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Sediment fill in the Middle America Trench inferred from gravity anomalies

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RESUMEN

Una secuencia de perfiles de anomalía de gravedad de aire libre a través de la Trinchera de Mesoamérica es usada para modelar el relleno sedimentario de los facies sedimentarios no consolidados pelágicos y hemipelágicos y del material parcialmente alterado del basamento. La diferencia entre los mínimos gravimétricos y batimétricos se utiliza en la estimación de la cantidad de los sedimentos de densidad baja. El efecto de gravedad de relleno es relativamente pequeño, sugiriendo que el proceso mayor en la Trinchera de Mesoamérica es la subducción de sedimentos y el raspar de los sedimentos pelágicos desde la cima de la placa oceánica subducida. El volumen de los sedimentos en la trinchera tiende a incrementarse hacia el sur desde Jalisco hasta Oaxaca. Esta tendencia está menos clara en la Cuenca de Guatemala. Hay una cierta correlación entre el monto de relleno sedimentario fresco y la velocidad de convergencia a la trinchera excepto los perfiles con una contribución terrígena de sedimentos o las áreas de subducción de las entidades batimétricas importantes.

PALABRAS CLAVE: Subducción, relleno sedimentario de la trinchera, anomalías de gravedad, Trinchera de Mesoamérica, México.

ABSTRACT

A sequence of free-air gravity anomaly profiles across the Middle America Trench are used to model the sediment fill of unconsolidated pelagic and hemipelagic sediment facies, and partially altered bedrock material. The shift of the free-air forearc low from the bathymetric minimum in the trench is used to estimate the amount of low-density sediment. The gravity effect of the fill is relatively small, suggesting that the dominant processes in the Middle America trench are sediment subduction and scraping of unconsolidated pelagic sediments from the top of the subducting oceanic plate. The sediment volume in the trench tends to increase southward from Jalisco to Oaxaca. In the Guatemala basin this tendency is less clear. There is some correlation between the amount of fresh sediment fill and the convergence rate at the trench, except for the profiles with an extensive terrigenous sediment contribution or the areas of subduction of prominent bathymetric features.

KEY WORDS: Subduction, trench sediment fill, gravity anomalies, Middle America Trench, Mexico.

INTRODUCTION

The Middle America Trench (MAT) is approximately parallel to the coast for more than 2600 km, from Jalisco to Costa Rica. This trench is associated with gravity and bathymetry minima. The northern section of the MAT is separated from its deeper southern section by the Tehuantepec Ridge that intersects the trench near 15°N, 95°W (Menard and Fisher, 1958). To the south, the MAT stops at the northeast trending Cocos Ridge.

The depth of the MAT varies between 4500 and 6500 m. Northwest of the Tehuantepec ridge, the MAT is shallower than in the Guatemala basin by approximately 1000 m. Northwest of Acapulco, the MAT is generally U-shaped in cross section, with a steeper landward slope and a flat bottom due to sedimentary fill (Fisher, 1961). Between Acapulco and the Tehuantepec ridge, the trench is segmented and forms a sequence of deeper basins up to 5000 m depth (Figure 1). Southeast of the Tehuantepec ridge, the MAT is wider and deepens to a maximum depth of 6400 m in the western Guatemala basin. The MAT is V-shaped here; it is also asymmetric with an irregular bathymetry. These morphological features may imply that the amount of sediments in the V-shaped trench regions is less that in the U-shaped MAT (Fisher, 1961; Moore, 1981).

Studies of the sediment fill in the northern part of the MAT are limited (e.g., Ross, 1971, Renard *et al*., 1980, Mercier de Lépinay *et al*., 1997). The Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) are restricted in Mexico and Guatemala to a few drilling clusters along the MAT (Underwood and Moore, 1995). The observed sedimentation rate on the landward slope of the MAT (DSDP

