# A geophysical investigation of the southern Jalisco block in the State of Colima, Mexico.

Laura Serpa, Stacy Smith, Cassandra Katz, Charles Skidmore, Robert Sloan and Terry Pavlis
*Department of Geology and Geophysics, University of New Orleans, New Orleans, U. S. A.*

Received: 2 October, 1990; accepted: 21 March, 1991.

**RESUMEN**

Se reportan estudios de geología y de campos potenciales en el Estado de Colima, México, para estudiar la extensión neotectónica previamente interpretada a través del Graben de Colima. Nuestros estudios indican que la extensión tectónica al sur del Volcán de Colima es nula o muy pequeña y que los rasgos interpretados previamente como estructuras extensionales son rasgos erosionales relacionados con antiguas deformaciones o a cortes de barrancas producidos por la rápida sedimentación del Volcán de Colima.

**PALABRAS CLAVE:** Colima, gravedad, magnetismo, tectónica, Volcán de Colima, México.

**ABSTRACT**

Geological mapping and potential field studies in the State of Colima, Mexico were conducted to study previously interpreted neotectonic extension across the Colima graben. Our studies indicate that little, or no, extension has occurred south of Volcan de Colima and that the features previously inferred to be extensional structures are instead erosional landforms related to older deformation and downcut streams due to rapid sedimentation from Volcan de Colima.

**KEY WORDS:** Colima Graben, gravity, magnetics, tectonics, Colima volcano, Mexico.

## INTRODUCTION

The collision of the East Pacific Rise with the western margin of North America during the late Cenozoic had a profound effect on the tectonic evolution of the western United States and northwestern Mexico (e.g. Atwater, 1970). A discontinuous record of that collision is preserved locally along the coast of northwestern Mexico but is largely obscured by subsequent sedimentation, volcanic activity and deformation. The East Pacific Rise is now approaching the Mexican coastline (Figure 1) near the border between the States of Colima and Michoacán and deformation associated with that impending collision now appears to be affecting a region, referred to here as the Jalisco block, comprised of portions of the States of Colima, Jalisco, and Nayarit (Luhr *et al.*, 1985). To examine this deformation,we initiated geological and geophysical studies in the State of Colima and the preliminary results of those studies are presented here.

The geophysical investigations (Skidmore, 1988; Skidmore and Serpa, 1988; Skidmore *et al.*, 1988; Serpa *et al.*, 1989 a,b; Katz, in prep.) consisted of the collection of records from 565 gravity and ground magnetic stations along major roads in the eastern portion of the state of Colima. These data were reduced and modeled to provide subsurface information on the locations of late Cenozoic basins and other features related to the regional deformation. Geologic mapping (Sloan, 1989; Sloan *et al.*,1988; Smith, 1990; Smith *et al.*, 1989 a,b) was conducted in an area south of the city of Colima to determine the extent of the neotectonic deformation in that region and to provide constraints for the interpretation of the geophysical data. As discussed in a subsequent section, the geologic mapping primarily provided information on the older, rather than the neotectonic, history of the region. For that reason, the geologic data are discussed in detail elsewhere (Sloan, 1989; Smith, 1990; Smith *et al.*, in prep.), and only a summary of geologic work is presented here.

## PREVIOUS STUDIES IN THE VICINITY OF THE JALISCO BLOCK

The Jalisco block (Figure 1) is bounded on the north by the Tepic-Zacoalco graben, on the east by the Colima graben, and on the west by the middle America trench which is, in that area, associated with subduction of the Rivera microplate beneath the North American continent. The study area is located in the southern portion of the Colima graben. Studies (e.g. Gastil *et al.*, 1979; López-Infanzón and Grajales, 1990; Zimmerman *et al.*, 1988; Campa and Coney, 1983; Pantoja-Alor and Barraza, 1986) indicate that magmatic arcs have existed along this convergent margin since the Jurassic. The youngest (Miocene to Recent) magmatic arc is the active Trans-Mexican Volcanic Belt located above the middle America trench and extending across central Mexico. The northern and eastern boundaries of the Jalisco block appear to be related to this volcanic trend with possible modifications in the boundaries related to the approach of the East Pacific Rise to the middle America trench.

There have been several studies of the plate configurations in the vicinity of the Jalisco block (Larson, 1972; Nixon, 1982; Molnar, 1973; Mammerickx and Klitgord, 1982; Eissler and McNally, 1984; Ness *et. al.*, 1985; Bourgois *et al.*, 1988; Skidmore, 1988; DeMets *et al.*, 1990).

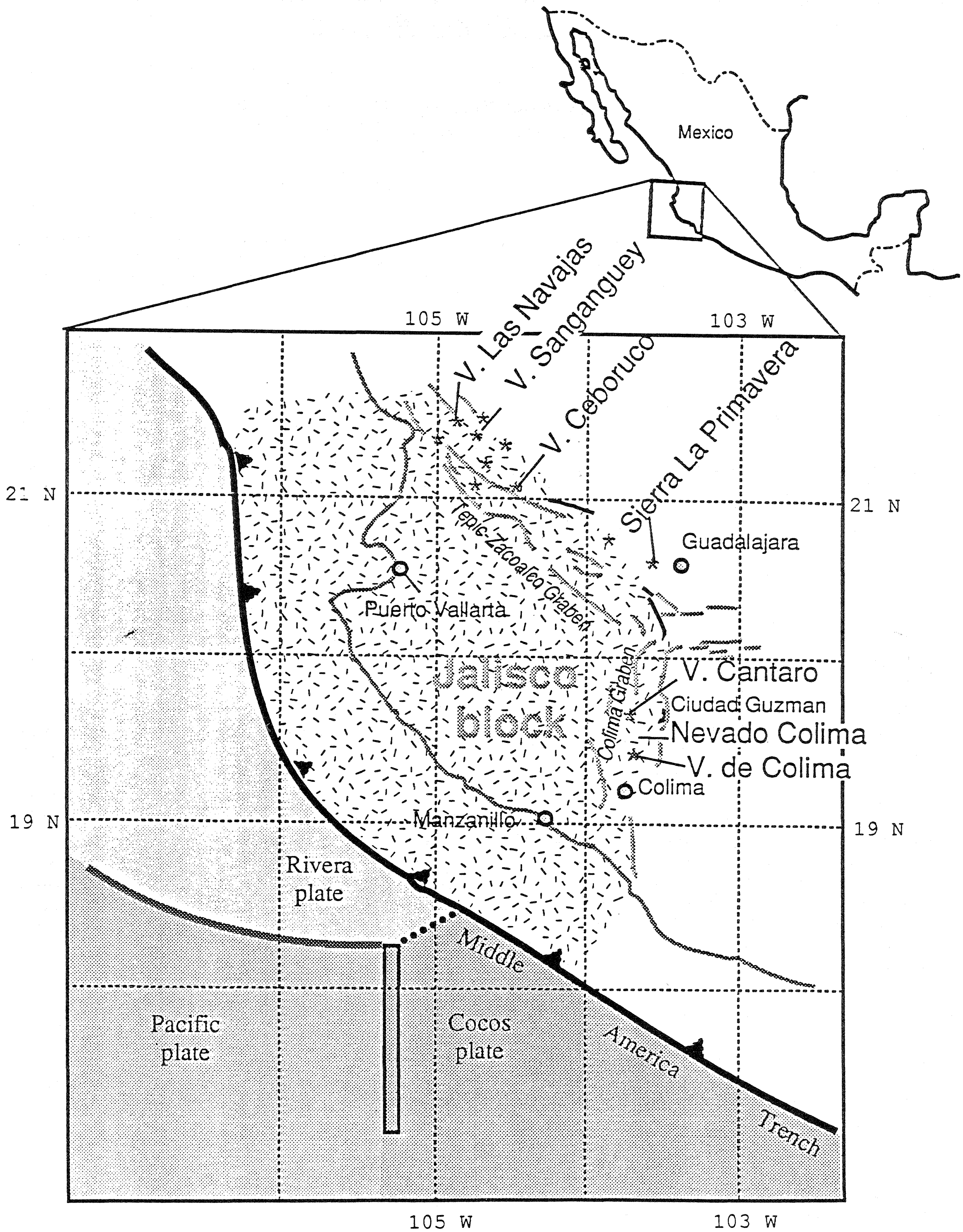


Fig. 1. Generalized tectonic map of west-central Mexico showing the location of the East Pacific Rise, separating the Pacific and Cocos plates, relative to the Jalisco block. Some volcanic edifaces are indicated with an asterisk and the grabens structures of the Jalisco block boundaries are shown in stipple. (modified from Luhr *et al.*, 1985, and Nelson and Sánchez-Rubio, 1986).

The intersections of the North American, Cocos, Rivera, and Pacific plates occur at two triple junctions west of the city of Manzanillo, Mexico, at the southern end of the Jalisco block (Figure1). Mammerickx and Klitgord (1982) suggest that at approximately 15 Ma these triple junctions were formed as a result of a series of ridge and transform jumps to accommodate the approach of the East Pacific Rise toward the middle America trench. Those plate reorganizations resulted in the approximate current plate configuration around 3.5 Ma. Based on their observations, Luhr and others (1985) further suggest that within the last 2 m.y., the Rivera ridge segment jumped landward to the position of the Colima graben, attaching the Jalisco block and the Rivera Plate to the Pacific Plate. In contrast, Bourgois and others (1988) identified faults off the coast of the southern Jalisco block which they suggest separate the Jalisco block from the Rivera microplate, indicating that the Jalisco block is still attached to North America.

The changing plate configurations had a major effects on the Jalisco block including the apparent transtensional deformation along the norhtern and eastern block boundaries during the past approximately 3.5 Ma (Nieto, 1987; Nieto and Guzman, 1988; Nieto *et al.*, 1985,1989; Damon *et al.*, 1979; 1985; Guzman, 1989; Guzman and Nieto, 1988; Allan, 1986). Those boundaries also are the site of much of the volcanic activity in the region (e.g. Luhr and Carmichael, 1980,1981; 1985; Luhr *et al.*, 1985; Allan, 1986; Allan and Carmichael, 1984; Nelson, 1980,1986; Nelson and Carmichael, 1984; Nelson and Livieres, 1986; Hegre and Nelson, 1985; Robin *et al.*, 1987; Carmichael and Depaolo, 1980; Carmichael and Luhr, 1985; DeRemer and Nelson, 1985; Gilbert *et al.*, 1985; Giosa and Nelson, 1985; Mahood, 1980,1981; Mahood *et al.*, 1985). The interior of the Jalisco block has not been studied as much as the boundary regions; however, the recent identification of volcanic activity within the interior of the Jalisco block (Wallace and Carmichael, 1990) may indicate that the deformation related to the approach o the East Pacific Rise is more widespread than previously recognized.

