Late Miocene to Quaternary extension at the northern boundary of the Jalisco block, western Mexico: The Tepic-Zacoalco rift revised

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Abstract

In the last decade several tectonic models have considered the Jalisco block (JB) as an incipient microplate which is rifting away from mainland Mexico since Pliocene time due to an eastward “jump” of the East Pacific Rise. These models predict normal and right-lateral faulting along the northern boundary of the JB, called the Tepic-Zacoalco rift (TZR). However, the Plio-Quaternary kinematics of the Jalisco block has remained unclear due to the scarcity of structural data along its boundaries. We present a new picture of the structure, the kinematics and time of deformation along the TZR obtained by geological and structural mapping integrated with subsurface stratigraphic data provided by deep geothermal drilling.

What has previously been defined as the TZR is actually a combination of different fault systems developed during Late Miocene (12–9 Ma), Early Pliocene (5.5–3.5 Ma) and, to a lesser extent, in Late Pliocene to Quaternary times. These structures can be grouped in three branches: 1) a northwestern branch, named the Pochotitán fault system, consisting of listric faults belonging to the Gulf Extensional Province; 2) a central branch made of en echelon grabens which reactivated the boundary between the JB and the Sierra Madre Occidental; 3) a southern branch constituted by detachment faults located inside the Jalisco block. The Pochotitán fault system is composed of north-northwest–trending, high angle normal faults which tilt up to 35° towards east-northeast blocks of the Sierra Madre Occidental succession. These faults accommodate at least 2,000 m of vertical displacement related to 12–9 Ma “Protogulf” extension. The central branch consists of two composite grabens developed along an older transcurrent deformation zone. The western one, the Compostela-Ceboruco graben, is a complex asymmetrical depression developed during Late Miocene and Pliocene time with vertical displacement exceeding 2,000 m. Toward the east is the Plan de Barrancas-Santa Rosa graben, a west-southwest–trending and 30-km-wide depression, bounded to the north by the Santa Rosa-Cinco Minas fault and to the south by the Plan de Barrancas fault and its buried southeastern prolongation detected by geophysical studies under the Tequila volcano and the southwestern part of La Primavera caldera. The graben displays a total vertical displacement of ~550 m mainly achieved during early Pliocene time. The southern branch is formed by the Amatlán de Cañas half-graben.
and the Ameca-San Marcos detachment fault. They are south- to southwest–dipping listric normal fault systems with a minimum of 1,400 m of vertical displacement largely produced during the Pliocene. Only the San Marcos faults show clear geologic evidence of Quaternary tectonic activity.

The great majority of the 295 measured mesofaults of Late Miocene to Quaternary age have pitches higher than 45° and inclinations ranging between 45° and 75°, typical of normal faults. The paleo-stress field has been computed by fault-slip data inversion and cinder cone alignment at 40 locations and the computed stress tensors are always extensional (vertical maximum principal stress). The average direction of extension ($\theta_{\text{Hmin}}$) is 72° for the Late Miocene extension in the Gulf area, whereas for Pliocene and Quaternary time, it ranges from 35° to 2°. Displacement of dated geologic units constrains an average minimum deformation rate for each fault system which decreases from 0.75 mm/yr for the Late Miocene to 0.1 mm/yr for the Quaternary.

These results confirm the absence of strike-slip deformation along the TZR in Plio-Quaternary times and indicate that the JB is not actively separating from the Mexican mainland. In our view, the TZR represents an intraplate deformation zone which reactivated the tectonic boundary between the Sierra Madre Occidental and the JB. These deformations are more likely related to plate boundary forces rather than to an eastward relocation of the East Pacific Rise under continental Mexico. The small divergent motion between the Rivera and Cocos plate and the steep subduction of the Rivera plate can account for the deformation observed at the boundaries of the Jalisco block.

INTRODUCTION

A comprehensive knowledge of the distribution and timing of deformation in western Mexico is crucial for any model of the opening of the Gulf of California and of the kinematics of the Rivera Plate (Fig. 1). Initial rifting of the California Peninsula from mainland Mexico in middle Miocene time was followed by a long period of “protogulf” extension until the formation of oceanic crust at about 5 Ma (Stock and Hodges, 1989; Lonsdale, 1991; Lyle and Ness, 1991). Southeast of the Gulf, however, sub-
duction did not stop and since ~5 Ma, the Rivera plate behaved independently from the Cocos plate (Atwater, 1970; Mammerrickx and Klitgord, 1982; Bandy and Yan, 1989; DeMets and Stein, 1990, Lonsdale, 1991). On the continent, these geodynamic events were reflected in the superposition, in space and time, of subduction- and rifting-related volcanism and by the development of the triple rift system of Chapala, Colima and Tepic-Zacoalco (Fig. 1)(Luhr et al., 1985; Wallace et al., 1992).

Luhr et al. (1985) and Allan et al. (1991) have proposed that the Colima and Tepic-Zacoalco rifts are the boundaries of an incipient microplate, the Jalisco block (JB), which would be rifting away from the North American plate since Pliocene times in response to an eastward jump of the East Pacific Rise (Fig. 1). As a consequence, the JB would be ultimately accreted to the Pacific plate as did Baja California in late Miocene times. Based on marine geophysical studies, Bourgois et al. (1988) and Bourgois and Michaud (1991) supported this conclusion, although they postulated that the JB is separated from the Rivera plate by the Barra de Navidad fault and the Tamayo fracture zone (Fig. 1) and consequently accretion will occur north of these structures. In both models, however, the JB should move toward the west-northwest, with pure normal faulting in the Colima rift and with both normal and right-lateral faulting in the Tepic-Zacoalco rift (TZR) (Allan et al., 1991; Bourgois and Michaud, 1991). Various amounts of right-lateral shear along the TZR and extension at the Colima rift are also proposed in some kinematic models of the Gulf opening in order to reconcile the higher rate of northwest displacement of the California peninsula with respect to the spreading rate at the Rivera rise (Humphreys and Weldon II, 1991; Lyle and Ness, 1991).