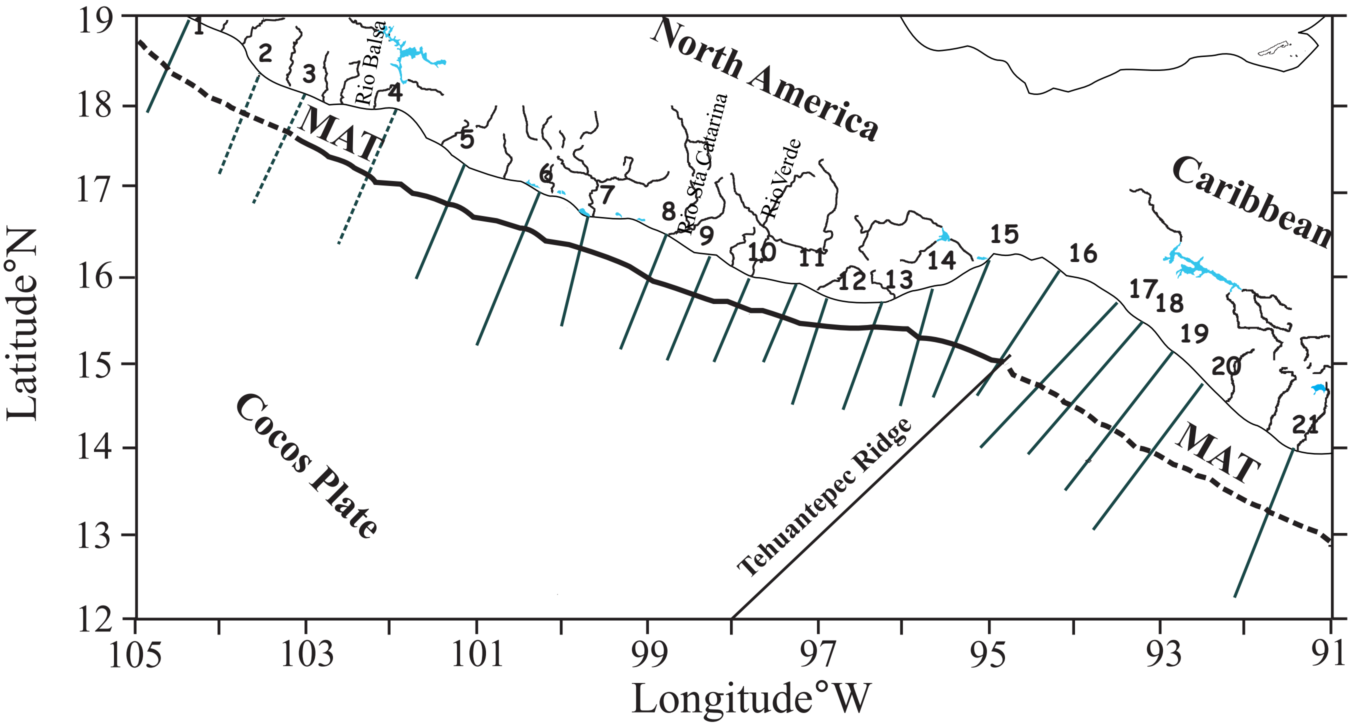

Fig. 1. The study area with the locations of the modelled profiles along the MAT. Light dashed lines indicate the tectonically complex profiles. These profiles are not modelled in this study. Heavy dashed MAT lines indicate subduction-erosion off Jalisco (Mercier de Lepinay *et al*., 1997) and off Guatemala (Aubouin *et al*., 1982, Aubouin *et al*., 1984). A segment of the MAT shown by solid line indicates subduction-accretion (Moore *et al*., 1981). Solid lines on the continent show the main rivers.

site 486, in front of Acapulco) is 1.46 km/m.y. (Ross, 1971), which is not sufficient to maintain a dynamic equilibrium in the subduction zone (Mountney, 1997).

Renard *et al*. (1980) observed a series of linear scarps, oblique to the MAT. The multi-beam echo-sounder survey shows that these scarps are parallel to the linear magnetic anomalies. They are interpreted as faults inherited from the East Pacific Rise and reactivated as they approached the trench. The estimate of maximum sediment thickness is ~400 m (Renard *et al*., 1980). There is no evidence of sediment accretion in the MAT.

Hilde (1983) showed that the graben-type pattern is well developed on the seaward slope of the MAT. This agrees with previous observations by Fisher (1961), Fisher and Hess (1963), and Renard *et al*. (1980). Hilde (1983) states that it is likely that sediment subduction prevails over accretion for the entire chain of Circum-Pacific subduction zones.

The present study originates from the observation that the gravimetric minimum, which is typical for deep oceanic trenches, does not coincide with the bathymetric minimum at the trench axis. Talwani (1968) made this observation for the gravity anomalies across the Aleutian and Japan Trenches. All along the MAT, the gravimetric minimum is located over the landward slope of the trench. The offset between the gravimetric and bathymetric minima suggests that there is a low-density sedimentary fill, which can be estimated in some cases by gravity anomaly modelling (Figure 2). The goal of this study is to estimate the amount of unconsolidated sediments accumulated in the MAT and its distribution along the trench. Such estimates are important, for example, in studies of subduction tectonics and sediment balance, interplate coupling, thermal modelling of subduction zones, and low-frequency tsunamigenic earthquakes.

SEDIMENTS IN SUBDUCTION ZONES

In addition to sedimentation, three principal tectonic processes control the trench fill at convergent plate boundaries: subduction accretion, sediment subduction, and tectonic erosion. Which of these processes is dominant depends on the state of stress at the subduction zone. Sediment subduction prevails when the interplate coupling or normal stress across the subduction zone is relatively low, and either accretion or tectonic erosion occurs when coupling is high (Uyeda and Kanamori, 1979; Dewey, 1980; Uyeda, 1982 and 1983).

Isacks *et al*. (1968) first suggested that normal fault structures or grabens that develop on subducting oceanic

