Available online at www.sciencedirect.com
SCIENCE DIRECT®
Earth and Planetary Science Letters 238 (2005) 64–77
EPSL
www.elsevier.com/locate/epsl

Tectonic evolution of the Tehuantepec Ridge

Marina Manea [a,b,*], Vlad C. Manea [a,b,*], Luca Ferrari [c], Vladimir Kostoglodov [a], William L. Bandy [a]

[a] *Instituto de Geofisica, UNAM, Ciudad Universitaria, Mexico D.F., Mexico*
[b] *Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA*
[c] *Centro de Geociencias, UNAM, Campus Juriquilla, Qro., Mexico*

Received 21 October 2004; received in revised form 21 June 2005; accepted 28 June 2005
Available online 22 August 2005
Editor: Scott King

Abstract

The Tehuantepec Ridge is one of the most prominent lithospheric structures of the Cocos Plate, yet its tectonic evolution has remained poorly constrained until now. Calculated ocean floor ages and spreading rates, morphostructural analysis of the ridge and the surrounding ocean floor are used to infer the tectonic evolution and pattern of the Tehuantepec Ridge and associated structures. The ocean floor age estimates south of the Tehuantepec Ridge suggest an age of ~26 Ma at the Middle America trench. A mean age difference across the Tehuantepec Ridge of ~7 Ma suggests that the Tehuantepec Ridge would be formed as a long transform fault on the Guadalupe plate, prior to 15 Ma.

The full-spreading rate estimates show that there might be a differential full-spreading rate across the transform fault between 15 and 5 Ma, when the oceanic plate just south of Clipperton Fracture Zone was decelerating between 15 and 10 Ma, then accelerating for the next 5 Ma. We propose a model in which between 13 and 8 Ma temporarily transpressional intratransform-spreading centers would have been existing as a consequence of the East Pacific Rise onset with an angle of ~10° clockwise with respect to the ceased Mathematician ridge. Our model estimates indicate that between 21 and 15 Ma a prominent pseudofault was formed south of the Tehuantepec Ridge due to an unstable offset on the Mathematician ridge that migrated northward. The Tehuantepec Ridge and the pseudofault trace bound a deeper oceanic basin than the surrounding area, with no corresponding anomalous depth on the western side of the East Pacific Rise. The complete absence of a pseudofault trace and a deeper oceanic basin on the western side of the East Pacific Rise, as well as the spreading rate changes, suggest the existence of a microplate embedded into the Cocos Plate just south of the Tehuantepec Ridge. Also, the asymmetric and sharp morphology of the Tehuantepec Ridge suggests that it may be the expression of a major transpressional structure along the former transform fault on the Guadalupe plate 15–20 Ma ago.

Keywords: Tehuantepec Ridge; Clipperton Fracture Zone; Guatemala Basin; Cocos Plate; microplate

* Corresponding authors. Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA. Tel.: +1 626 395 6948; fax: +1 626 564 0715.
E-mail address: marina@gps.caltech.edu (M. Manea).

0012-821X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2005.06.060

1. Introduction

According to the classic view of Plate Tectonics, transform plate boundaries are characterized by narrow strike-slip deformation zones parallel to a small circle around the Euler pole of relative motion between the two plates. In some cases, however, deformation can deviate from pure strike-slip so that transform faults may accommodate a compressional component of deformation [1,2]. Here we analyze the case of the Tehuantepec Ridge (TR) (Fig. 1), located on the Cocos Plate at the eastern prolongation of the Clipperton Fracture Zone (CFZ). Whereas other fracture zones from the East Pacific Rise (EPR) toward the Middle America Trench (MAT) (i.e. Orozco, O'Gorman) are curved, the TR is characterize by its straightness (Fig. 1).

Several articles have argued that the ridge separates the Cocos Plate in two parts with distinct tectonic regimes and age [3–8]. According to these papers the difference in ages ranges across the transform from 8 to 12 Ma. Using a mean gravity profile over TR, Manea et al. [9] found a mean age difference across TR of ~7 Ma. By contrast the difference in age across the CFZ east of the EPR is only 1.6 Ma [10–12]. This suggests that something unusual has happened in the Guatemala Basin just south of TR. Using the spectral technique (admittance) to free-air gravity and bathymetry data over TR, Manea et al. [9] found a median value of 8 Ma (in the interval 2– 17 Ma) for the oceanic lithosphere at the time of TR onset.

A few authors tried to explain the nature of the TR. Herron [13] considers this structure as the result of a hot spot trace. The sharp and asymmetric morphology of the ridge (Fig. 2), however, suggests that this is a tectonic rather than a volcanic feature. Truchan and Larson [14] consider the ridge as a hinge fault separating the part of the Cocos Plate subducting beneath the North America plate to the northwest from that

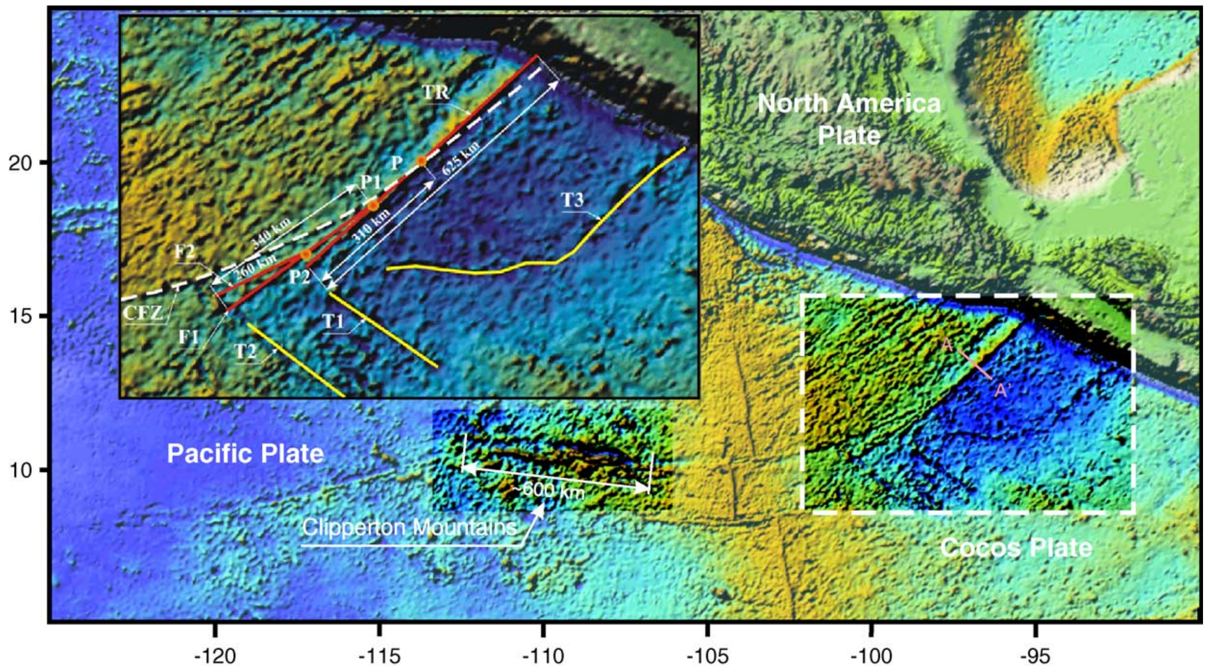


Fig. 1. Bathymetry (based on Smith and Sandwell [31]) and location of the study area. The inset represents an enlargement of the study area and associated tectonic features: Tehuantepec Ridge, F1 and F2 (red continuous lines) and the two ending fractures oblique to Tehuantepec Ridge (T1 and T2); P = intersection point between Clipperton Fracture Zone (white dashed line) and Tehuantepec Ridge, P1 is the intersection between F1 and Tehuantepec Ridge, P2 is the intersection between F2 and F1; T1, T2 and T3 (yellow continuous lines) are deep fractures in Guatemala Basin. The pink line AA′ represents the cross-sections over the Tehuantepec Ridge bathymetry shown in Fig. 2.

