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Regional tectonics of western Mexico and its implications for the northern boundary of the Jalisco block

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RESUMEN

El rift Tepic-Zacoalco en el occidente de México se ha considerado como el resultado de un fallamiento dextral y normal de edad Plio-Cuaternaria, producido a lo largo de la frontera norte del bloque de Jalisco debido a un proceso de riftogénesis que lo separa de la placa de Norteamérica. Estudios geológicos y estructurales de campo llevados a cabo en Nayarit y en Jalisco revelan que dicha frontera es más amplia de lo que se había considerado con anterioridad y que desde el Mioceno Tardío no ha habido deformación transcurrente a lo largo de ésta.

La estructura en la frontera consiste de un sistema de semifosas y fosas tectónicas que se formaron en tiempos diferentes después de una fase transpresiva de edad Mioceno Medio. Parte de estas estructuras se formaron durante la separación de la Península de Baja California de la parte continental de México en el Mioceneo Tardío- Plioceno Temprano. La tectónica extensional del Plioceno Tardío y Cuaternario está concentrada en la parte sur de la frontera y, de acuerdo con datos microtectónicos, está caracterizada por un patrón del esfuerzo mínimo alineado NNE-SSW. Estos datos, combinados con la dirección de la extensión en el graben de Colima, indican un posible desplazamiento del bloque Jalisco hacia la trinchera. Nuestros resultados, en conjunto con estudios sísmicos y de movimientos de placas, hacen dudar de los modelos que hipotetizan un proceso de riftogénesis activo para el Plio-Cuaternario del bloque Jalisco. Sugerimos en cambio que la tectónica extensional a lo largo de las fronteras norte del bloque de Jalisco desde el Plioceno Tardío al Cuaternario podría ser un rasgo pasivo inducido por el movimiento diferencial de la placa Rivera con respecto a las placas adyacentes (placas de Cocos y Pacífico).

PALABRAS CLAVE: Tectónica, oeste de México, rift Tepic-Zacoalco, bloque de Jalisco, riftogénesis pasiva.

ABSTRACT

The Tepic-Zacoalco rift of western Mexico had been considered the result of right-lateral and normal faulting of Plio-Quaternary age produced along the northern boundary of the Jalisco Block by its rifting away from the North America plate. Geologic and structural field studies in the States of Nayarit and Jalisco revealed that the boundary is wider than previously reported and that since late Miocene no major strike-slip deformation has been occurring along it.

The structure of the boundary consists of a system of half-grabens and grabens which formed at different times after a transpressional phase of middle Miocene age. Part of these structures formed in connection with the separation of Baja California from mainland Mexico in late Miocene-early Pliocene. The late Pliocene and Quaternary extensional tectonics is mainly concentrated in the southern part of the boundary and according to microtectonic data is characterized by an average NNE-SSW trending minimum stress axis. These data, combined with the direction of extension in the Colima graben, indicate a possible trenchward displacement of the Jalisco Block. Our results, together with seismological and plate motion studies raise doubts about the models which hypothesise a Plio-Quaternary active rifting of the Jalisco Block. We suggest instead that the late Pliocene to Quaternary extensional tectonics along the Jalisco Block boundaries could be a passive feature induced by the differential motion of the Rivera plate with respect to the adjacent Cocos and Pacific plates.

KEY WORDS: Tectonics, western Mexico, Tepic-Zacoalco rift, Jalisco block, passive rifting.

INTRODUCTION

Western Mexico displays a peculiar type of volcanism and a complex tectonic evolution which reflects the geodynamic setting of the region. The young oceanic crust of the Rivera Plate has been subducting beneath the North America plate with an absolute motion independent from the adjacent Cocos and Pacific plates at least from the Pliocene (DeMets and Stein, 1991; Stock, 1993) (Figure 1). The continental tectonics of western Mexico is dominated by three extensional fault systems with a broad N-S, E-W and NW-SE orientation which form a triple junction some 50 km south-southwest of Guadalajara (Demant, 1981) (Figure 1). They roughly define three elongated depressions which have been called Colima, Chapala and Tepic-Zacoalco rifts (Luhr *et al.*, 1985). The finding of unusual varieties of alkaline lavas of Plio-Quaternary age in this region led to hypothesise the existence of active rifting that might cause the separation of a microplate, the Jalisco Block (JB), from the North America plate along the Colima and Tepic-Zacoalco rifts (Luhr *et al.*, 1985; Allan *et al.*, 1991; Wallace *et al.*, 1992). This model implicitly assumes that subduction of the Rivera plate has stopped. It predicts that the JB will