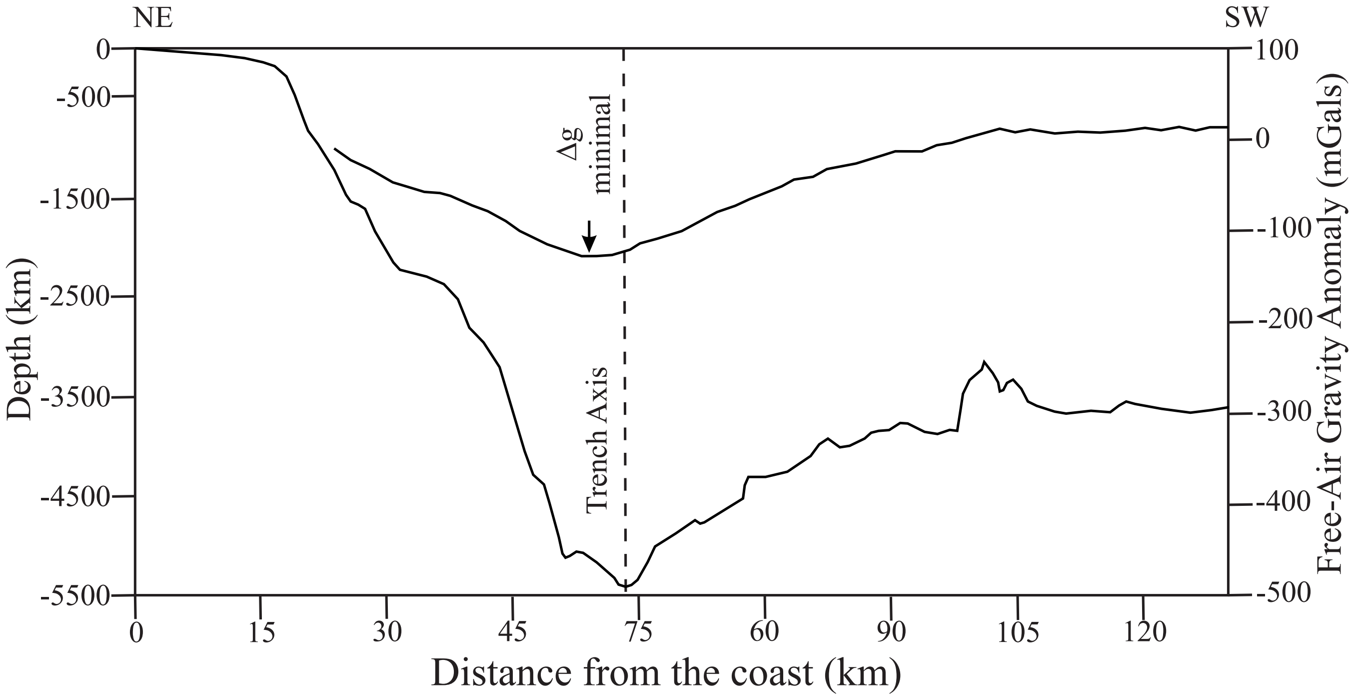

Fig. 2. Example of free-air gravity anomaly, Δg, and bathymetry profiles across the Middle America trench. The minimum of Δg does not coincide with the trench axis. This suggests low-density sediment fill in the trench.

plates might facilitate sediment subduction. Normal faults are common on the seaward slope of trenches (Hilde, 1983, Renard *et al*., 1980). These faults are associated with tension acting on the subducting plate. Graben formation occurs initially near the outer topographic high, in front of the trench. Graben depth increases as the oceanic plate moves down for some 400 m or more towards the trench. Graben-type structures provide traps on the subducting plate where trench sediments are captured and subducted (Figure 3).

In general the terrigenous input to the MAT is insufficient for a dynamic trench fill balance. The continuous supply of sediments to the trench is balanced by the removal of sediments from the inner trench wall by subduction or accretion when the equilibrium is maintained (Mountney, 1997). Thus, the sediment facies should be normally small in the trench fill complex. We would expect that unconsolidated pelagic facies are the main source of trench fill material, which is scraped off the top of the oceanic plate as it is subducting the trench. Higher density, consolidated pelagic sediments must be totally subducted, otherwise the total sediment fill within the MAT should be ~10 times higher than the observed values.

In non-accretional subduction zones, the volume of subducted sediments should depend on the pelagic sedimentation rate and the sedimentation duration, which is proportional to the A age of the oceanic lithosphere in the trench. The convergence rate, V (km/yr), may also be an important parameter for the sediment subduction (e.g., Kostoglodov, 1988; Mountney, 1997).

This study is concerned with the unconsolidated, lower density phase of trench sediments, which develops from the removal of relatively fresh top cover of the pelagic sediments, *h*, plus some terrigenous component. The specific volume of unconsolidated sediment fill is the volume of a unit length (1 km) of sediment fill, *SVSF,* which produces the observed gravity effect. It depends on the fresh sediment input into the MAT, the sediment consolidation rate, Vc (km/yr) and the sediment subduction flux:

$$SVSF \sim [(hV + S_t w)\text{-}V_c w]^* t \ , \qquad (1)$$

where *h* (km) is the mean thickness (assumed constant) of the soft pelagic sediment cover scraped off the top of the subducting plate; S_t (km/yr) is the average terrigenous sedimentation rate in the MAT, which may depend on the coast-trench distance and on the proximity to the estuaries of large rivers; *w* (km) is the trench width, and *t* (yr) is the time (see Figure 3).

