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Elastic thickness of the oceanic lithosphere beneath Tehuantepec ridge

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RESUMEN

La relación entre la batimetría y la anomalía de gravedad de aire libre se analizó por medio del método de la admitancia para 7 perfiles que cruzan la cordillera de Tehuantepec. La evaluación de la edad de la litosfera para el tiempo cuando se formó la cordillera de Tehuantepec se calculó a través de los análisis de la admitancia experimental y del espesor elástico. Se calculó la admitancia, interpretada en términos del espesor elástico isótropo de la placa de Cocos debajo de la cordillera de Tehuantepec. El modelo de compensación isostática más apropiado para ajustar los datos observados es el de una litosfera oceánica que se comporta como una placa elástica con un espesor de 10±5 km. La forma de la admitancia (con valores bajos para longitudes de onda grandes) sugiere que la cordillera está compensada isostáticamente. La relación entre la edad de la litosfera oceánica y el espesor elástico para una temperatura de corte de 450 °C, da una estimación mediana de 8 Ma (en un intervalo de 2-17 Ma) para el momento de formación de la cordillera de Tehuantepec sobre la placa de Cocos.

PALABRAS CLAVE: Cordillera de Tehuantepec, espesor elástico, admitancia, modelación gravimétrica.

ABSTRACT

Relationship between bathymetry and free-air gravity is analyzed by computing response function (admittance) for 7 shipborne profiles crossing the Tehuantepec ridge (TR). The age of the lithosphere at the time of bathymetric loading of the TR is deduced from the experimental admittance and the elastic thickness, Te. Admittance is interpreted in terms of isotropic elastic plate thickness. The oceanic lithosphere is assumed to behave as an elastic plate 10±5 km thick. Low admittances at low wave-numbers suggest that TR is isostatically compensated. We estimate a median value of 8 Ma (in the interval 2-17 Ma) for the age of oceanic lithosphere at the time of TR onset.

KEY WORDS: Tehuantepec ridge, elastic thickness, admittance, gravity modeling.

INTRODUCTION

One of the most prominent bathymetric features in Guatemala basin is the Tehuantepec Ridge. The nature of this major structure and the age of its formation are still unknown. This ridge is considered bathymetrically similar to the great fracture zones of the northeastern Pacific (Menard and Fisher, 1958) and forms a major structural boundary, separating the Cocos plate in two regions (Figure 1), tectonically distinct (DSDP 67 - Aubouin *et al*., 1982; Manea *et al*., 2003). Although Klitgord and Mammerickx (1982) proposed a difference in ages between these two compartments of ~12 Ma, their study confirmed that the identification of ages in the southern part has been proved to be very difficult. The low amplitude of the magnetic anomalies in Guatemala basin (Anderson, 1974) make problematical to obtain reliable crustal ages. Wilson (1996) mentioned a difference of ~ 8 Ma using paleontological dating for anomaly identification, meanwhile, Couch and Woodcock (1981) give an age difference of ~ 10 Ma. One hypothesis for the TR formation comes from Herron (1972), who considered the TR as the result of a hot spot trace. Truchan and Larson (1973) mistrust the possibility that the TR is a fracture zone continuation of the Siqueiros Transform Fault. They considered the TR as a hinge fault separating the Cocos Plate which is underthrusting the North America plate to the northwest and the Caribbean plate to the southeast. The study of Couch and Woodcock (1981) for this area shows discordance between the two compartments that defines the TR shape within the Cocos Plate: the northwestern compartment seems to be older and thicker than the southeastern one. Their gravity model of the cross section normal to the TR is contradictory to the estimated age of the Cocos Plate in Guatemala Basin from the relation between the oceanic floor depth and age (Parsons and Sclater, 1977). The Cocos plate lithosphere being subducted beneath the Caribbean plate is older, colder and therefore thicker than the portion of the Cocos plate underthrusting the North America plate.

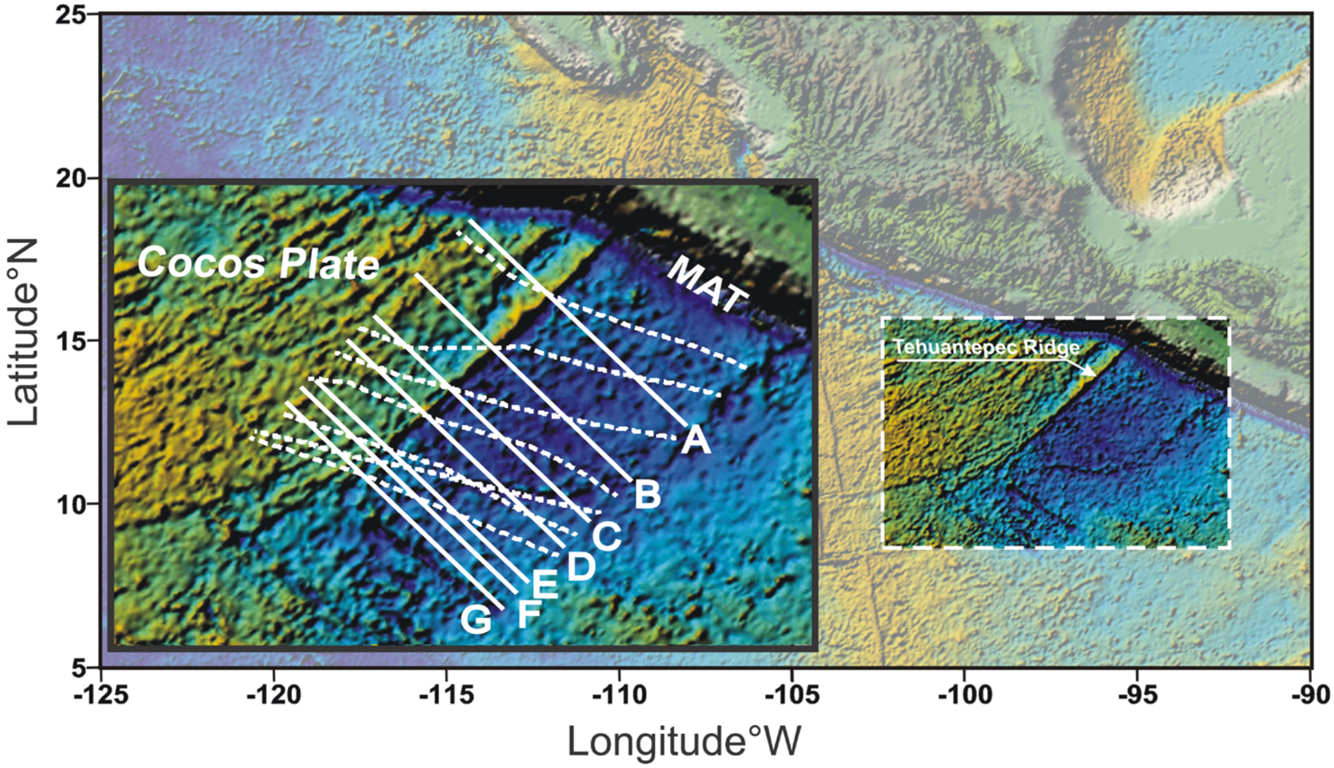

Fig. 1. Bathymetry (based on Smith and Sandwell, 1997) and location of the study area. Inset: Location of the gravity and bathymetry profiles. Dashed lines represent the ship-tracks; solid lines show the profiles projected perpendicular to the TR. MAT, Middle America Trench.