The above models have been proved only partially by geologic data. Purely extensional tectonics have been reported at least in the northern Colima rift (Sayula graben) where early Pliocene rocks have been downfaulted a minimum of 2.5 km (Allan, 1985; 1986) following a east-west direction of extension (Barrier et al., 1990). On the other hand, the structure and kinematics of the TZR are poorly known and controversial. Some workers defined the TZR as a series of grabens and right-lateral pull-apart basins of Pliocene to Holocene age (Barrier et al., 1990; Allan et al., 1991; Garduño and Tibaldi, 1991) and active right-lateral faulting has been claimed in its eastern part (Nieto-Obregón et al., 1985; Allan et al., 1991; Moore et al., 1994). However, structural field studies in various areas of the TZR found only extensional deformation in Late Miocene to Quaternary rocks (Gastil et al., 1978; Allan, 1986; Michaud et al. 1991; 1993; Nieto-Obregón et al., 1992; Quintero and Guerrero, 1992) and indicated that the rift consists mainly of half-grabens developed at different times since the Late Miocene (Ferrari et al., 1993, 1994a and b; Rosas-Elguera et al., 1993). In addition the occurrence of various episodes of alkaline, OIB-type, volcanism along the TZR (Righter and Carmichael, 1992, 1993; Moore et al., 1994; Righter et al., 1995) also suggests an overall extensional tectonics for this region.

Although several studies have addressed the tectonics of western Mexico, a complete study of the distribution and timing of Neogene deformation is still missing. To fill this gap, we undertook a structural field study of the fault systems in the region between the Pacific coast and the western tip of the Chapala lake (Fig. 1). This work is based on a parallel geologic mapping study presented in a companion paper (Ferrari et al., this issue) to which we refer for a description of the geology of the region. Important information on the three-dimensional structure of the TZR was also provided by the deep geothermal wells of the Comisión Federal de Electricidad.

Ferrari et al. (1994a) and Ferrari (1995) showed that left-lateral transpression and right-lateral transtension occurred in middle to late Miocene time along the boundary between the Sierra Madre Occidental (SMO) and the JB and pre-dated the extensional deformation. A more detailed study of the shearing phase will be presented in a forthcoming paper (Ferrari, in preparation). Here we present data which constrain the geometry, the kinematics and the timing of the late Miocene to Quaternary faulting along the northern boundary of the Jalisco block and allow a first estimate of the deformation rate through time. Our results demonstrate not only that the tectonic regime was dominantly extensional since Late Miocene time, but also that most of the deformation is pre-Quaternary in age. This has major implications for the previous model of the tectonics of the JB which will be discussed in the last section.

A REVISION OF THE TEPIC-ZACOALCO RIFT

Previous definitions

The Neogene fault systems between the western tip of Lake Chapala and the Tepic area were generally defined as the "Tepic-Chapala graben" by Demant (1979) and Luhr et al. (1985); these works were mainly concerned with the volcanology and the petrology of the region and no description of the fault systems was given. Allan et al. (1991) introduced the name “Tepic-Zacoalco rift” and provided a structural description based mainly on interpretation of aerial photographs and satellite images. They defined the TZR as “a series of pull-apart basins and grabens (...) largely confined between two general bounding fault systems, the Mazatán fault system to the south and the Pochotitán fault system to the north” (Allan et al., 1991).

The Mazatán fault system was originally mapped by Gastil et al. (1978) as a northwest-trending structure about 40 km long, which affects pre-late Miocene rocks. Allan et al. (1991) drew this fault from the Pacific coast to the southeast of Amatlán de Cañas (Fig. 2) and claimed that it cut Pliocene rocks. The same authors depicted the Pochotitán fault system as a northwest-trending fault with both strike-slip and normal motion which runs approximately along the Rio Santiago from the Aguaamilpa area to the Santa Rosa dam (Fig. 2).

Structure of the Tepic Zacoalco rift and time of faulting

Introduction. The results of our field mapping indicate that the TZR is neither a graben nor a single rift confined between two
bounding faults. Rather, it consists of several fault systems not connected to one another and with different geometry and age (Fig. 2). Particularly, we agree with Gastil et al. (1978) in considering the Mazatán fault as a pre-Miocene structure. On the other hand, the Pochotitán fault system of Allan et al. (1991) consists of distinct faults with different age and kinematics. The fault systems previously included in the TZR can be divided into three types according to their structure, kinematics and tectonic location (Fig. 2):

1) listric faults north of Tepic, belonging to the Gulf Extensional Province (Stock and Hodges, 1989; Fenby and Gastil, 1991) or, in a more general sense, to the southern Basin and Range (Henry and Aranda-Gomez, 1992);

2) en-echelon grabens between Compostela and Guadalajara which reactivated the boundary between the SMO and the JB;

3) south-verging half-grabens located inside the Jalisco block (“Ameca tectonic depression” of Nieto-Obregon et al., 1992).

In the next section we describe the structure and the age of these fault systems. Table 1 summarizes the features of each fault system.

**The Gulf extensional province. Pochotitán fault system.** We propose to retain the name Pochotitán fault system (PFS) for a series of normal faults which cut the SMO plateau at the latitude of Tepic (Fig. 2 and 3). These faults are grouped in a 30-km-wide belt between Volcán Las Navajas and Sierra Alica (Fig. 3), where ash-flows as young as 19 Ma old crop out in faulted blocks, tilted up to 35° towards east-northeast in a step-like structure. Individual faults strike 140° to 180°, dip toward the southwest and show a dominant dip-slip motion produced by east-west to east-northeast–west-southwest–trending extension (Fig. 3, Table 2). The eastward tilting of the volcanic rocks increases toward the west, which suggests that the master fault has a listric geometry at depth.

The vertical displacement of the PFS is impressive. The SMO ash flows stand at 2160 m asl in the Sierra Alica and crop out at ~500 m asl on the left side of the Rio Santiago (Fig. 3). But

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**Figure 2.** Tectonic map of the study area showing the main tectonic depression of the TZR and the boundary between JB and SMO (after Ferrari et al., this issue). PFS = Pochotitán fault system; ME = Mecatan graben; PV = Puerto Vallarta graben; AC = Amatlán de Cañas half-graben; PB = Plan de Barrancas fault; AM = Ameca fault; SM = San Marcos fault; TE = Techaltula fault (Sayula half-graben); SJ = Volcan San Juan; SA = Volcan Sangangüey; TE = Volcan Tepetiltic; SP = San Pedro caldera; CE = Volcan Ceboruco; TEQ = Volcan Tequila; LP = La Primavera caldera.
if we suppose that in early Miocene time the SMO ash-flows formed a large plateau reaching southernmost Baja California—where Hausback (1984) reported possibly correlative rocks—the total vertical displacement would exceed 2,000 m, as the ash flows are now buried under the Nayarit coastal plain.