The Colima volcanic complex, located near the center of the Colima graben, consists of three southward younging calc-alkaline composite volcanoes; Cantaro, Nevado and Colima. The Colima complex has been extensively studied by a number of investigators (e.g. Allan, 1986; Allan and Carmichael, 1984; Luhr and Carmichael, 1980; 1981,1982; Medina, 1985; Robin *et al.*, 1987). Luhr and others (1985) indicate that the region surrounding the volcanic complex experienced both calc-alkaline and alkaline volcanism during the past approximately 2 Ma. Similarly, cinder cones near Sanganguey, along the Tepic-Zacoalco rift, have erupted alkaline lavas (Nelson and Carmichael, 1984; Nelson and Livieres, 1986) and pantelleritic obsidians have erupted from Las Navajas, north of Sanganguey (Hegre and Nelson, 1985), in addition to the calc-alkaline volcanism in these areas. Luhr and others (1985) suggest the alkaline volcanism is an indication of crustal rifting, while contemporaneous eruption of both magma types suggests the margins of the Jalisco block are tapping diverse magma sources suggestive of a transition from subduction to extensional tectonics.

Structures along the boundaries of the Jalisco block also indicate deformation of a mixed type. Analogy with the Baja California Peninsula, which separated from the North American mainland as a result of earlier impingement of the East Pacific Rise against North America, suggests that the northern boundary of the Jalisco block should experience right-lateral strike-slip deformation and the Colima graben northwest-directed extension during the collision. Right-lateral faulting has been documented in the Río Santiago area on the northern side of the Tepic-Zacoalco graben with significant (5-10 mm/yr) Holocene displacement rates (Nieto, 1987; Nieto *et al.*, 1985). Similarly, Allan (1984,1985) and Skidmore (1988) have identified 1 to 4 km of vertical offset locally on the bounding faults of the Colima graben. However, recent studies (Smith, 1990; Skidmore, 1988; Guzman, 1989; Guzman and Nieto, 1988; Nieto *et al.*, 1989) have also found evidence of significant strike-slip deformation in the Colima graben and extension in the Tepic-Zacoalco rift. Thus, the structures along the borders of the block appear to reflect transtensional deformation with a net displacement between the Jalisco block and the interior of North America oriented in approximately a southwest-northeast.

## GEOLOGY OF THE STUDY AREA

To examine the deformation of the Jalisco block, geologic mapping (Sloan, 1989; Smith, 1990) was conducted south of the city of Colima at a scale of 1:50,000 within the region commonly referred to as the Colima graben (Figure 2). This is the landward area closest to the approaching East Pacific Rise and, thus, it should be the region most strongly affected by the offshore tectonic events. Previous regional studies (e.g. Clark *et al.*, 1982; Damon *et al.*, 1981; Gastil, 1983; Gastil *et al.*, 1978, 1979; Pantoja-Alor and Barraza, 1986; Zimmerman *et al.*, 1988) indicate that the rocks of the region formed as part of an upper Mesozoic magmatic arc and associated basin deposits. Geologic mapping by Smith (1990) and Sloan (1988) summarized below, as well as the extensive mapping by Pantoja-Alor and Barraza (1986), drilling reports from Salazar (1983), and lithostratigraphic studies (Michoud *et al.*, 1987) in the vicinity of the study area, form the basis for much of our knowledge of the geology of the Colima region.

As part of their work, Sloan (1989) developed and Smith (1990) modified an informal stratigraphic nomenclature for the rocks in the study area which differs in some respects from that previously established by Romero and others (1974), Salazar (1983), and Pantoja-Alor and Barraza (1986). Those differences reflect alternatives in correlation of different rock sequences and, although the nomenclature may change with additional work, those changes should not affect the interpretations presented in this paper.

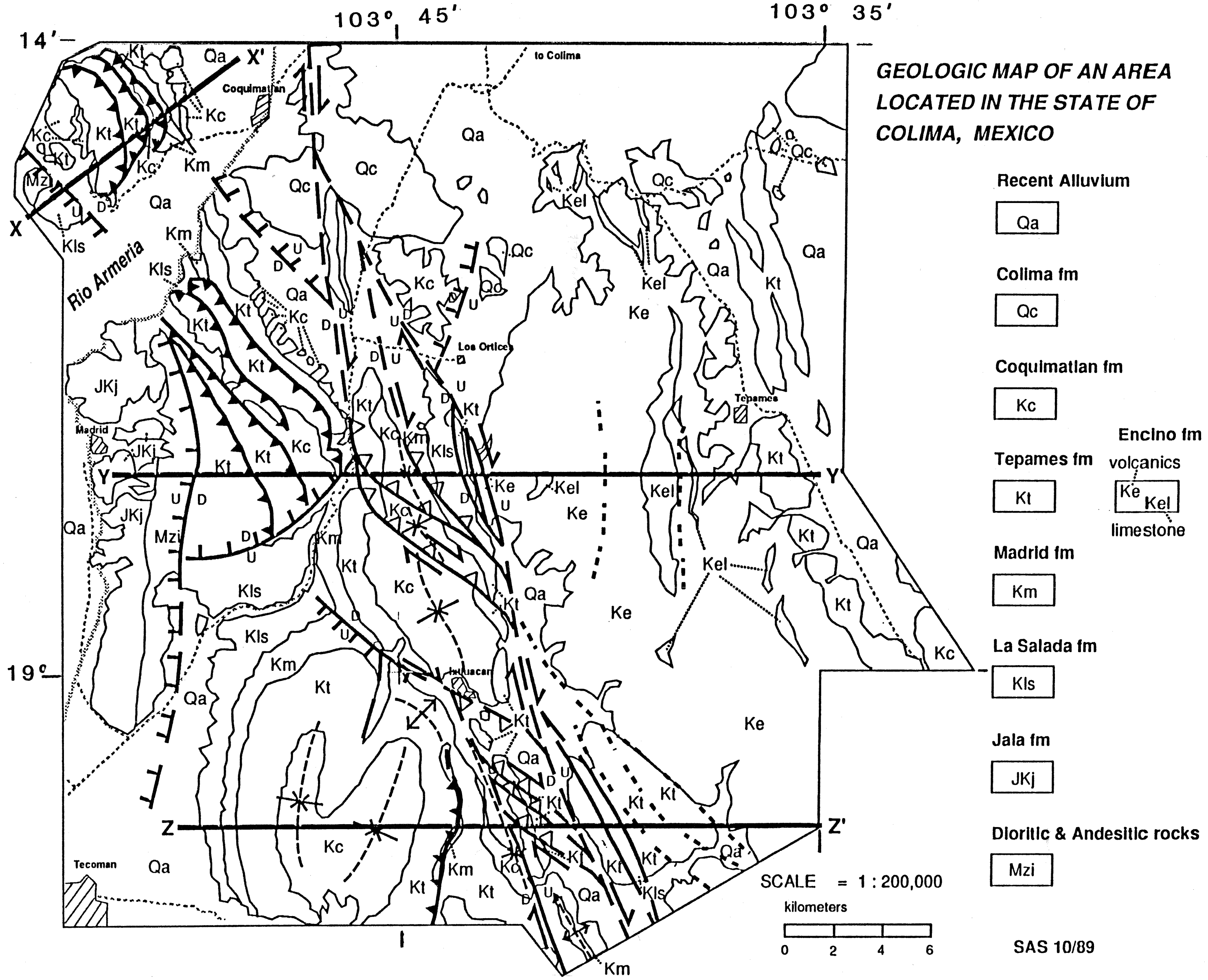


Fig. 2. Geologic map of the study area (Smith, 1990)

The sedimentary rocks in the study area (Figure 2) include a variety of clastics, carbonates, and evaporites of lower to middle Cretaceous age and Plio-Pleistocene valley fill composed of gravels, volcanic debris, and alluvium. Igneous rocks include intermediate to felsic intrusives and extrusives ranging in age from early Cretaceous to Quaternary in age. No metamorphic rocks were mapped in the study area but a variety of metamorphic rocks, ranging from migmatites to metasedimentary and metavolcanic rocks, of late Paleozoic to Mesozoic age have been reported for surrounding regions.(López-Infanzón and Grajales, 1990). Thus, those metamorphic rocks may also underlie the study area.

Structural features in the study area (Figures 2 and 3) can be divided into two groups: those produced by a Mesozoic compressional event and a younger set of transpressional features that clearly post-date the compression but for which no age has yet been established. The compressional features include folds and thrusts with a general northwest trend and northeast vergence. Basement appears to be involved in the thrusting along the western side of the study area but gypsum and shale cored folds in the central portion of the study area suggest the deformation also involved movement of layers above a decollement. Based on depositional relationships and unconformities, Smith (1990) suggests the compression is related to uplift of the region during the emplacement of the Puerto Vallarta-Río Santiago batholith in the late Cretaceous.

The compressional features are overprinted by a system of north-northwest-trending, high-angle faults and related folds which cut through the center of the study area and are interpreted by Smith (1990) to be part of a major dextral transpressive fault system. Evidence for this transpression includes the juxtaposition of distinctly different rocks across the high angle fault system and the presence of structures characteristic of transpression (e.g. Sylvester, 1988; Wilcox *et al.*, 1973). Our differences in stratigraphic nomenclature, discussed previously, may be due, in part, to the apparent absence of transitional facies between the primarily volcanic Encino formation and sedimentary Madrid and La Salada formations which are separated by the high-angle fault zone (Figure 2). Along the fault zone right-lateral offsets of oppositely-dipping beds and fold axial traces can be observed and "positive flower" structures (Wilcox *et al.*, 1973) give further evidence for the transpressional deformation (Figure 3).

The timing and amount of strike-slip motion across the zone of transpression have not been established. Smith (1990) suggests the faulting may be associated with the inferred removal of the Chortis block in southern Mexico at approximately 20 Ma (Wadge and Burke, 1983) or with the right-lateral oblique subduction of the Farallon plate beneath southwest North America sometime between very latest Cretaceous and the early Paleogene (Beck, 1981). We have found no evidence to suggest that the strike-slip deformation is directly related to the most recent tectonic events (i.e. the approach of the East Pacific Rise) in the area. However, the location of the transpressional zone along, and its parallelism with, the apparent eastern boundary of the Jalisco block suggest that structure may have influenced the subsequent deformation of the region.

