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Tectonics of the offshore Manzanillo and Tecpan basins, Mexican Pacific, from heat flow, bathymetric and seismic data

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RESUMEN

Se ha propuesto que la separación del Bloque de Jalisco es la consecuencia principal de la subducción oblicua diferencial de las placas de Rivera y de Cocos debajo de la de Norte América y de la interacción entre las cuatro placas. El análisis vectorial de la subducción de Rivera y Cocos con respecto a Norte América arroja una frontera de desplazamiento lateral entre las placas oceánicas, cuya velocidad es de 4.2 cm/año, que coincide en su orientación con lineamientos estructurales interpretados en el Bloque Jalisco y con el Graben Colima. Muchas estructuras en el rango de N30°-40°E y N60°-70°E en el Bloque Jalisco son similares a las observadas en el área de Tecpan, entre Zihuatanejo y Acapulco. Estos resultados concuerdan con la interpretación hecha con información geofísica marina de detalle obtenida abordo de B/O "Akademik Nikolai Strakhov" durante Febrero-Marzo de 1989 en el área frente a las costas de Manzanillo y Tecpan, incluyendo perfilado sísmico de reflexión, batimetría y 122 mediciones directas de flujo de calor. Además, se efectuaron 39 estimaciones de flujo de calor con base en la identificación a partir de los perfiles sísmicos de capas de gas en la cubierta sedimentaria del talud continental de Manzanillo. En la región limitada por cañones submarinos de la Cuenca de Manzanillo, el perfilado sísmico y la batimetría indican levantamiento reciente asociado con fallamiento de desplazamiento lateral. El flujo de calor en la porción occidental de la Cuenca de Manzanillo varía entre 20 y 35 mW/m^2 (promedio de 28±6 mW/m^2), mientras que en la porción oriental el promedio es de 51±7 mW/m^2. En ambas áreas se observa fallamiento lateral con componente vertical. El área con flujo de calor bajo se asocia con la presencia de una porción del batolito costero que se movió hacia el mar a lo largo de fallas de desplazamiento izquierdo en el Bloque de Jalisco. El flujo de calor promedio en la parte oriental de la Cuenca de Manzanillo concuerda con valores típicos medidos frente a las costas de Tecpan, Guerrero, del orden de 55±8 mW/m^2. Un flujo de calor mayor de 100 mW/m^2 fue medido en la pendiente oceánica de la trinchera. Se le atribuye a la edad joven de la corteza con respecto a la corteza continental o bien a la presencia de fuentes locales de actividad magmática o hidrotermal en el Graben El Gordo.

PALABRAS CLAVE: México, Cuenca de Manzanillo, Tecpan, Bloque Jalisco, Trinchera Mesoamericana, flujo de calor, perfiles sísmicos de reflexión, batimetría.

ABSTRACT

Separation of the Jalisco Block has been proposed to be the main result of oblique differential subduction of the Rivera and Cocos plates beneath North America and of the interaction between the four plates. Vector analysis of the subduction process of the Rivera and Cocos plates relative to North America results in a N11°E trending strike-slip fault boundary between the oceanic plates (at 4.2 cm/yr). Most of the onshore structures are in the range of N30°-40°E and N60°-70°E, as in the Tecpan area (between Zihuatanejo and Acapulco). These results agree with the interpretation of detailed marine geophysical data collected by the R/V "Akademik Nikolai Strakhov" during February-March 1989 off Manzanillo and Tecpan. The data include seismic reflection profiles, swath bathymetric data, and 122 new direct heat flow data. Also 39 indirect heat flow values were estimated based on location of gas-hydrate layers in the Manzanillo continental slope from seismic records. In the Manzanillo Basin seismic profiling and swath bathymetric data indicate a recent uplift associated with strike-slip faulting. Heat flow ranges between 20-35 mW/m^2 (average of 28±6 mW/m^2) in the western Manzanillo Basin and 51±7 mW/m^2 in the eastern basin. Both areas are bound by strike-slip faulting with a vertical component. The low heat flow is attributed to a portion of the coastal batholith that may have moved seaward along left-lateral faults in the Jalisco Block. The average heat flow value in the eastern portion is typical of the continental slope of the Middle American Trench; as measured off Tecpan, Guerrero, at an average of 55±8 mW/m^2. High heat flow (>100 mW/m^2) was found on the oceanic slope of the Middle American Trench. It is attributed to the younger age of the oceanic crust and/or to surface hydrothermal and local magmatic sources in the area of the El Gordo Graben.

KEY WORDS: Mexico, Manzanillo Basin, Tecpan, Jalisco Block, Middle American Trench, heat flow, seismic reflection profiles, bathymetry.

INTRODUCTION

Over the past few years, Soviet and Mexican scientists have conducted joint research studies on heat flow and geothermal conditions in continental and oceanic regions of Mexico.

On land, the research was largely based on isotopic gas analysis and helium content of fluids from thermal springs. Using a correlation of regional isotopic helium composition with terrestrial heat flow (Polyak *et al.*, 1979), we estimated 37 heat flow values in sites located in southern Mexico (Polyak *et al.*, 1985). This approach may be useful in areas where no direct determination of heat flow is possible. The data are in good agreement with Smith *et al.* (1979) and Ziagos *et al.* (1985).

Off the Atlantic and Pacific coasts of Mexico the lack of consistent heat flow data prevents a correlation of heat flow variations with the regional geologic structure and the tectonics. Part of the work in the Atlantic has been reported in Khutorskoy *et al.* (1990). Recent heat flow results at 46 sites along the Middle American Trench offshore Mexico were described by Sugrobov *et al.* (1989) and Prol-Ledesma *et al.* (1989).

In this paper we present the results obtained during cruise 8 of R/V "Akademik Nikolai Strakhov" (1989) along the Middle American Trench off Mexico. We concentrated on an area off Manzanillo, Colima (Figure 1), which has attracted the attention of geologists in recent years. Luhr *et al.* (1985), Allan, (1986) and Bourgois *et al.* (1988) agree that the active Colima Graben is a rift that extends offshore, and that its present development may be linked to an eastward jump of the East Pacific Rise into this region. This would indicate that the Jalisco Block is moving to the northwest in the direction of Baja California. It may be a modern equivalent of the process that gave birth to the opening of the Gulf of California some 4.5 Ma ago (Atwater, 1989).

An international team led by French scientists (project SEAMAT) conducted a marine geophysical survey of some sections of our study area (Bourgois *et al.*, 1988). Their preliminary results indicate the presence of rift structure(s) (Manzanillo Rift and El Gordo Graben), implying that the Jalisco Block is composed of oceanic and continental crust. From SEABEAM and seismic data, these authors find a N30°E to N40°E preferred trend of major faulting (normal faulting throughout), which changes direction inland (Allan, 1986) and disagrees with the known rates of displacement and the principal directions of relative motion between the Rivera, Cocos and North American plates.

Our detailed bathymetric (MULTIBEAM) and seismic profiling included a total of 38 direct heat flow determinations offshore Manzanillo. In addition, 39 indirect heat flow values were estimated, based on the location from seismic records of the gas-hydrate layer in the sedimentary cover of the continental slope of the Middle American Trench. Rifting mechanisms are usually reflected in the thermal field, and tend to show anomalously high heat flow and large dispersion in heat flow values (Von Herzen and Anderson, 1972). Thus, we expected to find a large dispersion of heat flow offshore Manzanillo. We determined the background heat flow on the continental slope of the Middle American Trench from 12 heat flow stations off Tecpan (between Zihuatanejo and Acapulco, Figure 1), where Karig *et al.* (1978) had found no evidence of rifting.

We review the tectonic evolution of the Manzanillo and Tecpan-Acapulco areas, and we present a structural dynamic model for the offshore Manzanillo area (Manzanillo Basin). This model is based on our heat flow results in the region, and discusses the lateral distortions of the geothermal regime and the influence of bottom topography and geological heterogeneities, using mainly two-dimensional finite-element modeling.

TECTONIC AND GEOLOGIC SETTING: MANZANILLO AND TECPAN AREAS

Detailed bathymetric surveys along the Pacific margin of southwestern Mexico (Karig *et al.*, 1978; Bourgois *et al.*, 1988) reveal remarkable similarities with tectonic features inland. In both areas surveyed, off Manzanillo and off Tecpan (between Zihuatanejo and Acapulco), the main geologic features are related to the presence of a poorly-understood triple junction west of the Manzanillo Basin, and to the contact between two large terranes in the Tecpan area (Figures 2 and 3).

Manzanillo quadrangle

Northeast of Manzanillo, the main tectonic feature is the Colima Graben. It has been described in detail by Allan (1986) as a possible rift zone associated with a continental rift-rift-rift triple junction. Two other structures associated with this triple junction are the east-west and NW-SE trending Chapala and Zacoalco grabens. The Manzanillo Basin would be located in the southern limit of the Jalisco Block (Allan, 1986). Based on the correlation and geometric evolution of plate boundaries in the Pacific Ocean, Luhr *et al.* (1985) suggested that the East Pacific Rise, between the Tamayo and Rivera fracture zones, is experiencing an eastward displacement toward the Colima Graben.

The present subduction velocity of the Rivera Plate under the Jalisco Block is estimated by Nixon (1982) at 2 cm/yr. The orientation of the velocity vector is consistent with the direction estimated from earthquake mechanism 32 of DeMets and Stein (1990), at N40°E ± 5°. The velocity is 1.9 ± 3 cm/yr at 19.4°N, 105.0°W; but near our study area the Cocos Plate is subducted under the North America Plate at 6 cm/yr. Using the picture of Klitgord and Mammerickx (1982), the poor magnetic resolution and the width of the Rivera Fracture Zone and the East Pacific Rise suggests the presence of a trench-trench-ridge triple junction near the Middle America Trench. Bourgois *et al.* (1988) inferred that a series of N30°-40°E trending normal faults define two grabens (El Gordo in oceanic crust, and Manzanillo in continental crust), which would be tectonically related to the Colima Graben as their fault boundaries project toward the coast.

From the structural map in Allan (1986, Figure 2), the Colima Graben in its northern and southern portions is defined by almost N-S trending normal faults. The general trend is N10°E in the central part near the coast, up to the juncture with the Zacoalco and Chapala grabens. Allan (1986) points out that the projection of the boundary between the Cocos and Rivera plates coincides with the southern limit of the Colima Graben.