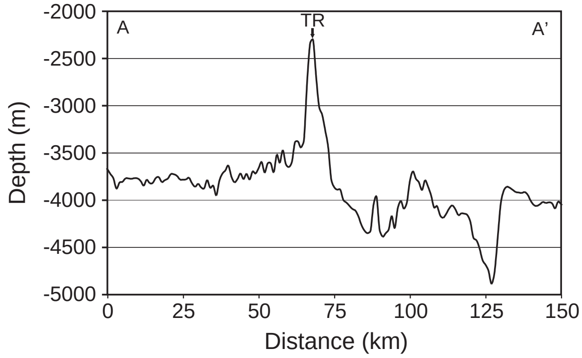


Fig. 2. Bathymetry profile AA′ from Fig. 1. Note the sharp and asymmetric morphology of the Tehuantepec Ridge.

subducting beneath the Caribbean plate to the southeast. Subsequent seismological studies [15,16] basically support this interpretation showing that the Cocos Plate increases its dip up to 45° and the depth of seismicity reaches 270 km to the east of the intersection between the TR and the MAT. However, the absence of seismicity rules out the possibility that the ridge is the product of an ongoing deformation process. Another study of Schilt et al. [17] suggests that TR initiated as a ridge–ridge transform which may have created the CFZ.

In this study we infer the age of the Cocos Plate just south of TR and Clipperton mountains using the relationship between the ocean depth and its age (half space cooling model). Accordingly, it is possible to infer the full spreading rate in this area (south of CFZ) and to compare it with the full spreading rate just north of the CFZ. To evaluate the success of this method we use for comparison the previous Cocos and Pacific plates age estimation in Guatemala Basin [5,7]. To constrain independently the age of the Cocos Plate at the trench we use the relation between the thermal parameter and the maximum depth of seismicity [18]. A recent study [19] shows that the oceanic crust is uniformly increasing in age from ~12.3 to ~16.2 Ma from northwest to southeast along the trench axis between the Orozco Fracture Zone and TR. Another study [20] shows a uniform age of ~24 Ma for the Cocos Plate along the trench offshore Costa Rica. We compare our plate age estimation at the trench with these two estimates.

Kanjorski [19] reports a slow down of the Cocos Plate north of TR ~12 Ma ago. This magnetic model uses a half spreading rate of 7.8 cm/yr from 12–17 Ma which decreases to 4.8 cm/yr between 5.5–12 Ma. In this work, we propose two possible models: one in which the TR may be the result of transpressional deformation due to different Euler poles for the Pacific–N. Cocos and Pacific–S. Cocos Plates, and an alternative model in which the TR and its associated structures represent the severe response of an old fracture zone to a ~10° clockwise change in direction of plate motion around 12 Ma.

2. Morpho-structural analysis

The TR is a ~625 km long linear structure, making an angle of ~45° with the coastline (Fig. 1). In cross-section, the bathymetry is highly asymmetric with an average difference of almost 1,000 m from one side of the ridge to the other (Fig. 2). To the northwest, an abyssal plain with depths of approximately 3500–3900 m flanks the TR. To the southeast of the ridge the Guatemala Basin is characterized by a rugged morphology and depth ranging between 4200–4800 m. Approaching the MAT the difference in bathymetry across the TR increases from ~400 to ~1110 m. Close to the trench the differential height diminishes again to nearly 850 m due to the bending of the plate. The ridge itself has an elevation of over 1000 m with respect to the adjacent NW plain (Fig. 2), which contrasts with the small relief of the Orozco and O'Gorman fracture zones to the northwest. The asymmetric and sharp morphology suggests that the TR may be the expression of a compressional structure, along a long transform fault (Fig. 2).

The TR intersects the CFZ near 13° N, 97° W and can be followed for about 310 km to the southwest within the Cocos Plate until it disappears. The intersection between the TR and the CFZ (point "P" in Fig. 1—inset) corresponds to magnetic anomaly 5A (~13 Ma) on the north side of the TR [19]. The region located at the southwestern end of the TR is characterized by two other bathymetric highs (F1 and F2) with a similar morphology (Fig. 1—inset). These two linear structures make an angle of ~10° and ~20° respectively with TR. F1 is a continuous and well-defined structure with a total length of ~340 km that intersects the TR at point "P1" (see Fig. 1). The second linear feature (F2) is shorter (~260 km), discontinuous and not as well pronounced as F1. Two remarkably similar deep fractures, T1 and T2, are located in the same region at an angle of ~80° and ~70° with the TR and F1 respectively. These deep fractures might be scars of ridge jumps, representing one possible manner to end up with very asymmetric spreading rates. T1 and T2 point toward the end of TR and F1, and they have a total length of ~250 and ~280 km, respectively. With a mean relief of ~800 m T1 is deeper than T2, which has an average relief of ~500 m. Another clear structure (T3) appears at the southeastern part of the Guatemala Basin. This is a trough with a mean relief of 200–300 m and two orientations. The part closer to the trench is parallel to the ridge whereas the rest is oblique with an angle of ~45°. The deeper Guatemala Basin is bounded by the TR, the MAT, T3 and T1.

To the west of the EPR, the mirror structures of the TR on the Pacific plate are the Clipperton Mountains (Fig. 1). This mountain chain has a total length of ~600 km, similar to the TR, but with heights up to 2500 m, and is flanked by a ~2000 m deep trough on its northern side, which have a flexural origin.

3. Age of the oceanic crust in Guatemala Basin

The age of the oceanic lithosphere just northwest of the TR has been successfully obtained from magnetic anomalies, and is considered to be about 16 Ma close to the trench [7,19]. Unfortunately, the low amplitude of the magnetic anomalies in the northern part of the Guatemala Basin [21] prevents us to obtain reliable crustal ages for this region located to the southeast of the TR. To estimate the age of the Cocos Plate in this region we used the method proposed by Gorbatov and Kostoglodov [18] to estimate the age of an oceanic plate at trench, A (Ma), from the maximum depth of seismicity, D_m (km), and the vertical component of the convergence rate, $V_\perp$ (km/Ma). The product $\varphi = V_\perp A$ is called the "*thermal parameter*" (Fig. 3) and its dependence on D_m is used to

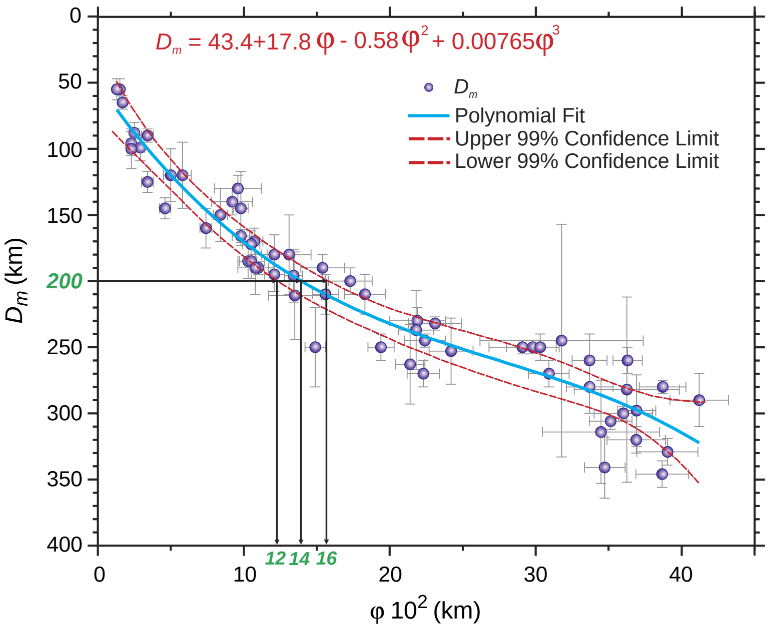


Fig. 3. The maximum depth of seismicity (Dm) in subduction zones is related with temperature and pressure conditions in the oceanic lithosphere sinking into the mantle. The age of oceanic plate at trench (A) can be inferred from the maximum depth of seismicity and the vertical component of the convergence rate (V) [18]. The product $\varphi = A * V * cos(\alpha)$ (α-dip of the subducted oceanic slab) is called "*thermal parameter*" and its dependence of Dm is used to infer the age of the oceanic crust at the trench.

infer the age of the oceanic lithosphere at the trench in front of Guatemala Basin. Using the data from Gorbatov and Kostoglodov [18], the best-fit polynomial curve for $D_m<350$ km is:

$$D_m = 43.4 + 17.8 \cdot \varphi - 0.58 \cdot \varphi^2 + 0.00765 \cdot \varphi^3, \quad (1)$$

where: $\varphi = V_\perp \cdot A$; $V_\perp = V \cdot \sin\alpha$; α - the angle of subduction.