Our geologic studies failed to find clear evidence of significant Plio-Pleistocene deformation in the study area suggesting that the previously inferred eastern boundary of the Jalisco block is inactive south of the city of Colima. Previous studies (e.g. Allan, 1986; Harrison and Johnson, 1988; INEGI maps) suggested that an extensional basin or series of basins exists between the approximate locations of the city of Guadalajara and offshore from the city of Manzanillo (Figure1). Those basins should trend through our study area; however, our mapping revealed no evidence of extensional deformation south of the city of Colima. The photo lineaments that formed the basis for the previous interpretations in the area are the result of erosional landforms related to the older compressional and transpressional deformation, as well as possible downcutting of streams due to sedimentation from Volcan de Colima during, at least, the last 4,000 years since its last major explosive eruption (Luhr *et al.*, 1985; Allan, 1986). The geophysical investigations, discussed below, further indicate that the Colima graben does not exist south of the city of Colima.

## GEOPHYSICAL INVESTIGATIONS

To further examine the subsurface characteristics of the study area, we collected 565 gravity and ground magnetic values with a station spacing of 0.8 km along major roads south of Volcan de Colima. The gravity data were reduced to simple Bouguer values using an assumed density of 2.67 g/cc and the 1980 International gravity formula. The gravity data are shown in Figure 4 with a 1 mGal contour interval. Five magnetic readings were collected at each site and those readings were averaged and corrected for diurnal variations to produce the total magnetic field map shown in Figure 5. Note that approximately 80 stations in the southern part of the study area were omitted from the magnetic map because magnetic storm activity precluded the accurate measurements of those data during the time of the survey. Based on our analysis of 50 stations that were repeated more than once (Skidmore, 1988; Katz, in prep.), the gravity values are believed to be accurate to within $\pm$ 0.8 mGals and the magnetic values to within $\pm$10 gammas.A detailed discussion of the accuracy of the data, methods of reduction, and a listing of the data values is given by Skidmore (1988) and Katz (in prep).

The dominant feature of the gravity data is a northeast-dipping gradient with a relief of 135 mGals (Figure 6) which is a typical characteristic of gravity data from convergent continental margins. This gradient is attributed here to an increase in crustal thickness from the coastal region toward the interior of the continent in a manner similar to the interpretation of Couch and Woodstock (1981) for gravity data south of our study area. We did not model

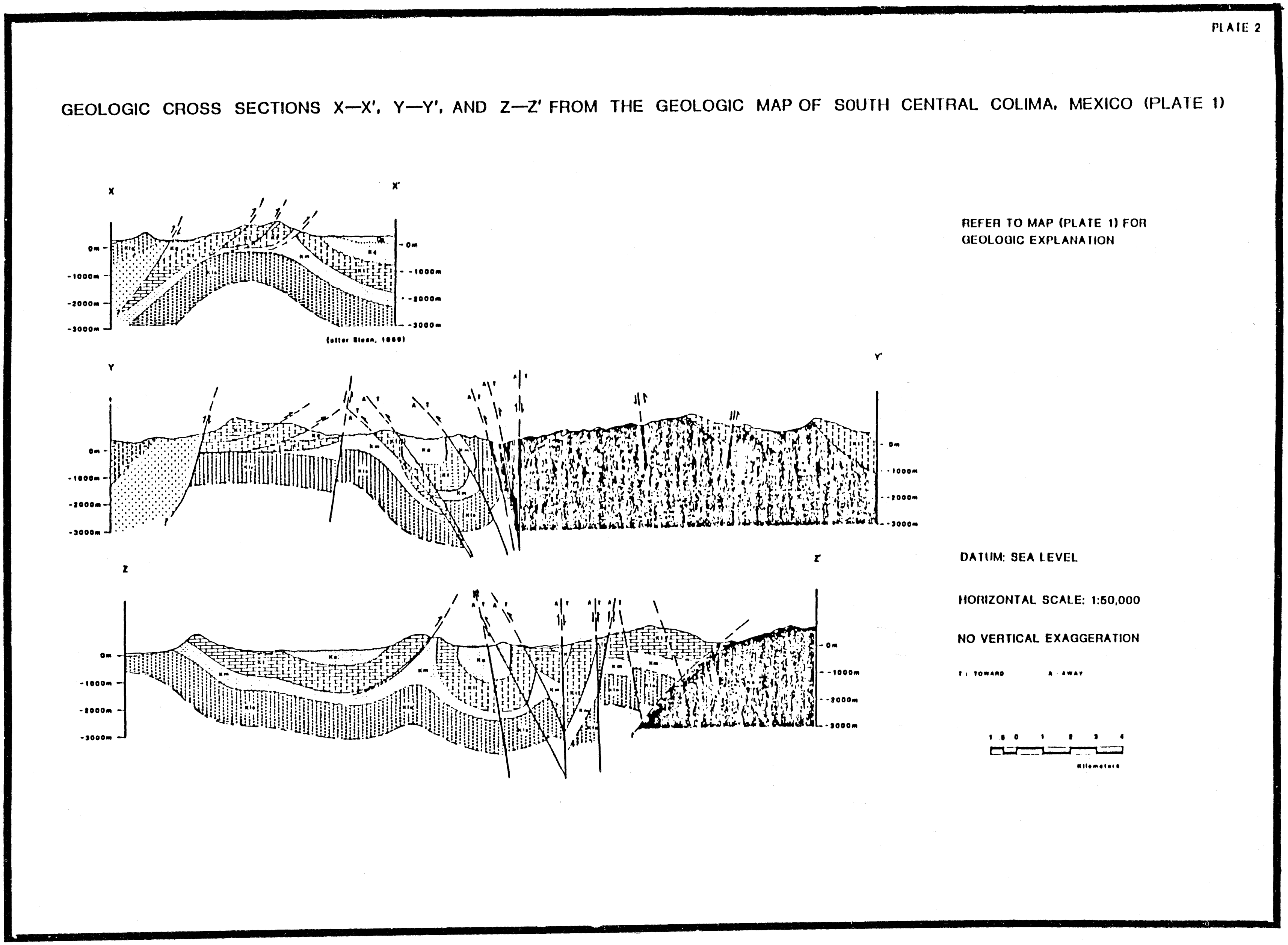


Fig. 3. Geologic cross-sections of the study area (Smith, 1990; Sloan, 1989).

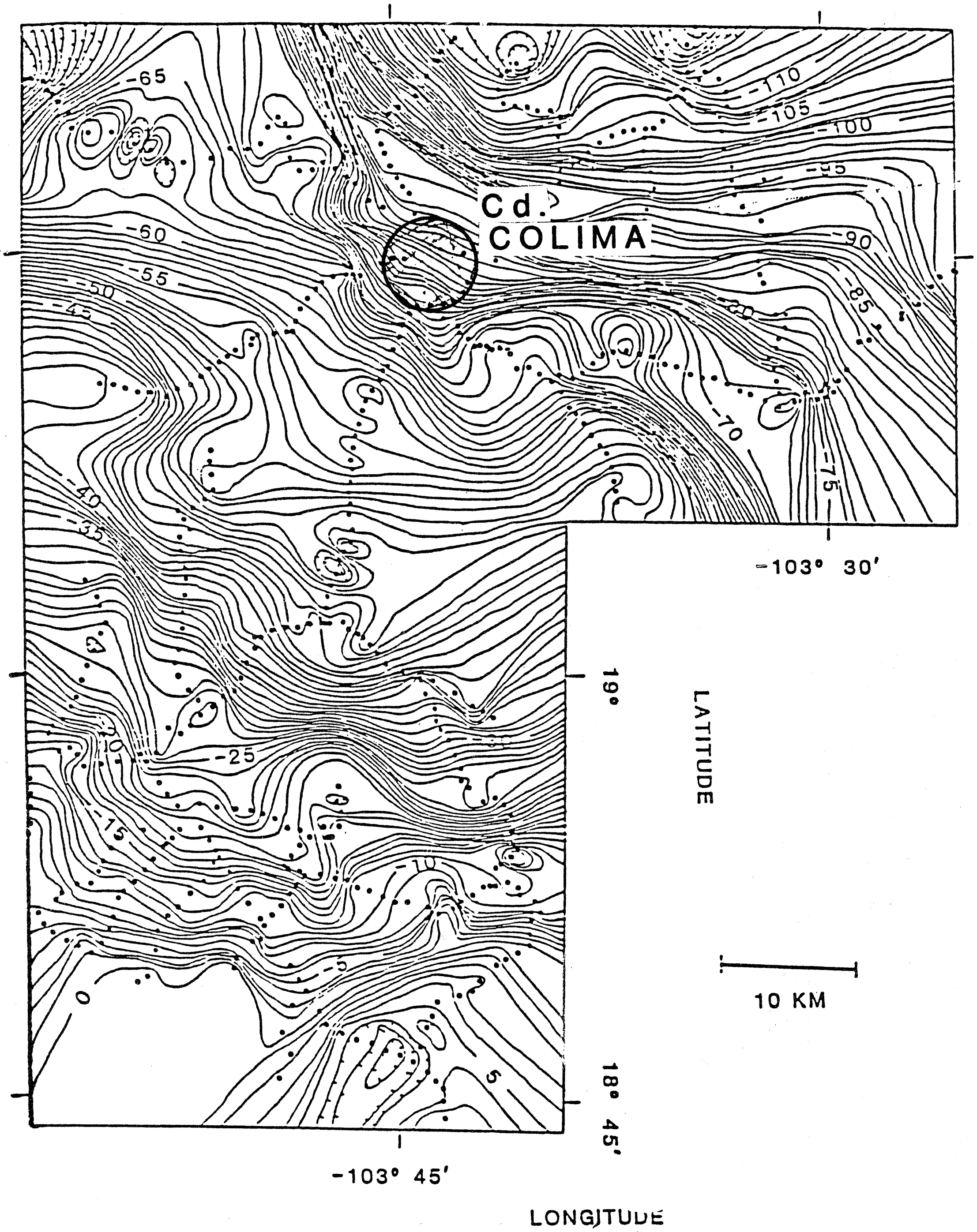


Fig. 4. Simple Bouguer gravity map (contour interval = 1 mGal). Dots show the location of gravity stations.

the changing crustal thickness because we had too little information on the depth and character of the base of the crust in this locality. To facilitate further discussion of the shallower features of the crust, the dipping plane corresponding to the gradient (strike N74°W, dip 1.67 mGals/km NE) was subtracted from the Simple Bouguer values to produce the residual gravity map shown in Figure 7. The residual gravity values were used to prepare the models shown in Figures 8, 9 and 10 and are discussed in more detail below.