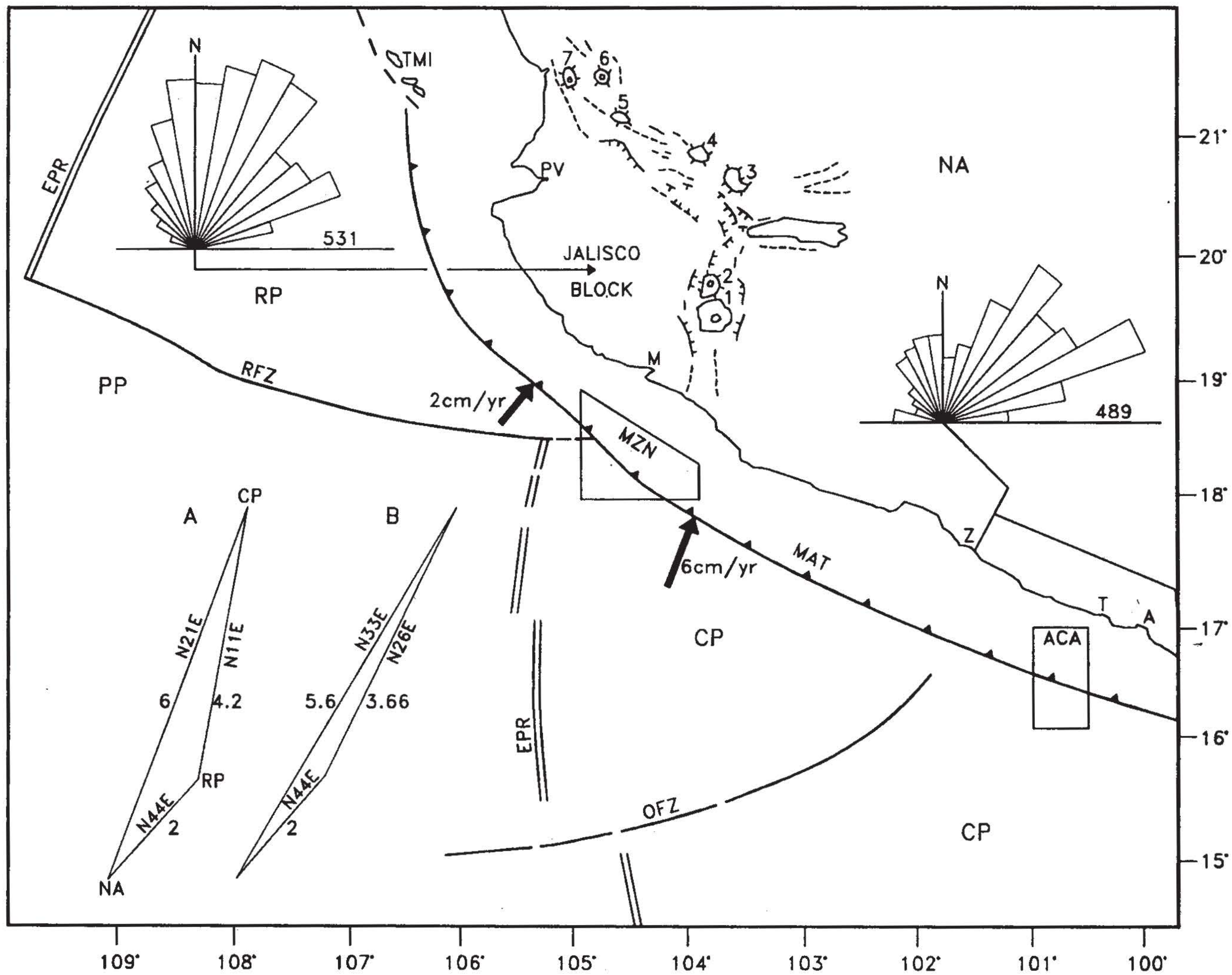


Fig. 1. Map of tectonic features in middle-western Mexico (Allan, 1986) and adjacent Pacific Ocean basin taken from Atwater and Severinghaus (1989). The relative motion vector diagram A was solved from Nixon (1982) and Drummond (1981) data, and vector NA-CP in diagram B was taken after DeMets and Stein (1990) (see text for details). Offshore study quadrangles are indicated as MZN (Manzanillo basin) and ACA (Tecpan). Rose diagrams indicate the lineament pattern for the Jalisco Block (531 lineaments) and for Tecpan (489 lineaments) obtained from structural interpretation of satellite photographs. Volcanoes in the area, after Luhr *et al.* (1985) are: 1: Volcán and Nevado de Colima, 2: Volcán Cántaro; Zacoalco graben, 3: Caldera La Primavera, 4: Volcán Tequila, 5: Volcán Ceboruco, 6: Volcán Sanganguey, 7: Volcán San Juan. Localities are given as: TMI= Tres Marias Islands, PV= Puerto Vallarta, M= Manzanillo, Z= Zihuatanejo, T= Tecpan, A= Acapulco.

We may correlate the structural lineaments from satellite photographs in the Colima Graben and the Jalisco Block with plate motion directions as determined from velocity vector diagrams. The orientation of the Rivera Plate (RP) and the Cocos Plate (CP) with respect to the North America Plate (NA) were taken from Nixon (1982; Figure 2), and the relative motions of CP-NA and RP-NA from Drummond (1981) and Nixon (1982). Our solution (A in Figure 1) suggests a left-lateral fault system as the most likely boundary between the Rivera and Cocos Plates. The resultant vector is oriented N11°E with a relative velocity of 4.2 cm/yr. This orientation is in good agreement with Nixon (1982).

The solution is also in general agreement with recent vector solutions by DeMets and Stein (1990). However, if we assume that the convergence of the Cocos-North America plates is N33°E at 5.6 cm/yr, as given by DeMets and Stein for the area near 17.5°N, 101°W, near our Tecpan quadrangle, the vector CP-RP is found to be N26°E, 3.6 cm/yr (solution B, Figure 1). This is more consistent with the rose diagram of structural lineaments in the Jalisco block.

The geometry used in both solutions (A and B, Figure 1) suggests that the northern portion of the East Pacific Rise, projected N10°E toward the trench (Klitgord and Mammerickx, 1982), should evolve into a left-lateral fault system. Structural lineaments interpreted from satellite photographs and from field evidence (Ferrari *et al.*, 1993; Carmichael, 1993) support this interpretation as does the geometry of the Colima Graben. Nixon (1982) and

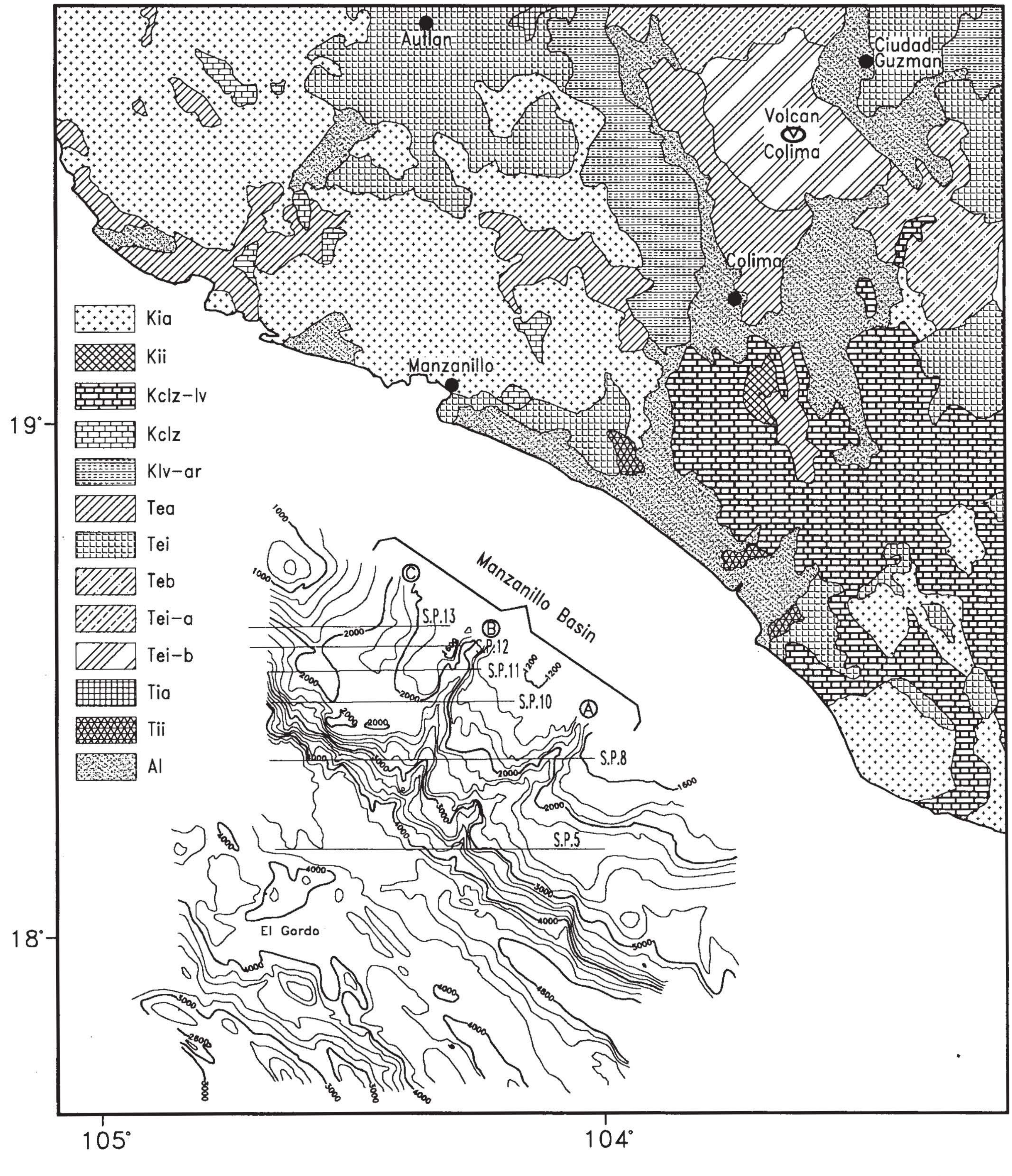


Fig. 2. Lithologic map of part of Jalisco Block and bathymetry of Manzanillo Basin (this survey), depth in meters. Ship tracks for seismic profiles are indicated by numbers 5,8,10,11,12 and 13. Lithology is modified from the 1:1,000,000 Guadalajara geologic map (INEGI): K= Cretaceous, T= undifferentiated Tertiary; Kia and Kii= acidic and intermediate intrusives, Klv-ar= volcanosedimentary sequence, Kclz-lv= limestones and minor volcanics, Kclz= limestones; Tia and Tii= acidic and intermediate intrusives, Tea= basic volcanics; Tei= intermediate volcanics, Teb=basic volcanics; Tei-a and Tei-b= intermediate to acidic and intermediate to basic volcanics, Al=alluvium. Letters A, B, and C indicate the head of canyons described in Figure 4.

Atwater and Severinghaus (1989) discuss shallow (0-33 km) earthquakes of magnitude M>4 which show a markedly narrow N-S linear trend of epicenters, starting at the juncture of the Rivera Fracture Zone and Middle American Trench. These shallow events are interpreted to be located in the continental crust and to be associated with strike-slip faulting; it is in agreement with our vector solution. Molnar (1973) and Eissler and McNally (1984) find fault plane solutions for two intermediate-size events in the same area which trend N10°E with left lateral motion, again in agreement with our analysis.

Except for a long and narrow sequence of Cretaceous sedimentary and volcaniclastic rocks west of Volcán Colima, trending N-NW (Pantoja-Alor, 1983; Pantoja-Alor and Estrada-Barraza, 1986), the Jalisco Block is underlain mostly by crystalline rocks. The Pacific margin from Cabo Corrientes to Manzanillo (~200 km) is dominated by granitoids of Cretaceous age (Gastil *et al.*, 1979), averaging 60 km wide (Figure 2). Toward the northwest trending graben of Tepic, acidic volcanics are covered by Pliocene (?)-Pleistocene basaltic volcanics. This volcanism shows a conspicuous N-S and NW trending distribution, following the structural boundaries of the block. As to the northwestern segment of the Jalisco Block, Nieto *et al.* (1985) documented dextral faulting, while extensive normal faulting apparently dominates the internal parts of the block. Most of the large, sparse structures trending close to N45°W are cut by normal faults associated with uplifting (?) and by N-S trending lineaments. The rose diagram of structural lineaments of the Jalisco Block (Figure 1) suggests that the concentrations in N30°-40°E and N60°-70°E are older than those observed in the range of N10°W to N30°E.

Tecpan quadrangle

The other surveyed area, offshore Tecpan, is located southeast of the Orozco Fracture Zone and of the Middle American Trench junction (Figure 3). One clear correlation between inland geology and morphology of the offshore continental margin is a large N60°-70°E trending canyon in the western portion of the survey area. It agrees with the structural lineaments interpreted in adjacent Guerrero State. The rose diagram of structural lineaments in the Jalisco Block lacks N-S oriented concentrations (Figure 1). Well-defined trends are found in the ranges of N30°-40°E and N60°-70°E; they may represent early (?) lineaments of the former block (Figure 1). Some of these lineaments have been identified as left-lateral strike-slip faults, similar to late Neogene regional structures in the Isthmus of Tehuantepec (Delgado-Argote and Carballido-Sánchez, 1990). There is a remarkable coincidence between the structural lineaments and mapped structures in the Tehuantepec Isthmus and the geometry of a triple junction. A rough lithologic correlation exists with the boundary of the Xolapa Complex and with the Eocene Batholith of Guerrero (40 to 38 Ma; P. Damon, pers. comm. (1986); Delgado-Argote, 1986; Delgado-Argote *et al.*, 1992); Pantoja-Alor, 1983). The Xolapa Complex has been described as a complex of metasedimentary and metaigneous rocks of Early Cretaceous age (128 and 144 Ma; Morán-Zenteno *et al.*, 1990). The last regional thermal event associated with magmatism was radiometrically dated as Oligocene along the Sierra Madre del Sur between northern Zihuatanejo, Guerrero and Puerto Angel, Oaxaca (Delgado-Argote *et al.*, 1992; Morán-Zenteno *et al.*, 1990; Bellon *et al.*, 1982). Furthermore, Bellon *et al.* (1982) reported 35.3 Ma old dioritic rocks below lower Miocene terrigenous sediments 50 km inland from the trench. The abrupt change in the bathymetry of the continental margin in the survey area between 100°38' W and 100°55' W (Figure 3) suggests a major geologic boundary between two tectonostratigraphic terranes, as found inland.

Bellon *et al.* (1982) believe that truncation of the continental margin offshore Mexico took place during late Miocene time. In addition, the NE trending lineaments observed inland developed during the left-lateral displacement of Central America relative to Mexico, as documented by Delgado-Argote and Carballido-Sánchez (1990) for the last 10 Ma in the Isthmus of Tehuantepec.