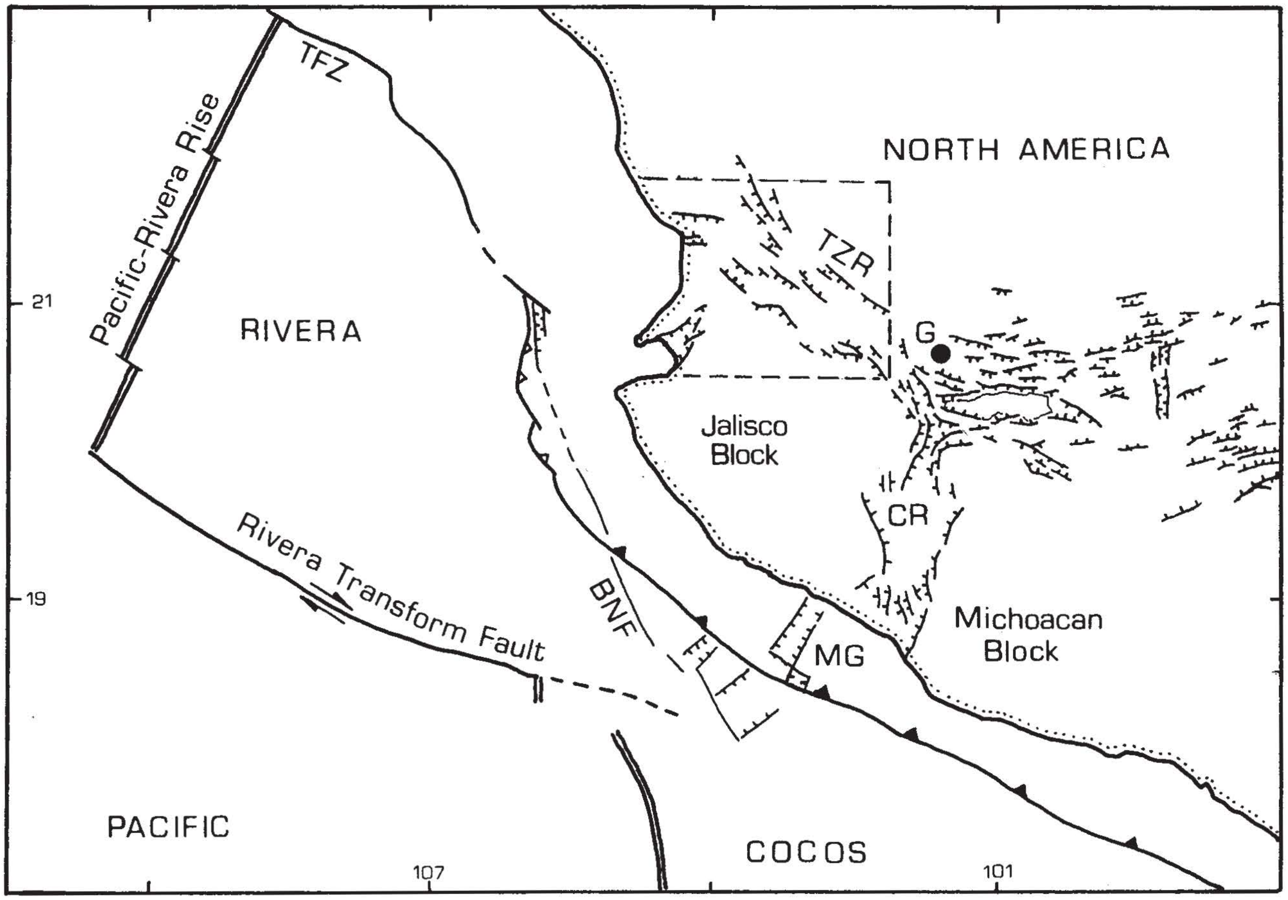

Fig. 1. Geodynamic framework of western Mexico. The four main plates are indicated in capitol letters. Double line shows the oceanic ridge. TFZ = Tamayo fracture zone; BNF = Barra de Navidad fault (Bourgois and Michaud, 1991); MG = Manzanillo graben; TZR = Tepic-Zacoalco rift; CR = Colima graben; G = Guadalajara. Dashed line indicate the study area. Marine geology based on DeMets and Stein (1990). Late Miocene to recent continental faults based on this work and our unpublished studies.

be accreted to the Pacific plate. Marine geophysical investigations have supported this conclusion (Bourgois *et al.*, 1988; Bourgois and Michaud, 1991), although would accretion of the JB occur to the north of the Tamayo fracture zone and the Barra de Navidad fault (Figure 1). In both cases, the motion of the JB would be westward or northwestward with pure normal faulting in the Colima rift and with a combination of normal and right-lateral faulting in the Tepic-Zacoalco rift (Allan *et al.*, 1991; Bourgois and Michaud, 1991).

An alternative interpretation proposes that the Colima rift is a passive feature produced (a) by east-southeastward displacement of the southern Mexico continental blocks (Michoacán and other blocks, Figure 1) induced by the oblique subduction of the Cocos plate (DeMets and Stein, 1990), or (b) in response to tensional stresses induced in the overriding plate by the subduction of the Rivera-Cocos plate boundary (Barrier *et al.*, 1990; Bandy and Hilde, 1992). Seismological studies (Eissler and McNally, 1984; Singh *et al.*, 1985) and model of current plate motion (DeMets and Stein, 1990) suggest that the subduction is still active for a considerable length of the Rivera subduction zone.

Recent field studies of continental tectonics indicates that, in the triple junction area, the three rifts developed at different times since the late Miocene (Barrier *et al.*, 1990; Michaud *et al.*, 1991, 1992). The E-W Chapala rift formed first between late Miocene and early Pliocene (Delgado, 1992), whereas the extension seems to be presently active 20 km to the south, in the Citala graben (Garduño and Tibaldi, 1991). The extension in the northern part of the Colima rift started in early Pliocene (Allan, 1986) and, according to local seismological recordings, seems to be active today (Suárez *et al.*, 1991). Anyway, no extensional tectonics seems to have occurred in late Tertiary and Quaternary south of Colima volcano (Serpa *et al.*,1992). The Tepic-Zacoalco rift has been considered a broad graben or rift (Demant, 1981; Luhr *et al.*, 1985), or a combination of extensional and right-lateral strike-slip structures (Barrier *et al.*, 1990; Allan *et al.*, 1991). Microtectonic studies (Quintero and Guerrero, 1992) reported a variety of extensional stress regimes all over the area in Plio-Quaternary times.

No comprehensive studies exist on the structure and the kinematics of the northern boundary of the JB. In this paper we present a first analysis of late Miocene to recent tectonic evolution of the boundary, based on regional geologic mapping and a preliminary macro- and mesostructural study of the main fault systems. The principal results are: (1) since late Miocene no major strike-slip deformation has been occurring along the northern boundary of the JB; (2) the boundary is wider than previously reported and consists of various extensional structures related to different geodynamic events; (3) the neotectonic activity is weak and is mainly concentrated in the southern part of the boundary; (4) according to the Quaternary direction of extension the possible displacement of the Jalisco Block is trenchward.

REGIONAL GEOLOGY

The study area covers the western sector of the Plio-Quaternary Mexican Volcanic Belt (MVB) in the States of Nayarit and Jalisco (Figure 1 and 2). In this area the WNW trending main axis of the MVB separates two different domains: the Sierra Madre Occidental (SMO) volcanic arc (McDowell and Keitzer, 1977; McDowell and Clabaugh, 1979) in the northeast, and the JB in the southwest (Figures 1 and 2).

The MVB consists mostly of basaltic cinder cones and shield volcanoes, andesitic to dacitic stratovolcanoes and dacitic to rhyolitic domes. Most of these volcanics yield Plio-Quaternary radiometric ages (Nixon *et al.*, 1987 and references herein; Wallace and Carmichael, 1989; Lange and Carmichael, 1991; Righter and Carmichael, 1992a).