DATA

The gravity data (Δg) used in this study are free-air anomalies from the Geophysical Data System (GEODAS) provided by the National Geophysical Data Center (NGDC) (Marine Trackline Geophysics, V 4.0). These data have an

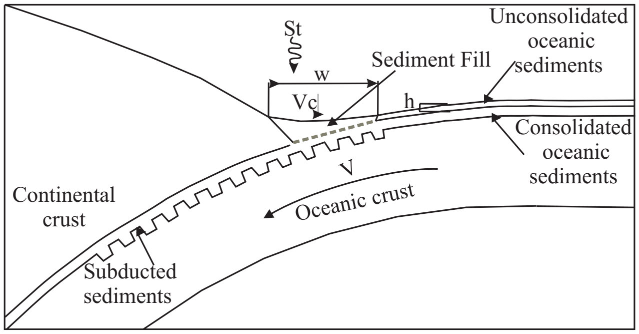

Fig. 3. Trench model with sediment fill and graben structures on the subducted oceanic plate. V (km/yr) is the convergence rate, Vc (km/yr) is the sediment consolidation rate, h (km) is the mean thickness (assumed constant) of the soft pelagic sediment cover scraped off the top of the subducting plate; St (km/yr) is the average terrigenous sedimentation rate in the MAT, which may depend on the coast-trench distance and on the proximity to the estuaries of large rivers; w (km) is the trench width and t (yr) is time.

accuracy of 3-7 mGals. The bathymetric data utilized for the modelling are retrieved from the Geodas bathymetric database (Marine Trackline Geophysics, V 4.0).

The study area (Figure 1) is a rectangle of 20°N, 105°W to 12°N, 91°W. We selected 17 profiles perpendicular to the trench axis from a total of 21 profiles available. The distance between profiles is 0.5° to 1°. The length of the profiles is 100 to 250 km. Profiles 2-4 cross a tectonically complex zone traversed by the Lázaro Cárdenas Canyon and the Orozco Fracture Zone. The Balsas river discharges a large amount of terrigenous sediments into this area. Therefore, the data along these profiles are dispersed and the sediment fill modelling is problematic.

Seismic record data and isopach maps from the IOC Geological/Geophysical Atlas of the Pacific (GAPA) project (Ladd *et al*., 1985) are used to develop the modelling results. Some reliable seismic data can be found along the northern part of the MAT, off Colima and Jalisco (Michaud *et al*., 2000) where a prominent horizontally layered sedimentary wedge was found. It should be noted that gravity methods detect only the unconsolidated wedge sediments, and the acoustic basement may not actually represent the base of the sediment cover (World Data Center for Marine Geology & Geophysics). Figure 4 shows seventeen analysed profiles of free-air gravity anomalies and bathymetry over the MAT. These profiles are subdivided into two groups: the northwestern part of the MAT (NW off the Tehuantepec Ridge), and the southeastern part (Guatemala Basin). From Figure 4, in all profiles, the Δg minimum is located over the landward slope of the trench.

The shallower dip of the Wadati-Benioff zone is constrained by seismicity data (e.g., Kostoglodov *et al*., 1996, Bandy *et al*., 1999). The thermal thickness of the subducting slab at the trench, *H*, is estimated from the *age~H* relation and the age of the oceanic crust (Klidgord and Mammerickx, 1982), using the geomagnetic polarity time scale by Cande and Kent (1995).

MODELLING SEDIMENT FILL

A strong, 100-162 mGal negative free-air gravity anomaly over the trench and the inner trench wall is observed (Figure 4). It is attributed to a mass deficit at the trench and low-density sediment fill. We are interested in determining the specific volume of the sediment fill, *SVSF*, along the MAT. The main trench features are the bathymetric and gravimetric lows and the difference between their locations, ξ, may be expressed in terms of the low-density, unconsolidated sedimentary fill which consist of the pelagic and hemipelagic sediment facies, and partially altered bedrock material. Gravity modelling helps to reveal the thickness and fill extension of these sediments within the trench.

We assume the same average densities of the rock and sedimentary material for all modelled profiles. Only the shapes of the layers are adjusted to fit Δg. The basic structure of modelled profiles is: 1) the oceanic water layer, 2) the continental crust of the overriding North American and Caribbean Plates, 3) the oceanic crust of the Cocos Plate and 4) the upper mantle.

The oceanic crust of 11 km thick (Sandwell, 2001) is modelled consisting of 3 layers: sediments, basalts and gabbros with the densities of 2.15, 2.5 and 2.8 g/cm^3 respectively (Sandwell, 2001, Morisson *et al*., 2001). The continental crust in the subduction zone consists of a thin sedimentary layer, 2.2 g/cm^3, in the continental slope region, an upper crustal layer of weathered granite, 2.75 g/cm^3, and a lower crustal layer, 2.9 g/cm^3. The sedimentary layer is formed from pelagic and hemipelagic sediments and from weathered granite fragments. The underlying upper mantle is of peridotite composition, 3.2 g/cm^3.

The gravity effect of the deep layers (e.g., upper mantle) is small and relevant only for the long wavelength regional modelling but not for a relatively short, 10-15 km wavelength free air gravity anomalies. Our models are restricted by the seismic estimates of the top of the basement and hence the thickness of the sediments for several profiles in the southern Mexico and Guatemala margins (von Huene, 1985).