The early Miocene ash flows are intruded by many mafic dikes, which strike parallel to the normal faults. These dikes have been dated at 11.9 Ma at El Zopilote mine, 20 km north of Figure 3 (Clark et al., 1981) and 11.5 Ma at the Aguamilpa dam (Ferrari et al., this issue, Table 2). At the dam shoulder, we measured 39 dikes which, on average, strike 238° and dip 73° (Fig. 3). Since most of the dikes are intruded orthogonally (± 5°) into the ash flows, and dikes and normal faults crosscut mutually, we consider the age of the dikes as representative of the inception of the exten-
sional faulting. Toward the west, the SMO ash flows are covered unconformably by alkali-basaltic lava flows (Cinco de Mayo plateau, Fig. 3) with Ar/Ar ages of 8.9 Ma (Righter et al., 1995) which dip 5° toward the coast. Although we cannot exclude some earlier normal faulting, these data indicate that most of the activity of the PFS is comprised between 12 and 9 Ma.

To the north, the PFS joins with other extensional fault sys-
tems bordering the eastern Gulf of California which show similar age and kinematics (Henry, 1989). To the southeast, the PFS is bounded by a system of east-northeast–west-southwest left-lateral normal faults (Fig. 3). These faults act as a transfer system between the region which underwent east-northeast–west-southwest exten-
sion to the north and the Santa Maria del Oro area (Fig. 3), which seems to have suffered only a Middle Miocene folding phase (Fer-

TABLE 1. SUMMARY OF THE LATE MIOCENE TO PRESENT EXTENSIONAL FAULT SYSTEMS OF WESTERN MEXICO

<table>
<thead>
<tr>
<th>Fault System</th>
<th>Strike</th>
<th>Fault Length*</th>
<th>Inclination of Hangingwall Blocks</th>
<th>Minimum Vertical Offset</th>
<th>Age of Faulting‡</th>
<th>Minimum rate of Displacement</th>
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<tr>
<td>Pochotlán fault system</td>
<td>140-155</td>
<td>35</td>
<td>20-35ENE</td>
<td>&gt;2000</td>
<td>45 - 85</td>
<td>11.5 - 9</td>
</tr>
<tr>
<td>Mecatán graben</td>
<td>0-10</td>
<td>5</td>
<td>0</td>
<td>300</td>
<td>0?</td>
<td>&lt;3.1</td>
</tr>
<tr>
<td><strong>CENTRAL BRANCH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Compostela graben</td>
<td>125</td>
<td>30</td>
<td>600</td>
<td>35?</td>
<td>4.5 - 2.3</td>
<td>0.27</td>
</tr>
<tr>
<td>Ceboruco graben</td>
<td>120</td>
<td>35</td>
<td>500</td>
<td>20-40NNE</td>
<td>2.3 - 1.1</td>
<td>0.41</td>
</tr>
<tr>
<td>Plan de Barranca - La Primavera</td>
<td>120</td>
<td>&gt;17</td>
<td>900</td>
<td>20SSW</td>
<td>11.5 - 9?</td>
<td>0.72</td>
</tr>
<tr>
<td>Cinco Minas fault</td>
<td>130</td>
<td>15</td>
<td>400</td>
<td>40?</td>
<td>5.5 - 3.9</td>
<td>0.25</td>
</tr>
<tr>
<td>Santa Rosa fault</td>
<td>120-130</td>
<td>37</td>
<td>450</td>
<td>30</td>
<td>3.2 - 1</td>
<td>0.05</td>
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<td><strong>SOUTHERN BRANCH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amatlan de Cañas half graben</td>
<td>80-100</td>
<td>20</td>
<td>10-25NNW</td>
<td>1500</td>
<td>20-60</td>
<td>5.5 - 3.5?</td>
</tr>
<tr>
<td>Ameça fault</td>
<td>80-110</td>
<td>34</td>
<td>1400</td>
<td>&lt;10NNE</td>
<td>35-60</td>
<td>?</td>
</tr>
<tr>
<td>San Marcos fault system</td>
<td>140-170</td>
<td>45</td>
<td>1550</td>
<td>10-45NNE</td>
<td>15-70</td>
<td>3.3? - 1</td>
</tr>
<tr>
<td>Puerto Vallarta graben</td>
<td>20-80</td>
<td>25</td>
<td>1000</td>
<td>135?</td>
<td>20-40</td>
<td>latest Miocene?</td>
</tr>
<tr>
<td>Sayula half graben</td>
<td>10-30</td>
<td>40?</td>
<td>?</td>
<td>2500**</td>
<td>90-110‡</td>
<td>5 - 3.4</td>
</tr>
</tbody>
</table>

*Length of the major fault within the fault system.
†Range of minimum principal stress direction from Table 2; question mark when inferred from fault orientation assuming a pure exten
dional deformation.
‡Time of fault activity constrained by dated stratigraphic unit on both side of the fault; question mark indicate values only partly constrained
by radiometric ages or geologic data. See text for details.
**According to Allan, 1986.
‡According to this work and to Barrier et al., 1991.
Figure 3 (this and opposite page). a) Geo-structural map of the Tepic region. The Pochotitán fault system (PFS) comprises the northwest to north-south–trending normal faults between the homonymous village and Sierra Alica and is separated by the folds of the Santa María del Oro area by a left-lateral normal transfer fault system that is inferred to continue south-westward. Also shown are stereograms (Schmidt projection, lower hemisphere) of mesofaults measured at sites numbered as in Figure 10 and Table 2. The stress tensor was calculated with the direct fault slip inversion method of 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 striae direction measured on the fault plane of the footwall block. Small triangles on great circles indicate calculated striae for the obtained tensor. The angle between measured and calculated striae is always less than 20°. Stereogram of site 1 represents poles to 39 dikes contoured at 2, 5, 10, 20 points per 1% area. b) Generalized stratigraphy to the east and to the west of the PFS. Elevation in meters above sea level. Isotopic ages from compilation in Ferrari et al. (this volume).
Mecatan graben. The 20-km-wide Mecatan graben is located in the coastal area west of Tepic. In this area Pliocene volcanic rocks are cut by four main normal faults with an east-west orientation (Fig. 2). The northern bounding fault has a topographic scarp of about 300 m and an inclination of about 60°. The southern faults have a maximum topographic relief of 140 m and cut a basaltic plateau dated at 3.2 Ma (Righter et al., 1995). Because of the intense alteration, no kinematic indicators have been observed on the fault planes. Late Quaternary volcanoes built inside the depression appear unfaulted, suggesting that the faults were active mostly in Late Pliocene to early Pleistocene times.