Within the SMO domain, pre-Tertiary argillites and limestones are intruded by granite plutons of late Oligocene age (Gastil *et al.*, 1979a; Soto and Ortega, 1982). These rocks are locally exposed in scattered outcrops along the lower part of the Río Grande de Santiago canyon. The greater part of the area, however, is covered by andesites and ignimbrites belonging to the SMO volcanic sequence which is at least 1, 000 m thick along the Río Grande de Santiago (Figure 2). North of the studied area, the ages of this volcanic province are grouped within 38-35 Ma, 31-26 Ma and around 23 Ma (see review in Montigny *et al.*, 1987; Demant *et al.*, 1989). In the study region, the SMO ignimbrites cover a younger time span ranging between 35 Ma and 19 Ma east of Tepic (Figure 2) (Damon *et al.*, 1979; Soto and Ortega, 1982), and between 24 and 17 Ma in the Presa de Santa Rosa area (Figure 2) (Nieto *et al.*, 1985, Quintero *et al.*, 1992). In the area north of Tepic and north of Guadalajara the SMO ignimbrites are covered by basalts and subordinate ignimbrites of late Miocene age (Watkins *et al.*, 1971; Gastil *et al.*, 1979a; Nieto *et al.* 1985; Moore and Carmichael, 1991). A rhyolitic and ignimbritc sequence also cover the SMO ignimbrites south of the Río Grande de Santiago between Santa Maria del Oro and Plan de Barranca (Figure 2). Field stratigraphic relationships suggest a late Miocene age for these rocks.

The basement of the JB is consists of pre-Tertiary rhyolitic ash-flow tuff and andesites, volcanoclastic deposits and turbiditic sequences resting on granitoid plutons. Early Tertiary andesites and dioritic dikes are locally exposed in the northern part of the JB (Gastil *et al.*, 1979a; Lange and Carmichael, 1991) whereas late Miocene basalts are emplaced along the Pacific coast north of Punta Mita (Figure 2) (Gastil *et al.*, 1979a and b). Basaltic and lamprophiric lavas of Plio-Quaternary age unconformably cover the basement of the JB in the San Sebastián and Mascota areas and along the Río Atenguillo valley (Figure 2) (Wallace and Carmichael, 1989; Lange and Carmichael, 1990; Righter and Carmichael, 1992a). These volcanics are regarded as the potassic volcanic front of the western MVB (Lange and Carmichael, 1991).

Dating of the ignimbrites exposed in the JB yield a K-Ar age of 114 Ma (Gastil *et al.*, 1979a) and a $^{39/40}$Ar age of 80 Ma (Wallace and Carmichael, 1989) whereas the age of emplacement of the granitoids range between 106 Ma and 85 Ma (Zimmermann *et al.*, 1988; Köhler *et al.*, 1988). This suggests that all these rocks are part of the same late Cretaceous magmatic arc which had been recognized southeastward along the Guerrero terrane (Campa and Coney, 1983; Monod *et al.*, 1993) and do not belong to the SMO volcanic arc.

STRUCTURE, KINEMATICS AND TIME OF FAULTING

Introduction

In the study area, pre-late Miocene rocks are affected by strike-slip and compressional deformation at various scales. Large folds involving SMO ignimbrites are exposed 15 km east of Santa María del Oro (Figure 2); their en-echelon arrangement suggests a possible origin by left-lateral transpression along 130°-140° striking basement faults. The age of deformation is limited to the middle Miocene since the folds involve ignimbritic units dated 19 Ma which are cut by 12-10 Ma old basic dikes which are not folded (Damon *et al.*, 1979). Many left-lateral reverse faults were observed southeastward along the Plan de Barrancas highway (Figure 2), left-lateral strike-slip faults are present further south-east along the Río Santiago and at the Santa Rosa dam (Figure 2). A mesostructural study of this deformation phase is in progress in order to understand its kinematics.

In the area comprised between the Río Grande de Santiago valley to the north and the Río Ameca valley to the south (Figure 2), the compressional and strike-slip structures are cut by normal fault systems. This broad area includes the Tepic-Zacoalco rift as defined by Allan *et al.* (1991), and the Ameca River Tectonic Depression of Nieto *et al.* (1992). It should be regarded as the complex boundary of the JB. In the following section we describe the extensional systems of this area from north to south. The motion of the main faults was deduced according to the geometry of the structures and by direct