The maximum depth of seismicity beneath southern Mexico, close to TR, is ~200 km [22], and the angle of subduction is ~43° [22]. The convergence rate is 7 cm/yr between the Cocos and North American Plates [23]. From Eq. (1), an age of 29 ± 4 Ma is obtained for the Cocos Plate at the MAT for southern Mexico (see Fig. 4).

An independent way to estimate the age of the Cocos Plate southeast of the TR is the half-space cooling model (*HSCM*). This equation predicts that the depth of the ocean increases with the square root of the distance from the ridge divided by spreading rate, or the square root of age of the ocean floor. The equation which gives the depth of the ocean floor, z, as a function of age, t, is the following [24]:

$$z(m) = 2600 + 350\sqrt{t}, \quad (2)$$

where t is in Ma.

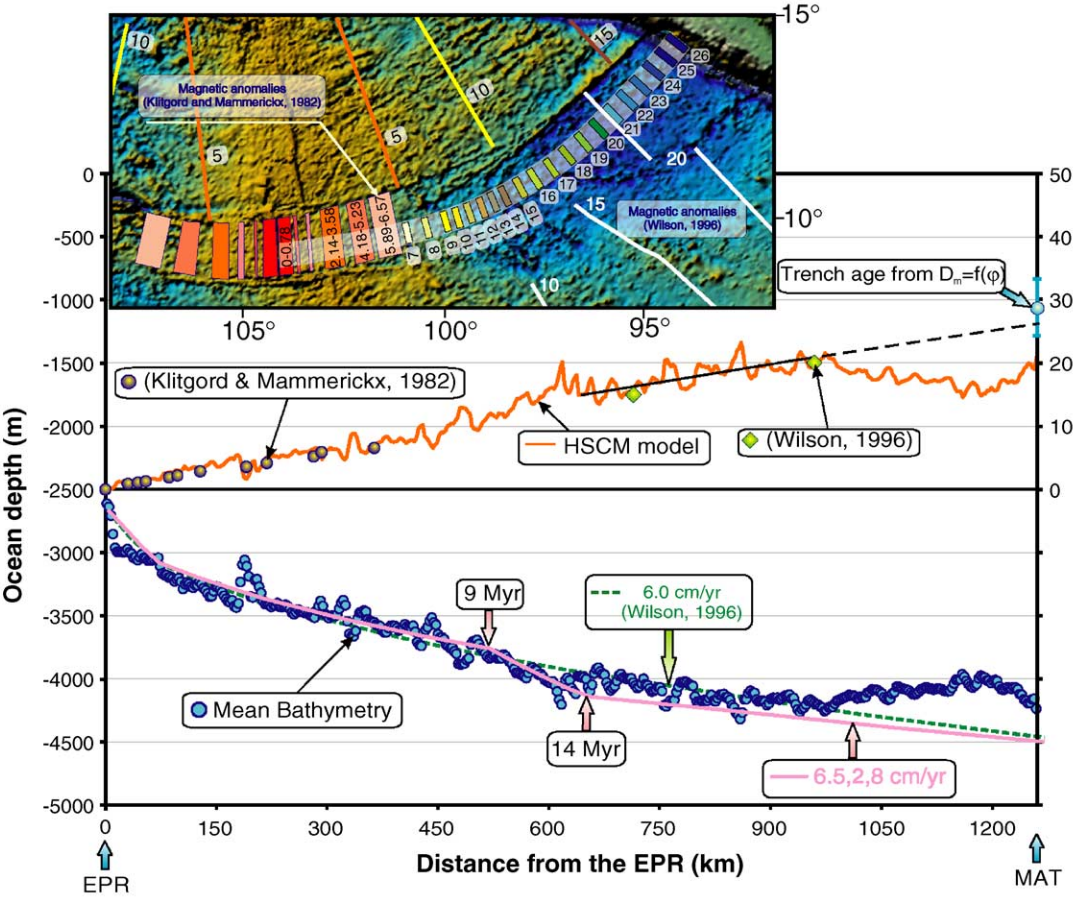


Fig. 4. Half Space Cooling Model used to predict the ocean bathymetry from ridge to trench, as a function of half-spreading rate, and also to predict the oceanic plate age in Guatemala Basin as a function of ocean depth. Using a constant spreading rate of 6 cm/yr [5] a reasonably good fit between the observed and predicted bathymetry is obtained (dashed green line). The best fit is obtained with a slower half-spreading rate of ~2 cm/yr between 9 and 14 Ma.

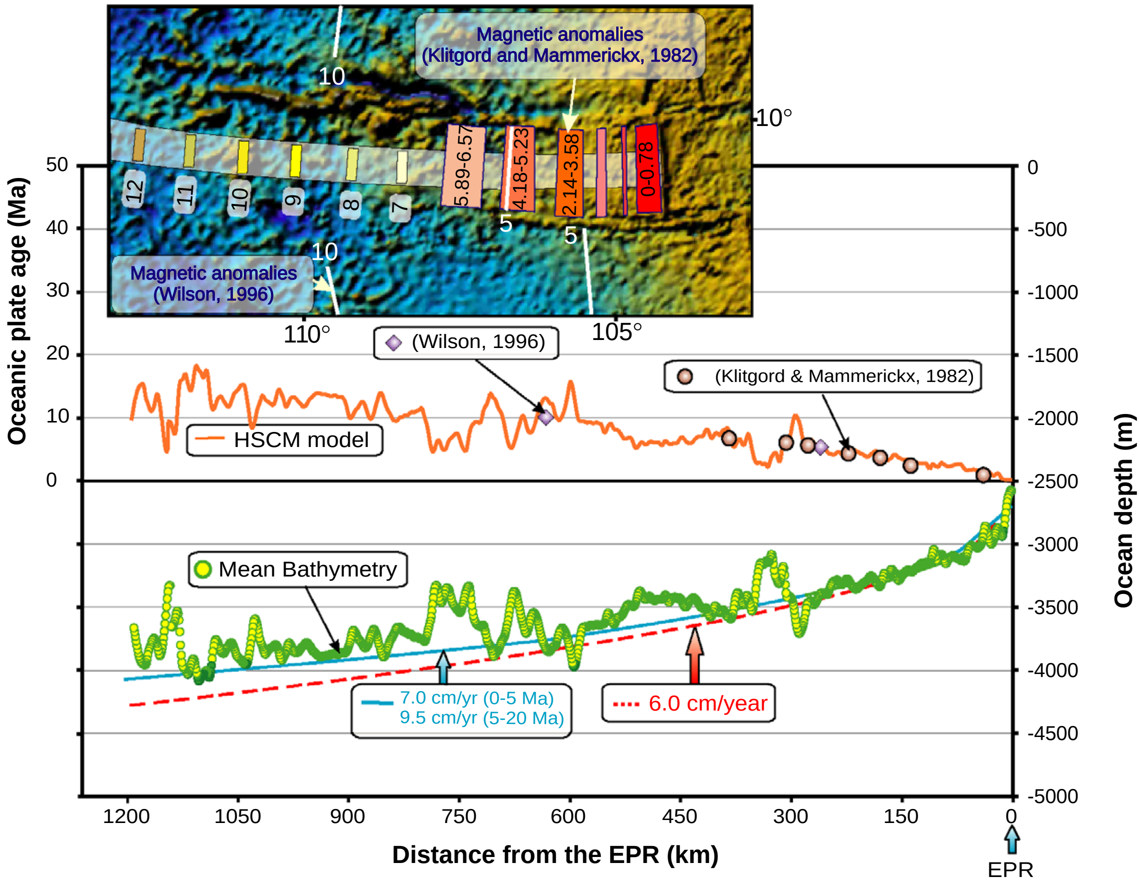


Fig. 5. Half Space Cooling Model used to predict the ocean bathymetry at west of East Pacific Rise and south of Clipperton Fracture Zone, as a function of half-spreading rate, and also to predict the oceanic plate age on the Pacific plate as a function of ocean depth. The best fit is obtained with a half-spreading rate of 7 cm/yr between 0 and 5 Ma and 9.5 cm/yr between 5 and 20 Ma.