Other normal faulting in coastal Nayarit. Righter et al. (1995) suggested the possibility of northwest trending normal faults affecting lavas dated at 1 Ma in the Jumatan area, about 25 km west-northwest of Tepic. Nevertheless we found that lava flows in this area are affected only by minor faults, with offset not exceeding 30 cm. Particularly, basaltic lavas dated at 8.9 Ma (Righter et al., 1995) at the end of the Highway 15 toll road are offset only by decimetric west-southwest–east-northeast normal faults. Thus the region to the west of PFS is probably still subject to a mild extensional stress regime but deformation has greatly decreased relative to the late Miocene and Pliocene times.

The fault systems along the boundary between SMO and JB. Between Compostela and the Santa Rosa dam, several west-northwest–striking normal faults define two major extensional structures developed along the boundary between the JB and the SMO (see Ferrari et al., this issue, for a definition of this boundary): the Compostela-Ceboruco graben and the Plan de Barrancas–Santa Rosa graben (Fig. 2). Based on the en-echelon pattern of these faults and on oblique right-lateral striations found in the oldest rocks, Ferrari (1995) suggests that these structures initially formed in a right-lateral transtensional zone which reactivated the JB-SMO boundary. However the large vertical displacements of these faults indicate that they behaved mostly as normal structures and mesostructural observations confirmed that the extensional motion was the youngest one.

Compostela-Ceboruco graben. Recent geothermal drilling revealed that this depression is formed by three segments: the Compostela graben to the west, the San Pedro central depression and the Ceboruco asymmetric graben to the east (Fig. 4). The Compostela graben is formed by two 120°–130° striking normal faults which border a 10-km-wide depression. The faults cut a rhyolitic complex of 4.6 Ma in the north (Gastil et al., 1978) and Cretaceous ash flows and granite of the JB in the south. No clear kinematic indicators were detected but the geometry of the faults suggests that they are mostly dip-slip. This is confirmed by the orientation of extensional joints in an Early Pliocene rhyolitic tuff (Fig. 4, site 5) which indicate north-northeast extension normal to the fault trend. The age of faulting must be early Pliocene since the bounding faults are partly covered by Late Pliocene and Quaternary lavas (Fig. 4). A rhyolitic dome complex of 2.3 Ma (Gastil et al., 1978), located inside the graben, is not affected by these faults but is cut by north-northeast–south-southwest and northeast-southwest–striking normal faults which downthrow the eastern part of the graben and form the depression where the San Pedro caldera developed (Fig. 4). A basaltic shield volcano dated at
1.1 ± 0.3 Ma (Ferrari et al., this issue) south of San Pedro caldera covers these faults, constraining the age of this extension to the Late Pliocene–Early Pleistocene. A deep geothermal well drilled just south of the San Pedro caldera (CB2, Fig. 4) found 51 Ma old rocks (Ferrari et al., this issue) correlative with the JB succession at 820 m of depth (Fig. 4). Taking into account the topographic relief, the vertical displacement in the San Pedro central depression is at least 1100 m. Comparison between stratigraphic sections and subsurface data indicates that the first 600 m of offset were attained in the early Pliocene whereas the remaining 500 m are related to the Late Pliocene–Early Pleistocene extension.

The knowledge of the Ceboruco graben has been recently enhanced by the drilling of a 2800-m-deep exploratory well under the southern side of the Ceboruco volcano by CFE (Fig. 4). Surprisingly, the well encountered rocks correlative with the JB succession at a depth of 2,400 m without crossing the SMO succession. The succession above the JB is composed of 1,800 m of aphyric to microporphyritic basaltic and andesitic flows with minor intercalation of ash flows and by ~600 m of andesites and rhyolites correlative with the Late Pliocene sequence of the San Pedro area (Fig. 4). The deeper 1800 m of the section have no comparative succession in the region other than the 11–9 Ma old San Cristobal basalts exposed in the Rio Santiago north of Guadalajara (Moore et al., 1994) and the 9 Ma old Cinco de Mayo basaltic plateau northwest of Tepic (Ferrari et al., this issue). Isotopic dating of the well cores is in progress.

The 1800 m must have developed at the beginning of late Miocene time in the Ceboruco area. The faults bounding this depression are now buried under younger rocks. The 120° striking, south-
Figure 4. Geo-structural map of the Compostela-Ceboruco area. SPC = San Pedro Caldera. Fault and geologic limits dashed when inferred. Ages are referred in the text. Stereogram represents poles to extensional joints contoured at 2, 5, 10, 20 points per 1% area. Also shown is the stratigraphy of two deep exploratory wells drilled by CFE with elevation asl in meters (not to scale).
west-dipping normal faults, exposed north of Cebrucro volcano are
related to a younger extensional phase which is responsible for
another 900 m of vertical offset (Fig. 4). Since these faults
cut a rhyolitic and ignimbritic sequence dated at 4.6–4.2 Ma at
the top (Gastil et al., 1978; Righter et al., 1995) and Late Plio-
cene rocks lie at the base of the depression beneath the Cebrucro
volcano, this second phase of extension must have occurred in
Early Pliocene time.