From this general description of the geologic and tectonic features, we propose that the N-S and NW trending structures, as well as the orientation of the Plio-Pleistocene volcanism in the Jalisco Block, are in agreement with a process of separation. Structural and geophysical evidence in the Jalisco Block testifies to an early Miocene deformation, at least along the northern and eastern boundaries (Serpa *et al.*, 1992; Sloan, 1989). Also, Nieto *et al.* (1989) have documented recent deformation and associated volcanism in the northern part of the block. The projection of the Colima graben toward the Manzanillo Basin is still a problem,since Serpa *et al.* (1992) have demonstrated from geophysical data that the Colima graben does not exist south of the the city of Colima.

On the other hand, the bathymetry offshore Tecpan, the trend of structural lineaments in the continent, and the age and distribution of the lithology suggest pre-Miocene deformation and present tectonic activity due to near-perpendicular subduction between the Cocos and North American plates.

STRUCTURAL SEISMIC INTERPRETATION OF MANZANILLO BASIN

A single-channel marine seismic reflection survey was performed in the Manzanillo Basin using two 1.5 liter air guns and a digital recording system. Processing of the seismic sections involved filtering (40-120 Hz), deconvolution, mixing (1:2:1 weighing) and automatic gain control (AGC). In order to correlate the results with the structural features onshore, six eastward-oriented sections were selected between 18°14' N and 18°37' N. This area extends from the Middle American Trench shoreward to the 1400m isobath (Figures 2, 4 and 5).

Seismic section 5 (Figures 4 and 5) shows in its eastern portion a submarine terrace underlain by a thick, slightly eastward-dipping sedimentary unit which fills a structural basin. The northward extension of this basin may correlate with the extension of the Colima Graben, where the base-

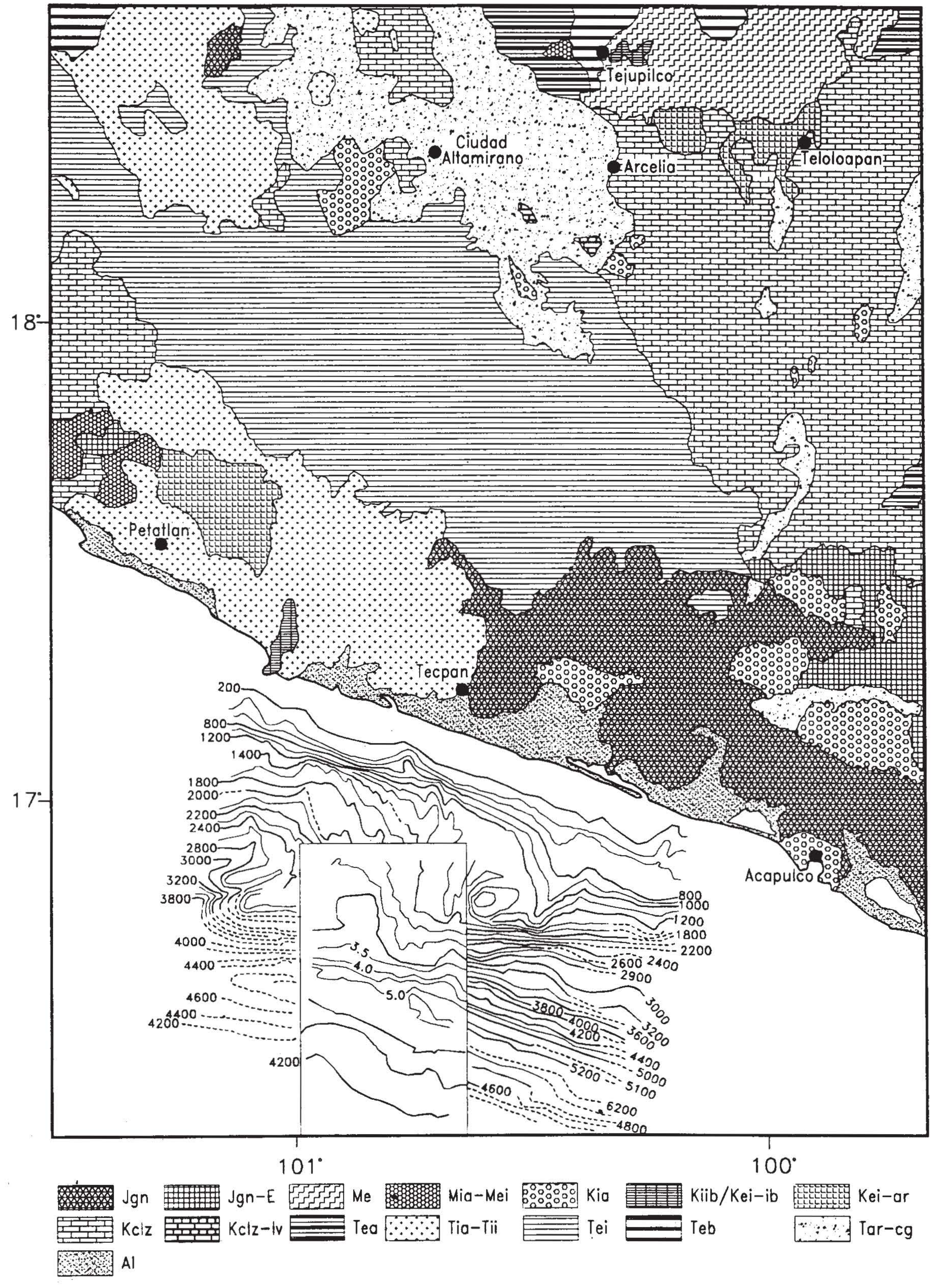


Fig. 3. Lithologic map of Tecpan area and bathymetry of survey area (in box, this study), and part of bathymetry after Karig *et al.* (1978) (in meters). Lithology is modified from the 1:1,000,000 Mexico geologic chart (INEGI): M= undifferentiated Mesozoic, Me= schists, Mia= granitoids, Mei= intermediate volcanics; Jgn and Je= Jurassic (?) gneisses and schists, K= Cretaceous, Kia= acidic granitoids, Kiib= intermediate to ultramafic intrusives, Kei-ib= intermediate intrusives and volcanics, and ultramafic intrusives, Kei-ar= volcanosedimentary sequence, Kclz-lv= limestones and volcaniclastics, Kclz= limestones, T= undifferentiated Tertiary, Tia= acidic intrusives, Tii= intermediate intrusives, Tea= acidic volcanics, Tei= intermediate volcanics, Teb= basic volcanics, Tar-cg= sandstones and conglomerates, Al= alluvium.

ment is made up in part by a Cretaceous volcanosedimentary sequence (Serpa *et al.*, 1992). This sequence, in the eastern-most part of seismic section 5, shows highly contrasting reflectors suggesting local basement. The top of the eastern terrace is disrupted by small normal faults dipping toward the trench. Their structural style is quite similar to that described in the accretionary wedge in the Middle American Trench off Oaxaca (Moore and Lundberg, 1986; Lundberg and Moore, 1986). Near and below the 3000 m isobath, the local basement presents a deep and narrow structure oriented N40°E (canyon A in Figures 2, 4 and 5). Canyon A is also observed in seismic section 8; its thin sedimentary fill suggests a recent origin. Just 5 km east of the trench (4500 m), the presence of two narrow structural depressions filled by sediments with slightly landward dipping reflectors could indicate the presence of accreted trench sediments (Lundberg and Moore, 1986). The trench-fill sediments are mostly undeformed, except that the lower layers are thought to be partially disturbed by topographic irregularities attributable to normal faulting of the oceanic crust.

Seismic section 8, some 18 km north of section 5, intersects the trench at an oblique angle. The eastern side of the canyon is thought to be related to a westward-dipping normal fault, while the western side is clearly affected by eastward-dipping faults, the resulting structural basin, apparently cuts a lithified sedimentary (Cretaceous ?) sequence. As in section 5, the narrow canyon lacks sedimentary fill, which indicates either a young age or the presence of strong bottom currents. Its western side is a horst-like structure made up by the same Cretaceous (?) sedimentary sequence. The western limit of the horst is a basin filled with at least 450 m of sediments, which may be equivalent to other Eocene-Oligocene continental basins related to strike-slip faulting in the Colima graben area as referred by Serpa *et al.* (1992). An alternative explanation to these contrasting seismic lithologies would be the presence of original Cretaceous forearc basins, typically associated with island arcs (Pantoja-Alor and Estrada-Barraza, 1986); or juxtaposed structures related to early Tertiary NNW-trending right-lateral high-angle faults as mapped by Smith (1990) and described by Ferrari *et al.* (1993). A 2 km wide and 330 m deep canyon trending N10°E (B in Figures 2, 4 and 5) flanks and cuts the thick sedimentary sequence. The reflection profile also shows that the canyon floor is underlain by horizontal reflectors. Since Canyon B lies along the offshore projection of Río Armería, and since the Plio-Pleistocene Colima Formation onshore is also deeply incised by the same river (Sloan, 1989), by analogy the sediments offshore within Canyon B are interpreted to be also of Plio-Pleistocene age. Canyon B might be related to a strike slip fault, but it has a westward vertical drop of about 75 m between the tops of its flanks. Several other small normal faults are observed before reaching the steep slope at the contact between the flat-lying trench sediments and the continental crust. There is poor seismic definition of the continental crust, which may be made up of crystalline rocks of batholitic affinity.

From sections 10 to 13, 5 km west of canyon B, in an interval between 8 to 12 km from the trench, an older fault- related basin (canyon C), 4 km wide, is filled by at least 400 m of sediments. The layers are slightly disturbed at depth, probably due to differential compaction, but they are nearly flat toward the top. This suggests continuous fault movement up to shortly before the uppermost sediments were deposited. Compared with the profile of DSDP Leg 66 off Oaxaca (Moore and Lundberg, 1986), the vertical disruption in the topographic profile off Colima is more pronounced, perhaps due to rapid uplifting. As in the slope off Oaxaca, the landward dipping reflectors in canyon C are slightly more tilted in sections 10 and 11 near the trench, than in sections 12 and 13 on the upper slope. This might indicate compression and uplift of the lowermost slopes, as also interpreted by Lundberg and Moore (1986) in the Middle American Trench. On both sides of the canyon, the walls contain similar reflectors to those described for the Cretaceous or Eocene-Oligocene sedimentary rocks. The trend of canyon C also averages N10°E, and has evidently developed inside an older basin. The eastern side of the canyon is strongly affected by normal faulting; index horizons show vertical displacements of 100 to 200 meters. One of the most faulted zone is a horst-like structure east of canyon C which shows a slight westward-tilting geometry, evident in the central part of seismic profile 13 and lower part of seismic profile 12. The deepest reflectors in profiles 12 and 13, west of canyon B, are interpreted as gas hydrates.

From the interpretation of the seismic profiles we conclude that the structural regime in the continental margin is that predicted from our vector analysis (Figure 1). All N-S structures may be associated with transtensional deformation which seems to hinge in the study area, and most normal faulting and associated wide basins would be due to uplifting along the continental margin.

Note in seismic profiles 5 and 8 the undeformed character of the sediments in the trench, and the lack of a clearly defined forearc basin. The main deformation in the continental margin is related to uplifting of the Pacific margin since late Neogene time, which affects probable Paleogene basins or may be penecontemporaneous to the Cretaceous island-arc internal basins.