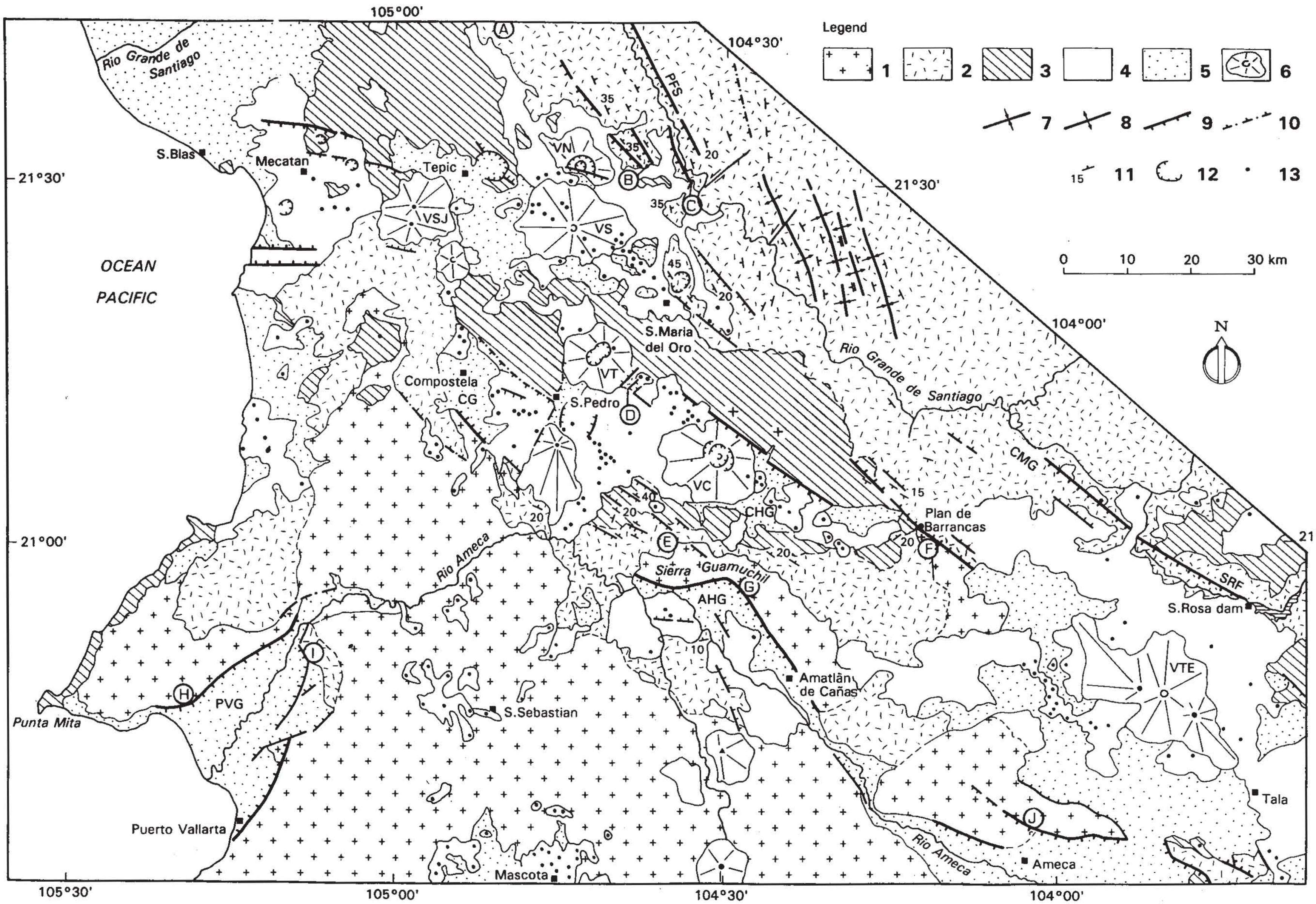

Fig. 2. Geologic and structural map of the northern boundary of the Jalisco Block. 1=Jalisco Block domain (Cretaceous to Eocene); 2=SMO sequence (Oligocene to middle Miocene); 3=Late Miocene basalts (a) and rhyolites (b); 4=Pliocene and Quaternary volcanics of MVB; 5=Quaternary alluvial and coastal deposits; 6=main stratovolcanoes of MVB. 7=sincline fold; 8=anticline fold; 9=normal fault; 10=inferred normal fault; 11=attitude of SMO ignimbrites (number indicates measured inclination); 12=craters and calderas; 13=Quaternary volcanic vents. Geologic limits dashed when inferred. Circled capitol letters refer to the sites of the structural stations presented in Fig. 3 and 4. PFS=Pochotitán fault system; CG=Compostela graben; CHG=Ceboruco half-graben; CMG=Cinco Minas grâben; SRF=Santa Rosa fault; AHG=Amatlán de Canas half-graben; PVG=Puerto Vallarta graben. VSJ=Volcán San Juan; VN=Volcán Las Navajas; VS=Volcán Sanganguey; VT=Volcán Tepetiltic; VC=Volcán Ceboruco; VTE=Volcán Tequila.

observation of fault slip. When feasible, these data were used to determine the paleo-stress field.

Pochotitán fault system

Allan *et al.* (1991) named Pochotitán fault system (PFS) a group of NNW-SSE lineaments running approximately along the Río Grande de Santiago. In the field, the PFS consists of a system of listric normal faults which sharply displaces the SMO sequences downward about 20 km east of Tepic. Most of the faults are concentrated in a 10-km-wide belt between volcán Las Navajas and the Río Grande de Santiago; the master fault is located east of the river. In this area the SMO ignimbrites outcrop in faulted blocks, tilted up to 35° towards NE in a domino-like structure. Individual faults strike 140°-155° and dip toward the SW with a dominant dip-slip motion. The total vertical displacement is estimated at over 1, 000 m. Microtectonic measurements in the SMO ignimbrites along the PFS indicate a minimum extensional stress ($\sigma3$) oriented 65°-85° (Figure 3 A, B1 and C). A second phase of extension with a NE-SW direction of extension has also been observed (Figure 3 B2). A normal fault parallel to the PFS (but with much less displacement) cut the Tepic caldera (Figure 2), which we consider of late Miocene age on a stratigraphical basis. The PFS ends to the south at the latitude of Sanganguey volcano.

Geologic evidence constrains the age of normal faulting along the PFS to the late Miocene. A sequence of basaltic flows which rests unconformably over the SMO tilted block gave ages of 11.2 and 9.9 Ma north of Tepic and 8.7 and 4.3 Ma north-east of Sanganguey volcano (Gastil *et al.*, 1979b; Soto and Ortega, 1982). In addition many basic dikes dated 11.7 to 10.9 Ma (Damon *et al.*, 1979; Soto and Ortega, 1982) cut the SMO units east of Río Grande de Santiago; they strike parallel to the PFS and are thought to be contemporaneous with the onset of this phase of extension. Furtheremore the PFS displays a geometry and a direction of extension very similar to other extensional fault systems of late Miocene age which border the Pacific coast north of the study area (Henry, 1989).

On the strength of these data we conclude that the Pochochitán fault system represents the southernmost part of the "Gulf Extensional Province" (Gastil *et al.*, 1975) which accompanied the initial opening of the Gulf of California in late Miocene time (Stock and Hodges, 1989).

Santa María del Oro graben

This 8-km-wide graben is cut into the SMO ignimbrites at about 15 km southwest of Sanganguey volcano (Figure 2). It is bordered by two normal faults striking 150° with a minimum of 300 m of vertical offset. Several cinder cones and the vent of Sanganguey volcano mark the prolongation toward the NW of the southern fault of the graben. The graben is filled by Pliocene and Quaternary basaltic flows (Gastil *et al.*, 1979a), which limits its formation to the late Miocene or earliest Pliocene.

Mecatán graben

The 20-km-wide Mecatán graben is located in the coastal area west of Tepic where MVB volcanics are cut by three major normal fault with an E-W orientation (Figure 2). Because of intense alteration, no kinematic indicators have been observed on the fault planes. The faults have a topographic scarp of about 140 m and cut a volcanic plateau dated 3.1 to 3.4 Ma (Righter and Carmichael, 1992b), but they do not affect lava flows from a recent centre 5 km south of Mecatán.

Compostela - Santa Rosa fault system

Between Compostela and the Santa Rosa dam several WNW-ESE striking normal faults are arranged in en-echelon pattern (Figure 2). They define five extensional structures: the Compostela graben, the Ceboruco and the Plan de Barranca half-grabens and the Cinco Minas and Santa Rosa faults.

The Compostela graben is formed by two 125°-130° striking normal faults which border a 10-km-wide depression. The faults cut a rhyolitic complex of probable late Miocene age in the north and the JB basement in the south; they are mostly covered by Plio-Quaternary volcanics of the MVB. The topographical offset is about 300 m, yet the real vertical displacement could be as much as 1, 000 m according to a high-resolution gravity survey (CFE unpublished data on the San Pedro-Ceboruco geothermal prospect). No clear kinematic indicators were detected, but the geometry of the faults suggests that they are mostly dip-slip. The age of faulting is late Miocene or early Pliocene since a rhyolitic dome complex of 2.3 Ma (Gastil *et al.*, 1979b) lies in the western part of the graben and is not affected by these faults. Pliocene rocks are cut by NNE-SSW and NE-SW striking normal faults which downthrow the eastern part of the graben (Figure 2). Striated fault planes with the same orientation cut the NW-SE faults in the adjacent SMO and JB rock units to the north and to the south of the graben; fault slip data inversion gave a NW-SE to WNW-ESE trending $\sigma3$ (Figure 3D and E). Dacitic domes dated 1.4 ± 0.28 Ma and a basaltic shield volcano dated 1.1 ± 0.3 Ma (C.F.E. 1991a) south of San Pedro are unaffected by these faults; this constrains the extensional phase to the Pliocene.