Plan de Barrancas-Santa Rosa graben. This 20-km-wide
depression is formed by the Santa Rosa-Cinco Minas fault to the
north and the Plan de Barrancas fault and its buried prolongation
to the south (Figs. 2 and 5). The Santa Rosa-Cinco Minas fault is
a 120°–130° striking normal structure which partly reactivated an
older strike slip fault zone (Michaud et al., 1991; Quintero et al.,
1992). The Rio Santiago canyon in the Santa Rosa area follows a
fault zone which displays many kinematic indicators of dip-slip
motion (Fig. 5, site 12) superimposed on two different strike-slip
deformations (Garduño and Tibaldi 1991; Michaud et al., 1991;
Ferrari et al., 1994a). These deformations affect a rhyodacitic ash
flow of the SMO with K-Ar ages of 16.9 Ma (Nieto-Obregon
et al., 1985) outside the fault zone and 13.6 Ma (Nieto-Obregon
et al., 1985) and 14.5 Ma (Moore et al., 1994) in the fault gouge.
The strike-slip motion took place before 8.52 Ma because it does
not affect basaltic flows of this age (dating in Nieto-Obregon
et al., 1985). The stratigraphy of the two sides of the fault zone
(located along Rio Santiago) indicates that about 450 m of dip-
slip motion occurred at the beginning of Pliocene time (Fig. 5b).
In fact a 5.5 Ma ignimbrite (Nieto-Obregon et al., 1985) is down-
faulted about 450 m on the northern bank of the Rio Santiago
whereas about 100 m of lacustrine sediments with a 4.6 Ma ign-
imbrite (Nieto-Obregon et al., 1985) interlayered in the upper
part are exposed only on the southern bank. Similar data are
deduced in the Cinco Minas area by Allan et al. (1991). Here, the
early Miocene plutonic and volcanic succession of the SMO is
downthrown at least 400 m along the western continuation of the
Santa Rosa fault. An exceptionally large fault plane bears many
striations indicating almost pure dip-slip motion (Fig. 5, site 9).
Alkaline basalts dated at 3.8 Ma old (Nieto et al., 1985) fill the
depression (Cinco Minas graben of Allan et al., 1991). A parallel
fault with opposite dip drops these basalt by ~50 m (Fig. 5a).
This last activity is restricted to the Pliocene-earliest Pleistocene since
basaltic lava flows with ages ranging between 1.4 and 0.8 Ma
(Moore et al., 1994) cover the fault 4 km southeast of Cinco
Minas (Fig. 5).

On the other side of the graben, the Plan de Barrancas fault
system consists of several 120° striking and northeast dipping
normal faults (Fig. 5) which downfault by about 400 m granite
belonging to JB and the SMO ash flows, that are found tilted up
to 25°. Slickensides on the fault planes show dip-slip motion
(Fig. 5, sites 7, 10, 11) superimposed on oblique slip and strike-
slip ones. Northeast of the main fault a pyroclastic sequence with
intercalation of lacustrine sediments is tilted up to 15° to the
south-southwest and faulted for a maximum of 30 m (Fig. 5,
site 8). Basaltic lava flows dated at 3.2 Ma (Moore et al., 1994) in
the nearby Hostotipaquillo area and covering this sequence are
tilted about 5° in the same direction. Quaternary basaltic and si-
lieic flows are horizontal. These structural relations indicate that
the Plan de Barrancas faults started to be active in the early Plio-
cene (or earlier) and that most of the motion took place before the
late Pliocene. In addition, aeromagnetic and gravimetric mod-
elling indicate that the fault can be continued southeastward under
the Tequila volcano up to the south of the La Primavera caldera
(Alatorre-Zamora and Campos-Enríquez, 1992) (Fig. 2). The
trace of this fault coincides with a prominent alignment of vents of
the Tequila volcano and other minor cinder cones (Fig. 5). The
stratigraphy of the geothermal wells drilled in the La Primavera
caldera (where resurgence equals or exceeds the collapse) con-
firm a ~450 m of vertical lowering of the late Miocene succession
with respect to the one exposed to the north of the Santa Rosa
fault (Fig. 5b). A reactivation of the Plan de Barrancas fault in
Quaternary times is indicated by normal faults with a maximum
of 50 m of vertical offset cutting the Magdalena domes and Cerro
Saaavedra, a dacitic dome dated at 0.63 Ma (Nixon et al., 1987)
just northwest of Volcán Tequila (Fig. 5).

In summary, both the time of faulting and amount of dis-
placement appear to match on the two sides of the Plan de Bar-
ranca-Santa Rosa graben. Most of the extension occurred at the
beginning of Early Pliocene time and was followed by minor
reactivation in the Late Pliocene and Quaternary.

The fault systems along the northern Jalisco block. The
southern part of the TZR consists of three large depressions devel-
oped entirely within the JB which control the course of Rio Ameca
(Fig. 2). These depressions, also named the Ameca tectonic depres-
sion (Nieto-Obregon et al., 1992), are geometrically independent
from the central TZR described in the previous section.

Amatlán de Cañas half graben. The Amatlán de Cañas half
graben is bounded to the north by a 40-km-long listric normal
fault which strikes 150° and 80° in its eastern and western part,
respectively (Guamuchil fault of Nieto-Obregon et al., 1992)
(Fig. 2). The fault is a single entity and its curvature is probably
due to reactivation of an older basement structure. Early Paleoc-
cene pyroclastic flow deposits and granite of the JB exposed at an
elevation of 2,000 m asl north of the fault were not encountered
in hydrogeologic drill holes which reach 500 m asl just south of
Amatlán de Cañas. Therefore the vertical displacement of the
Guamuchil fault is at least 1,500 m (Fig. 6). The western part of
the depression is filled by an undated granitic conglomerate tilted
up to 24° toward the north-northwest and by a horizontal basaltic
plateau dated at 3.4 Ma (Righter and Carmichael, 1992). In the
central and eastern part of the depression basaltic volcanoes with
ages of 0.66 Ma (Righter and Carmichael, 1992) cover another,
different conglomeratic sequence. Paleomagnetic studies suggest
a mean, post-depositional tilting of about 12° toward the N of
Plio-Quaternary basalts (Nieto-Obregon et al., 1992), although
Figure 5 (this and following page). a) Geo-structural map of the Plan de Barranca-Sta. Rosa graben. The Plan de Barranca fault system is inferred to continue under the Tequila volcano and related vents, thus paralleling the Santa Rosa fault. Ages are referenced in the text. Stereograms of mesofaults as in Figure 3. b) Generalized stratigraphy to the north and to the south of Rio Santiago in the Santa Rosa dam area, with elevation asl in meters.
no tilting is appreciable in the conglomeratic sequence underlying the 0.66 Ma old El Rosario basalts, about 10 km northwest of Amatlán. These basalts are downfaulted not more than 50 m by a normal fault parallel with the eastern segment of the Guamuchil fault but dipping to the northeast. According to these geologic data, the Amatlán half-graben must have formed mostly before the emplacement of the 3.4 Ma old basaltic plateau and minor normal motion has occurred since then into the Quaternary.