HEAT FLOW MEASUREMENT TECHNIQUE

We have followed a similar approach to that presented by Detrick *et al.* (1986), Courtney and White (1986) and Khutorskoy *et al.* (1990), where a high density of heat flow measurements per unit area was achieved. The averaging of heat flow data on the sea bottom yields more reliable thermal conditions than single estimates at stations several tens to hundreds of miles apart. The measurement density in our current study areas, the Tecpan and Manzanillo quadrangles, ranged from 2 to 4 heat flow determinations per 10 square nautical miles. In this study we used an upgraded version of the thermal probe described in Khutorskoy *et al.* (1990). An additional builtin inclinometer was installed in the probe's electronic compartment,

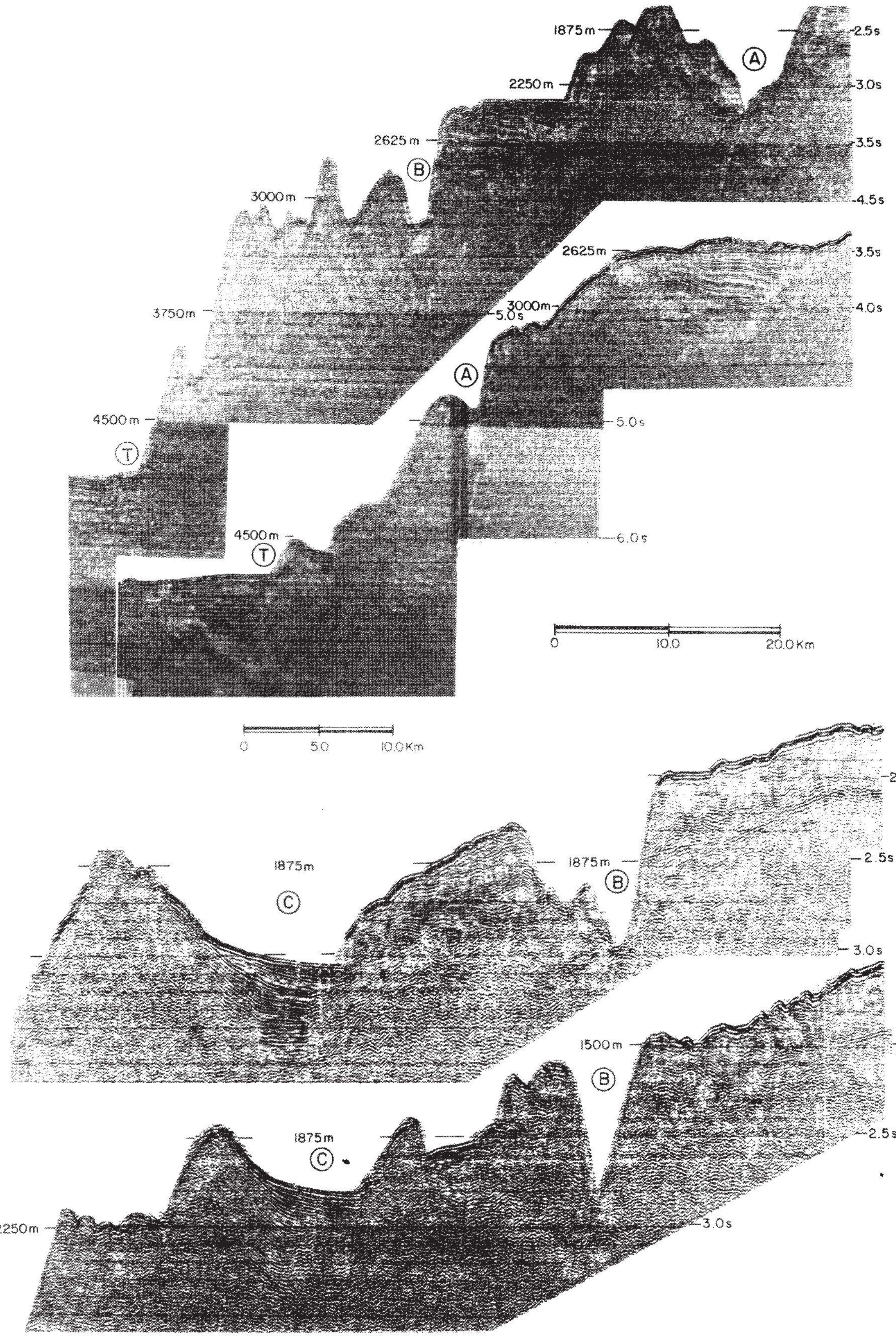


Fig. 4. Single channel reflection profiles of the Manzanillo basin. Ship tracks are E-W as indicated in Figure 2; letters A, B, and C correspond to the canyons shown in the bathymetry of the same figure, and T denotes the trench zone. Depth is given in meters assuming a water velocity of 1500 m/s and two-way travel time in seconds.

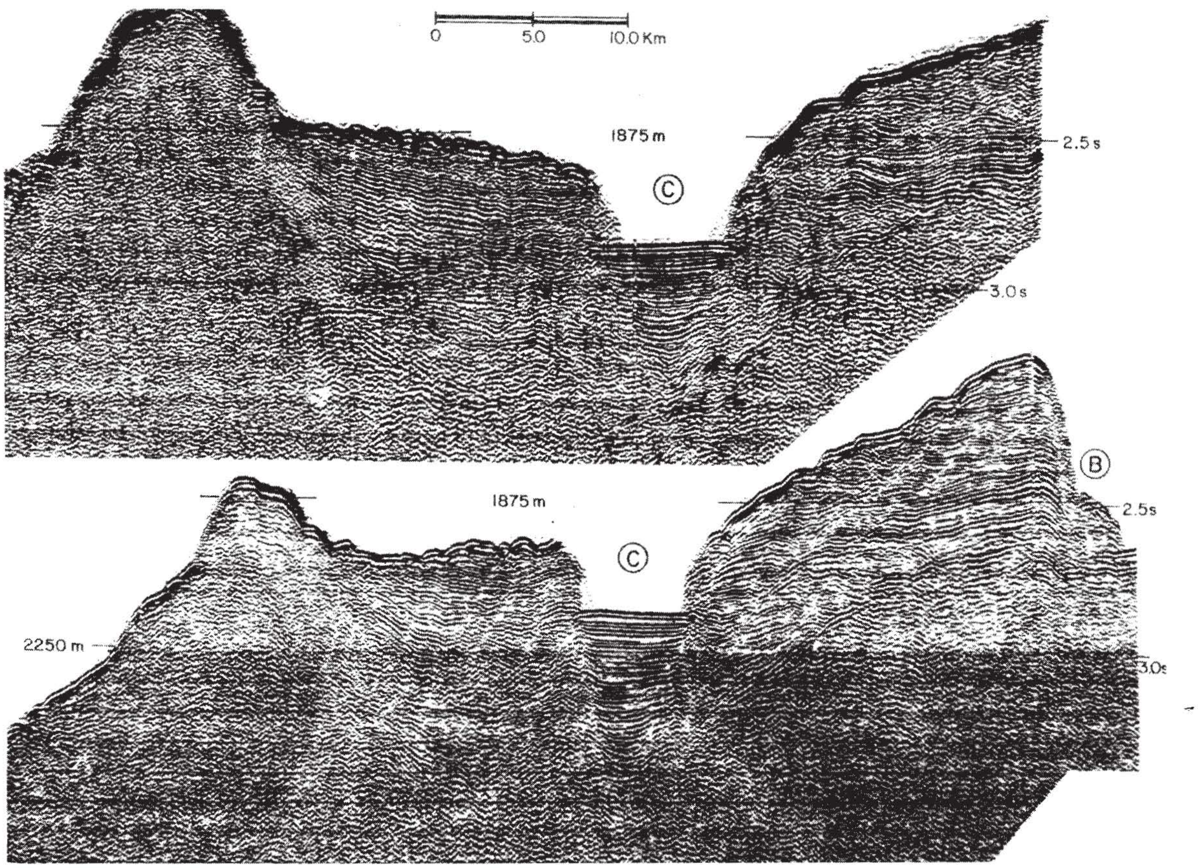


Fig. 4. (Cont.).

allowing for corrections tobe performed when the angle of penetration exceeded 10° from vertical. Some modifications to the real-time processing code allowed a better control of the experiment, through graphical and numerical output of the thermal parameters.

HEAT FLOW MEASUREMENT RESULTS

Tecpan Quadrangle

The background heat flow on the continental slope of the Middle American Trench,was derived from 12 heat flow measurements taken off Tecpan (Table I). The stations were in the sediment-filled basins of the continental slope. Single-channel seismic and MULTIBEAM profiling was conducted throughout this area. In Figure 6 we show the location of the measuring sites, the estimated heat flow in mW/m^2, and the bathymetry obtained from MULTIBEAM data.

Thermal measurements of the water column showed low temperatures of 1.73°-1.74°C between depths of 2600 to 2800 meters. At greater depth there is a slight temperature increase; for example, the thermal gradient between 2400 and 3000m depth is 0.05 mK/m. Most heat flow measurements in this area were made under isothermal conditions at sea bottom.

No particular trend was found in the thermal conductivity distribution of bottom sediments versus depth. Variations do not exceed instrumental errors. In contrast, the geothermal gradient at some sites (21, 23, 24 and 25) showed a slight decrease with depth within the bottom sediments (Table I). For example, at station 25, the gradient decreased from 87±10 mK/m at the probe's upper interval (0.5m), to 53±7 mK/m in the lower interval (1.5m). This change may be attributable to upward migration of water in the sediments.

Seven stations were located on an isometric terrace-like basin northwest of the study area (Figure 6). Within this basin, the heat flow varied from 53 to 59 mW/m^2 (55±3 mW/m^2 on the average) and the thermal conductivities ranged from 0.84 to 1.05 W/m•K. The other five stations, southeast from this basin, showed more scatter in heat flow (38 to 104 mW/m^2). However, at station 26 only the first measuring interval of the thermal probe penetrated into the sediments (Figure 6). Eliminating the lowest and highest values, the average heat flow in the Tecpan quadrangle is 55±8 mW/m^2.

The scatter of heat flow in this area can be accounted for by possible upward-migrating sedimentary fluids and/ or by the influence of topography and refraction of terrestrial heat flow. These last two factors were quantitatively estimated by numerical modeling, as shown bellow.

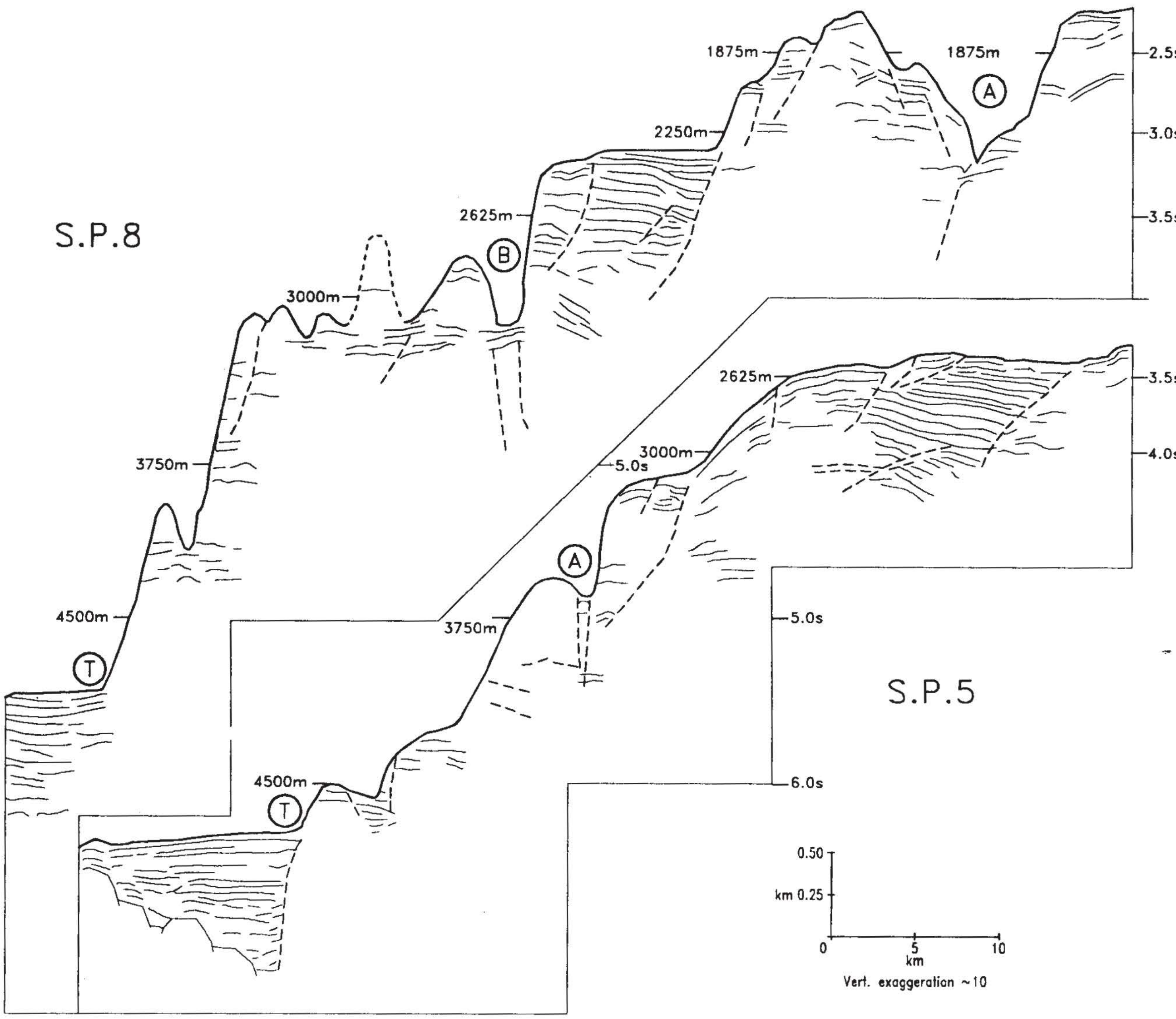


Fig. 5. Tracings and interpretation of seismic profiles of Figure 4. GHL denotes the gas hydrate layer. See text for discussion.