The age of the oceanic plate is calculated for two mean depth profiles: one from EPR toward the MAT and crossing the Guatemala Basin (Fig. 4) and another one on the Pacific Plate just south of the CFZ (Fig. 5). A very good correlation between the ages predicted with HSCM and magnetic anomalies for ages <~6.5 Ma [7] is obtained. Also the 20 Ma magnetic anomaly in Guatemala Basin just south of TR from [5] is in good correlation with our estimate of ~20.8 Ma (Fig. 4). Approaching the trench, the ocean depth decreases due to the bending of the oceanic lithosphere. Therefore an underestimated plate age is obtained and these estimates should not be used. Instead a regression line from the ages unaffected by the bending, gives an age estimate at the trench of ~26 Ma. This value is in good agreement with the plate age at the trench inferred from the dependence between D_m and φ (29 ± 4) Ma (Fig. 4). The above estimations indicate that the difference in age across the TR at the trench is ~10 Ma. The age difference across TR increases from ~4 Ma at the southeastern edge to ~10 Ma at the trench (Fig. 4) with a mean age discrepancy of ~7 Ma. This result is in good agreement with the mean age difference estimate across TR inferred from gravity modeling of ~7 Ma [9]. Also, the trench age estimation of ~26 Ma correlates with the age of the Cocos Plate at the trench offshore Costa Rica of ~24 Ma [20] (Fig. 6).

For the second profile, also a good correlation between the ages predicted with HSCM and magnetic anomalies [5,7] for ages <~6.5 Ma is obtained.

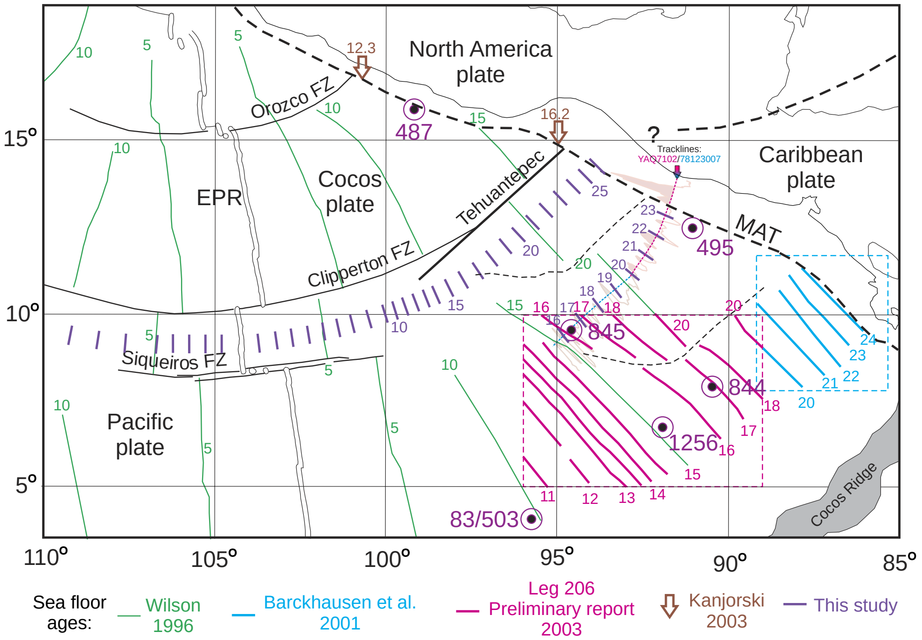


Fig. 6. Age map of the Cocos Plate and corresponding regions of the Pacific Plate. Dashed thin isochrons at 5 Ma intervals are from Wilson [5]. Thin continuous isochrons are from ODP Leg 206 [32]. Dashed thick lines are from Barckhausen et al. [20]. Arrows represent Cocos Plate ages at the Middle America Trench from Kanjorski [19]. Selected DSDP and ODP sites that reached basement are indicated by circles. The ages inferred from HSCM in the present study are in solid segments.

South of T3 fault, we estimated the oceanic plate age using the magnetic anomalies. Two long (about 300 km each) and reliable (no fault offset) ship tracks (YAQ7102 and 78123007) were extracted from GEODAS database and merged into a single profile. Then, a synthetic anomaly (geomagnetic time scale from Cande and Kent [25]) was compared with the observed one. A magnetization of 10 A/m in a 500 m thick layer was used. A good correlation between the synthetic and observed anomaly is observed (Fig. 7). Our estimate provides an age of ~23.5 Ma at the trench (Fig. 7) which is in good agreement with trench age estimates southward in front of Costa Rica of ~24 Ma [20]. The off trench age estimate correlates well with the estimations of Wilson [5], although a small offset of ~0.4 Ma exists for the 20 Ma isochrone (Fig. 6).

4. Spreading rates estimates across the Clipperton Fracture Zone and Tehuantepec Ridge

A major issue in achieving a reliable time evolution of oceanic crust across important fracture zones is to infer the spreading rate history. The most reliable method is based on magnetic anomalies. Unfortunately, as south of TR no magnetic anomalies are available, in this case we use the HSCM to predict the ocean bathymetry from ridge to trench, as a function of spreading rate. A reasonably good fit between the observed and predicted bathymetry is obtained using a constant half-spreading rate of 6.0 cm/yr [5] (Fig. 4—dashed green line). The best fit is obtained if we consider a period of very slow half-spreading rate of ~2 cm/yr between 9 and 14 Ma (Fig. 4—continuous violet line).

On the western-flank south of CFZ, a good fit between the observed and predicted bathymetry is obtained using two half-spreading rates of 7.0 cm/yr (0–5 Ma) and 9.5 cm/yr (5–20 Ma) (Fig. 5). The preponderance of the asymmetric spreading between the two flanks for age >5 Ma is obvious (Fig. 8B). However, these values of half-spreading rates (inferred from HSCM) might be used with precaution because they have large uncertainties up to 2 cm/yr. More reliable spreading rates are obtained using the magnetic anomalies, but HSCM is useful

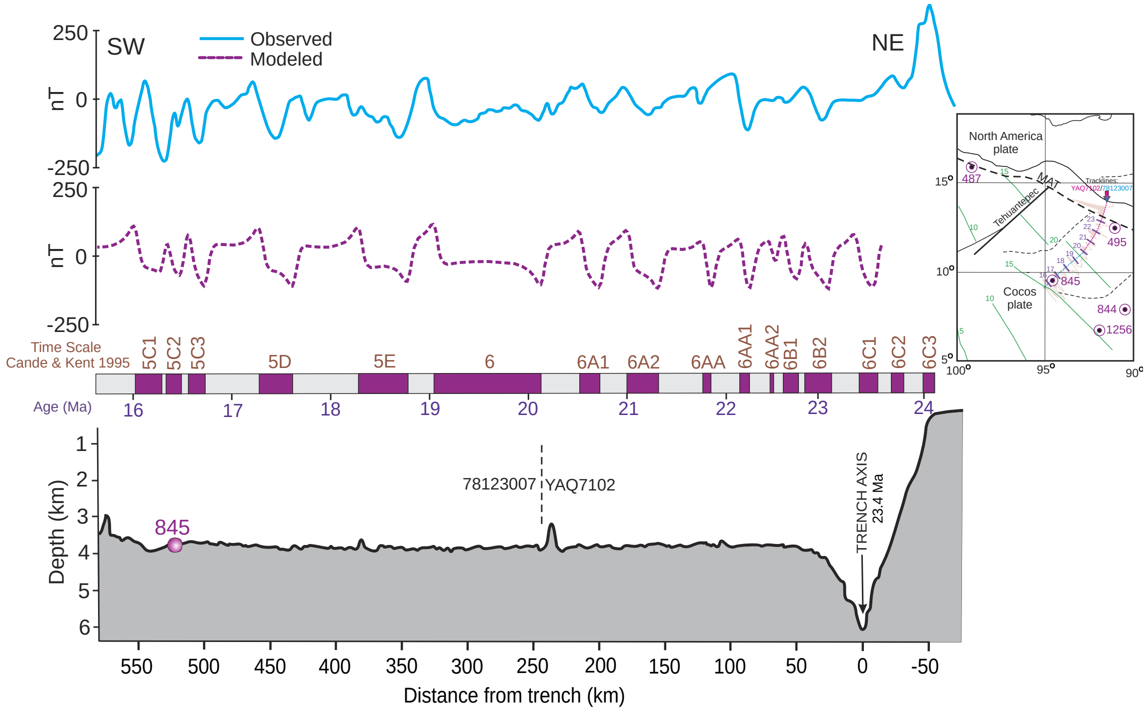


Fig. 7. Observed (solid curve) and synthetic (dashed curve) magnetic anomaly profiles south of T3 structure in Guatemala Basin. Two merged ship tracks were used (YAQ7102 and 78123007) from the GEODAS database. A magnetization of 10 A/m in a 500 m thick layer was used. The geomagnetic time scale is from Cande and Kent [25]. The right inset shows the track locations. Continuous lines represent the isochrones from Wilson [5]. Short solid lines normal to the ship track lines represents our age estimations. Circles indicate DSDP and ODP sites that reached basement.

for the regions where no magnetic lineations are available.