In order to express the accuracy of the modelling results, the mean difference, $<\Delta g - \Delta gm>$, and its standard deviation, between the observed, Δg, and modelled, Δg_m, anomalies are shown in Figure 5. The standard deviation of the mean difference between the observed and modelled free-

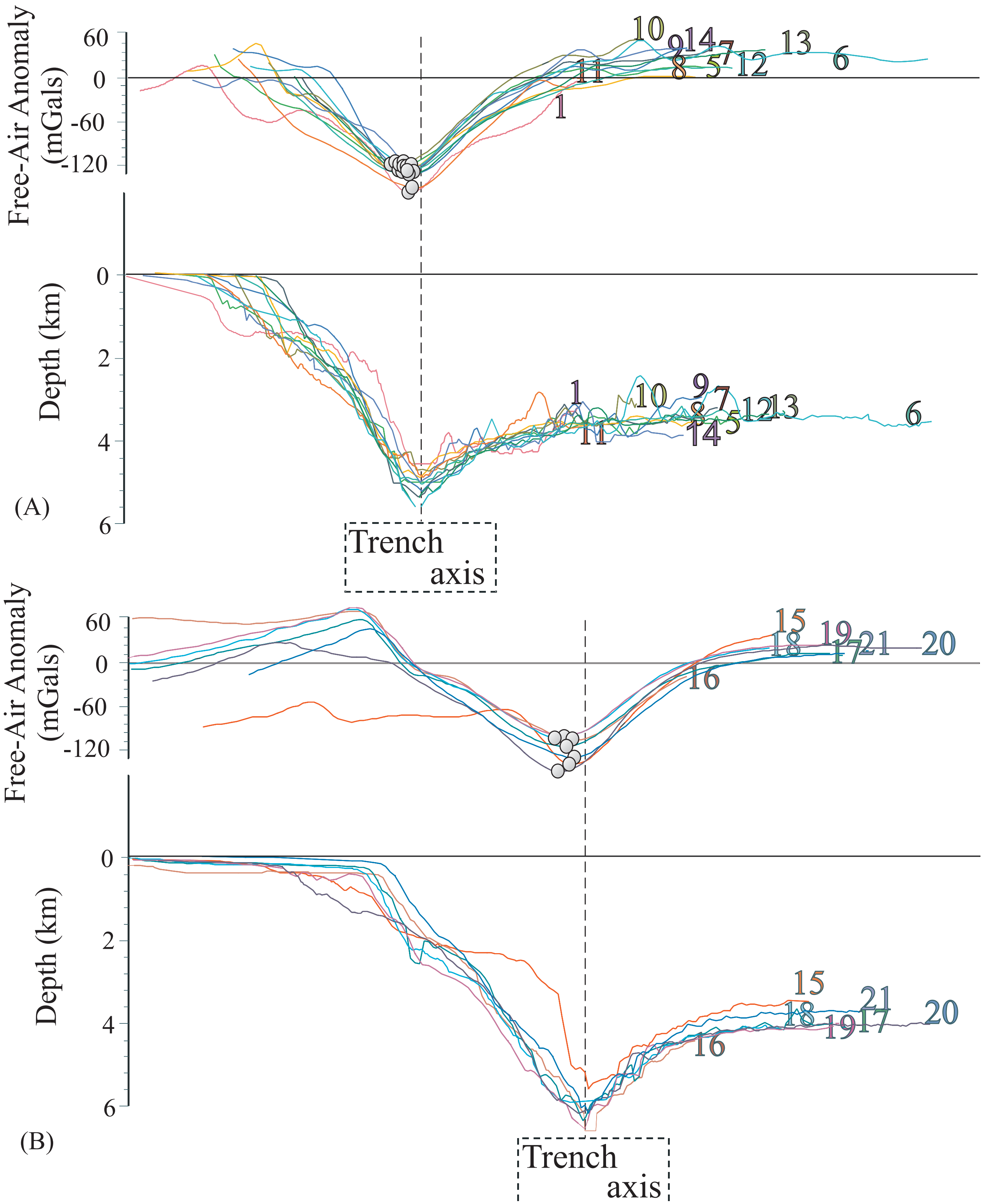

Fig. 4. Seventeen profiles of free-air gravity anomalies (Δg) and bathymetry crossing the MAT. (A) Profiles 1 and 5-14, located northwest of the Tehuantepec ridge. (B) Profiles located to the southeast of the Tehuantepec ridge (Guatemala basin). The circles on the free-air gravity anomaly curves show the positions of Δg minima.

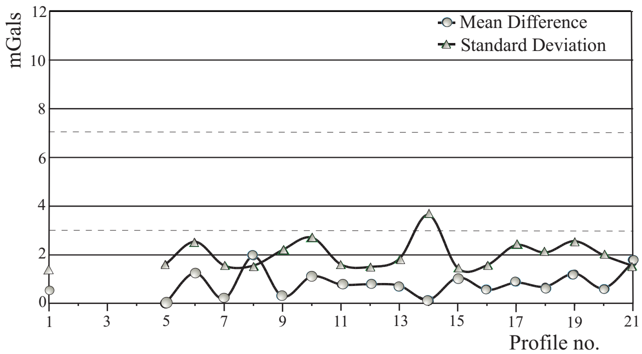

Fig. 5. Mean difference between the observed and modeled free-air anomalies for each profile. The accuracy range of the observed Δg data (GEODAS) is 3-7 mGal (dashed lines) and the standard deviation of the mean difference between the observed and modelled free-air anomalies is 1-4 mGal.