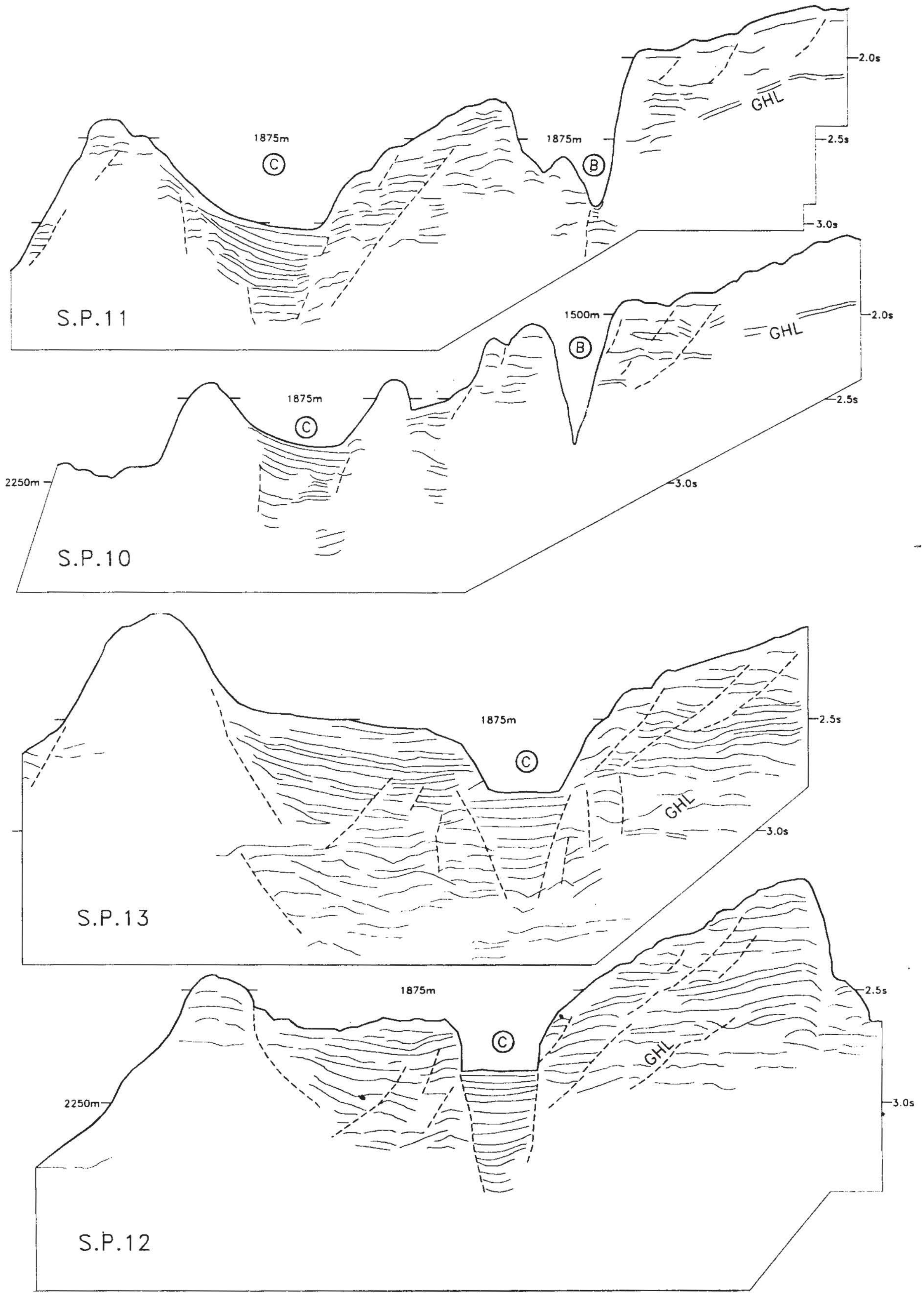
Manzanillo Quadrangle

In this area we established 32 stations on the continental slope, 11 stations on the oceanic side and one station on the Middle American Trench axis. The data are given in Table II. In addition, heat flow was indirectly determined at 39 sites on the continental slope from the inferred position of the gas-hydrate layer, delimiting the BSR boundary (Yamano *et al.*, 1982). The location of stations is shown in Figure 7. The bathymetry was obtained from the MULTIBEAM system of numerous tracks in the area. Single-channel seismic recording was performed along these tracks, which helped us to choose appropriate sites for deployement of the thermal probe.

Three well-defined submarine basins were found on the continental slope, orthogonal to the trench axis, as shown in Figure 7 and as discussed above. The widest western basin is presumably the "Manzanillo Rift" (Ness *et al.* 1981), where we carried out a large set of heat flow determinations. The center and eastern basins pertain to an uplifted(?) section of the continental slope. A total of ten heat flow sites are located in the eastern canyon. Most indirect heat flow determinations are situated on the uplifted (?) section of the continental slope and others are located in the canyons.

In the western basin, for depths ranging between 2180 to 2200 m, the thermal sounding of the water column showed stable temperatures between 2.14 to 2.16°C. As we proceeded towards the flanks of this basin, bottom temperatures increased up the slope ranging from 2.24°C for station 63 (2071 m depth) to 2.28°C at station 65 (1972 m depth) (Table II).

The bottom layer on the flanks of this basin shows a 90 mK/m vertical thermal gradient, indicating that the layer is far from isothermal. This makes it difficult to estimate reliable heat flow values with a single measurement interval



S.P.11
1875m
C
1875m
B
GHL
2.0s
2.5s
3.0s
S.P.10
1500m
B
GHL
2.0s
1875m
C
2.5s
2250m
3.0s
S.P.13
1875m
C
GHL
2.5s
3.0s
S.P.12
1875m
C
GHL
2.5s
2250m
3.0s

Fig. 5. (Cont.).

Table 1

Geothermal results in the Tecpan quadrangle

Site Number	N Lat. / W Long.	H ,m / h	T(°C) / K (W/m*K) 2.0	1.5	1.0	0.5	0.0	Tw,°C	q±Δq mW/m²	Tilt angle deg.	Code*
12B	16°45.70′	3108	-	1.918	1.890	1.858	1.827	1.799	53 ±3	8	3Aa
	100°51.00′	>1.5	-	0.95	0.86	0.84					
13A	16°44.20′	3078	1.907	1.877	1.847	1.818	1.788		54 ±3	7	4Ac
	100°49.70′	>2.0	0.95	0.93	0.93	0.89					
13B	16°44.20′	3078	-	1.862	1.826	1.795	1.766	1.746	57 ±3	27	3Aa
	100°49.60′	>1.5	-	0.93	0.91	0.86					
19A	16°49.41′	2806	1.866	1.844	1.810	1.799	1.745		56 ±3	9	4Dc
	100°52.78′	>2.0	1.00	0.95	0.91	0.87					
20A	16°47.60′	3025	1.911	1.880	1.845	1.814	1.784		59 ±3	6	4Ac
	100°52.95′	>2.0	0.99	0.94	0.93	0.89					
21B	16°46.37′	3040	1.896	1.877	1.843	1.816	1.790		53 ±3	7	4Dc
	100°53.45′	>2.0	1.05	1.00	0.99	0.98					
23A	16°39.50′	2616	1.845	1.828	1.809	1.788	1.765		38 ±2	6	4Ac
	100°43.50′	>2.0	1.02	0.99	0.93	0.88					
24A	16°40.58′	2411	-	1.852	1.832	1.800	1.736	1.721	76 ±4	8	3Ca
	100°48.80′	>1.5	-	0.99	0.95	1.03					
25A	16°40.50′	2620	-	1.845	1.831	1.805	1.774	1.731	48 ±3	7	3Ca
	100°42.75′	>1.5	-	1.02	1.02	1.03					
26A	16°41.68′	2411	-	-	-	1.807	1.760	1.764	104 ±8	6	1-b
	100°44.90′	0.5	-	-	-	1.12					
27A	16°39.91′	3001	1.858	1.842	1.816	1.794	1.733		40 ±2	6	4Dc
	100°39.79′	>2.0	1.01	0.95	0.94	0.89					
29A	16°43.79′	27.56	1.880	1.858	1.822	1.790	1.753		59 ±3	4	4Dc
	100°47.31′	>2.0	1.01	0.97	0.91	0.86					

number: number of intervals of thermal probe where heat flow was estimated
*Code: capital letter: behaviour of thermograms: A-linear, B-increasing, C-decreasing, D-mixed
small letter: behaviour of water temperature near bottom: a-no inversion, b-inversion, c-erratic

Table 2

Geothermal results in the Manzanillo quadrangle

Site Number	N Lat. / W Long.	H ,m / h	T(°C) / K (W/m°K) 2.0	1.5	1.0	0.5	0.0	Tw,°C	q±Δq mW/m²	Tilt angle deg.	Code*
20A	18°36.10′	2167	-	-	-	2.211	2.165	2.165	>104 ±8	1	1-a
	104°24.14′	<0.5	-	-	-	1.141					
21A	18°38.34′	2203	-	2.220	2.204	2.187	2.174	2.164	27 ±2	18	3Aa
	104°23.82′	>1.5	-	0.92	0.89	0.85					
22A	18°36.01′	2215	2.226	2.210	2.187	2.172	2.166		27 ±1	3	4Dc
	104°25.63′	>2.0	0.96	0.94	0.90	0.87					
23A	18°35.03′	2215	2.214	2.202	2.183	2.171	2.163		22 ±1	8	4Dc
	104°25.76′	>2.0	0.92	0.91	0.88	0.85					
24A	18°32.99′	2200	2.210	2.196	2.175	2.161	2.154		24 ±1	5	4Dc
	104°26.78′	>2.0	0.94	0.89	0.87	0.85					
25A	18°32.89′	2188	-	2.198	2.172	2.155	2.150	2.143	23 ±2	8	3Da
	104°27.92′	>1.5	-	1.00	0.91	0.87					
26A	18°31.99′	2195	2.197	2.180	2.162	2.148	2.149	2.149	31 ±2	5	3Aa
	104°27.87′	~1.9	0.96	0.98	0.90	0.86					
27A	18°30.97′	2169	2.200	2.185	2.159	2.147	2.137	2.137	32 ±2	6	3Da
	104°27.34′	~1.9	0.94	0.94	0.88	0.91					
34A	18°23.73′	1893	-	2.363	2.321	2.266	2.191	2.191	101 ±6	10	2Cb
	104°05.27′	~1.4	-	1.09	1.01	0.94					
36A	18°15.75′	2266	2.008	1.992	1.967	1.930	1.886		57 ±3	3	4Cc
	104°05.15′	>2.0	0.99	0.96	0.92	0.90					
37A	18°17.75′	2073	2.156	2.141	2.113	2.076	2.063	2.063	51 ±3	1	3Ca
	104°08.19′	~1.9	1.03	0.96	0.93	0.89					
38A	18°19.70′	2151	-	-	-	1.890	1.848	1.876	91 ±7	3	1-b
	104°11.05′	>0.5	-	-	-	1.08					
39A	18°17.49′	2558	1.890	1.889	1.851	1.821	1.792		45 ±2	2	4Dc
	104°11.73′	>2.0	0.97	0.92	0.91	0.91					

Table 2 (Cont.)

GEOTHERMAL RESULTS IN THE MANZANILLO QUADRANGLE

Site	N Lat.	H ,m	T(°C) / K (W/m°K)					Tw,°C	q±Δq	Tilt angle	Code*
Number	W Long.	h	2.0	1.5	1.0	0.5	0.0		mW/m²	deg.	
45A	18°17.58′	3175	1.907	1.885	1.850	1.823	1.795		55 ±3	6	4Dc
	104°15.55′	>2.0	1.03	1.01	1.00	0.96					
46A	18°19.34′	2617	1.799	1.746	1.724	1.685	1.668		71 ±4	7	4Dc
	104°13.55′	>2.0	1.11	1.14	1.09	1.05					
47A	18°19.96′	2270	-	-	1.554	1.528	1.516	1.504	41 ±3	3	2Ba
	104°10.60′	>1.0	-	-	1.15	1.08					
62A	18°32.87′	2168	-	2.256	2.241	2.223	2.224	2.176	20 ±1	14	3Da
	104°29.68′	>1.5	-	1.00	0.99	0.88					
63A	18°35.04′	2071	-	2.295	2.284	2.263	2.257	2.243	26 ±2	14	3Da
	104°29.66′	>1.5	-	1.15	1.03	0.97					
64A	18°35.86′	2049	-	2.229	2.285	2.266	2.257	2.235	28 ±2	11	3DA
	104°27.43′	>1.5	-	1.11	1.04	0.93					
65A	18°38.00′	1972	-	-	2.322	2.302	2.285	2.285	45 ±5	8	1-b
	104°26.90′	~0.9	-	-	1.11	0.95					
67A	18°36.43′	2210	2.282	2.279	2.256	2.241	2.228		26 ±2	11	4Dc
	104°24.29′	>2.0	1.07	1.01	0.96	0.91					
68A	18°29.83′	2174	2.245	2.231	2.211	2.197	2.172		35 ±2	3	4Dc
	104°27.87′	>2.0	1.08	1.01	1.03	0.88					
69B	18°29.27′	1995	-	-	2.278	2.262	2.216	2.216	26 ±2	7	2Aa
	104°23.66′	>1.0	-	-	0.95	0.90					
74A	18°17.68′	3292	-	-	-	1.879	1.857	1.828	53 ±5	5	1-a
	104°21.82′	~0.9	-	-	-	1.21					
75A	18°20.04′	2547	1.929	1.905	1.887	1.862	1.845		45 ±5	3	4Dc
	104°19.97′	>2.0	1.13	1.04	1.00	1.00					
84A	17°51.58′	2895	1.903	1.886	1.863	1.842	1.821		37 ±2	4	4Ac
	104°44.11′	>2.0	0.98	0.93	0.91	0.90					

Table 2 (Cont.)