A half-spreading rate of 6.5 cm/yr for the eastern EPR flank, north of CFZ is inferred from magnetic anomalies [5]. For the eastern flank, north of TR, a recent work of Kanjorski [19] proposes the following half-spreading rates: 4.8 cm/yr (5.5–12 Ma) and 7.8 cm/yr (12–17 Ma). With a mean half-spreading rate for the west flank of 6.5 cm/yr inferred from magnetic anomalies [5] we obtain a symmetric spreading rate rather than an asymmetric one (Fig. 8A).

Within the large uncertainties in half-spreading estimations from HSCM, a comparison between the two full-spreading rates (Fig. 8C) suggests that there is a predominant differential full-spreading rate across the fracture zone at least for ages less than 10 Ma. A faster production of oceanic crust just south of CFZ would have led to important shortening of the long EPR offset along the CFZ through time.

5. Tectonic models for the Tehuantepec Ridge and associated structures

5.1. The Tehuantepec Ridge as a transpressional transform structure

We present two tectonic models for the origin of the TR. The first model assumes that the differential full-spreading rates N and S of the TR also existed before 15 Ma. This model for the early evolution of the TR is built on some basic constraints deduced in the previous sections: 1) the asymmetric and sharp morphology of the TR, 2) the mean difference in age of ~7 Ma across the ridge, and 3) a differential full-spreading rate across TR for ages >15 Ma.

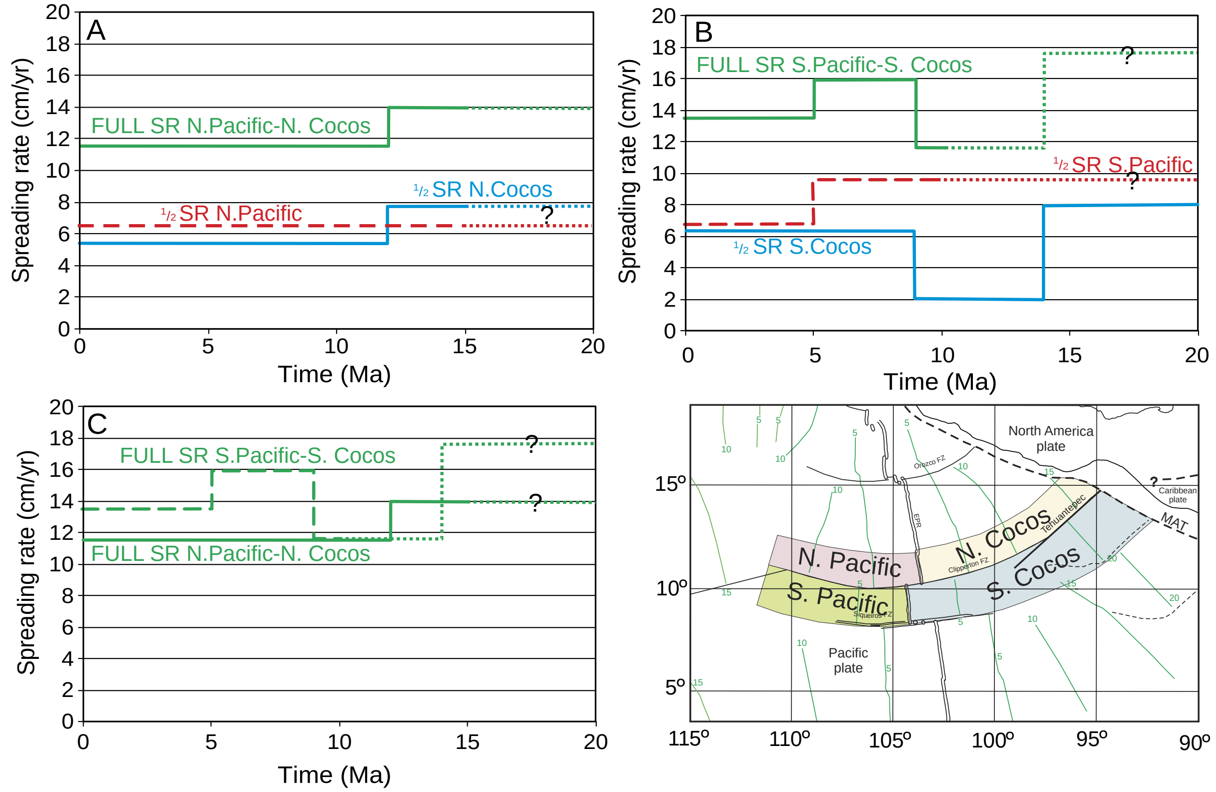


Fig. 8. Half and full spreading rates for North Pacific and North Cocos and South Pacific and South Cocos areas (right lower inset): A—dashed line represents the half-spreading rate for North Pacific (from HSCM); continuous line represents the half-spreading rate for North Cocos [19]; dotted lines for ages greater than 15 Ma where no data are available. B—red-dashed line represents the half-spreading rate for South Pacific (from HSCM); blue continuous line represents the half-spreading rate for South Cocos (from HSCM) and green continuous line is the full spreading rate for South Pacific–South Cocos (note the preponderance of asymmetric spreading); C—comparison between the full spreading rate for North Pacific–North Cocos and the full spreading rate for South Pacific–South Cocos. The dotted lines with a question mark in each figure is where no age data are available to infer the spreading rates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In order to explain the ~7 Ma age jump across TR we propose a long offset had existed on the Guadalupe plate prior to 15 Ma. Assuming a half-spreading rate of ~6 cm/yr, the total length of the transform fault would have been around 400 km. This is a very long transform fault if we compare it with its present length of only ~100 km.

This discontinuity in the full spreading rates prior to 15 Ma might have generated an incipient transpressional deformation along the long transform fault, which began to build the sharp and asymmetric TR. Younger lithosphere along transform would deform relatively easily because it is thin and hot, therefore the deformation should have localized across the active transform.

5.2. Response of the Tehuantepec Ridge to ridge jump

It has been proposed by Menard and Atwater [26,27] that severe changes in direction of relative plate motion might change the transform and spreading-ridge orientation and also may create a new set of transform faults and short spreading ridges. One of the best examples in this case is the Kane Fracture Zone situated in the North Atlantic Ocean (Fig. 9). Tucholke and Schouten [28] studied in detail the Kane Fracture Zone, and showed that this transform has exhibited specific structural responses to changes in relative plate motion. They proposed that during rapid counter-clockwise change in direction of relative plate motion,