The Ceboruco half-graben (CHG) is formed by two 120° striking listric faults that dip to the SW and tilt about 20° to the NNE the Sierra Guamuchil block. The northernmost fault has a 500 m high scarp cut into a rhyolitic and ignimbritic sequence attributed to middle or late Miocene (Soto, 1991); the other parallel fault is revealed by the alignment of several cinder cones and domes and the vents of Ceboruco and Tepetiltic volcanoes (Figure 2). According to geologic data provided by a geothermal exploration well recently drilled under the southern flank of Ceboruco volcano, the total vertical offset of the CHG faults is at least 800 m. The geomorphic features of the fault scarp rule out a Quaternary age for this faulting. In addition, the CHG is filled by at least

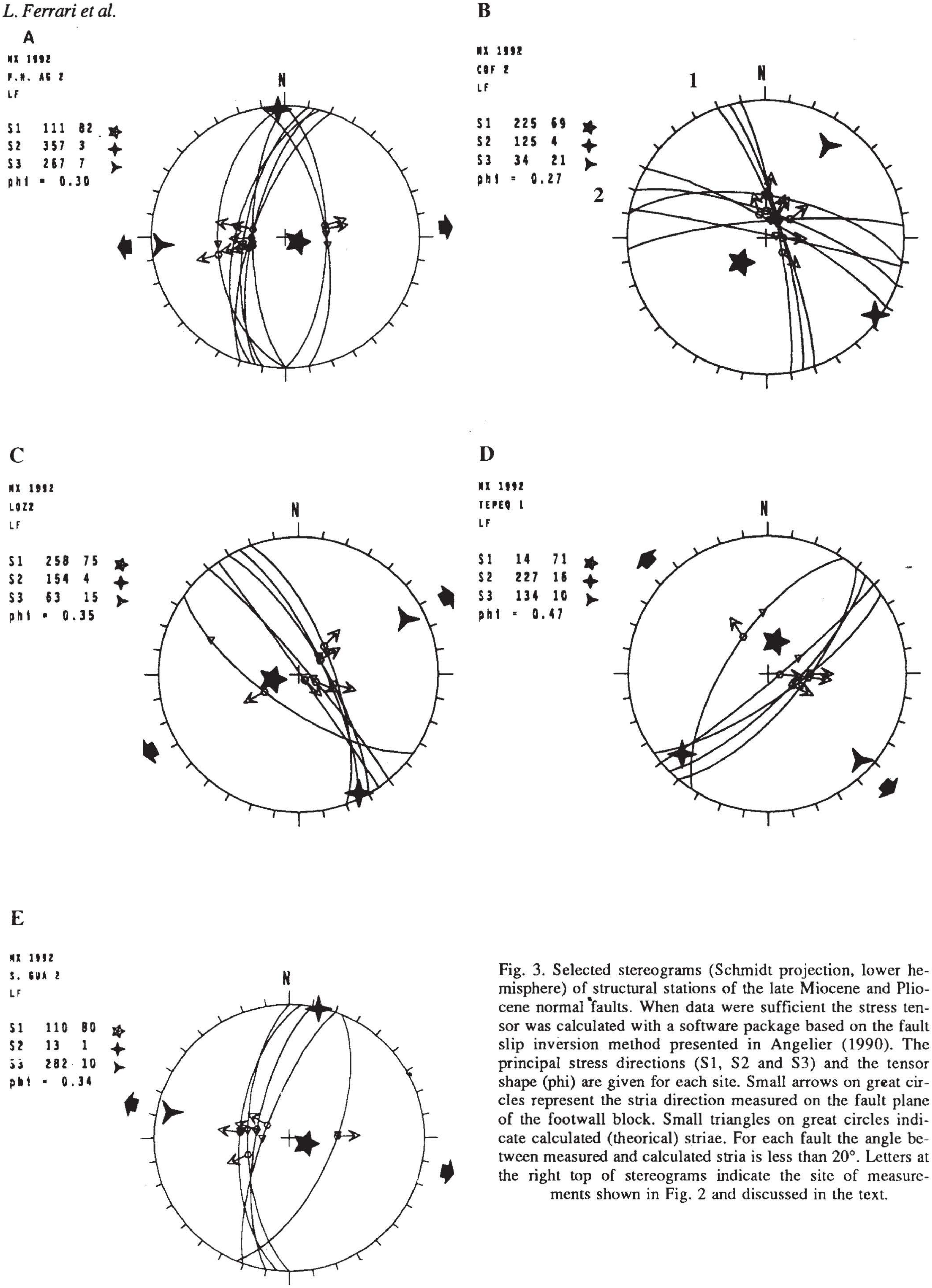

Fig. 3. Selected stereograms (Schmidt projection, lower hemisphere) of structural stations of the late Miocene and Pliocene normal faults. When data were sufficient the stress tensor was calculated with a software package based on the fault slip inversion method presented in Angelier (1990). The principal stress directions (S1, S2 and S3) and the tensor shape (phi) are given for each site. Small arrows on great circles represent the stria direction measured on the fault plane of the footwall block. Small triangles on great circles indicate calculated (theorical) striae. For each fault the angle between measured and calculated stria is less than 20°. Letters at the right top of stereograms indicate the site of measurements shown in Fig. 2 and discussed in the text.