**Ameca-San Marcos fault system.** This system is formed by three main segments dipping from south to southwest which bound to the north the Ameca and the Zacoalco depressions (Fig. 7). The first segment, the Ameca fault, is a 34 km long normal fault striking 80° to 110°. The western part of the fault displaces a Cretaceous pluton of the JB down at least 1,400 m whereas to the east (La Vega), it cuts lacustrine deposits and basaltic flows of probable Pliocene age. Fluvio-lacustrine deposits south of the fault and presently undergoing erosion are tilted up to 10° toward the north-northeast. The central segment, between Ahuisculco and Acatlán, is 20 km long and strikes 145°–155° (Fig. 7). Here the fault cuts an ash-flow succession attributed to the Late Miocene-Early Pliocene (Ferrari et al., this issue) and secondary conjugated faults cut also Pleistocene volcanoes as well as the Acatlán ignimbrite (Wright and Walker, 1981) with vertical offset not exceeding 100 m. The third segment, the San Marcos fault, is a 160°–170° striking structure with a length of 20 km which cuts Early Pliocene as well as Early Pleistocene rocks (Allan, 1986; Delgado-Granados, 1992). Many faults sub-parallel to this fault affect a 15-km-wide zone between Zacoalco and Atemajac, where pre-Late Pliocene rocks are tilted up to 45° toward the northeast (Fig. 7). This “domino style” geometry suggests that the San Marcos fault is a southwest-dipping listric detachment structure, as already hypothesized by Allan (1986). Nevertheless, the lack of a geologic marker throughout the area prevents an estimation of the amount of extension. The faulting history can be estimated considering the stratigraphy of the deep geothermal well drilled by CFE west of the San Marcos fault (Fig. 7b). A succession correlative with the Early Pliocene one exposed east of the fault was encountered in the well at a depth of 650 m after 750 m of lacustrine sediments. However a basaltic-andesite cinder cone dated at 0.99 Ma (Allan, 1986) overlying the lacustrine sediments and built against the fault plane 5 km north of San Marcos is only affected by small normal faults with a maximum of 10 m of displacement. Therefore a vertical offset of about 1550 m was attained between Early Pliocene and 1 Ma and only about 100 m of displacement occurred since then. This conclusion is supported by the fact that Late Pliocene to present rocks are never tilted more than 10°. At any rate, the Ameca-San Marcos fault system is the only fault system in the TZR with clear geologic evidence of tectonic activity in Middle to Late Pleistocene times. Suárez et al. (1994) recognized a great earthquake having occurred in the Zacoalco region in the 16th century and recorded a moderate microseismic activity in the faulted zone between Zacoalco and Atemajac.

**Puerto Vallarta graben.** This structure does not belong to the TZR as defined in Allan et al. (1991), yet we consider that it developed under the same extensional tectonic framework as the
rest of the TZR. The Puerto Vallarta graben (Fig. 2) is bounded by two main 25°–45° striking fault systems which drop by at least 600 m a plutonic complex dated at 85 Ma (Zimmermann et al., 1988). The western segment of the northern fault is ~east-west striking and is parallel to a 800 m high scarp observed offshore near Puerto Vallarta bay (Fisher, 1961). On the eastern part of the graben, other minor faults strike 70° (Fig. 2). A poorly consolidated fluvial conglomerate in the southeast part of the graben is also affected by 30°–40° striking normal faults with a minimum vertical drop of 50 m and produced by northeast trending extension. The age of formation of the Puerto Vallarta graben is difficult to establish because rocks affected by the

Figure 6. a) Generalized stratigraphy of the Amatlán de Cañas half-graben with elevation asl in meters. b) Stereograms of mesofaults at sites along the Amatlán Fault (see Fig. 3 for explanation and Fig. 10 and Table 2 for location).
faults are Cretaceous in age. However, the faulted conglomerate in the eastern part of the graben requires that extension continued until recent times. As Bönhel et al. (1992) pointed out, the age and the isotopic similarity between the Los Cabos and the Puerto Vallarta batholiths indicate that the southern tip of Baja California was located along the coast north of the Puerto Vallarta graben prior to the detachment of the peninsula. Since the Puerto Vallarta graben parallels the rifted margins of those batholiths, we speculate 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).

Microtectonic analysis and paleostress determinations

Methodology. A microtectonic study of the fault systems described in the previous section was carried out at 32 sites and data are presented in Figs. 3, 4, 5, 7, 8 and 9. We measured the geometry and sense of slip of a total of 295 striated faults. These represent everywhere the last phase recorded that can be referred to late Miocene to Quaternary times. The paleostress regime responsible for the observed deformation was computed by fault slip data inversion with the method of Angelier (1990) and the relative results are illustrated in Fig. 10 and listed in Table 2. The orientation of minimum horizontal principal stress (σ_{Hmin}) has been also calculated through a linear regression of 7 alignments of Quaternary cinder cones and the results are listed in Table 3 together with previous determinations presented by Suter (1991).