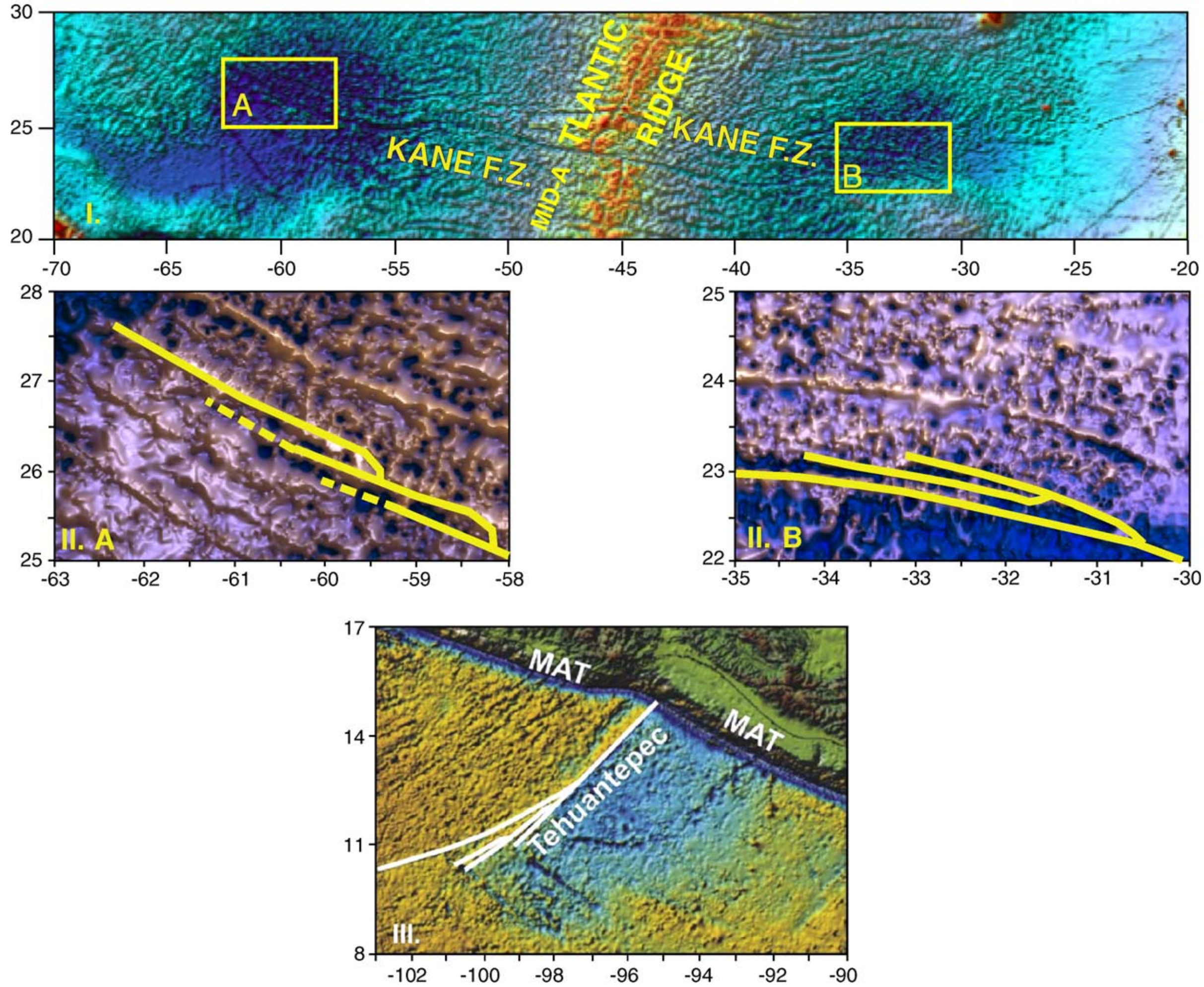


Fig. 9. I. Bathymetric map of the Kane Fracture Zone based on Smith and Sandwell [31]; II. A–B The offset in flowline represents the response in relative plate motion 92 Ma. Note the similarity of structures from II.B. and those associated to Tehuantepec Ridge (Fig. 1).

the magnitude of the reorientation might be so large that a single new transform fault cannot be accommodated within the preexisting transform valley. In this case the transtension adjustment across the active transform will produce a series of short spreading centers near the existing transform valley. The trace of this readjustment on both flanks of the Middle Atlantic Ridge is represented by a series of linear structures (Fig. 9II.B) very similar to the F1 and F2 structures situated at the end of the TR (Fig. 1). In this study we proposed a model that might explain the fracture pattern associated with the TR (Fig. 10). Two spreading rises (the former Mathematician Ridge - MR) with a right-lateral offset represent the initial stage of the model (Fig. 10A). Around 13 Ma ago, the MR ceased and the new formed EPR was rotated ~10° clockwise with respect with the former rise (Fig. 10B,C). Three new short transform faults were created within or close to the existing transform valley and two new short spreading ridges. Intriguingly, the angle between the F1 and the TR and F1 and F2 is ~10°. After 13 Ma, the southern spreading ridge propagated northward, causing the end of one of the newly created short spreading centers (Fig. 10D). In this way, the development of the

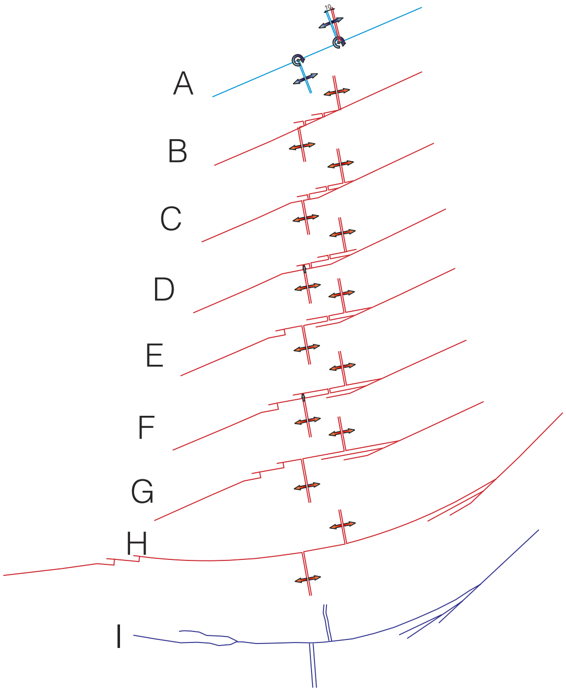


Fig. 10. A–G Model summarizing the severe response of a fracture zone to an approximately 10° clockwise change in direction of plate motion around 13 Ma. Continuous lines are transforms valleys. Thin parallel lines are spreading axis. Dashed twin paired lines are abandoned spreading axis. Dashed single lines represent old crust. H–I. Resulting structures of the western and eastern limbs of the Clipperton Fracture Zone. Note the similarity of the resulting structures with F1, F2 structures associated with the Tehuantepec Ridge.