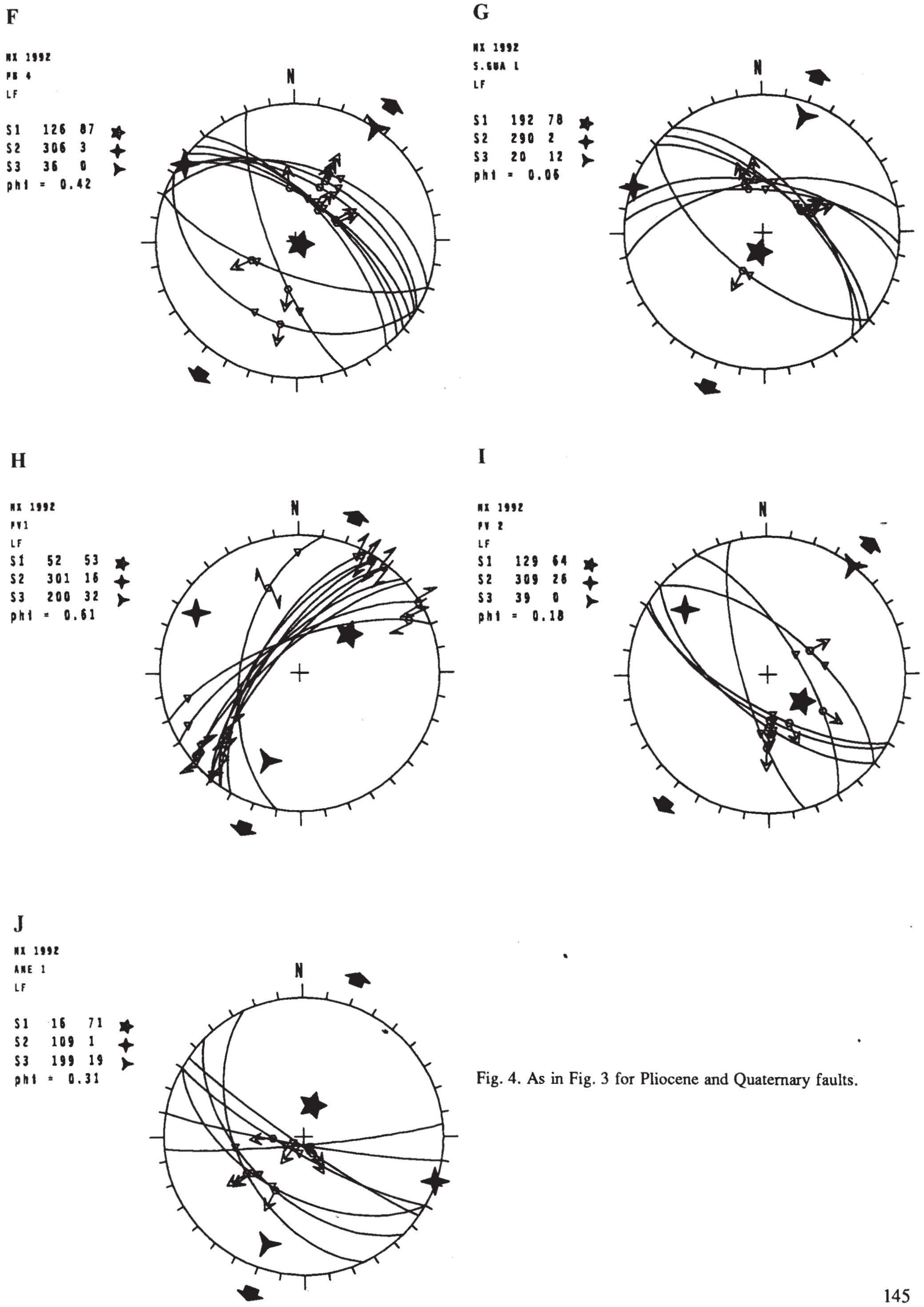

Fig. 4. As in Fig. 3 for Pliocene and Quaternary faults.

250 m of andesites and dacites (CFE unpublished wells data) which correlate with the Pliocene sequence of the San Pedro area. This implies that the formation of the CHG took place in early Pliocene or even earlier.

The Plan de Barrancas half-graben is constituted by several 120° striking and NE dipping listric normal faults distributed between the village of the same name and the Río Grande de Santiago (Figure 2). The main fault has at least 400 m of vertical displacement and cuts the JB basement and the SMO sequence which is tilted 20°-30° to the SSW. Slickensides on the fault planes indicate dominant dip-slip motion produced by a NE-SW trending $\sigma3$ (Figure 4F). West of Plan de Barrancas a rhyolitic and ignimbritic secuence is tilted only 15° and is probably contemporaneous with the faults movement. A younger ignimbrite covers in unconformity the SMO tilted block east of Plan de Barranca and overlies basaltic flows clearly correlated with the ones dated 3.77 Ma (Nieto *et al.*, 1985) in the nearby Cinco Minas area. This implies that these faults were active in early Pliocene or earlier. Along the prolongation of this fault system, toward the southeast, is the prominent alignment of vents of the Tequila volcano and other minor cinder cones. In between, the Plan de Barrancas faults disappear under Pliocene volcanics and Quaternary alluvial sediments of the Magdalena plain.

The 135° striking Cinco Minas graben has been described by Allan *et al.* (1991). According to the stratigraphic relations of the rock units dated by Nieto *et al.* (1985) they concluded that at least 400 m of dip-slip motion occurred along the northeastern fault before early Pliocene. About 100 m of additional displacement took place during Pliocene.

The 120° striking Santa Rosa fault forms the southeastern extension of the Cinco Minas fault (Figure 2). In the Santa Rosa dam area, Garduño and Tibaldi (1991) and Michaud *et al.* (1991) found evidence of several phases of deformation. Here a 16.9 Ma old ignimbritic sequence (Nieto *et al.*, 1985) was affected by transcurrent tectonics (Santa Rosa shear zone) followed by two extensional episodes. The transcurrent motion was first left-lateral (Michaud *et al.*, 1991) and then right-lateral (Garduño and Tibaldi 1991). It took place before 8.52 Ma because basaltic flows of this age are not affected (dating in Nieto *et al.*, 1985). The main extensional phase took place before 4 Ma (Michaud *et al.*, 1991) with a NE-SW trending $\sigma3$ which reactivated the Santa Rosa shear zone, producing a minimum of 500 m of vertical displacement. Other smaller normal faults indicate the occurrence of a second extensional phase with a NW-SE trending $\sigma3$ during the Pliocene (Quintero and Guerrero, 1992). The fault is presently inactive since a late Pleistocene basaltic cone is not affected by the extensional tectonics (Michaud *et al.*, 1991), Quintero *et al.* (1992).

While the age of faulting is not well constrained for each of the structures of the Compostela-Santa Rosa fault system, their geometric and kinematic similarity strongly suggests that they developed jointly during late Miocene and/or early Pliocene times.