GEOTHERMAL RESULTS IN THE MANZANILLO QUADRANGLE

Site Number	N Lat. / W Long.	H ,m / h	T(°C) / K (W/m°K) 2.0	1.5	1.0	0.5	0.0	Tw,°C	q±Δq mW/m²	Tilt angle deg.	Code*
88A	17°53.62′	2777	-	2.142	2.023	1.892	1.792	1.791	223 ±12	3	2Aa
	104°43.90′	~1.4	-	0.89	0.90	0.90					
91A	17°49.93′	2787	-	-	1.875	1.845	1.808	1.789	60 ±6	8	2Aa
	104°44.16′	~1.1	-	-	0.89	0.90					
107A	18°08.23′	4298	2.375	2.301	2.218	2.143	2.204		144 ±8	7	4Ac
	104°42.94′	>2.0	1.02	0.93	0.91	0.88					
110B	18°09.19′	3851	2.261	2.197	2.127	2.060	1.990		129 ±7	5	4Ac
	104°35.90′	>2.0	1.02	0.97	0.95	0.91					
111A	18°08.60′	4023	2.397	2.297	2.190	2.087	1.979		208 ±11	9	4Ac
	104°34.80′	>2.0	1.08	1.01	0.97	0.94					
112A	18°08.95′	4177	2.166	2.124	2.081	2.040	1.999		84 ±5	7	4Ac
	104°33.29′	>2.0	1.03	0.97	1.04	1.00					
113A	18°11.80′	4338	-	2.044	2.021	1.992	1.980	1.966	43 ±3	8	3Da
	104°23.93′	~1.9	-	1.00	1.00	1.00					
115C	17°59.41′	3854	2.126	2.084	2.035	1.996	1.950		79 ±4	8	4Ac
	104°31.19′	>2.0	0.91	0.91	0.92	0.90					
116A	17°44.81′	3058	1.935	1.920	1.900	1.377	1.846		40 ±2	7	4Cc
	104°39.67′	>2.0	0.94	0.89	0.88	0.88					
117A	17°51.13′	2840	-	-	-	1.893	1.842	1813	90 ±2	7	1-a
	104°44.05′	~0.9	-	-	-	0.90					
118A	17°59.00′	3270	1.908	1.889	1.867	1.242	1.814		41 ±2	6	4Ac
	104°54.33′	>2.0	0.95	0.90	0.87	0.84					
118B	17°59.13′	3268	1.889	1.872	1.849	1.831	1.804		36 ±3	8	4Ac
	104°54.29′	>2.0	0.93	0.88	0.84	0.82					

*Code: same as used in TABLE I

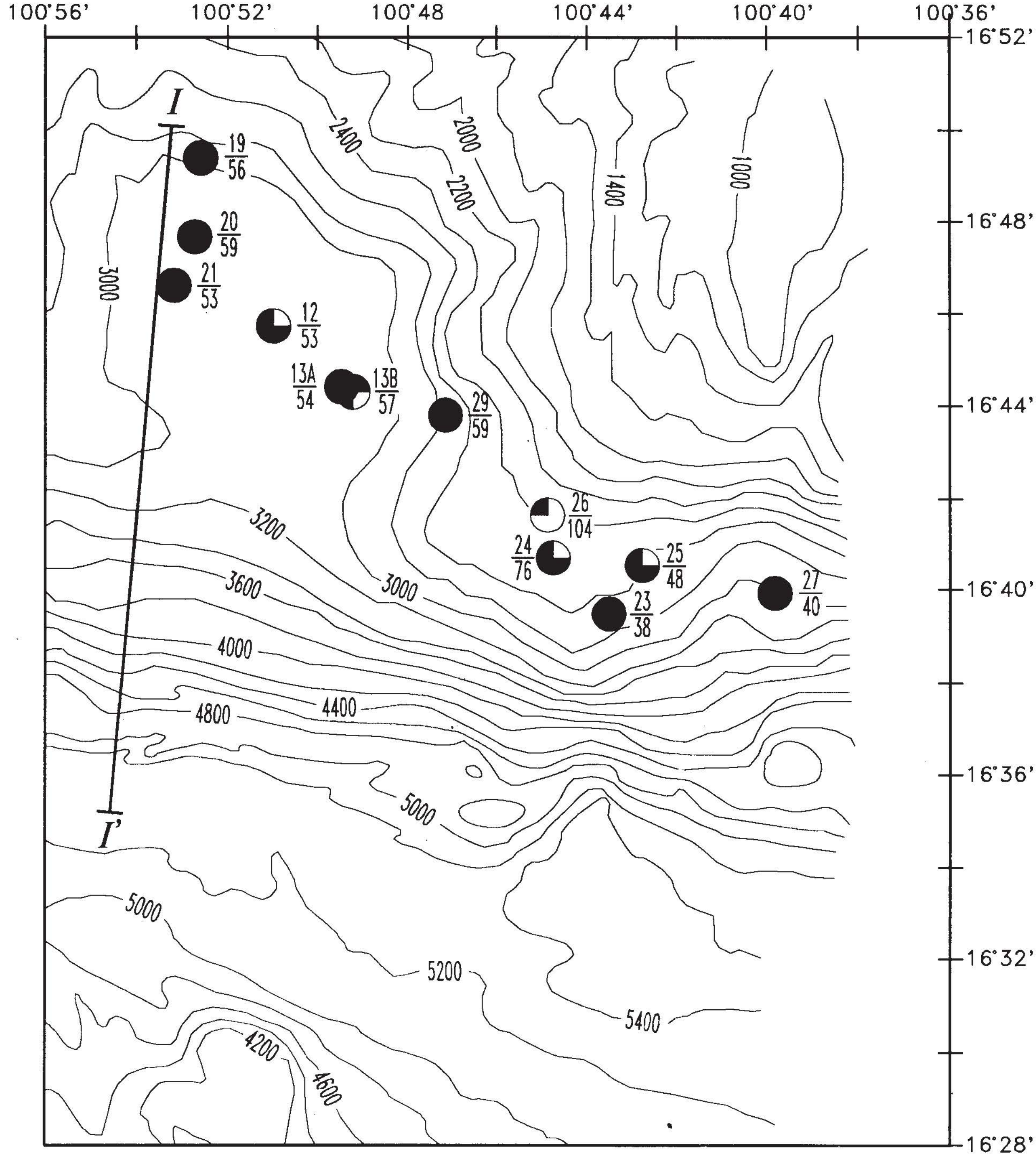


Fig. 6. Location of heat flow sites in the Tecpan area. Top number denotes the site number and bottom number is heat flow in mW/m² (Table I). Full circles denote total penetration of the thermal probe. Partially filled circles represent those sections of the thermal probe for which no heat flow was estimated. For example, station 26, only one, out of four intervals of the thermal probe were used. Bathymetry is from MULTIBEAM swaths and contoured in meters. Profile I-I' was used for modeling.

of the thermal probe. The corresponding data were disregarded, as also for station 20.

At individual sites the variation in thermal conductivity did not exceeded the instrumental error. Hence, spatial variations in thermal conductivity for this area are reliably accounted for. Most stations within the central part of this basin showed low thermal conductivities (0.85-0.96 W/m•K) as compared to stations on the flank (1.02-1.09W/m•K). These differences are probably caused by higher compaction and lack of sedimentary deposition on the flanks.

The heat flow determination in this western Manzanillo basin shows 12 anomalously low values ranging from 20±1 mW/m² at site 62 to 35±2 mW/m² at station 68

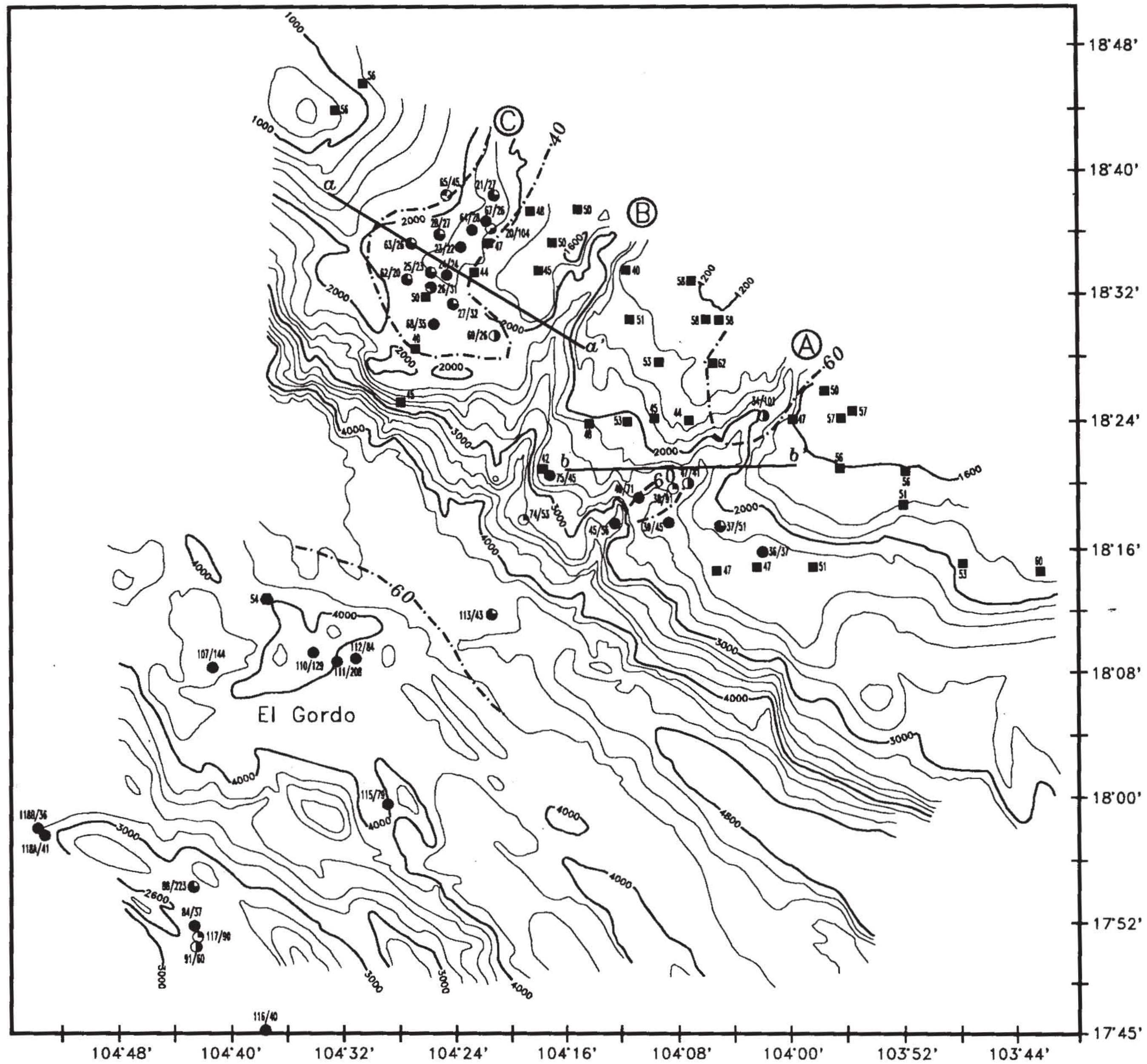


Fig. 7. Location of heat flow sites in the Manzanillo area. Same comments used in Figure 6 apply to the filled and partially filled circles of the graph. Squares denote the sites where heat flow was indirectly estimated from the BSR reflector on the slope of the Middle American Trench and the number denotes heat flow in mW/m^2. The hexagon denotes a site with 54 mW/m^2 measured by Von Herzen and Anderson (1972). Profiles a-a' and b-b' were used for modeling. Bathymetry is from MULTIBEAM swaths and contoured in meters.

(Figure 7). This area is nicely delimited by a 40 mW/m^2 contour. The somewhat low heat flow, as compared to background values obtained offshore Tecpan, may be caused by the presence of a large block of granitoids from the Jalisco Block or perhaps by some type of surface distortion of the thermal field. The effects of the rate of sedimentation, vertical fluid migration, rugged bottom topography and thermal refraction, will be discussed in the next section.

Ten direct estimates of heat flow were made in the eastern canyon. On both flanks of this canyon several direct and indirect estimates were obtained. The overall thermal conditions for this area differ considerably with those in the western basin. At stations 34, 36, 37, 39 and 46, heat flow decreases with depth, while its absolute value at each probe's measuring interval is two to three times higher than for stations in the western basin. Differences in the canyon's bottom water temperature were also present. Thus, the bottom water temperature at station 20 (flank of western basin) was 2.17°C at a depth of 2167 m, while the temperature at station 38 (eastern canyon) at a depth of 2155 m was 0.3°C lower.

A similar situation occurs for sites 21 and 36, both at an approximate depth of 2200 m. The difference in bottom water temperatures between the western and eastern sections may be indicative of cold oceanic water influx into the eastern canyon from deeper parts of the ocean. A more detailed study of this phenomena is beyond the scope of our study. As can be seen from Figure 7, our indirect heat flow estimations for the eastern section of this quadrangle agree well with the measurements conducted *in-situ*.

A single heat flow station was established on the trench axis. It yielded a value of 43±2 mW/m^2 which is typical for the estimated heat losses through the Middle American Trench (Sugrobov *et al.*, 1989) as for data gathered in other deep trenches.

A total of 11 additional measurements was obtained from the oceanic crust in the Manzanillo quadrangle, comprising an area around the presumed "El Gordo Volcano" and the nearby Rivera Fracture Zone and East Pacific Rise. Variations of thermal gradients and thermal conductivities versus depth for these sites remained quite stable. We found 208±11 mW/m^2 at the center of the "El Gordo" rise, which is a much higher value than in the continental section of the Middle American Trench. At the periphery of the rise, station 115 yielded 79±4 mW/m^2, still above the average for the Middle American Trench. At the southwestern part of the Manzanillo quadrangle we found high heat flow at sites 88 and 117.

HEAT FLOW MODELING RESULTS

Numerical modeling was accomplished using a 2-D finite element code. This code solves the non-stationary heat conduction equation for a set of boundary conditions and for a given combination of thermal properties in a geologic cross section. A triangular finite element mesh was used. The temperature between nodes was expressed by a first order polynomial.

In general we used 210 elements with a refined mesh size where appropriate, i.e. along contacts of dissimilar thermal properties. The solution to the heat equation was calculated at 242 nodes in the mesh. The initial boundary conditions were: (a) zero temperature gradient at the edge of the mesh, (b) constant heat flow at the lower boundary, (c) zero temperature at the water-sediment interface and (d) no internal heat sources.

Tecpan Quadrangle

For this area, we modeled profile I-I' of Figure 6. We used a constant lower boundary heat flow value of 55 mW/m^2, located at a depth of 6 km bellow the ocean surface. From the interpretation of single-channel seismic records in the area, we developed an initial model which com-prises: (a) an upper unconsolidated sedimentary cover with K=1 W/m•K and heat capacity c=1300 J/kg•K, (b) a more consolidated sedimentary layer with K=1.3 W/m•K and heat capacity c=1000 J/kg•K and (c) an acoustic basement with K=2.5W/m•K and c=963 J/kg•K. The sea water is assumed infinitely conductive with a heat capacity c=4190 J/kg•K.

The model and the results are shown in Figure 8. The top curve represents the calculated q_s/q_d ratio, where q_s is the heat flow at the surface of the model and q_d is the deep background heat flow. This ratio thus reflects the local distortions due to topographic and refraction effects. As can be seen from Figure 8, the q_s/q_d ratio for stations located on the north end of this profile is unity. The measured mean heat flow of 58 mW/m^2 for these three sites can safely be attributed to background heat flow for the area. From the curve of q_s/q_d ratio as one proceeds south, local relief and the contrast in thermal properties between sediments and acoustic basement will cause scatter of measured heat flow. For this transect, the scatter in the observed heat flow data may be caused by surface distortions. We are confident that the average heat flow for the continental slope of the Middle American Trench in this quadrangle can be placed at 55 mW/m^2.

Manzanillo Quadrangle

We have followed a similar approach in the modeling of this area. Two profiles shown in Figure 7 were modeled. Profile (a-a') is located in the western basin and the other (b-b') crosses the eastern canyon.

From the model, the observed q_s/q_d ratio for profile a-a' is shown in Figure 9. We used constant heat flow of 27 mW/m^2 for the initial model, at a depth of 2.5 km from the ocean surface, with the same thermal conductivities of sediments and acoustic basement as those given for the Tecpan region. From the q_s/q_d ratio, the background heat flow is highly distorted near the canyon flanks. The measured heat flow values for stations located near the boundary between sediments and acoustic basement need to be increased by up to a maximum of 40% in order to attain the background heat flow. Notice that, for stations located in the center of the basin (where anomalous low heat flow was obtained), the q_s/q_d ratio shows no significant influence from distortions due to topography or refraction.

The results for the eastern profile b-b' are shown in Figure 10. We used the same parameters as in the previous case, but the initial model had a constant heat flow of 45 mW/m^2 at a depth of 4 km from the ocean surface. Again, the q_s/q_d ratio depicts the influence of distorting effects along the canyon's flanks. The sites located in the central part of the eastern depression are free from surface effects.

The anomalous low heat flow in the western depression of Manzanillo cannot be accounted for by these 2-D models. Let us consider now the effects of rates of sedimentation and other mechanisms that may be responsible for low heat flow in this region, especially the vertical migration of fluids within sediments.

The only available data on sediment deposition rates are given by Ross (1971), who worked NW of our area. It appears that the Manzanillo basin falls within Ross's classification as a landward slope composed mainly of glauconitic-rich sediments. Sediments are sandy to silty clays

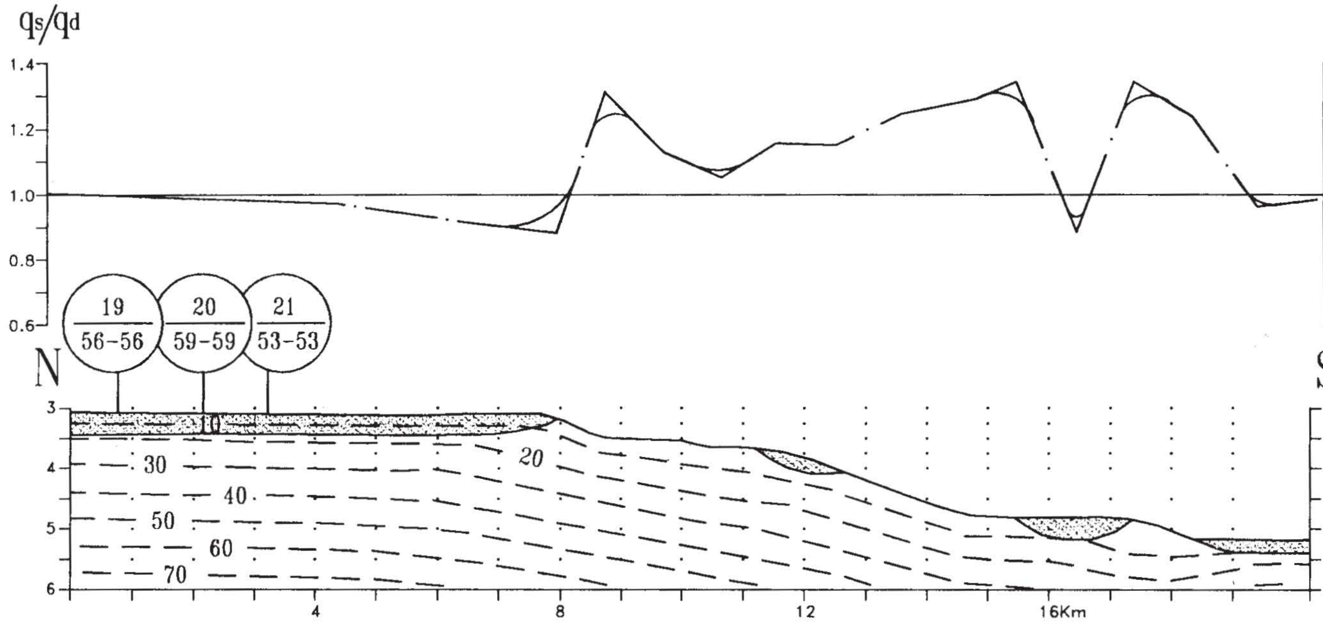


Fig. 8. Model and modeling results for profile I-I' of Figure 6. Depths are given in kilometers from the ocean surface and obtained from bathymetric profile. At a depth of 6 km we used a constant heat flow lower boundary condition of 55 mW/m^2. To the north we placed two layers of sediments in contact with acoustic basement (see text for thermal parameters used). Measured (corrected) and calculated heat flow for stations 19, 20 and 21 are the same (bottom numbers in circles, in mW/m^2). Isotherms are shown in °C. The ratio qs/qd of surface to background (deep) heat flow reflects only topography (refraction) and discontinuities between sediments and acoustic basement, to the south.

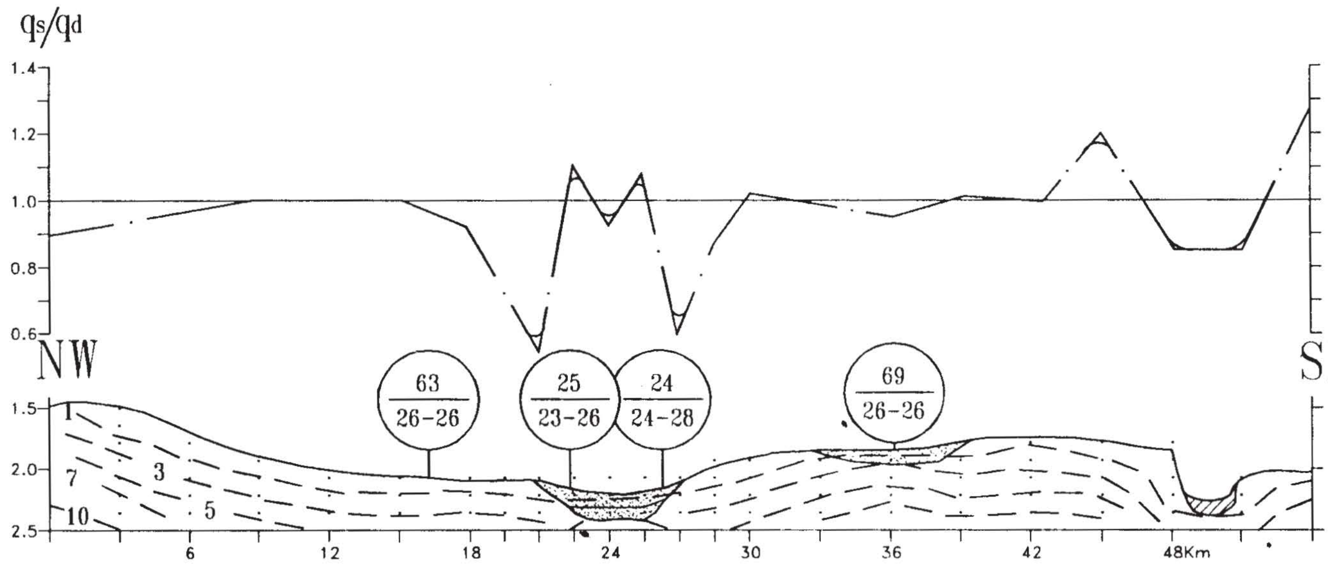


Fig. 9. Results from modeling profile a-a' (Figure 6) in western Manzanillo basin. Depths are in kilometers from ocean surface (from bathymetric chart). Constant heat flow of 25 mW/m^2 was used as lower boundary condition for modeling. Thermal parameters used are explained in the text. Heat flow values in mW/m^2 from the model (second number to the right, below station locations) is similar to the measured heat flow. The ratio q_s/q_d shows the same effects as in the model for Tecpan area (Figure 8).

with terrigenous materials associated with a structural high and a lack of significant amounts of biogenic material. Station 338B (Ross, 1971),on the landward flank of the Middle American Trench slightly to the NW of our quadrangle (19° N, 115°24' W), shows an average rate of sedimentation of 13cm/1000yr, obtained from radiocarbon dating. However, the surface age of core 338B was rather high for the area, representing a relatively slow deposition

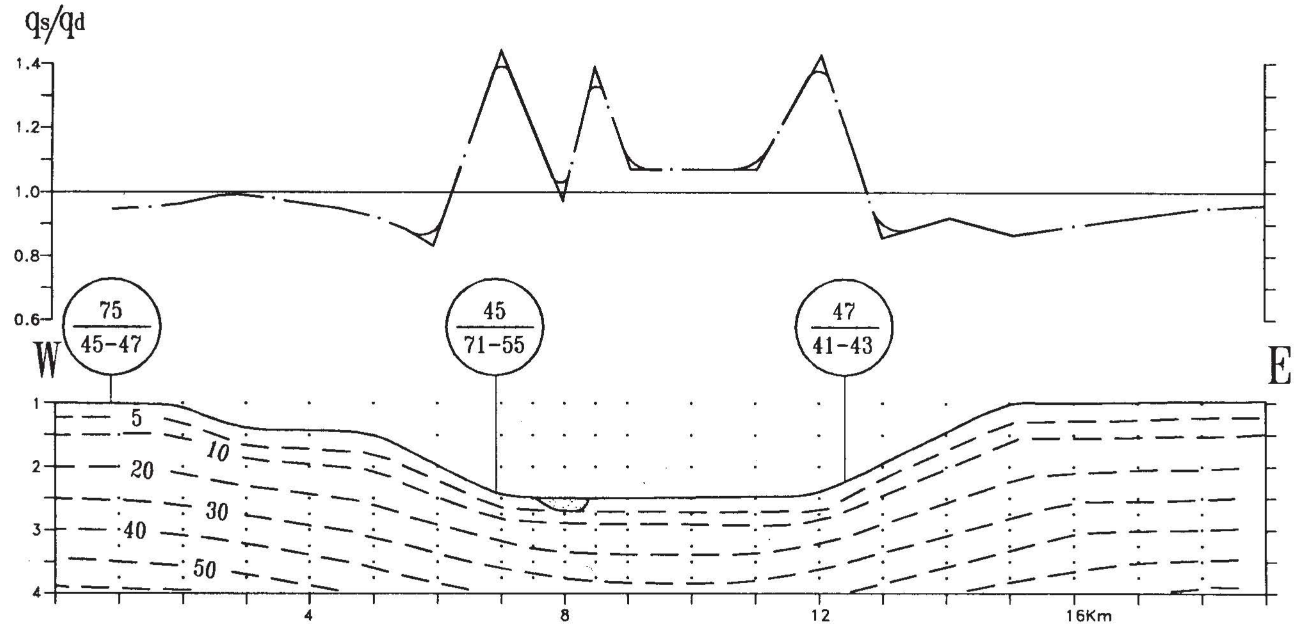


Fig. 10. Modeled section of the eastern side in Manzanillo basin (profile b-b' of Figure 6). Same comments apply as those in Figures 8 and 9. Station 45 was projected onto this profile and the calculated and measured heat flow are different.

or reworking of slowly deposited sediments. If we extrapolate these rates to our study area, and we apply corrections for the last 5 to 10 Ma (Hutchison, 1985), we can not increase the measured heat flow in Manzanillo basin by more than 5%.

Consider next the vertical migration of fluids in the bottom sediments. Let us consider a sedimentary layer of thermal conductivity *K*, heat capacity *c* and density *ρ*; then the rate *v* of vertical migration of fluids between two points ΔZ apart is given by

$$v = \frac{K}{c\rho\Delta Z}\,\frac{\Delta T_{i+1}}{\Delta T_i}$$

We need to calculate the temperatures ΔT_i's associated to this interval (Z is positive downwards). For this purpose, we apply a one-dimensional model of vertical stationary heat mass transfer, using constant temperature boundary conditions for the sedimentary layer.

We used station 24 (Figure 7) located in the central part of Manzanillo basin. If we assume K=0.9W/m•K, c=4190 J/kg•K (water) and ρ=1000 kg/m^3, within ΔZ=0.5 m, the vertical migration rate *v* in the first meter interval (0-1m) of sediments is 2.98 x 10^{-7} m/s (9.4 m per year). For the second interval (1-2m) it amounts to 1.53 x 10^{-7} m/s (4.8 m per year). These relatively high rates are capable of strongly distorting the conductive heat flow.

At station 24, in the first ΔZ=0.5 m interval we measured a heat flow of 12 mW/m^2. If we correct for the rate of vertical migration we obtain 26 mW/m^2 for this interval. Our estimated instrumental error, together with the error due to use of a simple 1-D model for this small interval, amounts to 20%. In conclusion, corrections for hydrodynamic influence should be applied for the depth intervals of our thermal probe when these account for a difference of more than 20%. We applied these corrections to stations 21 to 27 and 62, 63 and 65. At station 68, the rates of migration vary with depth from 1.38 x 10^{-7} to 0.85 x 10^{-7} to 1.38 x 10^{-7} m/s (2.6 m per year). When the appropriate corrections are applied at two of the measured intervals, we obtained 70 and 77 mW/m^2. The uncorrected heat flow for these same points was 112 mW/m^2 and 90 mW/m^2, respectively.

In summary, the results from modeling in the Manzanillo quadrangle allow us to differentiate between heat flow variations caused by surface topography and by thermal refraction from other sources. Corrections to data in the western basin were made from a quantitative analysis of vertical fluid migration.

DISCUSSION AND CONCLUSIONS

Let us return to Figure 1 which defines the tectonic working hypothesis for our major study area. We argue that the boundary between the Rivera Plate and the Cocos Plate, which trends approximately N11°E, features predominantly left-lateral relative motion involving continental crust in the landward slope of the Middle American Trench. From our previous work in the continent, and from the bathymetry and the seismic interpretations, we conclude that the area of study has been subjected to extensive transtensive and normal faulting (mainly during Miocene time), with underthrusting of the oceanic crust, and on the landward side to a strong uplift of the continental slope of the Middle American Trench.

The orientation of the principal canyons in the Manzanillo quadrangle is consistent with the direction of faulting, as derived from the relative motion of the Rivera and Cocos plates. They are, no doubt, of tectonic origin. On either side of canyon C, we find dissimilar thermal regimes. To the southeast, the heat flow is typically above 45 mW/m^2, a figure found along the continental slope of the Middle American Trench in several localities. To the northwest, we find rather low heat flow (26 mW/m^2), which supports the existence of dissimilar geology on either side of this boundary. From continental geology and from the low heat flow it is concluded that the basement, in the western section of our study area, may be composed mainly by granitoids belonging to the Jalisco Block. This is a deep seated structure which has been mobile, subjected to strong deformation (mainly uplifting), and has therefore been unable to establish stable thermal gradient. In particular, we surmise that metamorphic and/or granitic rocks may underlie the sedimentary sequence observed in seismic profiles 10 to 13, in the zone of low heat flow, northwest of canyon C.

The idea of a possible seaward extension of the Colima Graben must be considered with some care. Our results indicate a lack of high heat flow associated with rifting, at least within the area of the Manzanillo quadrangle. Since recent volcanic activity is absent in this area, and since the presence of a rift zone south of the city of Colima is not geophysically supported (Serpa *et al.*, 1992), a local transpressive regime may be inferred. The high heat flow in the El Gordo Graben suggests the presence of a discrete structure, independent from the continental margin.

The active continental margin along the Pacific coast of Mexico has a fairly constant average background heat flow. From measurements taken off Tecpan and Manzanillo (except in the western basin), plus the results of Sugrobov *et al.* (1989) and Prol-Ledesma *et al.* (1989) in an area SE of Manzanillo (off Petacalco), the heat flow averages from 50 to 60 mW/m^2 on the continental slope of the Middle American Trench.

Along the trench axis, and along the seaward slope of the Middle American Trench (near the Rivera Plate-Cocos Plate-East Pacific Rise junction), the heat flow shows a larger scatter. The regional heat flow exceeds 100 mW/m^2, with a large dispersion in the data, which may reflect recent tectonomagmatic and hydrothermal activity in the oceanic plate, in the area of the El Gordo Graben. Along the trench axis, only four heat flow measurements were made. They show relatively low heat flow (40 mW/m^2). The data is not enough to arrive to any conclusions relative to the Middle American Trench. However, these figures are in agreement with evidence of low heat flow in other deep sea trenches (Vaquier *et al.* 1967, Yamano and Uyeda, 1988).

These results, together with those reported in previous work by Khutorskoy *et al.* (1990), Polyak *et al.* (1985), Sugrobov *et al.* (1989) and Prol-Ledesma *et al.* (1989), help give an overall picture of the geothermal regime offshore Mexico. On both the Pacific and the Atlantic margins, we find an average heat flow around the 50 mW/m^2 value (Figure 11). At the passive Atlantic margin, the heat flow reflects relatively old active geodynamic processes and a great thickness of the continental lithosphere; at the Pacific margin, it reflects the results of active tectonism which has created over- and under-thrusting of oceanic crust, uplift of the continental slope, and a probable transcurrent motion near the Middle American Trench, which disturbs deep heat flow.

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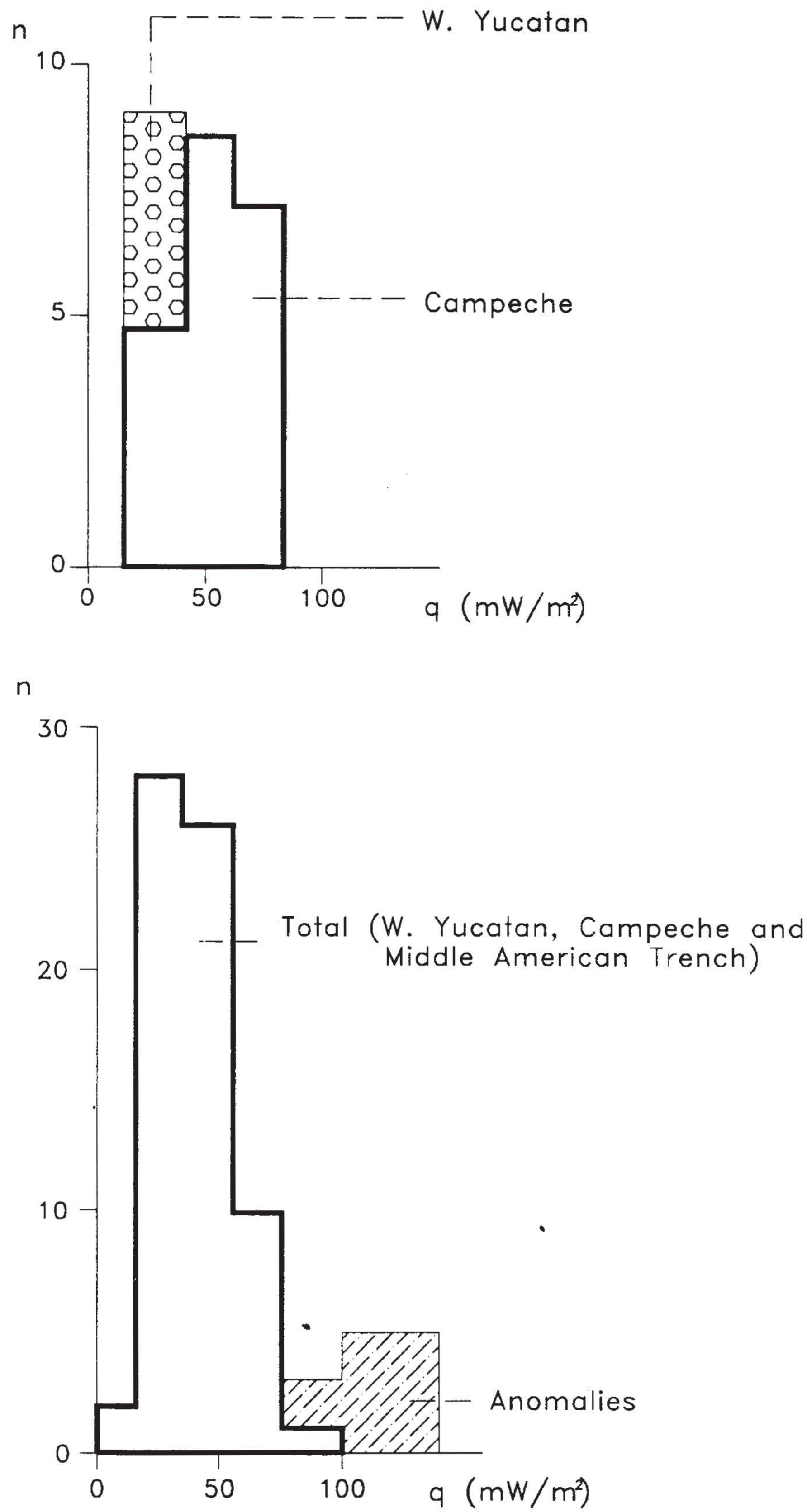

Fig. 11. Top: histogram from data in Khutorskoy *et al.* (1990) for west Yucatán peninsula and Campeche canyon in the Mexican Atlantic. Mean heat flow is 49±14 mW/m^2. Bottom: histogram for all data including this study. Mean heat flow is 49±20 mW/m^2.

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