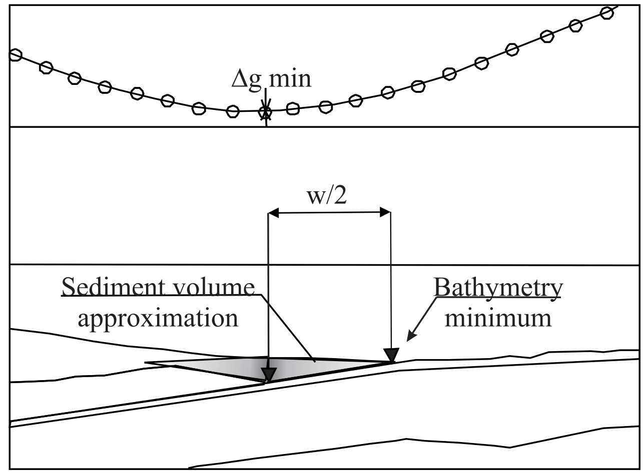

Fig. 6. Geometric approximation of the specific sediment fill volume. Grey areas representing sediment fill are determined using the difference between the locations of gravimetrical and bathymetric minima and the modeled ocean floor surface. W/2 is the half width of the sedimentary fill.

air anomalies is 1-4 mGal, which is within the accuracy range of the observed Δg data (GEODAS) of 3-7 mGal.

The difference in locations between the bathymetric and gravimetric minima, ξ, suggests the lateral extension of the trench fill. After the maximum depth and extension of the trench sediment fill is obtained from the gravity anomalies modelling, the estimate of the specific volume of the sedimentary fill, SVSF, is done using a simple geometric approximation shown in Figure 6. We assume that the sediment fill is symmetric in the V-shaped trench basement. The SVSF in the trench is roughly proportional to ξ, hence the smaller is ξ the less is the sediment fill. In fact this relation comes out from the previous studies by Menard and Fisher (1958), Fisher and Hess (1963), Renard *et al*. (1980), and Hilde (1983).

RESULTS AND DISCUSSION

The minimum free-air gravity anomaly across the MAT does not coincide with the bathymetric minimum. In the northwestern part of the MAT (Figure 7a), the difference, ξ, between locations of the bathymetric minimum (trench axis) and the gravimetric minimum is small, ξ = 0.44 - 0.80 km, (see profiles 1-4 in Jalisco and Michoacán, Figure 1). This difference systematically increases up to ξ = 2.05 - 9.19 km in the central part of the MAT (profiles 6-9, 11,12 in Guerrero and Oaxaca, Figures 1 and 7b-7d), but it noticeably decreases, ξ = 0.5 - 2.18 km, in front of the Tehuantepec Ridge (profiles 13-15, Figure 1). In the Guatemala basin, southeast of the MAT (Figure 7e,f), the difference between the gravimetric minimum and the trench axis is approximately constant along the entire trench. This difference is relatively small, ξ = 2.73 - 4.80 km (profiles 16-21, Figure 1). The profile 19 is an exception, ξ = 5.75 km, probably due to higher local terrigenous sedimentation. Profile 10 (Figure 8) has an anomalously high ξ = 9.18 due to a large amount of terrigenous sediments supplied to the trench by the Verde River. This suggests that an important amount of terrigenous sediments might be focused mainly in front of the large rivers.

Estimates of ξ for profiles 10, 13 and 14 are apparently outliers, provoked by some local effects (e.g., contribution of high terrigenous sedimentation and probable tectonic erosion or lesser sediment fill over the subducting Tehuantepec ridge, profiles 13-16). The *SVSF* and the age of the oceanic lithosphere do not change noticeably in the Guatemala basin trench (except may be for Profile 19 where ξ is higher because of the strong terrigenous contribution). Note that the mean *SVSF* in the Guatemala basin is lower than that for the northwestern part of the MAT.

The plot of *SVSF* as a function of *V* (Figure 9) shows that there is a general tendency of augmenting the *SVSF* as the convergence rate is increasing. This trend is more distinct for the northwestern part of the MAT and is not so clear in the Guatemala basin where the boundary and convergence rate between the Caribbean and the Cocos plate are very poorly known. It is possible that there are the two distinct sedimentary regimes in the northwest and southeast segments of the MAT. The average terrigenous sedimentation rate, St, within the Guatemala basin trench is expected to be lower than that in the northwestern part of the MAT, which could be merely an effect of a drastic change in the coast-trench width across the Tehuantepec ridge. The longer transportation distance should diminish the terrigenous sedimentation rate at the MAT.

A difference in the plate coupling is also a conceivable factor, which have some bearing on the scrapping and accre-