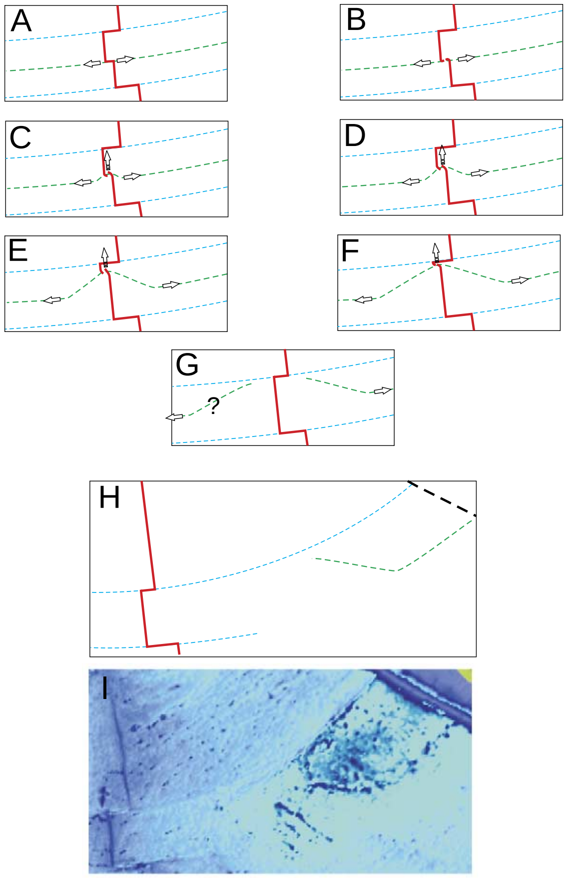
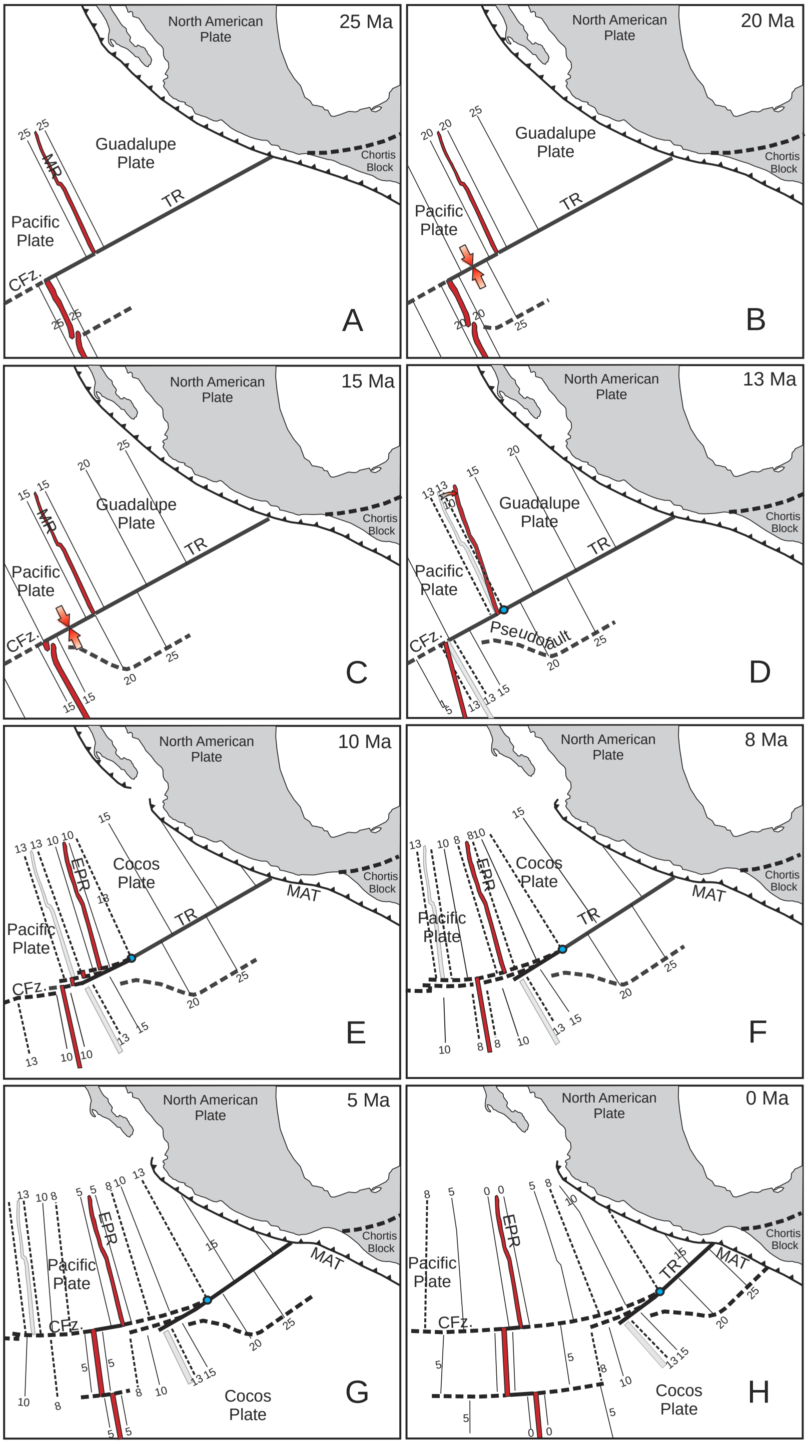


Fig. 11. Schematic model for T3 formation as a pseudofault. An "*unstable offset*" (caused by overlapping spreading centers) might form and then migrate northward along the ridge crest with time (A–G). The southern ridge segments is lengthening and the northern one is shortening with time until the "*unstable offset*" reaches the stable transform fault (G). Note the remarkable similarity between the model output (H) and the observed T3 structure (I). No "mirror" image of T3 on the Pacific plate can be an evidence that these marks might be microplate related.

southernmost of the three short fracture valleys on the eastern limb of the initial fracture zone ceased. The same process continued until all the short transform faults and ridges disappeared, resulting in the structures that we can see today (Fig. 10E–I). The similarity between the output of this model (Fig. 10I) and the

Fig. 12. A. A long offset would have been existed on the Guadalupe Plate for ages prior to 15 Ma. B,C. The unusual sharp shape of the TR (Fig. 2) can be the expression of some transpression that might have been occurred along the long transform fault prior to ~15 Ma (red arrows). An unstable offset that migrated northward between 21 Ma and 15 Ma would have produced a pseudofault. D. The intersection between the curved CFZ and the linear TR is proposed to be the time when the Mathematician ridge ceased and the new EPR was formed. E. A ~10° counterclockwise change in direction of relative plate motion changed the transform and spreading-ridge orientation and also may create a new set of unstable transform faults and short spreading ridges. F. The unstable transforms vanished, living the F1 and F2 marks on the Cocos Plate. Also, the T1 structure is an expression of an extinct ridge. G. The last important episode in our scenario is the onset of the Siqueiros transform fault about 7–5 Ma ago. H. Note the good similarity between the present day model output and the actual structures in Guatemala Basin (Fig. 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


25 Ma
North American Plate
Guadalupe Plate
Pacific Plate
Chortis Block
MR
TR
CFz.
A
20 Ma
North American Plate
Guadalupe Plate
Pacific Plate
Chortis Block
TR
B
15 Ma
North American Plate
Guadalupe Plate
Pacific Plate
Chortis Block
MR
TR
CFz.
C
13 Ma
North American Plate
Guadalupe Plate
Pacific Plate
Chortis Block
TR
CFz.
Pseudofault
D
10 Ma
North American Plate
Cocos Plate
Pacific Plate
Chortis Block
EPR
TR
MAT
CFz.
E
8 Ma
North American Plate
Cocos Plate
Pacific Plate
Chortis Block
EPR
TR
MAT
F
5 Ma
North American Plate
Pacific Plate
Cocos Plate
Chortis Block
EPR
MAT
CFz.
G
0 Ma
North American Plate
Pacific Plate
Cocos Plate
Chortis Block
EPR
TR
MAT
CFz.
H

actual structure on the Cocos Plate is remarkable. Although the Clipperton Mountains do not look very similar with the predicted structures on the western limb of the CFZ, they do appear to be about the same age. The structure T3 (Fig. 1) might be a fracture zone that turned into an unstable transform offset, finally suffering an along-ridge axis migration. A schematic model for T3 formation is proposed in Fig. 11. Pseudofaults are a type of non-transform offset that forms on a mid-ocean ridge. They are "*unstable offsets*" because they migrate along the ridge crest with time. Usually they are caused by overlapping spreading centers where one of the adjacent ridge segments is lengthening and the other one is shortening with time (Fig. 11A–F). The notable match between our model output and the observed T3 structure (Fig. 11H,I) strongly suggest that T3 is a pseudofault trace. A corresponding pseudofault trace on the Pacific Plate is not seen, suggesting the existence of a microplate embedded into the Cocos Plate just south of the TR.

6. Summary and conclusions

In this study we propose a tectonic model related with the time evolution of the TR and associated bathymetric structures in the Guatemala Basin. The absence of reliable magnetic anomalies just south of the TR led us to infer the crustal ages using indirect methods like HSCM and maximum depth of intraslab seismicity. Using the method proposed by Gorbatov and Kostoglodov [18], we obtained an age of the Cocos Plate at the MAT just south of the TR of 29 ± 4 Ma (Fig. 4). The crustal ages in the deeper Guatemala Basin are inferred using the HSCM. Further south, outside of the deeper part of the Guatemala Basin, we used a magnetic profile to gather the crustal ages (Fig. 7). The results clearly show that the deeper oceanic basin just south of the TR is older than the surrounding areas.

