and is replaced by a purely compressive regime of the Nazca Plate with a trending nearly perpendicular to the Peru Trench. Of course, this simply results from the boundary conditions imposed to their model, which include a strong coupling between the Nazca and the South America Plates off Ecuador.

To summarize, the opening of the Mendana Rift since 3.5 to 4 Ma induces a motion of the Nazca Plate north of it, where the Nazca Plate becomes partly locked due to increasing coupling with the South America Plate. The compressional stresses would then result in fealure where a pre-existing zone of weakness exists : the Trujillo outer pseudo-fault, which becomes a compressive feature : the Trujillo Trough the TT, the N-S compression results in right-lateral transpressive deformation, while almost pure thrusting occurs along the Vera Fracture Zone, which is oriented nearly perpendicular to the compression (Fig. 8).

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