Amatlán de Cañas half-graben

The Amatlán de Cañas half-graben (AHG) is produced by a 40-km-long listric normal fault which strikes 150° and 80° in its eastern and western part respectively (Guamuchil fault, Nieto *et al.*, 1992). The fault is a single entity and its curvature is probably an inherited feature of the Sierra Guamuchil basement block which, according to microtectonic measurements, has been reactivated by a NNE-SSW trending $\sigma3$ (Figure 4G). The Guamuchil fault displaces by at least 1000 m down toward the south a block containing a basaltic plateau of late Pliocene to middle Pleistocene age (Righter and Carmichael 1992a). According to paleomagnetic data, basalts from this plateau have been tilted about 15° toward the N (Nieto *et al.*, 1992). A conglomeratic sequence produced by the erosion of the Sierra Guamuchil is often intercalated with the basalts. In the western part of the AHG it is tilted up to 24° toward the NNW. The fault scarp displays well-preserved triangular facets. The conglomerate is also cut by small normal faults. These observations suggest that the Guamuchil fault was probably active during the Quaternary.

Puerto Vallarta graben.

The Puerto Vallarta graben (PVG) is formed by two main 35°-45° striking fault systems which drop (at least 600 m) a plutonic complex dated 85 Ma (Zimmermann *et al.*, 1988). On the eastern part of the graben other minor faults strike 70° (Figure 2). Microtectonic measurements at one site near the NW border fault in the granite show oblique extension with a 20° trending $\sigma3$ (Figure 4H); a similar direction of extension was found in an undated ignimbrite at the northeastern tip of the graben (Figure 4I). Extension in this direction could not have produced the greater part of the depression and is probably related to a subsequent reactivation. A poorly consolidated fluvial conglomerate in the SE part of the graben is also affected by 30°-40° striking normal faults with a minimum vertical drop of 50 m. We found only one striated fault plane with a pitch of 60° toward the W.

No absolute datings constrain the age of formation of the PVG. Nevertheless, as Böhnel *et al.* (1992) pointed out the age and the isotopic similarity between the Los Cabos and the Puerto Vallarta batholiths indicates that the southern tip of Baja California was located along the coast north of Punta Mita (Figure 2) prior to detachment of the peninsula. Since the PVG parallels the rifted margins of those batholiths we suppose that it developed during the final separation of Baja California from the North America plate, in late Miocene-early Pliocene times (Stock and Hodges, 1989). However, the faulting of the infilling conglomerate requires that tectonics was still active in recent times.

Ameca faults

A horst of Cretaceous granite belonging to the JB basement rise up to 2600 m a.s.l. at about 5 km north of

Ameca (Figure 2). The horst is bounded to the south by a 15 km long normal fault striking 80° to 110°. Fault slip was measured at one site north of Ameca. The observed motion was dominant dip-slip with a small right-lateral component and gave a NNE-SSW $\sigma 3$ (Figure 4I). The fault scarp displays a fresh morphology but no other data help in determining the age of faulting.

DISCUSSION AND CONCLUSIONS

The geologic and structural data reported in the previous sections indicate that the northern boundary of the Jalisco block underwent a multiphase tectonic evolution since the Miocene. We will present a preliminary interpretation of these data and will discuss their main implications for the tectonics of the JB.

Geodynamic evolution

When analyzed at a global scale, the tectonics of the region appears to be strictly related to the geodynamic evolution of the Pacific margin of Mexico. The middle Miocene transpressive phase is coeval with the final subduction of the Guadalupe plate and the progressive collision between the East Pacific Rise and the North America plate along southern Baja California (Mammerickx and Klitgord, 1982). This process took place between 20 and 10.6 Ma with a relative convergence motion oriented 303°-317° (Stock and Hodges, 1989). This vector implies an oblique convergence which should have produced a left-hand transpression within the continent. The left-lateral faulting at the Santa Rosa dam and in the Plan de Barranca area and the en-echelon folds of the SMO ignimbrites, may be the result of this geodynamic event.

The late Miocene onset of E-W to ESE-WNW extension along the PFS correlates well with the late Miocene circum-gulf extension (Gastil *et al.*, 1975) which, as Stock and Hodges (1989) pointed out, was caused by the Pacific-North America relative motion in the period 10.6 - 5.5 Ma, prior to the definitive separation of Baja California from mainland Mexico.

Due to the uncertainity about the age of faulting and about the exact direction of extension in some areas, the interpretation of the region south of the PFS is more complicated and still speculative. At the present state of the art we can propose the following scenario.

The en-echelon arrangement of the Compostela-Santa Rosa fault system (CSFS) could be the product of right-lateral transtension along a 110° trending deformation belt, probably related to right-lateral strike-slip motion observed at the Santa Rosa dam (Garduño and Tibaldi, 1991). If this assumption is correct, the CSFS could have originated in response to a initial displacement of the JB toward the WNW, probably together with the Baja California peninsula (Figure 5A), and it might have acted as a transfer zone accommodating the extension in the PFS with the extension occurring further to the east (diffuse or localized in the Guadalajara area). In this hypothesis the brief right-lateral transtension started at about 10 Ma and turned to extension at the end of late Miocene (with $\sigma 1$ replacing $\sigma 2$ as the vertical stress and $\sigma 3$ remaining NE-SW oriented) following the plate reorganization which led to the separation of Baja California and to the individualization of the Rivera plate (Figure 5B-1). The detachment of Baja California created a new rift along the coast north of Punta Mita and led to the formation of the PVG and to a generalized NW-SE extension in the western part of the study area. This rift, together with the CSFS and the PFS, formed a rift-rift-rift continental triple junction in the Tepic area (Figure 5B-2).

During the late Pliocene and Quaternary, a new extensional tectonics affected the coastal area (Mecatán graben) and the southern part of the JB boundary (Zacoalco fault, AHG, PVG and perhaps the Ameca fault)(Figure 5C). A local seismic network operating during a 1-year-long survey in 1990 (C.F.E., 1991b) recorded only 8 events of Magnitude ≤3 in the study area (Figure 2) these were located in the AHG and PVG. Microtectonic data (Barrier *et al.*, 1990, this work) and cinder cones alignments (Suter, 1990) indicate that the Quaternary extensional regime is characterized by a NNE-SSW trending $\sigma 3$. This stress field, however, would allow the uprising of mafic magmas also along suitably-oriented old faults in other part of the studied area.

Implications for the evolution of the Jalisco block

The deformations along the northern boundary of the Jalisco block have been related by Luhr *et al.* (1985), Bourgois *et al.* (1988) and Allan *et al.* (1991) to the westward rifting of the JB away from Mexico mainland and its progressive transfer to the Pacific plate. The model is based on three main assumptions: (a) the presence of a component of right-lateral motion along the Tepic-Zacoalco rift, (b) progressive inactivation of the Rivera-Pacific Rise and of the Acapulco trench west of the Manzanillo graben (Figure 1), and (c) active spreading at the Guadalajara triple junction. As a result of our study and other recent works all these hypotheses are questionable.