Combining these results with the crustal ages from magnetic anomalies north of TR and west of EPR [5,7], we show that a differential motion across the CFZ might have existed since at least 15 Ma ago. In order to explain the ~7 Ma age jump across TR we propose a model in which a long offset would have existed on the Guadalupe Plate prior to 15 Ma (Fig. 12A). A similar case is shown by Bird et al. [29] who explain that prior to the Juan Fernandez microplate, the EPR and Pacific–Antarctic–Nazca triple junction were offset by a long transform. The unusual sharp shape of the TR (Fig. 2) may be the expression of some transpression that might have been occurred along the long transform fault prior to ~15 Ma (Fig. 12B,C). The presence of the prominent T3 structure in Guatemala Basin (Fig. 1), is proposed to be the effect of an unstable offset that migrated northward between 21 and 15 Ma, being actually a pseudofault trace. The intersection between the curved CFZ and the linear TR corresponds to an age of ~13 Ma. This age is proposed to be the time when the MR ceased and the new EPR was formed (Fig. 12D). This severe ~10° counterclockwise change in direction of relative plate motion changed the transform and spreading-ridge orientation and also may create a new set of unstable transform faults and short spreading ridges (Fig. 12E). With time, these unstable structures vanished, leaving the F1 and F2 marks on the Cocos Plate (Fig. 12F,G). Also, the T1 structure is an expression of an extinct ridge. The length of the Clipperton Transform Fault decreased through time due to differential motion between north and south Cocos-Pacific Plates across TR and CFZ (Fig. 8C). The last important episode in our scenario is the onset of the Siqueiros Transform Fault ~7 Ma ago (Fig. 12G).

Our model explains the peculiar morphology of the TR and adjacent Guatemala Basin as well as the significant difference in age at the trench (~10 Ma) (Fig. 12H). The results indicate that an incipient microplate, corresponding with the deep Guatemala Basin, may have started to form out of the main Cocos Plate at ~13 Ma. The T1, T3, F1 and F2 look very similar to microplate pseudofaults along the Juan Fernandez and Easter Microplate in the South Pacific [29,30]. This is good evidence that these are indeed microplate related, and a "mirror" image of these features would not be seen on the Pacific Plate. Their spreading rate changes should also be considered as a microplate and a propagation event. This microplate would have been bounded by the TR and by the pseudofault T3. Alternatively, the Cocos Plate was behaving in a nonrigid fashion with the TR and the Guatemala Basin accommodating diffuse intraplate deformation.

Acknowledgments

We thank Joann Stock for helpful discussions that improved the quality of this article. We also thank Marco Guzmán Speziale, Rob Pockalny and Stuart Clark for their constructive critics and comments. This study was supported by grants CONACyT G25842-T, 37293-T, 36681-T and Internal Project B111. Also some funding was provided by Centro de Geociencias, UNAM, Juriquilla, Qro., Mexico.

References

[1] D.G. Gallo, P.J. Fox, K.C. Macdonald, A sea beam investigation of the clipperton transform fault: the morphotectonic expression of a fast slipping transform boundary, J. Geophys. Res. 91 (1986) 3445–3467.
[2] L.J. Sonder, R.A. Pockalny, Anomalous rotated abyssal hills along active transforms: distributed deformation of oceanic lithosphere, Geology 27 (1999) 1003–1006.
[3] DSDP Leg 66, Shipboard party, Middle America trench, Geotimes 24 (1979) 20–22.
[4] DSDP Leg 84, Shipboard party, Challenger drills again off Guatemala, Geotimes 27 (1982) 23–25.
[5] D.S. Wilson, Fastest known spreading on the Miocene Cocos–Pacific Plate boundary, Geophys. Res. Lett. 23 (1996) 3003–3006.
[6] R. Couch, S. Woodcock, Gravity structure of the continental margins of southwestern Mexico and northwestern Guatemala, J. Geophys. Res. 86 (1981) 1829–1840.
[7] K.D. Klitgord, J. Mammerickx, Northern east Pacific rise; magnetic anomaly and bathymetric framework, J. Geophys. Res. 87 (1982) 6725–6750.
[8] M. Manea, V.C. Manea, V. Kostoglodov, Sediment fill of the middle America trench inferred from the gravity anomalies, Geofis. Int. 42 (4) (2003) 603–612.
[9] M. Manea, V.C. Manea, V. Kostoglodov, M. Guzman-Speziale, Elastic thickness of the lithosphere below theTehuantepec Ridge, Geofis. Int. 44 (2) (2005) 157–168.
[10] R.A. Pockalny, Evidence of transpression along the clipperton transform: implications for processes of plate boundary reorganization, Earth Planet. Sci. Lett. 146 (1997) 449–464.
[11] S.M. Carbotte, K.C. Macdonald, East Pacific rise 8°–10° 30′: evolution of ridge segments and discontinuities from SeaMARC II and three-dimensional magnetic studies, J. Geophys. Res. 97 (1992) 6959–6982.
[12] S.M. Carbotte, K.C. Macdonald, Comparison of seafloor tectonic fabric at intermediate, fast, and super fast spreading ridges: influence of spreading rate, plate motions, and ridge segmentation on fault patterns, J. Geophys. Res. 99 (1994) 13609–13631.
[13] E.M. Herron, Sea-floor spreading and the Cenozoic history of the east-central Pacific, GSA Bull. 83 (1972) 1671–1692.
[14] M. Truchan, R.L. Larson, Tectonic lineaments on the Cocos Plate, Earth Planet. Sci. Lett. 17 (1973) 46–432.
[15] L. Ponce, R. Gaulon, G. Suarez, E. Lomas, Geometry and state of stress of the downgoing Cocos plate in the Isthmus of Tehuantepec, Mexico, Geophys. Res. Lett. 19 (1992) 773–776.
[16] H. Bravo, C. Rebollar, A. Uribe, O. Jimenez, Geometry and state of stress of the Wadati-Benioff zone in the Gulf of Tehuantepec, Mexico, J. Geophys. Res. 109 (2004), doi:10.1029/2003JB002854.
[17] F.S. Schilt, D.E. Karig, M. Truchan, Kinematic evolution of the northern Cocos Plate, J. Geophys. Res. 87 (B4) (1982) 2958–2968.
[18] A. Gorbatov, V. Kostoglodov, Maximum depth of seismicity and thermal parameter of the subducting slab: general empirical relation and its application, Tectonophysics 277 (1997) 165–187.
[19] M.N. Kanjorski, Cocos Plate structure along the Middle America subduction zone off Oaxaca and Guerrero, Mexico: influence of subducting plate morphology on tectonics and seismicity, PhD thesis (2003) University of California, San Diego.
[20] U. Barckhausen, C.R. Ranero, R. von Huene, S.C. Cande, H.A. Roeser, Revised tectonic boundaries in the Cocos Plate off Costa Rica: implication for the segmentation of the convergent margin and for plate tectonic models, J. Geophys. Res. 106 (B9) (2001) 19207–19220.
[21] R.N. Anderson, D.W. Forsyth, P. Molnar, J. Mammerickx, Fault plane solutions on the Nazca plate boundaries and the Easter plate, Earth Planet. Sci. Lett. 24 (1974) 188–202.
[22] C.J. Rebollar, V.H. Espindola, A. Uribe, A. Mendoza, A.P. Vertti, Distributions of stresses and geometry of the Wadati-Benioff zone under Chiapas, México, Geofis. Int. 38 (2) (1999) 95–106.
[23] C. DeMets, R.G. Gordon, D.F. Argus, S. Stein, Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions, Geophyis. Res. Lett. 21 (1994) 2191–2194.
[24] D.L. Turcotte, G. Schubert, Geodynamics, 2nd edition, Cambridge University Press, New York, NY, 2002.
[25] S.C. Cande, D.V. Kent, Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic, J. Geophys. Res. 100 (1995) 6093–6095.
[26] H.W. Menard, T.M. Atwater, Changes in direction of sea floor spreading, Nature 219 (1968) 463–467.
[27] H.W. Menard, T.M. Atwater, Origin of fracture zone topography, Nature 222 (1969) 1037–1040.
[28] B.E. Tucholke, H. Schouten, Kane fracture zone, Mar. Geophys. Res. 10 (1988) 1–39.
[29] R.T. Bird, D.F. Naar, R.L. Larson, R.C. Searle, C.R. Scotese, Plate tectonic reconstructions of the Juan Fernandez microplate: transformation from internal shear to rigid rotation, J. Geophys. Res. 103 (B4) (1998) 7049–7067.
[30] R.L. Rusby, R.C. Searle, A history of the Easter microplate, 5.25 Ma to present, J. Geophys. Res. 100 (B7) (1995) 12,617–12,640.
[31] W.H.F. Smith, D.T. Sandwell, Global sea-floor topography from satellite altimetry and ship depth soundings, Science 277 (1997) 1957–1962.
[32] Leg 206, Preliminary report, An in situ section of upper oceanic crust formed by superfast seafloor spreading, Ocean Drilling Program, Texas A&M University (2003).