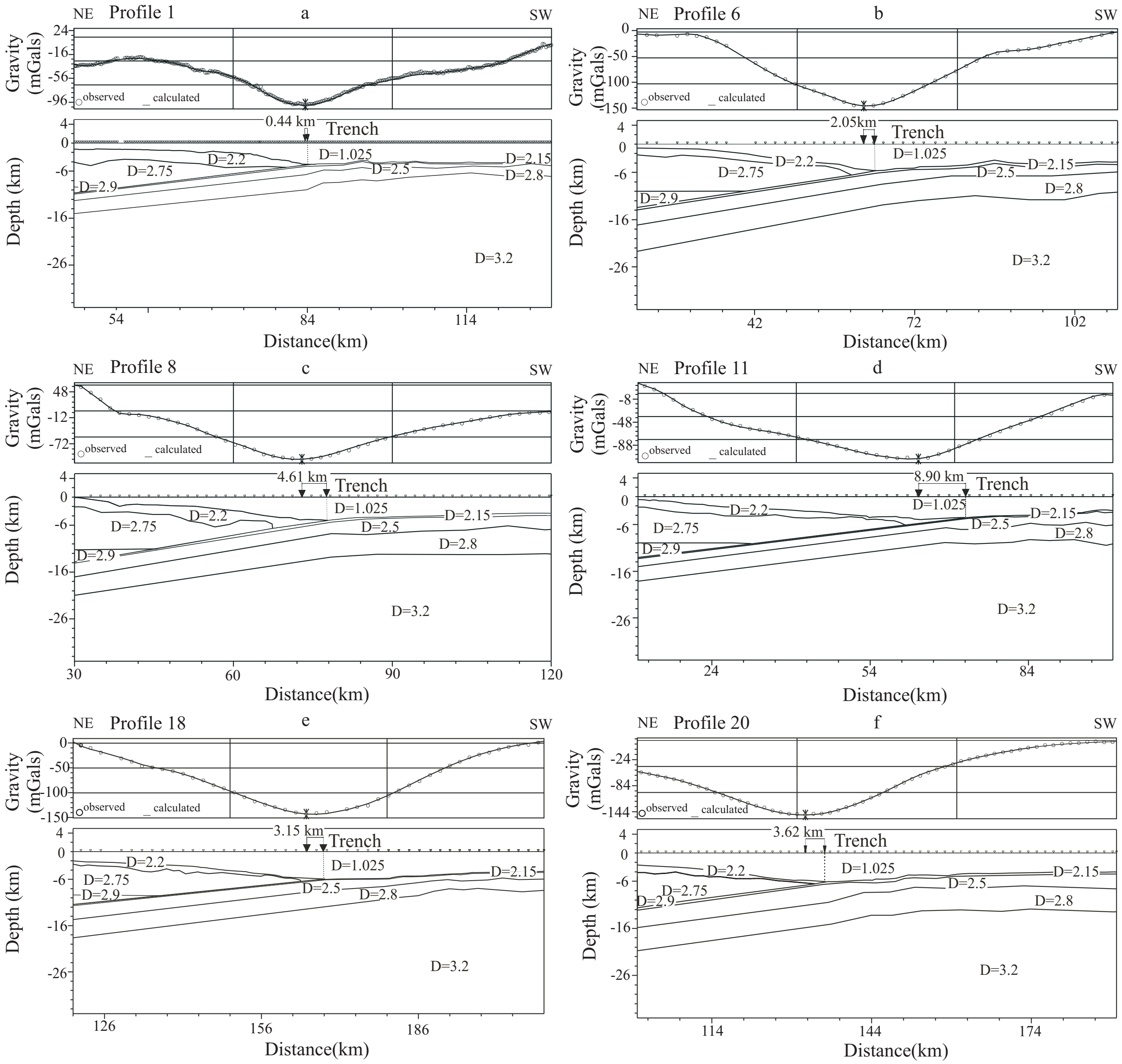

Fig. 7. Examples of free-air gravity anomaly profiles and gravity models at the northwestern part (a-d) and the southeastern part (e,f) of the MAT. The modelling was done for the entire length of the profiles (100-250 km) but only the trench segments of the profiles are shown. Vertical exaggeration is 1.21. The distance between the arrows is w/2 (half width of the sediment fill). D is the density in g/cm^3.

tion of the sediments from the subducting oceanic plate. We may suspect the higher interplate coupling to the northwest of the Tehuantepec ridge, where the Cocos plate is relatively younger, $A < 16$ Ma.

A relatively small overall value of the *SVSF* estimated from the free-air anomaly modelling is the strongest argument for sediment subduction. The volumes of accreted wedge sediments are incomparably less than these volumes calculated under the assumption that all deposits transported with the oceanic lithosphere to the trench have been accreted (Scholl *et al*., 1977). However, an accurate evaluation of the sediment subduction/accretion balance is not yet possible at the MAT (as well as on the global scale) because of the lack of reliable data. Thus, some seismic profiles normal to the MAT in order to provide the depth of the acoustic basement surface and thickness of slope deposits are needed for a better evaluation of the SVSF.