1) We show that the northern boundary of the JB is not restricted to the so-called Tepic-Zacoalco rift but comprises a wide region developed between late Miocene and Quaternary. This region is characterized by extensional tectonics, and no major trascurrent faulting has been occurring in Plio-Quaternary times. Many of the extensional structures developed in late Miocene and/or early Pliocene, more likely in relation to the opening of the Gulf of California.

2) The late Pliocene and Quaternary extensional structures are sparse and developed mainly in the southern part of the boundary. The rate of Quaternary extension is low and the seismicity is scarce far from the triple junction area. Similarly in the Colima rift the seismicity seems concentrated in the northern part of the structure

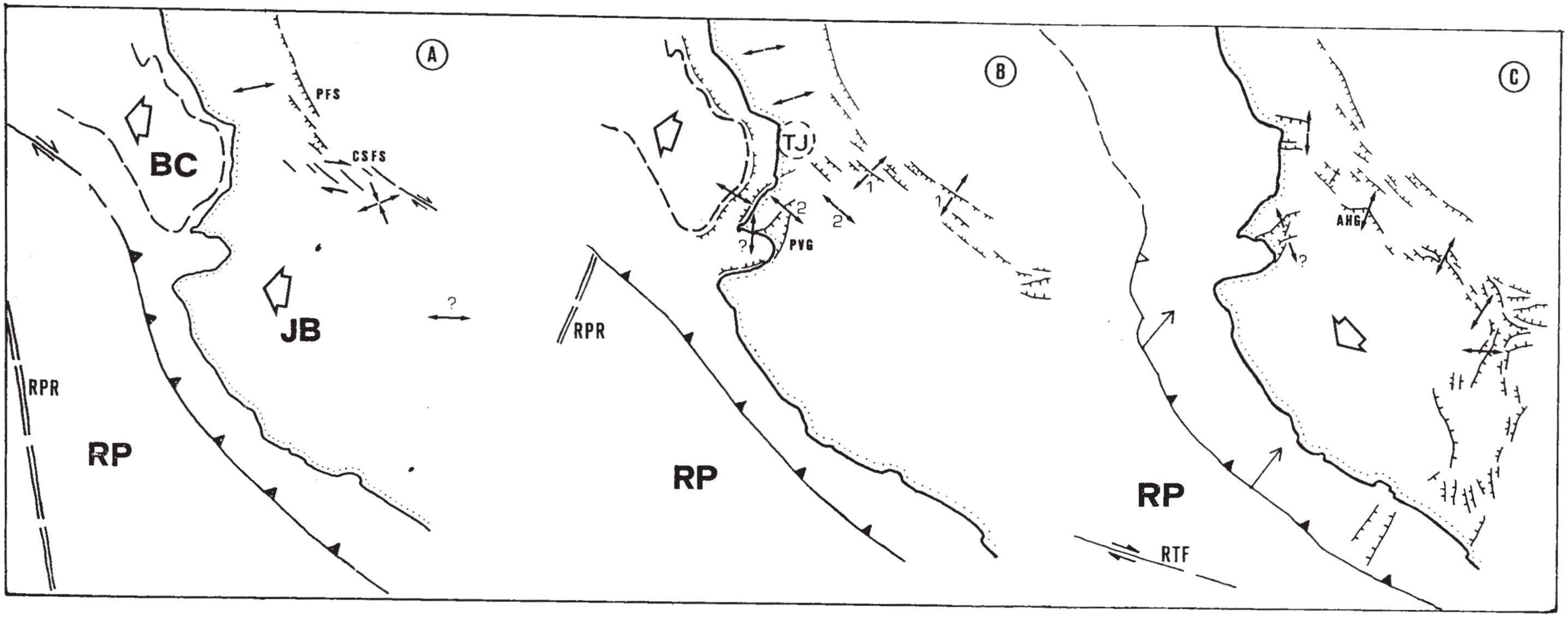

Fig. 5. Speculative tectonic evolution of western Mexico since the end of middle Miocene discussed in the text. A = 10-8 Ma; B = 8-3 Ma (1=late Miocene, 2=early Pliocene). C = late Pliocene-Present. TJ = paleo-triple junction. Large arrows indicate absolute motion of blocks; small arrows indicates mean direction of horizontal stresses deduced from fault slip data inversion presented in this work, in Barrier *et al.* (1990) and Garduño and Tibaldi (1991). Question mark indicates inferred directions. Thin arrows starting at the trench indicate relative motion direction between Rivera and North America plates as predicted by DeMets and Stein (1990) 3.0-M.y.-average model. BC = Baja California; RP = Rivera Plate; JB =Jalisco Block; RPR=Rivera-Pacific Rise; CSFS=Compostela-Santa Rosa fault system; RTF=Rivera Transform Fault. Other abbreviations as in Fig. 2.

(Suárez *et al.*, 1991), whereas the southern part of the rift seems inactive (Serpa *et al.*, 1992).

3) The asymmetric geometry of most of the structures which form the Plio-Quaternary boundary of the Jalisco block suggests that they are detachment faults typical of passive rifting (Wernicke, 1985; Lister *et al.*, 1986). A similar structure has been suggested for the northern Colima graben (Michaud *et al.*, 1992).

4) The direction of extension in Plio-Quaternary times was mostly NNE-SSW along the northern boundary of the JB and probably E-W in the Colima rift (Barrier *et al.*, 1990). The combination of these vectors implies a motion of the JB toward the SW, nearly parallel to the vector of convergence between the Rivera plate and the JB predicted by global circuit models (Figure 5C) (DeMets and Stein, 1990; Stock, 1993). This increases the amount of convergence to be accommodated at the trench and supports an active subduction of the Rivera plate, already suggested by seismological and plate motion studies (Eissler and McNally, 1984; Singh *et al.*, 1985; DeMets and Stein, 1990). Active subduction also implies that the JB is kinematically independent from the RP and will not be accreted to the Pacific plate.

In conclusion, several lines of evidence suggest that the extensional deformations at the boundaries of the JB need not to be related to active rifting of the block. Since the boundaries of the JB approximately coincide with the boundary of the Rivera plate, we think that rifting in western Mexico should be explained by a mechanism related to the subduction of the Rivera plate. If the Rivera plate has a divergent motion with respect to the adjacent Cocos and Pacific plates, extension should be expected along the continental prolongation of its boundaries.

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