The data used in this study are from the GEODAS NGDC database (Marine Trackline Geophysics, v 4.0) and consist of bathymetry and free-air gravity anomaly data across the TR. An estimation of the oceanic lithosphere elastic thickness, *Te*, beneath the TR is performed using the observed data. Then we compare these results with several estimates of *Te* obtained from theoretical models of isostatic compensation, and select the best model. The main goal of this study is to propose a possible mechanism and an approximate age of the TR formation. A new gravity modeling was performed for an averaged profile crossing the TR (Figure 2) and the isostasy was analyzed using the admittance techniques (Watts, 2001) in order to infer the oceanic plate elastic thickness, *Te*, below the TR.

ELASTIC THICKNESS ESTIMATION

The gravitational admittance is the wavenumber parameter that modifies the topography so as to generate the gravity anomaly (Watts, 2001). This parameter contains information on the state of isostasy for a surface topography feature. Variations of the sea floor bathymetry constitute a load distribution on the oceanic lithosphere, which reacts elastically (isostatic compensation) with the formation of a flexural depression, bulge and root. It has been known for some time that the spectral techniques can be used to better quantify the degree of isostatic compensation of oceanic bathymetric features. The theory of admittance technique is described in detail in a recent book by Watts (2001).

Spectral techniques employ the relationship between gravity and topography over a surface load (the TR in our case), which varies as a function of its wavelength. To determine the appropriate compensation mechanism of such a load, the frequency content of observed gravity and topography data is compared with the spectra of the predictions for different isostatic models, such as those of Airy or Vening-Meinesz (flexure model). The isostatic response in the spectral domain for theoretical models depends also on the effective elastic thickness, *Te*, of the oceanic plate. Under the same load, a thin plate would produce a greater flexure (lower amplitude of the admittance function) than a thick slab. The best fit between the observed admittance and theoretical admittances for various *Te*, will give us the elastic plate thickness.

Observed admittance

In this study we use bathymetry and free-air gravity anomaly profiles from the GEODAS NGDC database (Marine Trackline Geophysics, v 4.0). Before applying the spectral technique, we removed the outliers by using a despiking

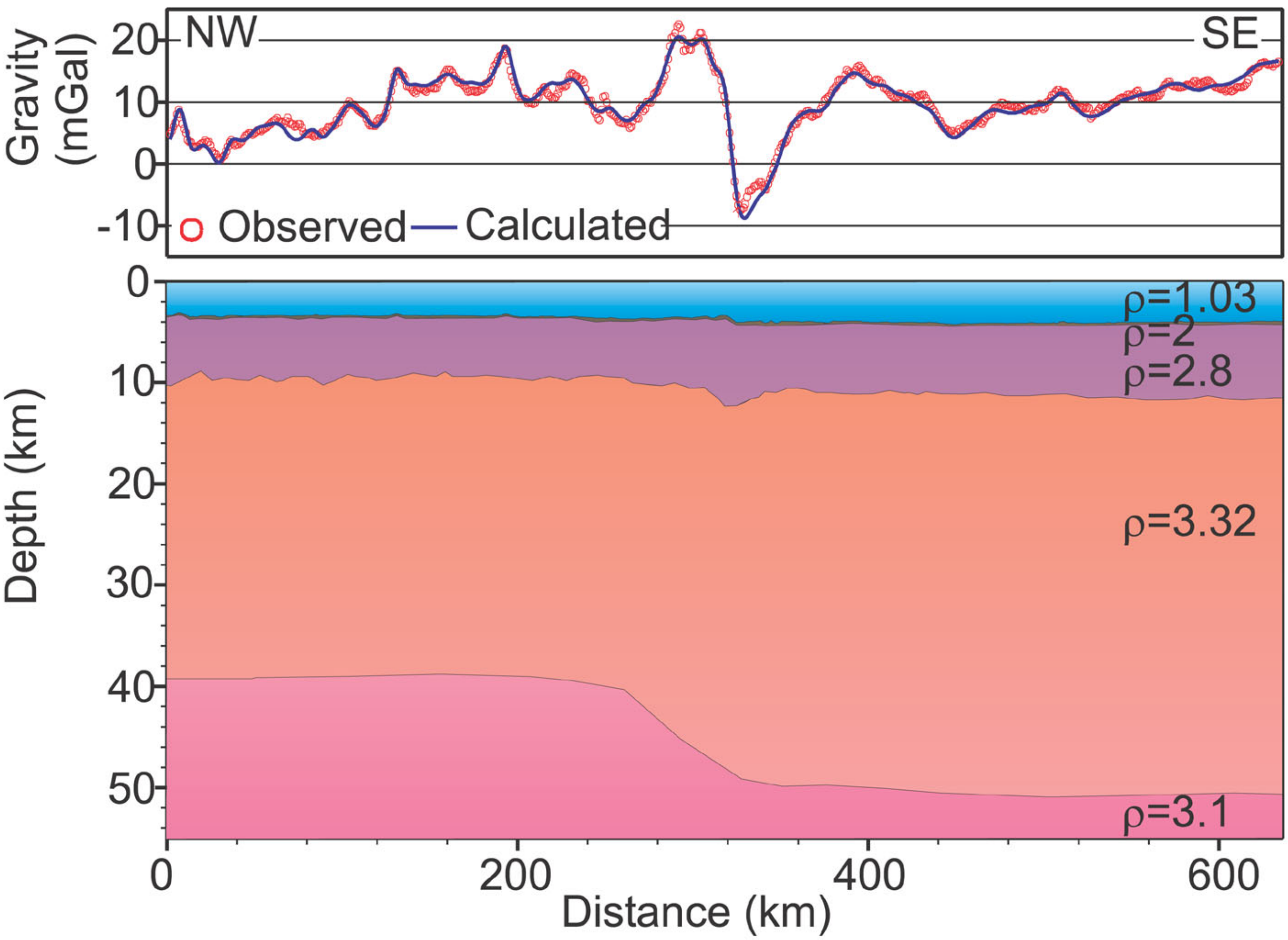

Fig. 2. 2-D density model along the mean profile averaged from the 7 profiles used for the admittance estimation. The densities are in g/cm^3 from Couch and Woodcock (1982). The upper continuous curve is the modeled anomaly. The circles represent the observed free air gravity anomalies. The density of 2.0 g/cm^3 corresponds to a very thin layer of oceanic sediments.

filter (Wessel and Watts, 1988). Then, computing the discrepancies in free-air gravity anomaly at intersecting ship tracks, we found 82 cross-over errors (COEs) with a standard deviation of 16.67 mGal. Using the algorithm of Wessel (1989) and Wessel and Watts (1988) for data adjustment, we excluded those profiles with COEs > 19 mGal, so that the standard deviation dropped to 10.76 mGal. Finally, only 7 profiles, which cross the TR were selected (Figure 1, inset). Since this spectral analysis requires a uniform data set (equally spaced and oriented), these profiles were projected perpendicular to the TR.

We estimated the *Te* by the means of the admittance techniques using orthogonal projections of the profiles to the TR. These projected profiles are all of an equal length of 482 km. A total of 512 samples of free air gravity anomaly and bathymetry data were obtained by interpolating each original profile. The resulting profiles are regularly spaced data set at intervals of 0.943 km. Wavenumber limits for these profiles are $0.0065 < k < 3.33$ ($k=2\pi/\lambda$; λ is wavelength). The trend of the data, including the mean was removed for each profile. The edges of the profiles were tapered using a cosine window of 10% of the total length of the profile (Kogan and Kostoglodov, 1981). Finally, the Fast Fourier Transform (FFT) of the sampled, trend-removed and tapered gravity anomaly and bathymetry data sets was applied to calculate the spectral estimates for each pair of profiles. The complex admittance, $Z^{obs}(k)$., cross-spectrum, $C(k)$, and power spectrum of bathymetry, $E_b(k)$, are given by:

$$Z^{obs}(k) = \frac{C(k)}{E_b(k)}, \quad (1)$$

$$C(k) = \frac{1}{N}\sum_{r=1}^{N} G(k)\cdot B(k)^{*}, \quad (2)$$

$$E_b(k) = \frac{1}{N}\sum_{r=1}^{N} B(k)\cdot B(k)^{*} \quad (3)$$

where:

$G(k)$ and $B(k)$ are the Fourier transforms of the observed gravity and bathymetry data, respectively, and N is the number of profiles (Tamsett, 1984). The "*" denotes the complex conjugate.

The measure of the fraction of energy in the gravity at a particular wavenumber, which can be attributed to the bathymetry load, is given by the coherence estimate,

$$\gamma^2(k) = \left(N \cdot \frac{C(k) \cdot C(k)^*}{E_g(k) \cdot E_b(k)} - 1 \right) / (N-1), \quad (4)$$

where the power spectrum of gravity anomaly, $E_g(k)$, is:

$$E_g(k) = \frac{1}{N} \sum_{r=1}^{N} G(k) \cdot G(k)^* . \quad (5)$$

Using the above admittance estimation assumes that the Cocos plate across the Tehuantepec ridge has the same effective elastic thickness on each side. However several works have recognized that the ridge separates the Cocos plate in two parts with distinct tectonic regimes and age (DSDP 66 and 84; Wilson, 1996; Couch and Woodcock, 1981; Klitgord and Mammerickx, 1982; Manea *et al.*, 2003). According to these papers the difference in age ranges from 8 to 12 Ma. Therefore, in order to perform a distinct admittance analysis, the original profiles were divided into two groups across the TR. The first data set, located north of the Tehuantepec ridge, is represented by 7 profiles, 187 km in length each, and the second data set, situated south of the Tehuantepec ridge, contains 7 profiles of 325 km. A total of 256 samples of the free air gravity anomaly and bathymetry data were extracted from each data set resulting into a regularly spaced data along each profile at intervals of 0.73 km ($0.0168 < k < 4.3$) and 1.27 km ($0.00967 < k < 2.47$) respectively. The data were processed in the same manner as for the entire profiles of 483 km crossing the TR.

Theoretical admittance

Theoretical models of isostatic compensation (Airy and Vening-Meinesz) contain the mean crust, T_c, and elastic plate thickness, Te, parameters. The theoretical curves of admittance for Airy isostatic compensation, $Z(k)^{Airy}$ (Figure 3A) and for the simple flexure isostatic compensation model, $Z(k)^{Flex}$ (Vening-Meinesz) (Figure 3B) are defined by the following equations (Watts, 2001):

$$Z(k)^{Airy} = 2\pi G(\rho_c - \rho_w) e^{-kd} (1 - e^{-kT_c}), \quad (6)$$

$$Z(k)^{Flex} = 2\pi G(\rho_c - \rho_w) e^{-kd} (1 - \Phi'_e(k) e^{-kT_c}), \quad (7)$$

where:

G - universal gravitational constant ($6.6726 \cdot 10^{-11}$ N·m^2/kg^2),
T_c - mean thickness of the crust,
ρ_c - density of the crust,
ρ_m - density of the mantle,
ρ_w - water density,
d - water depth,

$$\Phi'_e(k) = \left(\frac{Dk^4}{(\rho_m - \rho_c)g} + 1 \right)^{-1}$$,- wavenumber parameter,

where:

$$D = \frac{ET_e^3}{12(1-\nu^2)}$$ - flexural rigidity,

E - Young's modulus (10^{11}N/m^2),
Te - elastic thickness,
ν - Poisson's ratio (0.25).

RESULTS

The profiles of bathymetry which cross the TR region indicate the existence of two distinct areas separated by the TR: the northwestern area characterized by depths between 3500-3900 m and the southeastern area, a part of the Guatemala Basin, with depths between 4200-4800 m, with the depth step of ~1000 m between the two. A gravity low of -7 to -8 mGal indicates the location of the boundary between the two areas. Our 2D gravity model (Figure 2) is in good agreement with the age vs. depth and age vs. lithospheric thickness relations and supports the hypothesis that the TR is a tectonic joint between two different segments of the Cocos plate, which is thicker to the southeast from the TR than to the northwest of it.

The phase, coherence and the amplitude of admittance function over the TR are shown in Figure 4. The trend of the observed admittance (Figure 4A) gives an estimate of the water depth of 4000 m, and the intersection of this line with the vertical axis provides a density estimate of the bathymetry of ~2.55 g/cm^3. The coherence is more than 0.5 for $0.0065 < k < 0.4$ ($966 > \lambda > 15$ km) suggesting that most of the energy in the free-air gravity anomaly is caused by the bathymetry. Within the same waveband the admittance and phase are smooth (Figure 4A,C). Figure 3 shows the admittance estimates together with theoretical curves for Airy isostatic compensation (Figure 3A) and simple flexure isostatic compensation models (Figure 3B). The errors of the admittance coefficients are computed from the coherence (Watts, 1978). The decrease of the admittance at low wave numbers indicates that the TR is isostatically compensated. The Airy model fits the observed admittance when the mean crustal thickness is of 20-40 km. These values are incompatible with the estimates of the oceanic crust thickness (7-8 km) and consequently the Airy model cannot be accepted as a possible isostatic compensation mechanism. A simple plate flexure model with *Te* = 10±5 km (Figure 3B) is more reasonable. The side wings of the filter (which is the inverse FFT of the admittance) coefficients are negative and do not decay asymptotically to zero (Figure 5) suggesting that the TR structure is isostatically compensated. The admittance estimated from the observations can be used to predict gravity anomalies, which are correlated with the bathymetry signal, by applying the inverse FFT to the product of $Z(k)\cdot E_b(k)$. A similarity between the observed and predicted gravity anomalies shown in Figure 6 indicates that the admittance technique is appropriate for the present study.

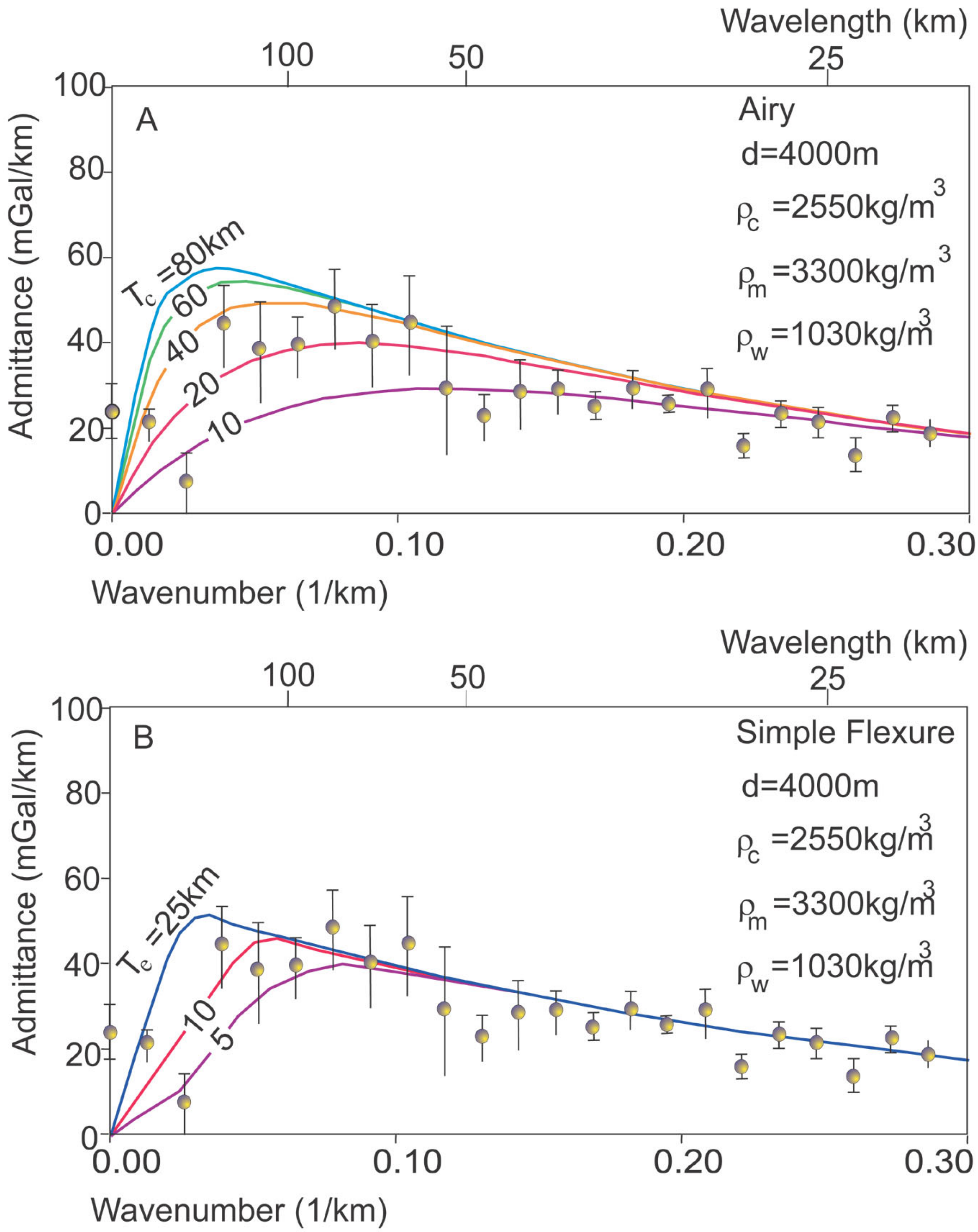

Fig. 3. Amplitude of admittance for low wavenumbers, k = 0.0-0.3. Observed (solid circles) and theoretical admittance (solid curves) for: A - Airy isostatic compensation, T_c is the mean thickness of the crust as a varying parameter of the model; B –simple flexure isostatic compensation model, *Te* is effective elastic thickness. Admittance errors are computed from the coherence (Watts, 1978). The best fitting curve is for the simple flexure model of the oceanic lithosphere with *Te* = 10 ±5 km.

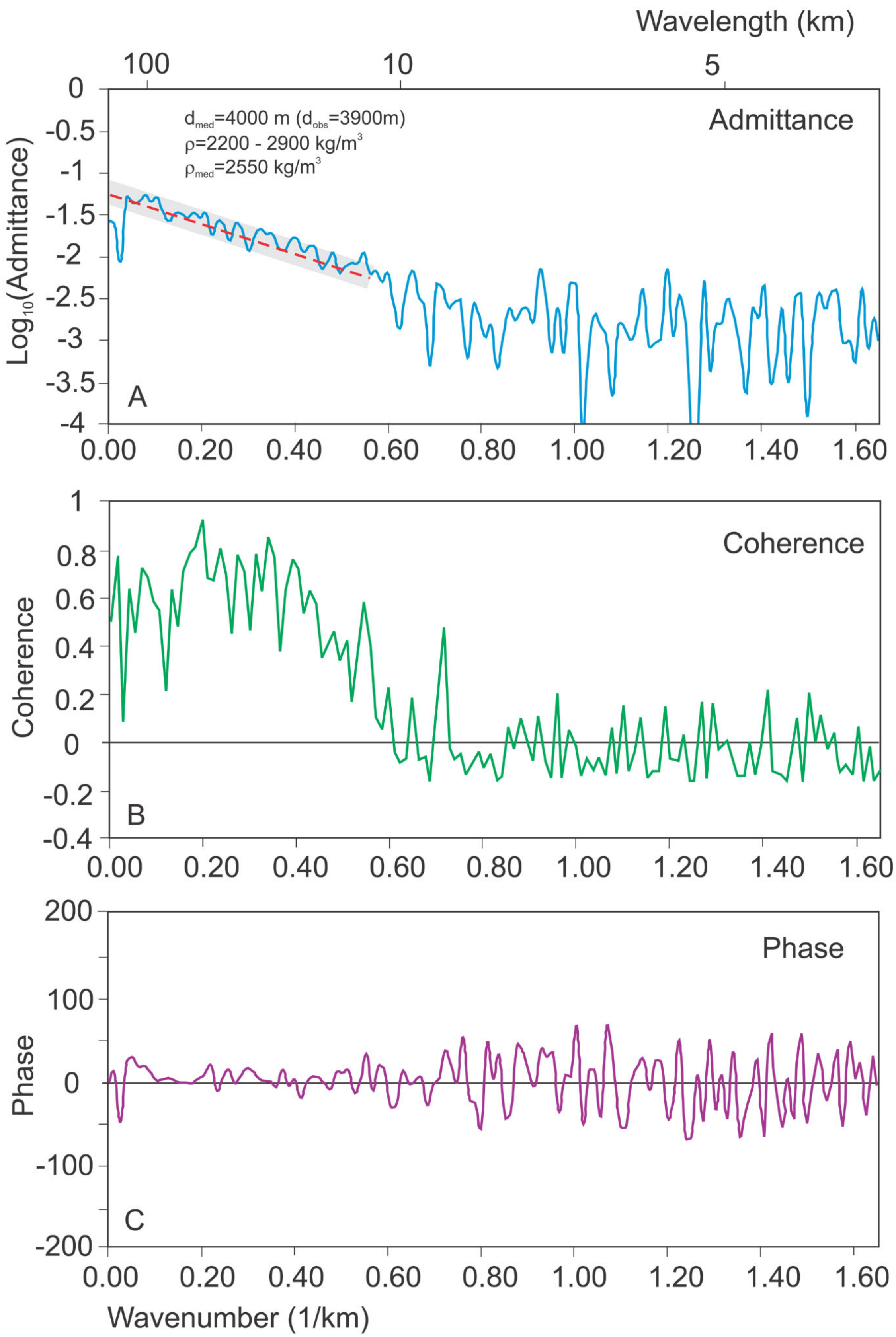

Fig. 4. A- Solid line is the calculated admittance. Dashed line is the regression line for $k < 0.5$. d_{med}, and ρ_{med} are calculated mean water depth and oceanic crust density respectively. B - the coherence is high for $k < 0.5$. C - estimated phase is close to zero for $k < 0.7$.

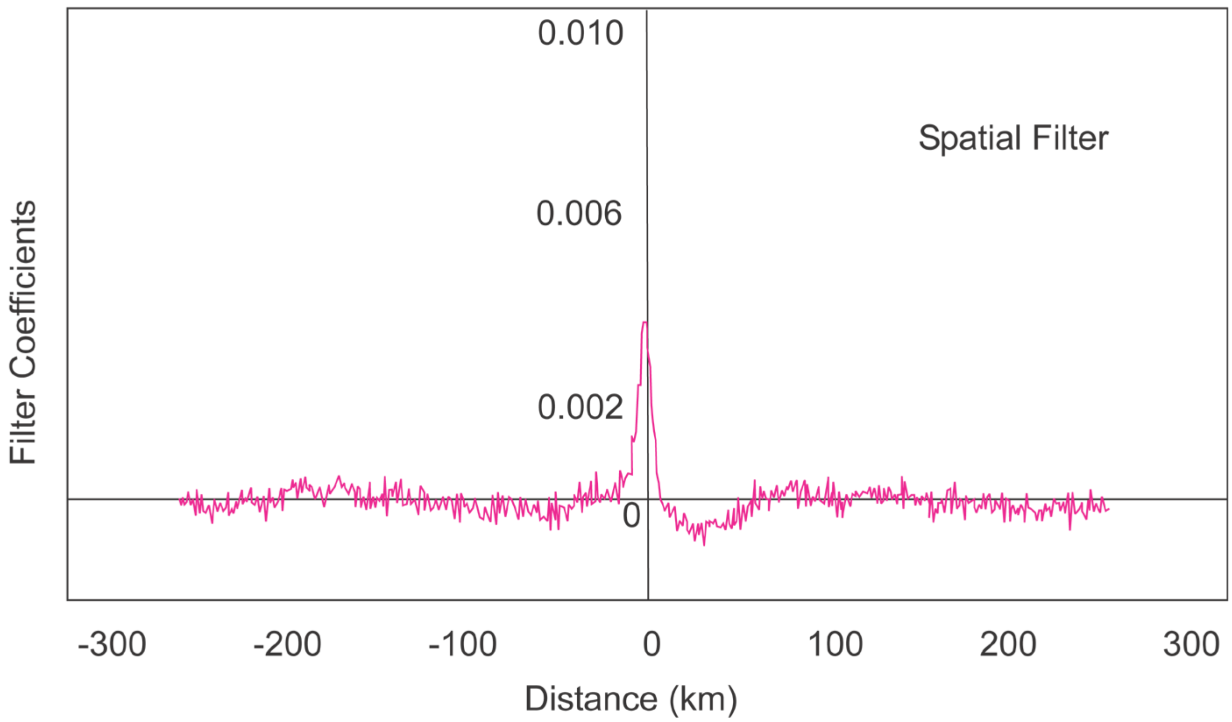

Fig. 5. Space domain filter obtained using the inverse FFT of the observed admittance. The shape of the filter side wings, which does not decay asymptotically to zero, ascertains that the TR is isostatically compensated.

Using the half space cooling model for the cut-off temperature of 450 °C, which corresponds to the transition from elastic to ductile behavior (Watts, 2001), the median estimate of age for the oceanic lithosphere at the time of the TR onset is 8 Ma, within the range of 2-17 Ma (Figure 7).

The results obtained for the two groups of profiles show that *Te* for the oceanic lithosphere south of the Tehuantepec ridge is of 10-15 km (Figure 9B). For the second set of profiles (north of Tehuantepec ridge) a high dispersion of the admittance prevents us from estimating a reliable *Te*, perhaps because of the very short length of the profiles. For this area, *Te* is apparently of 5-10 km (Figure 9A). It also seems that there is somewhat less scattering of the admittances at low wavelengths when the data are divided in two areas with respect to the TR (Figure 8). This observation may suggest that there is an apparent difference in *Te*, across the Tehuantepec ridge.

According to Watts (2001), the oceanic fracture zones are characterized by distinct shapes and specific isostatic responses. Using yield strength envelopes for the oceanic lithosphere with the thermal age of 16 Ma and 26 Ma, Watts (2001) obtained a difference in *Te* of ~6 km. The simple flexure model, which considers a continuous plate beneath the TR with a constant effective elastic thickness, yields a *Te* estimate of 10±5 km. Thus, the isostasy of a fracture zone with a ~10 Ma offset between the adjoining segments of the lithosphere (*Te* change is of ~6 km) may, as the first approximation, be modeled by a lithosphere with constant *Te*.

2D GRAVITY MODELING ACROSS TEHUANTEPEC RIDGE

Using an averaged free-air gravity anomaly profile (mean from 7 profiles used for observed admittance estimation), we obtained a 2D density model (Figure 2). The densities are the same as those used by Couch and Woodcock (1982): 1.03 g/cm^3 for sea water, 2.0 g/cm^3 for sediments, 2.8 g/cm^3 for basalts and gabbros, 3.32 g/cm^3 for the oceanic lithosphere, and 3.1 g/cm^3 for the asthenosphere. The model shows that the oceanic lithosphere SW of the TR is thicker (~50 km) than in the NW area (~38 km). Using the relationship between the thickness of the oceanic lithosphere and its age (Turcotte and Schubert, 1982), the age in the SE area is ~17 Ma, and ~10 Ma in the NW. The average crustal density of 2.55 g/cm^3 inferred from the admittance analysis (Figure 4), is lower than the density value (2.8 g/cm^3) used in the 2D density model. This normal density value of 2.8 g/cm^3 for the oceanic crust is within the density range predicted by means of admittance (2.2-2.9 g/cm^3).

CONCLUSIONS AND DISCUSSION

In their study Couch and Woodcock (1981) suggested a split of the Cocos plate in two distinct parts, but argued

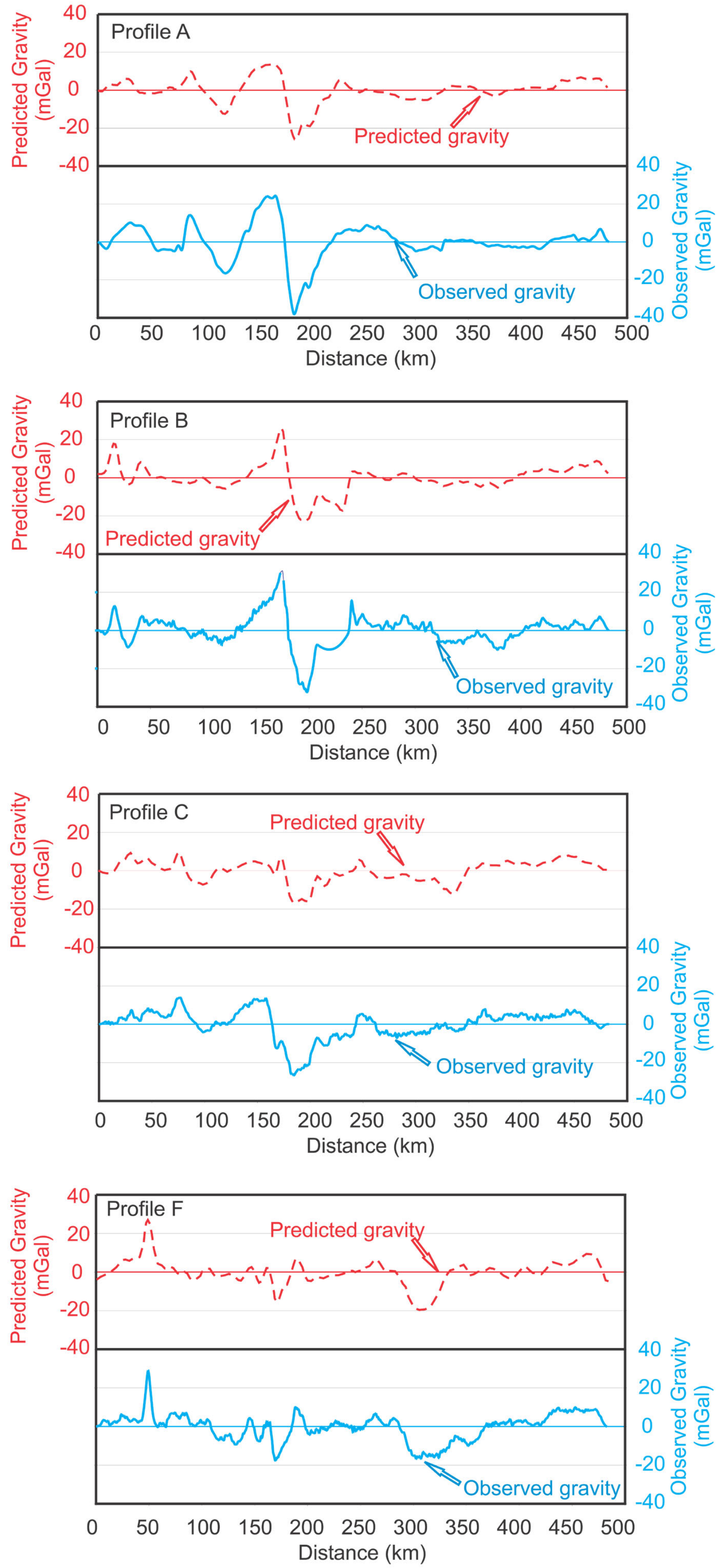

Fig. 6. Observed (solid lines) and predicted (dashed lines) gravity anomalies for profiles A, B, C and F (see Figure 1).

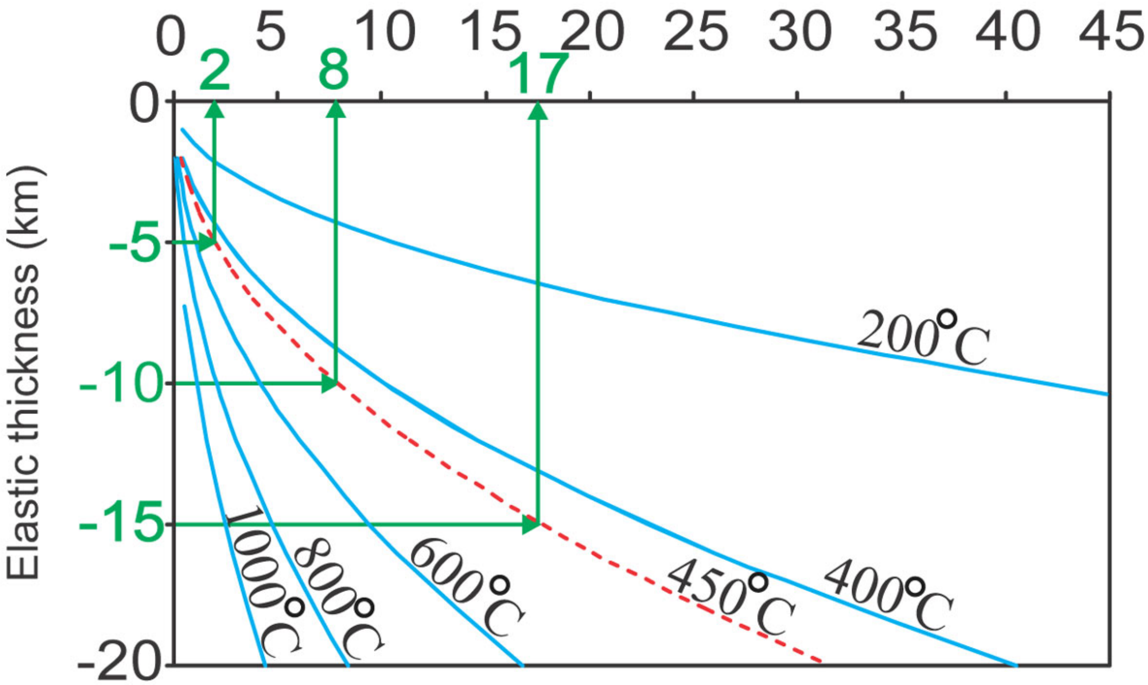

Fig. 7. Plot of *Te* against the age of the lithosphere at the time of onset of the TR. The isotherms are calculated for the half-space cooling model. For the estimated *Te* = 10±5 km the median value of the plate age is 8 Ma (in the interval of 2-17 Ma).

that northwest of the TR the Cocos plate is thicker than to the southeast. This conclusion is in obvious contradiction with other studies (e.g., Truchan and Larson, 1973; Kligord and Mammerickx, 1982). Using an average free-air gravity profile crossing the TR (mean of 7 profiles used for the admittance estimation), we carried out a 2D gravity modeling that distinguishes the older oceanic lithosphere southeast of the TR as thicker and colder (with a lower thermal gradient) than the lithosphere to the northwest of the TR. The mean age difference across the TR is about of 7 Ma.

The estimation of the elastic thickness, *Te*, was inferred from the analysis of the experimental admittance. The best fitting to the $Z^{obs}(k)$ is the simple flexure isostatic model with *Te* of 10±5 km. Best fitting Airy model gives an overestimated, unreal thickness of the oceanic crust, T_c, of 30±10 km. Low observed admittance for low wavenumbers and also the shape of the filter coefficients show that the TR is compensated isostatically. Using the assessed values for *Te* and applying the half-space cooling model, the age estimate of the oceanic lithosphere at the time of the TR onset is of ~8 Ma.

The admittance estimates for the set of profiles crossing the TR show a noticeable data scattering at wavelengths of λ = 4-6 km (Figure 4A). After dividing the data in two distinct parts (NW and SE of the TR), the resulting admittances are apparently less scattered at short wavelengths (Figure 8). This observation suggests a change in *Te* across the TR related to the instant Cocos plate age increase. In order to search for this difference in *Te*, we perform the admittance analysis separately for both NW and SE sets of truncated profiles. The results show that in the NW area where the crust is younger, *Te* is apparently of ~5-10 km, while in the SE area *Te* is of ~10-15 km (Figure 9). The higher scattered admittance for the NW area (Figure 9A) is probably caused by insufficient length (187 km) of the profiles used in the analysis. On the other hand, the longer profiles (325 km) used in the SE area result in less scattered admittance for low wavenumbers and a more reliable *Te* estimate (Figure 9B).

Because of the unreliable *Te* result for the NW area we cannot infer a significance in the difference in *Te* estimates for the Cocos plate, NW and SE of the Tehuantepec ridge. It then may be acceptable, as the first approximation, to use a simpler model which allows the same elastic thickness of the lithosphere across the TR.

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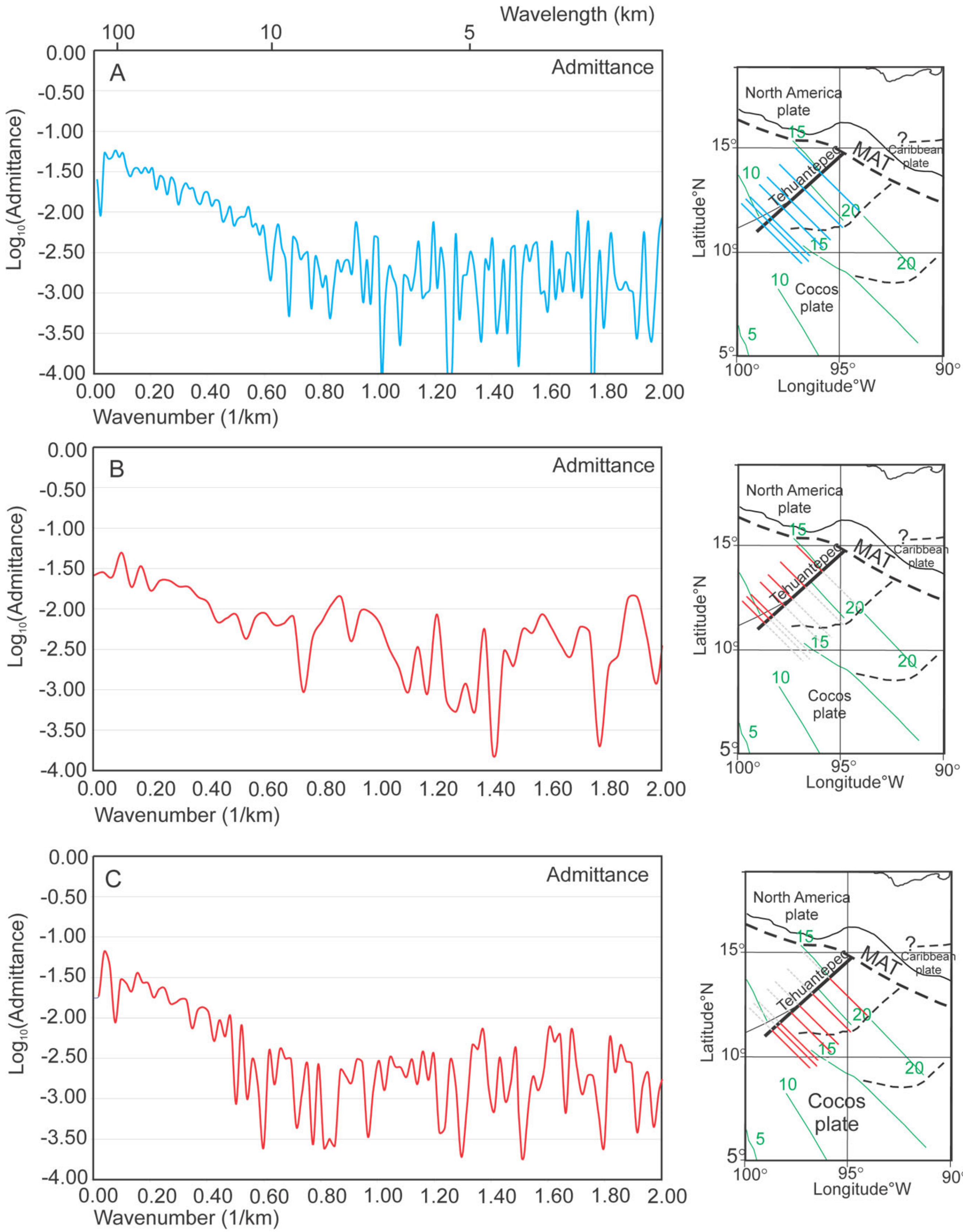

Fig. 8. A - calculated admittance for profiles across the TR; B - calculated admittance for profiles situated NW of the TR; C – calculated admittance for profiles located SE of the TR. Note a relatively less scattered admittance estimates at short wavelengths when the analysis is done with separated datasets. Right side insets show the location of the profiles. Isochrones are based on Wilson (1996).

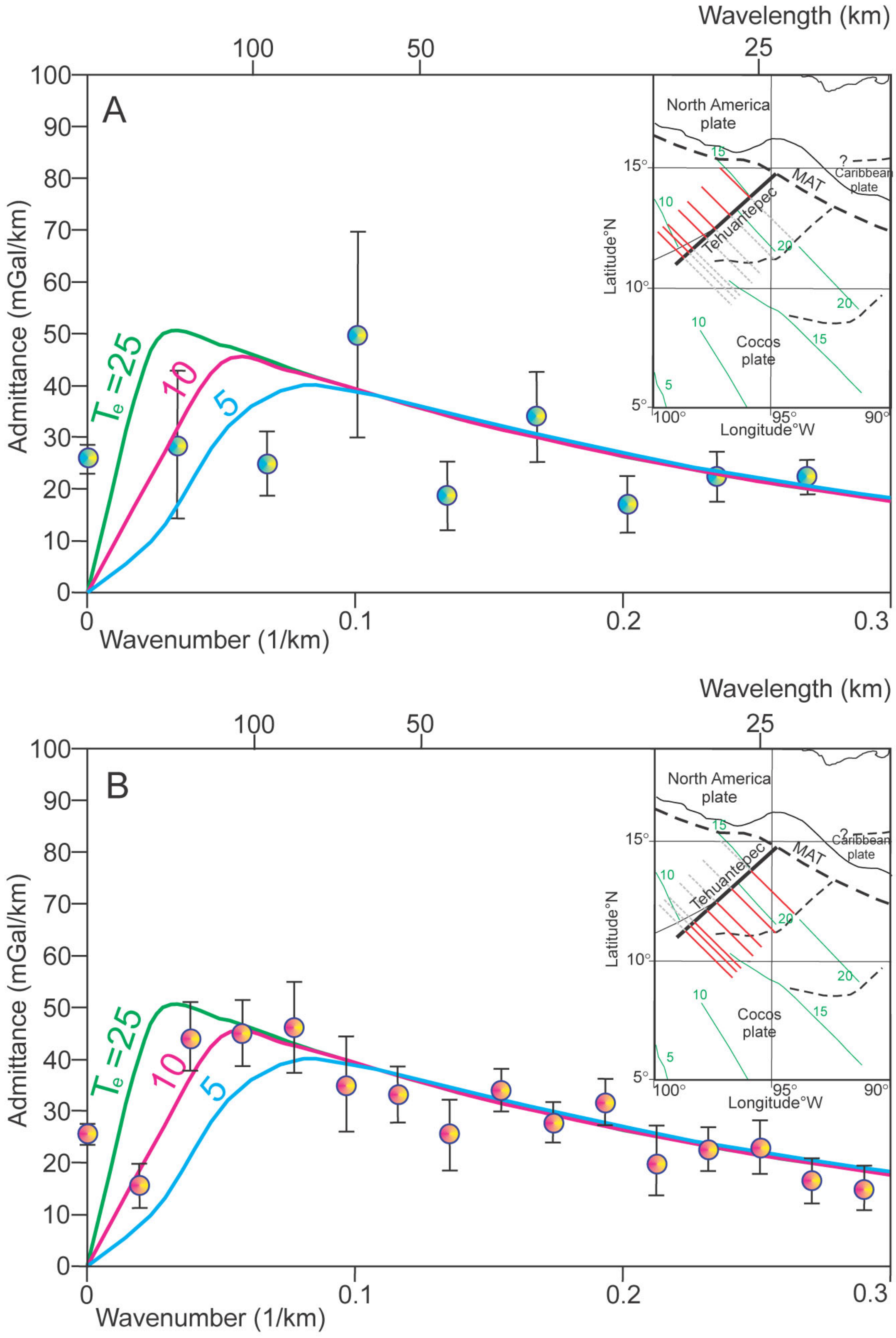

Fig. 9. Admittance estimates for two sets of truncated profiles: NW and SE of the TR. Observed admittance (solid circles) and theoretical $Z(k)$ curves for simple flexure isostatic compensation model: A - for the NW area, B - for the SE area. Errors of the observed admittance are computed from the coherence (Watts, 1978). The best fitting model for the SE area is a simple flexure of the oceanic lithosphere with Te = 10-15 km. For the NW area a reliable Te estimation is not possible due to a large dispersion of the observed admittance. The insets show the location of the profiles and the age isochrones based on Wilson (1996).

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