The interpretation of these data was constrained with subsurface models along three profiles (Figures 8, 9 and 10) for which densities and magnetic susceptibilities typical of the inferred rock types (Table 1) were used. These models are considered preliminary estimates of the subsur-

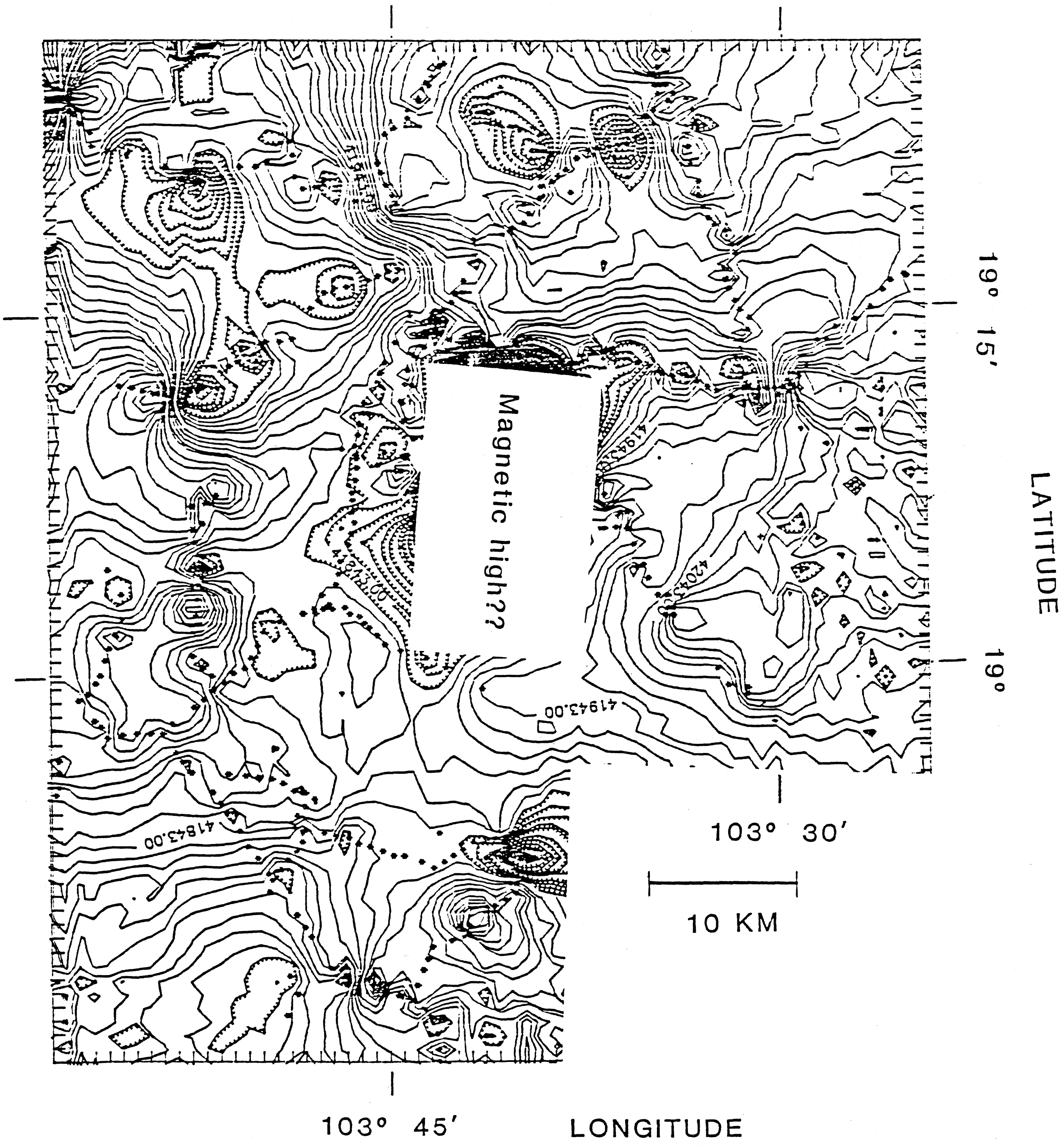


Fig. 5. Total magnetic field map (contour interval = 10 gammas). Dots show the location of magnetic stations.

face rock distribution because neither the magnetic susceptibilities nor densities of rocks collected in the field area have yet been measured and our modeling program does not yet allow for the incorporation of the remanent magnetization data which Alva-Valdivia and others (1990) have shown to be important factors within the study area. However, the use of a simultaneous modeling program (Serpa and Cook, 1984) reduces the ambiguity associated with potential field data by providing a single geologic model to explain both the gravity and magnetic data. Thus, the preliminary models should provide a reasonable guide to the general subsurface distribution of major rock types in the study area and future modeling should further refine that information.

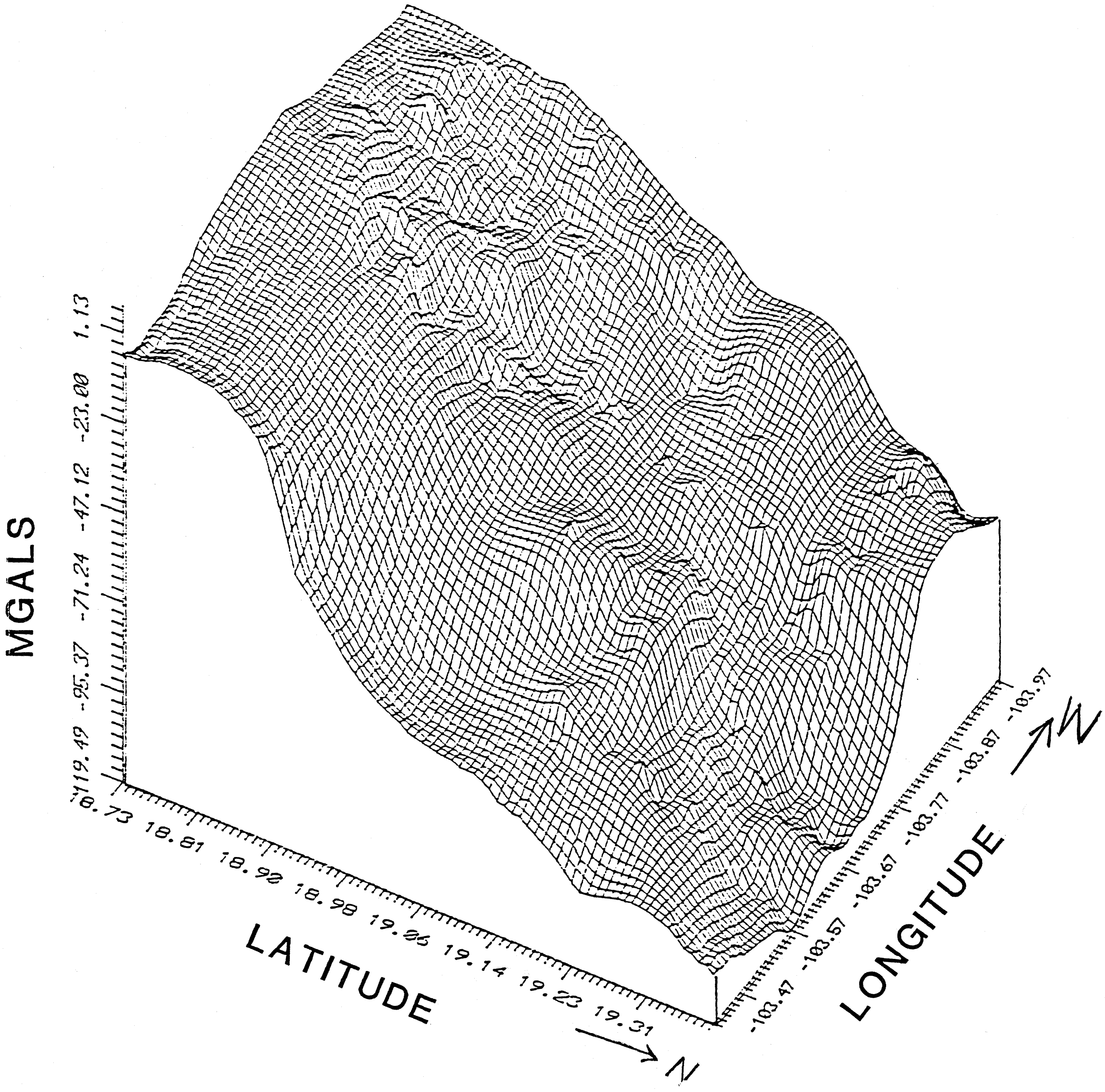


Fig. 6. Block diagram of simple Bouguer gravity values showing the regional trend.

## DATA INTERPRETATION

Major anomalies on the residual gravity map are divided into 4 major regions: two gravity lows in the north-northeastern and southern parts and two gravity highs in the northwestern and eastern parts, respectively, of the study area. Those anomalous regions are separated by steep northwest-trending and northeast-trending gradients which intersect at a gravity saddle just south of the city of Colima. The pattern of magnetic anomalies is more complicated than the gravity anomaly pattern but there does appear to be a correlation of broad (long-wavelength) magnetic anomalies with the gravity lows and higher frequency magnetic anomalies concentrated in the areas of gravity highs.

The northern gravity low and corresponding broad magnetic high coincides spatially with the distribution of debris avalanche deposits from the eruption of Nevado de Colima approximately 4000 years ago (Luhr *et al.*, 1985) and is attributed here to low density and moderate to low magnetic susceptibility sediments and avalanche deposits

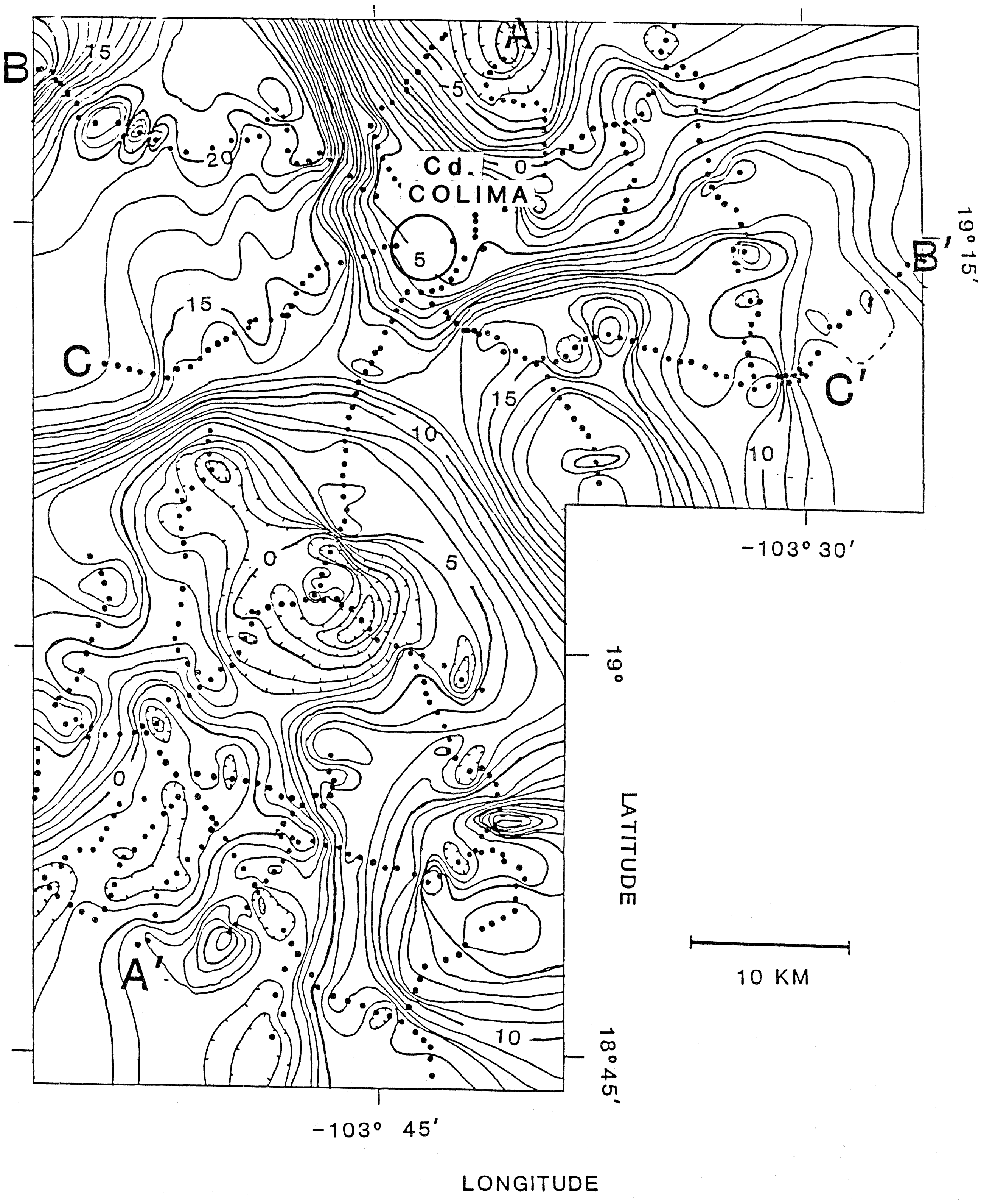


Fig. 7. Residual gravity map (contour interval = 1 mGal). Dots show the location of gravity stations. Letters designate the locations of geophysical models shown in Figures 8, 9 and 10.

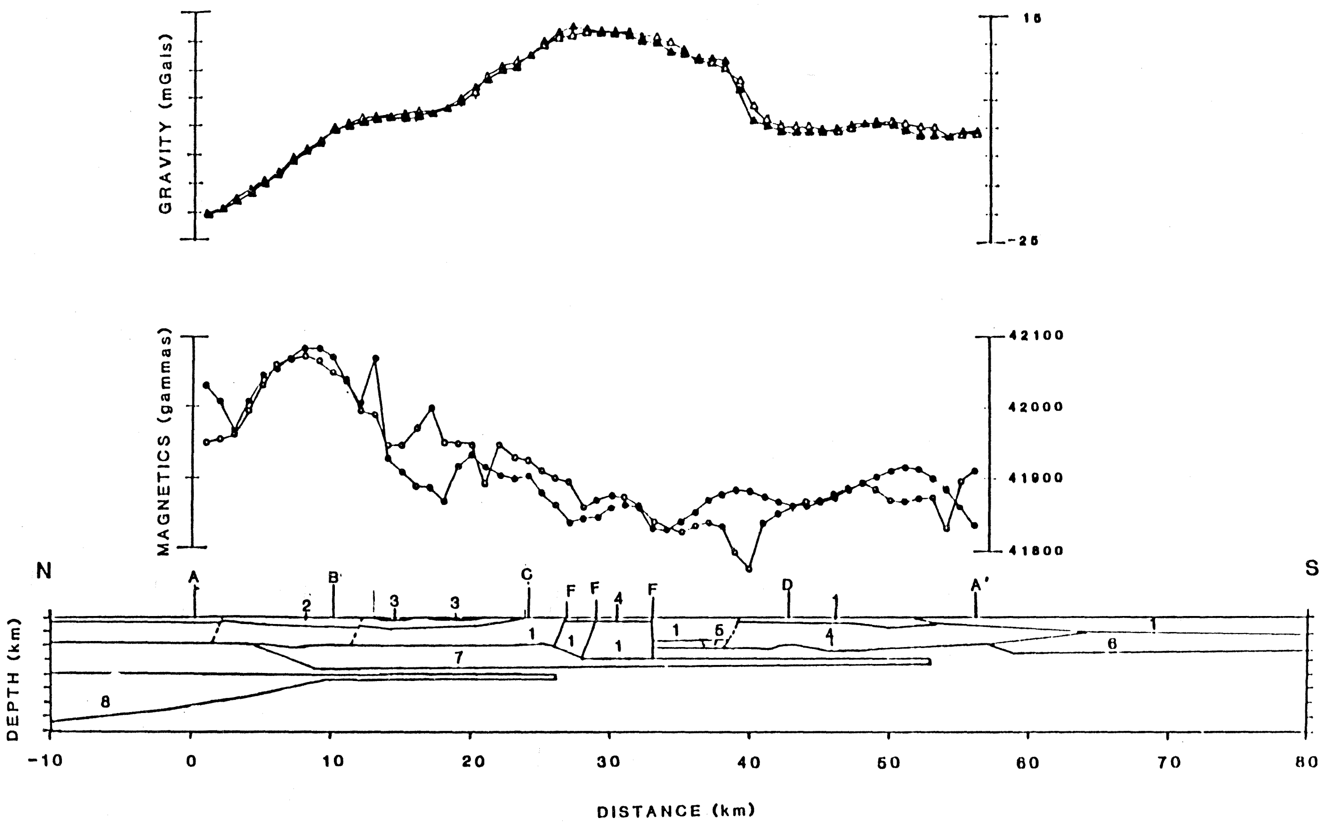


Fig. 8. Profile A-A': preliminary gravity and magnetic model of the subsurface corresponding to the position indicated in Figure 7. Letters B and C indicate the intersections with profiles B-B' and C-C' respectively. F indicates the position of mapped faults (see Figure 2). See Table 1 for a description of the parameters used in the models (body nos. 1-8).

within a basin along the southern side of Volcan de Colima. Modeling (Figures 8 and 9) suggests the basin is approximately 1.5 km deep along its western boundary and shallows to the east. No distinctive eastern boundary is indicated by the existing data and, thus, the basin is suggested to be a half-graben, bounded on the west and south by normal and oblique-slip faults. The relatively long wavelength of the magnetic high suggests the avalanche deposits do not have a high magnetic susceptibility and the main source of the magnetic high is inferred to lie beneath the basin fill, possibly a continuation, down-thrown to the north, of the volcanic rocks exposed south of the city of Colima or intrusive rocks related to either the Puerto Vallarta batholith or the more recent volcanic activity in the region.

The gravity high and magnetic low on the east side of the avalanche deposits correlates spatially with the Cretaceous sedimentary rocks which include low density evaporites, moderate density sandstones, and high density carbonates, all of which are inferred to have low magnetic susceptibilities. Granodiorites associated with the Puerto Vallarta batholith crop out to the west of the study area and are inferred to underlie the sedimentary rocks in that area. The range of magnetic susceptibilities (Alva-Valdivia *et. al.*, 1990) measured within the batholith and similarly aged igneous rocks in the vicinity of the study area is extreme and varies markedly with location such that no reasonable estimate could be made for our area. As a result, the relatively low magnetic susceptibility used to model the intrusive rocks could produce a significant over-estimation of the volume of those rocks in the subsurface.

The southern gravity low and associated magnetic low correlates with the area of evaporites, folds, and thrusts mapped by Sloan (1989) and Smith (1990). The low density and magnetic susceptibility of the thick evaporite sequence is thus inferred to be the major source of the anomalies in this region (Figure 10). The western boundary of these low anomalies is marked by a shallow gradient of approximately 1 mGal/km in the gravity data and a linear trend of magnetic highs and lows which appear to correspond to the easternmost limit of the basement-involved thrusting (Smith, 1990) where basement rocks reach relatively shallow levels. The eastern boundary appears to coincide with the zone of transpression that juxtaposes sedimentary and mafic volcanic rocks in the east against the evaporite cored folds in the west. The gravity high and rapidly changing magnetic values on the east side of the map area reflect the higher density and magnetic susceptibilities of the volcanic rocks.

## DISCUSSION

The major features of the gravity and magnetic data correlate well with the mapped geology of the region and

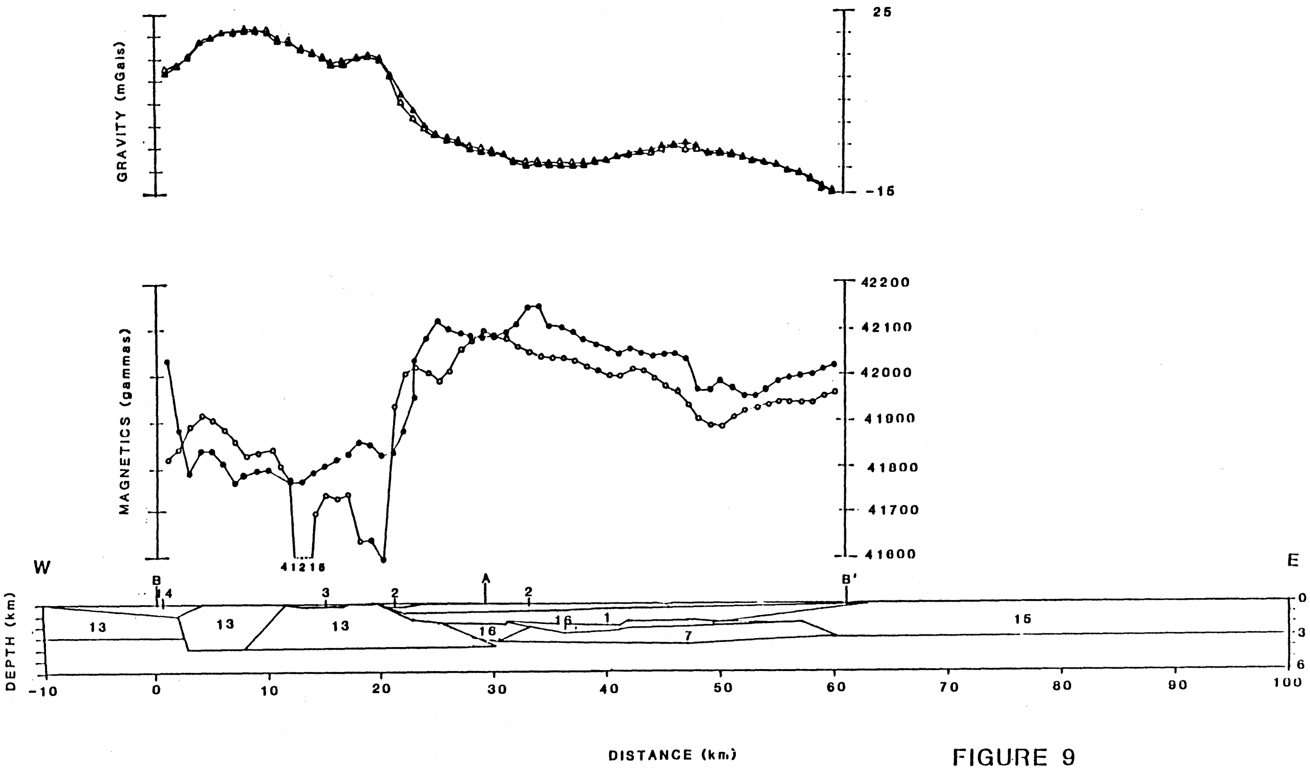


Fig. 9. Profile B-B': preliminary gravity and magnetic model of the subsurface corresponding to the position indicated in Figure 7. Letter A indicates the intersections with profile A-A'. See Table 1 for a description of the parameters used in the models.

models of the distribution of the various lithologic units (Figures 8, 9, and 10) are similar to the previously prepared cross-sections (Sloan, 1989; Smith, 1990) derived from the surface geology of the region (Figure 3). The geophysical data provide additional information on the thickness of basin fill north of the city of Colima and on the possible depth of faulting and thicknesses of the various lithologic units. One result of this study is the lack of evidence from either the geophysical or the geological data for extension in the area south of the city of Colima. This is a somewhat surprising result in view of the location of the survey area in what has previously been inferred to be an actively extending boundary of the Jalisco block in the continental region closest to the approaching East Pacific Rise. (e.g. DeMets *et al.*, 1989; Luhr *et al.*, 1985; Allan, 1986; Harrison and Johnson, 1988)

There appears to be a well-developed extensional basin north of the city of Colima which must have existed prior to the explosive eruption of Nevado de Colima 4000 year ago because it confines the avalanche deposits from that eruption. Neither the avalanche deposits nor the younger basin sediments appear to have been disturbed by faulting. River terraces exposed on either side of Río Ameria along the western boundary of the basin are not offset and, similarly, there is no apparent offset of avalanche deposits across Río El Naranjo both of which have been suggested to be fault boundaries of the graben. It is possible that the rate of sedimentation in this area is sufficiently high to mask some evidence of recent faulting, but the geologic data indicates that, if any extension has occurred across the basin during the past 4000 years, it is minor (i.e. significantly less than 1 mm/yr).

South of the city of Colima, there is no evidence to suggest that extension has occurred at any time during the late Cenozoic.The area of the southern gravity low does not correspond to an area of alluvial fill, such as might be expected in an extensional setting, but rather to an area of high topography where thick evaporite deposits associated with early Cretaceous folding and thrusting appear to be the low density source of the gravity anomaly. We cannot preclude the possibility that extension may have reactivated some pre-existing structures, but an examination of those structures did not reveal any evidence of neotectonic activity. Thus, we must conclude that any extensional activity in this area is minor so that it has essentially produced no physical record.

We consider several possible explanations for the apparent lack of extension south of Volcan de Colima, including the following: (1) the eastern boundary of the Jalisco block is not a neotectonic feature; (2) rifting associated with the Jalisco block originates in the north and has propagated south to Volcán de Colima, but not beyond the city of Colima; (3) localized extension in the vicinity of some of the volcanoes is due to magmatic stresses that vary in intensity with time; (4) transform faulting in the vicinity of Volcán de Colima offset the extensional displacements away from the study area; and (5) some

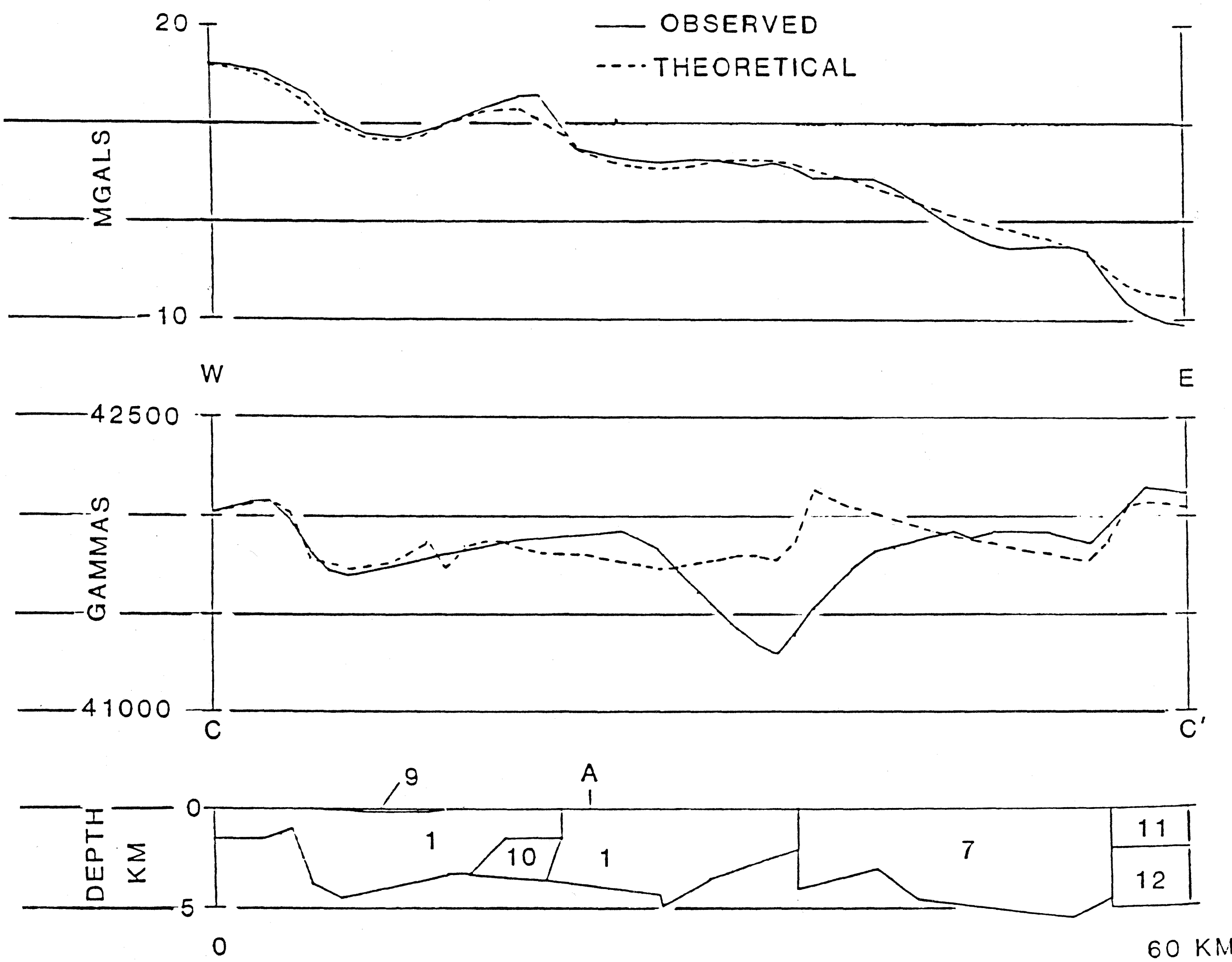


Fig. 10. Profile C-C': preliminary gravity and magnetic model of the subsurface corresponding to the position indicated in Figure 7. Letter A indicates the intersection with profile A-A'. See Table 1 for a description of the parameters used in the models.

combination of the above factors. None of the possible explanations can be dismissed on the basis of evidence in our field area, but the first appears unlikely in view of the evidence for active extension north of Volcán de Colima where playa lakes occupy a narrow low region bounded by steep mountains on either side. Allan (1985) has indicated the presence of up to 4 km of basin sediments in that area.

Luhr and others (1985) previously suggested that the eastern boundary of the Jalisco block could be a southward propagating rift, because of the southward younging of the volcanic centers in the Colima volcanic complex. The mechanism for the rift propagation and its relationship to the tectonic events offshore from the Jalisco block are unclear. That mechanism could provide a possible explanation for the apparent limited rifting between Volcán de Colima and the city of Colima, as well as the apparent lack of rifting south of the city.

The third possible explanation is that inflation of the crust above a rising magma body, possibly combined with the presence of a linear zone of weakness related to the earlier strike-slip faulting in the Colima graben area (Smith, 1990), could be the cause of much of the extension along both continental boundaries of the Jalisco block. This mechanism is particularly attractive because it would also provide an explanation for the extension in the Tepic-Zacoalco graben and for the apparent southward migration of volcanism along the Colima graben trend. This possible mechanism is not inconsistent with the previous interpretation of a propagating rift and is a commonly cited explanation for early rifting during the breakup of a continental

Table 1

Listing of densities and magnetic susceptibilities assumed for the subsurface models (Figures 8, 9 and 10).

| Body no. | Density contrast g/cc | Susceptibility (cgs) | Assumed rock type |
|---|---|---|---|
| 1 | 0.03 | 0.0012 | Ls & vol |
| 2 | -0.03 | 0.002 | avalanche |
| 3 | -0.10 | 0.001 | alluvium |
| 4 | -0.10 | 0.000 | alluvium |
| 5 | -0.27 | 0.000 | evaporites |
| 6 | -0.12 | 0.000 | alluvium |
| 7 | 0.03 | 0.004 | igneous rx |
| 8 | -0.50 | 0.000 | terrain adj |
| 9 | -0.25 | 0.0052 | alluvium |
| 10 | 0.15 | 0.0012 | igneous |
| 11 | -0.015 | 0.0072 | igneous |
| 12 | -0.02 | 0.0092 | igneous |
| 13 | -0.17 | -0.003 | igneous |
| 14 | -0.01 | -0.0035 | limestone |
| 15 | -0.15 | 0.007 | igneous |
| 16 | 0.001 | 0.008 | igneous |

landmass (Dewey and Burke, 1973). Because magmatic activity has been occurring along the Trans-Mexican Volcanic belt since well before the approach of the East Pacific Rise, the mechanism does not need to be related to that event, but the coincidence in timing of the extensional activity with the ridge-approach would suggest that there is a possible association.

The fourth explanation (a transform offset of extension away from the study area) is attractive in view of the geophysical data presented here and more regional geophysical studies (de la Fuente and Aiken, in press; Skidmore, 1988), that indicate there are several approximately east-trending features in the Jalisco block. One such feature in our data is the gravity gradient and saddle that separates the two large gravity lows. That gradient correlates with the southern boundary of the avalanche deposits and associated basin deposits south of Volcán de Colima and continues westward across the study area. The geologic structure associated with that gradient is not exposed in our area nor has the geophysical trend been associated with any feature mapped in adjacent regions. Thus its continuation as a transfer structure is speculative at this time. However, we suggest that it could connect to some feature offshore, such as the Barra de Navidad fault zone (Bourgois *et al.*, 1988) to transfer the extension to that region.

At this time we cannot distinguish between the possible explanations for the lack of extension in our study area. The last two hypotheses are somewhat more attractive to us because they can be tested with additional geological and geophysical studies. Geologic mapping in the interior of the Jalisco block, particularly along the east-trending geophysical anomalies, should indicate whether there has been recent activity on those features. Similarly, deep seismic reflection and refraction studies should provide new information on the distribution of magma within the crust and its relationship to the areas of extension. Thus, continued study of the Jalisco block should provide new and important information on this enigmatic area.

## ACKNOWLEDGEMENTS

The authors wish to thank Ricardo Padilla y Sánchez, Jorge Nieto Obregón, Guillermo Castellanos, Héctor López and Gustavo Calderón for their assistance and advice in establishing this project. Special thanks are due to Gabriela Mora Alvarez, Francisco Orozco Pérez, Steve Byrnes, Mary Beitia, Mahony, and Sandra for their assistance in the data collection. Listings and/or computer disks of the geophysical data presented in this paper can be obtained at no charge from L. Serpa. Acknowledgement is made to the Donors of The Petroleum Research Fund, administered by the American Chemical Society, for the partial support of this research. Additional support was provided by the University of New Orleans, Department of Geology and Geophysics, and a Penrose Grant to Cassandra Katz.

## BIBLIOGRAPHY

ALLAN, J. F., 1984. Geological studies in the Colima graben, SW Mexico: unpubl. Ph.D. Dissertation, Univ. of Calif., Berkeley,136 p.

ALLAN, J. F., 1985. Sediment depth in the northern Colima graben from 3-D interpretation of gravity: *Geofís. Int., 24,* 21-30.

ALLAN, J. F., 1986. Geology of the northern Colima and Zacoalco grabens, southwest Mexico: Late Cenozoic rifting in the Mexican Volcanic Belt: *Geol. Soc. Am. Bull., 97,* 473-485.

ALLAN, J. F. and I. S. E. CARMICHAEL, 1984. Lamprophyric lavas in the Colima graben, SW Mexico: *Contrib. Mineral. Petrology, 88,* 203-216.

ALVA VALDIVIA, L. M., J. URRUTIA-FUCUGAUCHI, H. BÖHNEL, and D. J. MORAN ZENTENO, 1990. Aeromagnetic anomalies and paleomagnetism in Jalisco and Michoacan, southern Mexico continental margin: *Tectonophysics,* 192, 169-190.

ATWATER, T., 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: *Geol. Soc. Am. Bull., 81,* 3513-3536.

BECK, M.E. and others, 1981. Northward translation of Mesozoic batholiths, western North America: Paleomagnetic evidence and tectonic, significance: *Geofís. Int., 20,* 143-162.

BOURGOIS, J., V. RENARD, J. AUBOUIN, W. BANDY, E. BARRIER, T. CALMUS, J-C CARFANTAN, J. GUERRERO, J. MAMMERICKX, B. DeLEPINAY, F. MICHOUD, and M. SASSON, 1988. Fragmentation en cours du bord ouest du continent Nord-Américain: Les frontières sous-marines du bloc Jalisco (Mexique) *C.R. Acad. Paris, 307,* p 1121-1130.

CAMPA, M. F. and P. J. CONEY, 1983. Tectono-stratigraphic terranes and mineral resource distributions in Mexico: *Can. J. Earth Sci.,* 26, 1040-1051.

CARMICHAEL, I. S. E. and D. J. De PAOLO, 1980. Nd and Sr isotopes in the lavas of Colima, Mexico: Geol. Soc. Am. Abstr. with Programs, 12, 398.

CARMICHAEL, I. S. E. and J. F. LUHR, 1985. Minettes and related lavas near Mascota, Jalisco, Mexico: Geol. Soc. Am. Abstr. with Programs, 17, 539.

CLARK, K. F., C. T. FOSTER and P. E. DAMON, 1982. Cenozoic mineral deposits and subduction-related magmatic arcs in Mexico: *Geol. Soc. Am. Bull., 93,* 533-544.

COUCH, R. and S. WOODCOCK, 1981. Gravity and structure of the continental margins of southwest Mexico and Guatemala: *J. Geoph. Res., 86,* 1829-1840.

DAMON P. E., J. NIETO and L. A. DELGADO, 1979. Un plegamiento Neogénico en Nayarit y Jalisco y evolución geomórfica del Río Grande de Santiago; Asoc. Ing. Minas Metal. y Geól. México, Mem. Tec. XIII, 156-191.

DAMON, P. E., M. SHAFIQULLAH and K. F. CLARK 1981. Age trends of igneous activity in relation to metallogenesis in the southern Cordillera: *Arizona Geol. Soc. Digest, 14,* 137-153.

DeMETS, C. and S. STEIN, 1990. Present-day kinematics of the Rivera plate and implications for tectonics in southwestern Mexico: *J. Geophys. Res*, in press.

De REMER, L.A. and S. A. NELSON, 1985. The geologic and chemical evolution of Volcan Teptiltic, Nayarit, Mexico: Geol. Soc. Am. Abstr. with Programs, 17, 561.

DEWEY, J. F. and K. BURKE, 1974. Hot spots and continental breakup: some implications for collisional orogeny: *Geology;* 2, 57-60.

EISSLER, H. K., and K. C. McNALLY, 1984. Seismicity and tectonics of the Rivera plate and implications for the 1932 Jalisco, Mexico, earthquake: *J. Geophys. Res., 89,* 4520-4530.

GASTIL, G., 1983. Mesozoic and Cenozoic granitic rocks of southern California and western Mexico: Geol. Soc. Am. Mem. 159, p. 265-275.

GASTIL, G., D. KRUMMENACHER and W. A. JENSKY, 1978. Reconnaissance geology of west-central Nayarit, Mexico: *Geol. Soc. Am. Bull., 90,* 839-857.

GASTIL G., D. KRUMMENACHER and J. MINCH, 1979. The record of Cenozoic volcanism around the Gulf of California: *Geol. Soc. Am. Bull., 90,* 839-857.

GILBERT, C. M., G. A. MAHOOD and I. S. E. CARMICHAEL 1985. Volcanic stratigraphy of the Guadalajara area, Mexico: *Geofís. Int., 24,* 169-191.

GIOSA, T. A. and S. A. NELSON, 1985. Gabbroic xenoliths in alkalinelavas in the region of Sanganguey volcano, Nayarit, Mexico: Geol. Soc. Am. Abstr. with Programs, 17, 593.

GUZMAN, A., 1989. Geología, petrología y geoquímica del campo volcánico de Amatlán de Canas, límites de los Estados de Jalisco y Nayarit: unpubl. thesis, UNAM, Mexico City, 47 p.

GUZMAN, A. and J. NIETO, 1988. Geología y Petrología del área de Amatlán de Canas: GEOS, Boletín Unión Geofísica Mexicana, (Epoca II), Número Extraordinario, Reunión Anual, Colima, p. 59.

HEGRE, J. and S.A. NELSON, 1985. Geology of Volcan Las Navajas, a Pleistocene trachyte/peralkaline rhyolite center in Nayarit, Mexico: Geol. Soc. Am. Abstr. with Programs, 17, 606.

HARRISON C. G. A. and C. A. JOHNSON, 1988. Neotectonics in central Mexico from Landsat data: Final Report, RSMAS, Univ. of Miami, Miami, FLA., USA, 127 p.

ROMERO S. G., J. CERVANTES and C. M. ZARATE, 1983. Las Encinas report on the Las Encinas iron mine southeast of Pihuamo, Jalisco: Asoc. Ings. Minas Metal Geol. Mexico, XV Convencion Nat. excursion # 1, p. 40-129.

LARSON, R. L., 1972. Bathymetry, magnetic anomalies, and plate tectonic history of the mouth of the Gulf of California: *Geol. Soc. Am. Bull., 83,* 3345-3360.

LOPEZ-INFANZON, M. and J.M. GRAJALES NISHIMURA, 1990. Geology, petrography and Potassium-Argon data of Igneous and metamorphic rocks in the Colima-Jalisco basin: upubl. abstr. of talk presented at the Symposium on the Tectonics, Volcanism, and Geophysics of Mexico held at the Univ. of New Orleans, New Orleans, LA, USA.

LUHR, J. F. and I. S. E. CARMICHAEL, 1980. The Colima volcanic complex, I, post caldera andesites from Volcan Colima: *Contrib. Mineral. Petrol. 71,* 343-372.

LUHR, J. F. and I. S. E. CARMICHAEL, 1981, The Colima volcanic complex, Mexico II, Late Quaternary cinder cones: *Contrib.Mineral. Petrol. 76,* 127-147.

LUHR, J. F. and I. S. E. CARMICHAEL, 1982. The Colima volcanic complex, Mexico III, Ash-and scoria-fall deposits from the upper slopes of Volcan Colima: *Contrib. Mineral. Petrol. 80,* 262-275.

LUHR, J. F. and I. S. E. CARMICHAEL, 1985. Contemporaneous eruptions of calc-alkaline and alkaline magmas along the volcanic front of the Mexican Volcanic Belt:*Geofís. Int., 24,* 203-216.

LUHR, J. F., S. A. NELSON, J. F. ALLAN and I. S. E. CARMICHAEL 1985. Active rifting in southwest Mexico: Manifestations of an incipient eastward spreading ridge jump: *Geology, 13,* 54-57.

MAHOOD, G. A., 1980. Geological evolution of a Pleistocene rhyolitic center - Sierra La Primavera, Jalisco, Mexico: *J. Volcanol. Geotherm. Res., 8,* 199-230.

MAHOOD, G. A., 1981. Chemical evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Jalisco, Mexico: *Contrib. Mineral, Petrol., 77,* 129-141.

MAHOOD, G. A., C.M. GILBERT and I.S.E. CARMICHAEL, 1985. Peralkaline and peraluminous mixed-liquid ignimbrites of the Guadalajara region, Mexico: *J. Volcanol. Geotherm. Res., 25,* 259-271.

MAMMERICKX J. and K. D. KLITGORD, 1982. Northern East Pacific Rise: evolution from 25 m.y.b.p. to the present: *J. Geophys. Res., 87,* 6751-6759.

MEDINA, M., 1985. On the volcanic activity and large earthquakes in Colima area, Mexico: *Geofís. Int., 24-4,* 701-708.

MICHOUD F., E. BARRIER, J. R. GEYSSANT and J. BOURGOIS, 1987. Una serie de plataforma Mesozoica (Tithonian-Cretacio Superior) en el Estado de Colima, oeste de Mexico, *Actas Fac. Ciencias Tierra, U.A.N.L. Linares, 2,* 63-65.

MICHOUD, F., J. BOURGOIS, E. BARRIER, and E. FOURCADE, 1989. La série Crétacée de Tecoman (Etat de Colima): conséquences sur les rapports structuraux entre zones internes et zones externes de l'édifice montagneux mexicain; *C.R.Acad. Sci. Paris, 309,* 587-593.

MOLNAR, P., 1973. Fault-plane solutions of earthquakes and direction of motion in the Gulf of California and on the Rivera fracture zone: *Geol. Soc. Am. Bull., 84,* 1651-1658.

NELSON, S. A., 1980. Geology and petrology of Volcan Ceboruco, Nayarit, Mexico: *Geol. Soc. Am. Bull., 84,* 1651-1658.

NELSON, S.A., 1986. Geología del Volcán Ceboruco, Nayarit, México con una estimación de riesgos de erupciones futuras: *Rev. Inst. Geol. Univ. Nac. Aut. Méx., 6,* 243-258.

NELSON, S.A. and I. S. E. CARMICHAEL, 1984. Pleistocene to Recent alkalic volcanism in the region of Sanganguey Volcano, Nayarit, Mexico: *Contrib. Mineral Petrol., 85,* 321-335.

NELSON, S. A. and R. A. LIVIERES, 1986. Contemporaneous calc-alkaline and alkaline volcanism at Sanganguey volcano, Nayarit, Mexico: *Geol. Soc. Am. Bull., 97,* 798-808.

NELSON, S. A. and G. SANCHEZ-RUBIO, 1986. Trans Mexican volcanic belt field guide; Vol. Geol. Assoc. of Can. and Instituto de Geología, UNAM, 108 p.

NESS, G. E., M. W. LYLE and A. T. LONSETH, 1985. Revised Pacific, North America, Rivera and Cocos relative motion poles: implications for strike-slip motion along the Trans-Mexican Volcanic Belt: *EOS, Trans. AGU, 66,* 849-850.

NIETO, J., 1987. Tectonic synthesis and seismic risk along the Rio Grande de Santiago fault in Jalisco, Mexico: in II Simposio Binacional de Mecánica de Rocas. Rdvsfod Unidos-Mexico:"La Mecánica de Rocas y el Fenómeno Sísmico", 28th U.S. Symposium on Rock Mechanics, Tucson, Arizona.

NIETO, J., L. DELGADO and P. E. DAMON, 1985. Geochronologic, petrologic, and structural data related to large morphologic features between the Sierra Madre Occidental and the Mexican Volcanic Belt:*Geofís. Int., 24,* 623-663.

NIETO, J. and A. GUZMAN, 1988. Morfoestructura y geoquímica de las rocas volcánicas de la depresión tectónica de Ameca en Nayarit y Jalisco: GEOS, Boletín de la Unión Geofísica Mexicana (Epoca II), Número Extraordinario, Reunión Anual, Colima, p. 4.

NIETO, J., J. URRUTIA-FUCUGAUCHI, E. CABRAL-CANO and A. GUZMAN, 1989. Evidence of a listric component in the Ameca River fault, implications of motion on the Jalisco block, Mexico: Geol. Soc. Am. Abst. with Programs, 21, A92.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted oceanic lithosphere: *Geol. Soc. Am. Bull., 93,* 514-523.

PANTOJA-ALOR, J. and S. E. BARRAZA, 1986. Estratigrafía de los Alrededores de la mina del Encino, Jalisco: *Bol. Soc. Geol. Mexicana, XLVII,* 1-15.

ROBIN, C., R. MOSSAND, G. CAMUS, J. M. CANTAGREL A. GOURGAUD and P. M. VINCENT, 1987. Eruptive history of the Colima Volcanic Complex (Mexico): *J. Volcanol. Geotherm. Res., 31,* 99-113.

SALAZAR, S. M., 1983. Estratigrafía y tectónica del área Manzanillo-Colima-Las Encinas, en el Estado de Colima: Asoc. Ings. Minas Metal. Geol. México, XV Convención Nat.excursiones #1, p. 4-12.

SERPA, L., 1990. Geophysical and geological studies of the Jalisco block, west-central Mexico, presented at the Segunda Reunión Nacional Volcán de Colima, February, 1990, Colima, Colima, México.

SERPA, L. and K. L. COOK, 1984. An application of simultaneous inversion modeling of gravity and aeromagnetic data to a geothermal study in Utah: *Geophysics, 49,* 1327-1338.

SERPA, L., C. KATZ, and C. SKIDMORE, 1989a. Potential field studies south of Volcán de Colima, Segunda Reunión Nacional Volcán de Colima.

SERPA, L., C. KATZ and C. SKIDMORE, 1989b. The southeastern boundary of the Jalisco block in west-central Mexico; abstr. EOS, Trans. AGU, 70, 1319.

SKIDMORE, C. M., 1988. A geophysical and tectonic study of thesouthern Colima graben, Mexico: unpubl. M.S. Thesis, Univ. of New Orleans, New Orleans, LA., USA, 89 p.

SKIDMORE C. M., C. C. KATZ, R. F. SLOAN and L. F. SERPA, 1988. A geophysical and tectonic study of the Colima Graben, Mexico, Geol. Soc. Am. Abst. with Prog. 20, 232.

SKIDMORE, C. M. and L. SERPA, 1988. A tectonic and geophysical study of the Colima graben and Rivera triple point, western Mexico; Programa Reunión Anual 1988, Unión Geofísica Mexicana, A.C., p. 2.

SLOAN, R.F., 1989. A geologic and tectonic study of the southern Colima graben, Colima, Mexico: unpubl. M.S. Thesis, Univ. New Orleans, New Orleans, LA, USA, 70 p.

SLOAN, R. F., T. L. PAVLIS, C. C. KATZ and C. M. SKIDMORE, 1988. A geologic and tectonic study of the southern Colima graben, Colima, Mexico; Geol. Soc. Am. Abst. with Prog., 20, 233.

SMITH, S. A., 1990. A geologic reconnaissance study of a middle Cretaceous marine volcanic arc: the stratigraphic evolution and subsequent strike-slip fragmentation of the Colima Basin; unpubl. M.S. Thesis, Univ. of New Orleans, 107 p.

SMITH, S. A., R. F. SLOAN, T. L. PAVLIS and L. F. SERPA, 1989a. Reconnaissance study of Cretaceous rocks in central Colima, Mexico: A volcanic arc deformed by right-lateral transpression; abstr. Unión Geofísica Mexicana Fall 1989 meeting.

SMITH, S. A., R. F. SLOAN, T. L. PAVLIS and L. F. SERPA, 1989b. Reconnaissance study of Cretaceous rocks in central Colima, Mexico: A volcanic arc deformed by right-lateral transpression; abstr. EOS, Trans. AGU, 70, 1313.

SYLVESTER, A. G., 1988. Strike slip tectonics: *Geol. Soc. Am. Bull., 100,* 1066-1073.

WADGE, C. and K. BURKE, 1983. Neogene Caribbean plate rotation and associated central American tectonic evolution: *Tectonics, 2,* 633-643.

WALLACE, P. and I. S. E. CARMICHAEL, 1990. Pliocene-Recent volcanism in the Jalisco Block near Los Volcanes, Mexico; unpubl. abstr. of talk presented at the Symposium on the Tectonics, Volcanism, and Geophysics of Mexico held at the Univ. of New Orleans, New Orleans, LA, USA.

WILCOX, R. E., T. P. HARDING and D. R. SEELY, 1973. Basic wrench tectonics: *Am. Assoc. Petr. Geol. Bull., 57,* 74-96.

WOODCOCK, N. H. and M. Fischer, 1986. Strike slip duplexes: *J. Struct. Geol., 8,* 725-735.

ZIMMERMAN, J. L., J. M. STUSSI, E. GONZALEZ-PARTIDA and M. ARNOLD, 1988. K/Ar evidence for age and compositional zoning in the Puerto Vallarta-Rio Santiago batholith (Jalisco-Mexico): J. South. *Am. Earth. Sci., 1,* 260-274.

---

Laura Serpa, Stacy Smith, Cassandra Katz, Charles Skidmore, Robert Sloan and Terry Pavlis
*Department of Geology and Geophysics*
*University of New Orleans*
*New Orleans, LA 70148, U. S. A.*