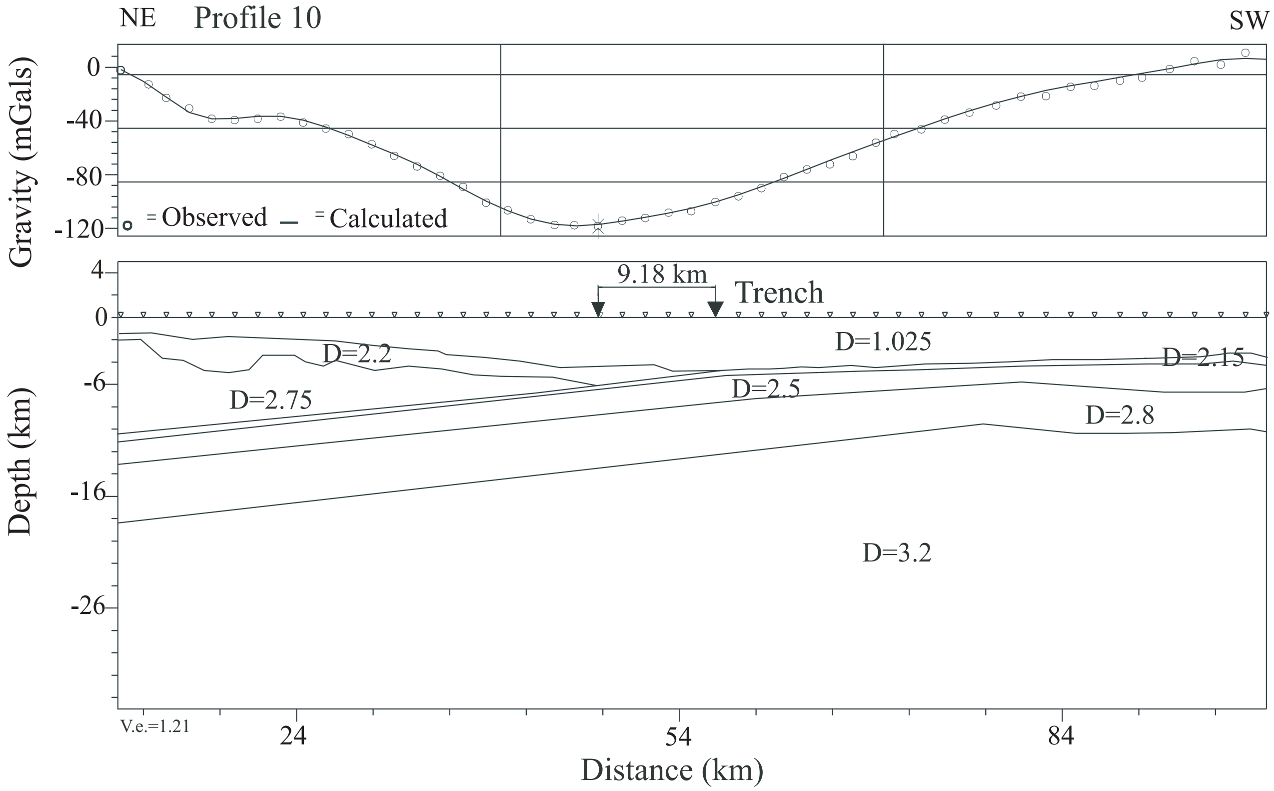

Fig. 8. Profile 10 shows an anomalously wide difference between the position of the gravity and bathymetry minima (w/2) due to a large amount of terrigenous sediments supplied by the Verde River into the trench.

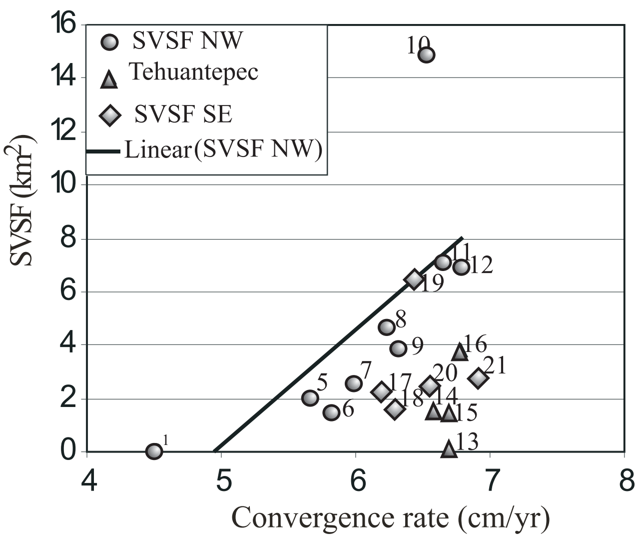

Fig. 9. Plot of *SVSF* as a function of V. Circles represent the SVSF northwest of Tehuantepec; triangles show the SVSF near the Tehuantepec ridge, and diamonds the SVSF in the southeastern part; a linear tendency between SVSF and the convergence velocity may be observed in the northwestern part. The outlier (profile 10) can be excluded from this analysis due to large terrigenous influence. The trend observed in the northewestern MAT is not valid for the Guatemala basin, where the boundary between the Caribbean and Cocos plate (and hence the convergence rate) are poorly known.

CONCLUSIONS

The estimated specific volume of the fresh sediment fill, *SVSF*, increases gradually along the MAT from *SVSF* ≈ 0 km^2 in Jalisco up to *SVSF* ≈ 7 km^2 in Oaxaca. The *SVSF* is contaminated in a few cases by a bulky terrigenous sediment contribution from large rivers (e.g., Profiles 10, 19) or a probable tectonic erosion process (e.g., Profiles 13-16). A rough linear relation is observed between the convergence rate, *V*, and the *SVSF*. This relation is more distinct in the northwestern part of the MAT, where Cocos plate is relatively young, *A* <16 Ma. The *SVSF* = *f*(*V*) relation is ambiguous in the Guatemala basin segment of the MAT. The average *SVSF* in the Guatemala basin is lower than the *SVSF* within the northwestern part of the MAT. This observation indicates that the tectonic regimes are different in these segments of the MAT (see DSDP 66 and DSDP 84). A relatively small estimated amount of the *SVSF* suggests that sediment subduction is the dominant tectonic process along the Mexican part of the MAT.

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