In recent times several workers have shown that fault interactions can produce multiple fault striations during the same event due to kinematic compatibility and stress field perturbation (Pollard et al., 1993; Cashman and Ellis, 1994; Nieto-Samaniego and Alaniz-Alvarez, 1995). This aspect is not taken into account in the inversion of fault-slip data to obtain the regional stress field, since all the methods assume that the fault striae represent the direction of the maximum shear stress acting on a newly formed or pre-existing plane (Angelier, 1979; Angelier, 1989 and reference therein). Fault interaction is likely to occur in the study region because of the high fault density. To minimize this problem, we tried to measure the larger fault planes and those cutting other ones—i.e. those with the higher probability of complying with the assumptions of the inversion methods and, also, the more recent ones. Even so, faults with incongruous orientations or striations relative to the dominant population appeared at some sites. As these faults usually display a high deviation between measured and calculated striae, they were discarded in the final computation. Although we may have missed some data in this way, the results are more likely representative of the local paleo-stress conditions.

Results. The trend of the measured mesofaults displays two dominant peaks at ~130° and 150° and a secondary maximum between 40° and 70° (Fig. 8). Although in several cases faults have a lateral component of motion, the great majority of them have pitches higher than 45° and inclinations ranging between 45° and 75°, typical of normal faults (Fig. 8). In addition, all the 32 stress tensors computed are characterized by a vertical maximum principal stress (Table 2).

As a whole, paleostress determinations for sites within the same fault system show a good consistency (Fig. 10). On average the direction of extension (σ_{Hmin}) was 72°±22° for the Late Miocene Pochotitán fault system (sites 1–4), 22°±13° for the Pliocene in the Plan de Barrancas–Santa Rosa graben (sites 5–12), and 35°±29° for the Pliocene in the Amatán de Cañas half graben (sites 13 and 15). For the Ameca-San Marcos fault system, σ_{Hmin} was 2°±25° during the Pliocene (sites 17, 18, 21, 25–29) and 31°±30° for the Quaternary (sites 22–24). The latter value is identical to the average direction of σ_{Hmin} deduced from Quaternary volcanic alignments (Table 3). Therefore these results indicate a consistent ~north-northeast direction of extension for the whole Pliocene and Quaternary in the TZR.

Site 30, adjacent to the north-northeast–trending bounding fault of the Sayula half-graben (Techaluta fault, Michaud et al., 1994) shows a east-southeast to southeast direction of extension which is compatible with the orientation of the structure (Figs. 9a and 10). The fault cuts 5.4–4.4 Ma old rocks (Allan, 1986); thus its motion has been partly concurrent with the San Marcos fault. This probably caused some oblique-slip reactivation of east-northeast–striking planes, as observed at site 29 (Fig. 9a). Other sites displaying a roughly southeast extension (6, 14, 16, 19, 20, 31 and 32) are located away from the main TZR fault systems and in rocks older than Pliocene. Macro-faults consistent with this orientation of extension are observed only in the San Pedro and in the Puerto Vallarta areas (Figs. 4a and 10). However, north-northeast–trending normal faults are reported south of the TZR in the Los Volcanes area (Wallace and Carmichael, 1992). We speculate that this extension, incongruous with the rest of the TZR, could belong to a Late Miocene or Early Pliocene (?) episode, recorded inside the Jalisco block, possibly related to east-southeast stretching of the JB during the final separation of Baja California and the formation of the Puerto Vallarta graben.

Tectonic episodes, rate of deformation and volcanic activity

The extensional tectonics which affected western Mexico in Late Miocene to Quaternary times can be envisaged in two large episodes: a) during the late Miocene (12–9 Ma), west-northwest–east-northeast extension, related to the initial opening of the Gulf of California, formed the Pochotitán fault system and perhaps initiated the Ceboruco graben; b) since 5.5 Ma, ~north-northeast extension produced the TZR. Based on the data presented in this paper, we consider the TZR formed by the tectonic depressions located at the JB-SMO boundary and along the northern edge of the JB.

Combining the age of faulting with the amount of displacement of dated geologic units, we estimate a minimum deformation rate for the fault systems forming the TZR (Table 1) (Fig. 11a). Although these data are in a few cases not well constrained, they show that the extensional tectonics has diminished in intensity with time. The higher rate of
Late Miocene to Quaternary extension, northern boundary of Jalisco block: Tepic-Zacoalco rift revised

Figure 7 (on this and following page). a) Geo-structural map of the Ameca-San Marcos fault system. Stereograms of meso faults as in Figure 3. b) Generalized stratigraphy of the Sierra de San Marcos and the San Marcos 2 well (after Venegas et al., 1985). Elevation asl in meters (not to scale).
deformation related to the opening of the Gulf of California shows absolute values consistent with those observed at developing plate boundaries. On the other hand, the low deformation rate for the Quaternary is compatible with the long earthquake recurrence time in the Zacoalco region estimated by Suárez et al. (1994) and is very similar to values obtained for active faults in the central MVB by Suter et al. (1995 and in press).

Volcanic activity in the region appears concurrent with the extensional phases. Assuming that dated samples are representative of the whole volcanism in a given period, a good correlation appears between extensional tectonics and the volcanic rate (Fig. 11b). Particularly, emplacement of mafic and alkaline magmas is strictly related to the main episode of extension, and a period of silicic and reduced volcanism between 8 and 5 Ma corresponds to an apparent decline in the tectonic activity.

**DISCUSSION AND CONCLUSIONS**

**Implications for previous tectonic models of the Jalisco block**

Perhaps the main outcome of our work is that the structure and the tectonic evolution of the TZR are more complex than those proposed in the past in the frame of broader geodynamic models. We feel that more structural and geochronologic information are still needed to elaborate a new comprehensive model on the tectonic evolution of western Mexico. Nevertheless the data presented in this work permit us to critically review older models and pose new constraints for future ones. The more important issues in this regard are the following:

1) *The tectonics along the northern boundary of the JB was extensional in Plio-Quaternary times.* Previous models have assumed the existence of Plio-Quaternary right-lateral structures in the TZR, ranging from pull-apart basins connected by strike-
slip faults (Barrier et al., 1990; Garduño and Tibaldi, 1991; Allan et al., 1991) to a single northwest-trending strike-slip fault (Tequila fault of Bourgois et al., 1988 and Bourgois and Michaud, 1991). On the contrary, we demonstrated that both macro- and microstructures developed in Late Miocene to Quaternary times are dominantly extensional. An active right-lateral motion at the Santa Rosa fault has been proposed by Nieto-Obregon et al. (1985) and Allan et al. (1991) and endorsed also in recent times by Moore et al. (1994) based on the fault pattern observed in aerial photographs. Although both stratigraphic and microtectonic data indicate that the strike-slip deformation is related to an older phase (Michaud et al., 1991; Quintero et al., 1992; Ferrari, 1995; this work), the most consistent element raised by these authors is the 0.2 to 1 cm/yr of right lateral displacement apparent from triangulation data in the dam area. Such a high deformation rate, comparable to those of plate boundary fault zones, implies a lateral displacement of 10 to 50 km in Plio-Quaternary times and a fault length of hundreds of kilometers (Walsh and Watterson, 1988; Cowie and Scholtz, 1992). This conspicuous fault, which should be clearly seen even from satellite imagery, is not found anywhere in western Mexico. Therefore the triangulation data are more easily explained as due to gravitational instability of rock blocks on both sides of the dam, as suggested by Quintero et al. (1992). In addition, there is no evidence for recent rotation about the vertical axes in the northern JB (Maillol and Bandy, 1994) as we should expect in a transcurrent tectonic regime.

2) The extensional fault systems in the TZR are geometrically and chronologically independent. Models postulating an active separation of the JB from the Mexican mainland require the TZR to be a single structure running from the triple junction to the coast, with a progressive structural development since Pliocene time. By contrast, we show that the TZR is formed by various fault systems not connected one to another and with different geometries and ages. This conflicts with the assumption of the JB as a rigid block pushed to the northwest by a relocation of the East Pacific Rise under the Colima rift.

3) Most of the extension is pre-Pleistocene, deformation rate is low and decreasing since Late Miocene. We show that most of the present configuration of the TZR has been attained before Pleistocene and that deformation is presently concentrated in the southeastern part of the TZR. Furthermore, the rate of Quaternary activity is very low if compared with the one expected for an active plate boundary zone. Estimated deformation rates are also at least one order of magnitude lower than those required by the models proposed by Humphrey and Weldon II (1991) and Lyle and Ness (1991) for the opening of the mouth of the Gulf of California.

Toward a new model

Our conclusion is that the structures developed at the northern boundary of the Jalisco block are the result of the superimposition of several tectonic episodes which reactivated the boundary between the JB and the SMO, and that the Tepic-Zacoalco rift is more akin to intraplate deformation produced by plate boundary forces (Ferrari et al., 1994a) rather than to active separation of a microplate (Luhr et al., 1985; Allan et al., 1991; Bourgois and Michaud, 1991).

In the case of the Colima rift, a close correlation exists between the continental deformation, the volcanism and the position of the Cocos-Rivera plate boundary at depth (Nixon, 1982; Bandy and Hilde, 1992; Stock and Lee, 1994). Particularly, the steeper angle of subduction of the Rivera plate with respect to the Cocos plate (Pardo and Suarez, 1993, 1995) and the small divergent motion between the two plates (Bandy, 1992; Bandy and Pardo, 1994) should induce the formation of a slab window which could explain the presence in the upper plate of the alkaline volcanism and the propagation of rifting southward from the Guadalajara triple junction (Barrier et al., 1990; Bandy, 1992; Bandy and Hilde, 1992; Serpa and Pavlis, 1994). In a similar manner, we think that extensional deformation and alkaline volcanism in the TZR are related to the steep (50°) Benioff plane (Pardo and Suarez, 1993) and the low convergence rate (DeMets and Stein, 1990) of the Rivera plate. Trench-normal extension is observed worldwide within the plates overriding retreating plate boundaries (Jarrard, 1986; Otsuki, 1989;...
Figure 9 (this and opposite page). Stereograms of mesofaults at sites not shown in Figures 3 to 7 (see Fig. 3 for explanation and Fig. 10 and Table 2 for locations). a) Sierra Tapalpa area. b) Sites within the JB and at the boundary between SMO and JB with ESE extension (see text for discussion).
Figure 10. Tectonic map with orientation of $\sigma_{H\min}$ as listed in Table 2. Also listed are average $\sigma_{H\min}$ direction, with standard deviation, for groups of sites along the same fault system.

### TABLE 3. STRESS ORIENTATION INFERRED BY ALIGNMENTS OF QUATERNARY VOLCANIC VENTS

<table>
<thead>
<tr>
<th>Alignment</th>
<th>Vents</th>
<th>Length (km)</th>
<th>Trend (azimuth)</th>
<th>Regression Coefficient</th>
<th>Quality*</th>
<th>$\sigma_{H\min}$ (azimuth)</th>
<th>Reference†</th>
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<tr>
<td>Southern Guadalajera</td>
<td>9</td>
<td>31</td>
<td>116</td>
<td>-0.971</td>
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<td>135</td>
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<td>1</td>
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<td>TEQ-C</td>
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<td>127</td>
<td>-0.885</td>
<td>B</td>
<td>37</td>
<td>1</td>
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<td>TEQ-S</td>
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<td>31</td>
<td>120</td>
<td>-0.799</td>
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*Quality ranking according to Suter, 1991.
†1 = this chapter; 2 = Suter, 1991.
Royden, 1993) and this deformation is usually accommodated along the volcanic arc (Hamilton, 1995). Applying the empirical relations of Otsuki (1989) for the convergence rates between plates, Delgado-Granados (1993) already predicted a late Pliocene to Quaternary extensional tectonics for the western MVB. Our field study confirms this inference and indicates that Mexico is not an exception to the general behavior of the world subduction systems.

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REFERENCES CITED

Bandy, W., 1992, Southwest propagating rifting along the Rivera-Cocos plate boundary and related deformation within western Mexico [abs]: Eos (Transaction American Geophysical Union), v. 73, p. 508.
Bandy, W., and Yan C.-Y., 1989, Present-day Rivera-Pacific and Rivera-Cocos relative plate motion [abs]: Eos (Transaction American Geophysical Union), v. 70, p. 1342.
Michaud, F., Quintero, O., Barrier, E. and Bourgeois, J., 1991, La frontière Nord du Bloc Jalisco (Ouest Mexique): localisation et évolution de 13 Ma à l’actuel:


