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Tectonic significance of an earthquake sequence in the Zacoalco half-graben, Jalisco, Mexico

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Abstract

We studied a sequence of small earthquakes that occurred during the months of April and May of 1997, in Jalisco, southwestern Mexico. The earthquakes were located along a set of active faults that form the Zacoalco half-graben (La Lima fault system), west of Lake Chapala, within the rift–rift–rift triple junction. A total of 33 events were located, with magnitudes ranging from 1.5 to 3.5, recorded by a portable array of broadband seismographs. We identified two groups of events: one corresponding to a shallow normal fault, synthetic to La Lima fault system, and another group associated with a deeper fault. The events that occurred on the synthetic fault show normal faulting oriented on a NW–SE plane, dipping shallowly towards the SW. The other group of mechanisms showed either a normal fault oriented NW–SE and dipping steeply to the NE, or a very shallow-dipping normal fault, dipping to the SW. Earthquake distribution and fault plane solutions suggest that the Zacoalco half-graben developed from blocks that rotate as slip occurs on listric faults. These mechanisms could represent the type of motion expected for larger earthquakes in the area, like the one that occurred in 1568. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

A rift–rift–rift triple junction dominates the continental tectonics of western Mexico. This junction is formed by three coalescing extensional systems: the N–S trending Colima rift, the E–W trending Chapala rift, and the NW–SE trending Tepic-Zacoalco rift (i.e. Nixon, 1982; Luhr et al., 1985; Allan 1986; Delgado and Urrutia, 1985; Allan et al., 1991). These main structures separate the Jalisco block (Fig. 1) from North America (Luhr et al., 1985). Although there is no agreement on the direction of motion of the Jalisco block with respect to North America, most researchers consider the block boundaries to be currently active (i.e. Allan et al., 1991; Delgado, 1992a; Michaud et al., 1994; Moore et al., 1994).

The Tepic-Zacoalco rift is a series of NNW-trending en echelon fault-bounded basins extending from the triple junction to the west coast of Mexico (i.e. Johnson and Harrison, 1989; Rosas-Elguera et al., 1996); the Zacoalco half-graben represents the southeastern limb (Fig. 2). This rift is the boundary between the Jalisco block and the Sierra Madre Occidental province (Allan et al., 1991). South of the Zacoalco half-graben, and coalescing with it, is the Sayula graben, the northernmost part of the Colima rift (Constantino, 1966; Allan 1986). The Colima rift extends south from the triple junction to the coast and continues offshore into the Manzanillo trough (e.g. Johnson and Harrison, 1990; Allan et al., 1991; Bandy et al., 1995). This rift separates the Jalisco block from the Michoacán block (Johnson and Harrison, 1990; Allan et al., 1991). The Chapala rift comprises the Chapala and Citala graben structures (Delgado and Urrutia, 1985; Delgado, 1992a; Michaud et al., 1994) extending

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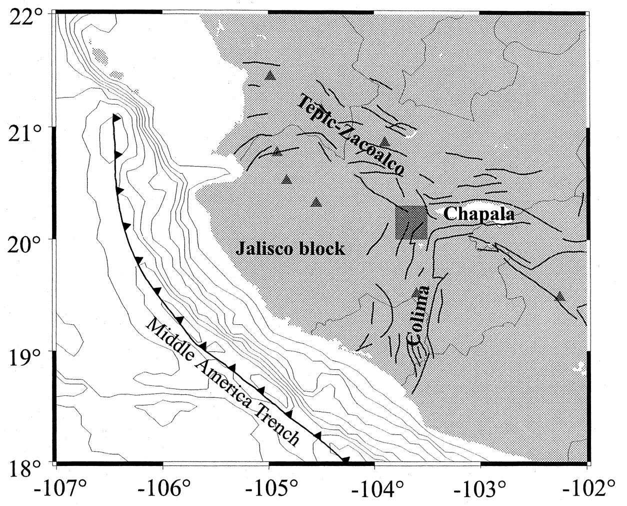

Fig. 1. Map shows the tectonic setting of the west-central margin of Mexico. Major fault systems (solid lines) define the Jalisco block and the rift–rift–rift triple junction. Dark shaded rectangle marks the studied area.

for more than 400 km towards the east along the Chapala-Tula fault zone. The Chapala rift separates the Michoacán and Guerrero blocks from the rest of North America (Johnson and Harrison, 1990). The Zacoalco, Sayula and Citala half-grabens join near the town of Zacoalco de las Torres, in the state of Jalisco, and represents the rift–rift–rift triple junction (Allan, 1986; Barrier et al., 1990; Michaud et al., 1991; Ferrari et al., 1994a).

The development of the triple junction structure probably started between 14.5 and 9 Ma, as a response to tectonic changes at the East Pacific Rise, and coincided with the initiation of the opening of the southern Gulf of California (Karig and Jensky, 1972; Larson, 1972; Mammerickx and Klitgord, 1982; Luhr et al., 1985; Stock and Hodges, 1989; Londsdale, 1995; Ferrari, 1995). However, the main development of the rift–rift–rift system, occurred between 6 and 4 Ma (Allan, 1986; Delgado, 1993; Ferrari and Rosas-Elguera, 1998). The major fault systems along these rifts are considered currently active (Luhr et al., 1985; Barrier et al., 1990; Garduño and Tibaldi, 1991; Delgado, 1992a; Rosas-Elguera et al., 1993; Michaud et al., 1993; Suárez et al, 1994; Ferrari et al., 1994b; Rosas-Elguera et al., 1996).

Geological evidence for activity at the triple junction includes landslides at main fault scarps, mud volcanoes, sag ponds, and modifications in stream geometry. These features were reported for the Ajijic fault system and the Pajacuarán fault of the Chapala graben (Palmer, 1926; Clements, 1963; Delgado, 1992a,b), and for the La Lima fault system (LFS) of the Zacoalco half-graben (Allan, 1986; Allan et al., 1991; Delgado, 1992a,b).

The LFS is one of the most important fault systems of the Zacoalco half-graben. Estimates indicate that the LFS has undergone vertical displacements exceeding 750 m during the last 1.4 Ma (Venegas et al., 1985; Allan, 1986; Delgado, 1992a). This represents a deformation rate of 0.5 mm/yr. One of the largest faults in this system is the 20-km long San Marcos fault, which exhibits a minimum vertical displacement of 1400 m that mostly occurred during Pliocene time (Allan, 1986). Ferrari and Rosas-Elguera (1998) deduced for the Zacoalco half-graben a changing deformation rate of 0.75 mm/yr during the Miocene to 0.1 mm/yr during Quaternary times. Faults related to LFS offset rocks younger than 0.65 Ma in the vicinity of the town of Acatlán, 10 km SW of Guadalajara (Allan, 1986). These faults show scarps up to 100 m of vertical displacement (Ferrari and Rosas-Elguera, 1998). The average direction of extension is 40, perpendicular to the trend of the faults (Delgado, 1992a; Ferrari and Rosas-Elguera, 1998).

There are few reports of seismic activity along the three major fault systems, except for two large earthquakes that occurred near the triple junction in the past 500 years. Suárez et al. (1994) analyzed reports for the December 1568 earthquake that caused heavy damages west of Lake Chapala. From damage reports, they estimated a magnitude larger than 7 for this event. From the reported intensity distribution, we estimate that the earthquake ruptured part of the faults that compose the Zacoalco and Sayula half-grabens. Reviews of earthquake damage reports from the 1800s localize another large earthquake at the vicinity of the triple junction (Figueroa, 1963; García-Acosta and Suárez, 1996). Judging from the damage distribution, the earthquake of February, 1875 occurred near the town of San Cristobal, 40 km north of Guadalajara (Fig. 2). This event probably had a magnitude larger than 6. Earthquake swarms in 1905, near Concepción de los Buenos Aires south of the Citala graben and at the southern Chapala graben indicate current activity on the fault systems (Palmer, 1926; García-Acosta and Suárez, 1996). Suárez et al. (1994) analyzed a cluster of small earthquakes that were recorded during a microseismic field study at the triple junction. The earthquake cluster was located at the western edge of the Sayula half-graben. A composite fault plane solution of three seismic events, indicated rupture along a normal fault, with one of the nodal planes oriented parallel to the trend followed by faults mapped by Barrier et al. (1990). These sequences, those reported by Ordoñez (1912) and Suárez et al. (1994), and the large events are clear evidence of current activity in the region.

Although there is geologic evidence of Quaternary activity on the Zacoalco half-graben, and large historical earthquakes may have ruptured part of these nor-

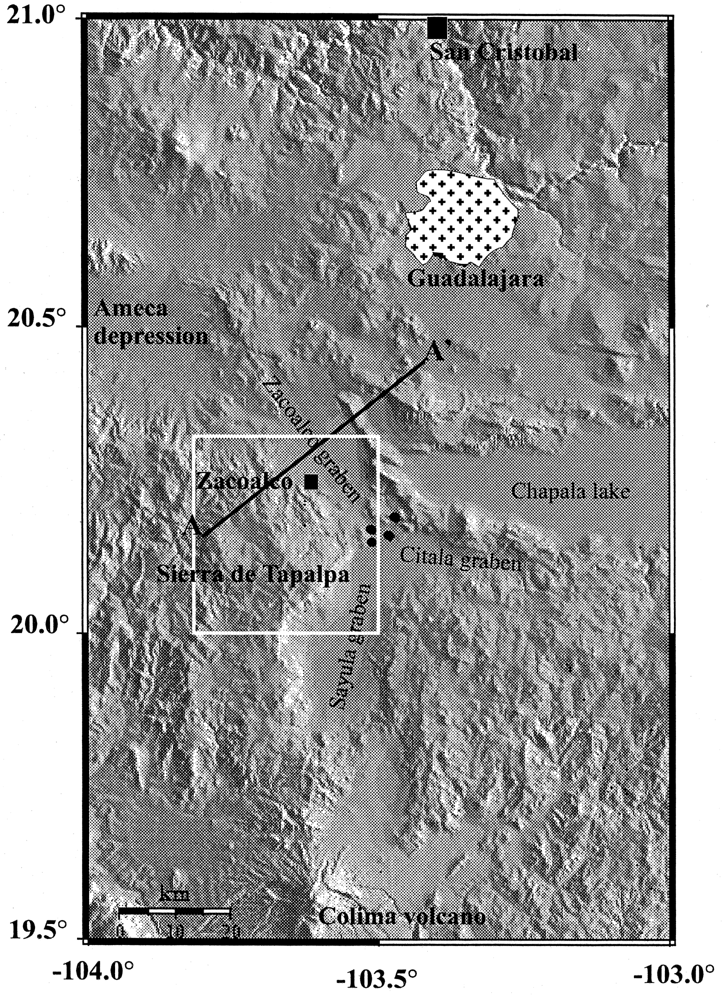

Fig. 2. Shaded-relief map showing first events (April 24, 1997) located by the Servicio Sismológico (dots) and cross section line for Fig. 7.

mal faults, there is no documentation of focal mechanism for the earthquakes or their relationship to mapped faults. Here we present a study of an earthquake sequence that occurred on the Zacoalco half-graben on April–May, 1997.

2. Earthquake sequence

On April 24, 1997, the Servicio Sismológico Nacional of Mexico reported 5 earthquakes located to the west of Lake Chapala (Fig. 2) with magnitudes between 3.4 and 4.1. Despite the great interest in the mechanisms of these events and their relationship to the numerous faults in the region, their magnitudes and the lack of stations close to the epicenters did not allow for a detailed source study. Four days later, a portable broadband seismic array of 4 stations was deployed in the field. Each seismic station consisted of a 24-bit RefTek digitizer, connected to a broadband Guralp velocity sensor (CMG-40 T).

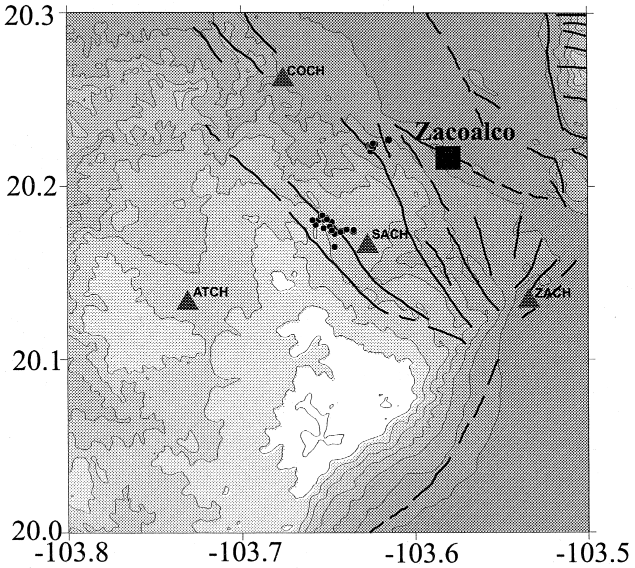

Fig. 3. Station (triangles) and seismicity distribution (dots). Major mapped faults are shown as lines.

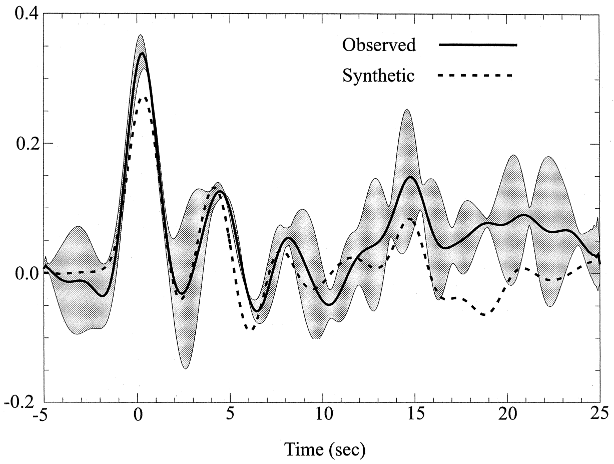

Fig. 4. Observed (solid) and synthetic (dashed) receiver functions. Shadow area marks the one standard deviation.

A total of 33 events were recorded on all 4 stations, from April 28th to May 18th (Fig. 3). The events were located using both P and S readings and P-wave polarization direction using the Seisan System of Lienart and Haskov (1995).

Fig. 3 shows station distributions and earthquake epicenters. We registered two earthquake sequences during the field survey. The first, and largest, sequence occurred at the base of the Sierra de Tapalpa. Events from this sequence were recorded from April 28th to May 14th. The other sequence of events was located about 8 km towards the NE, and began on May 15th.

3. Crustal structure

Lacking a reliable crustal structure for the area, we used the P-wave from a teleseismic event recorded on the four stations to obtain an average crustal model from a receiver function (Owens et al., 1984). Energetic P-waves arriving at almost vertical angles at the base of the crust are converted into SV waves at crustal discontinuities. These converted phases are mainly recorded on the radial component. The source and path effects are removed from the radial seismogram by deconvolving the vertical component from the radial, leaving the converted phases and the multiple reverberations within the crust (Langston, 1979). We calculated the receiver functions by using a frequency-domain deconvolution, with water-level protection against divisions by zero. The signals were then filtered with a Gaussian filter to generate low-frequency records. Receiver functions from each station were stacked to obtain an average receiver function (Fig. 4), with information about the average structure below the array. The average function was then modeled by three strong discontinuities; one representing the transition between the upper sedimentary layer and the upper crust, a mid-crustal discontinuity, and the Moho. Seismic-wave velocities and layer depths were varied until a match was found between the observed and the synthetic receiver functions (Fig. 4). Unfortunately, receiver functions carry only information of the wave's travel-time. For this reason, a trade-off between depth discontinuity and wave speeds is inevitable. Modeling, not only the first-order conversions, but the multiples may reduce this trade-off. Because of the trade-off, Moho depth could be made shallower by selecting higher velocities in the lower crust. Nevertheless, in view of the lack of any other information in the area, the model obtained (Table 1) is considered a good approximation of the crustal structure. This model was used in the location of the earthquakes.

Table 1
Crustal structure

Thickness (km)	P wave (km/s)	S wave (km/s)	Density (kg/m^3)
1.2	3.6	2.0	1.9
6.8	5.2	2.9	2.4
22.0	5.8	3.3	2.6
Half space	7.3	4.2	3.1

4. Earthquake locations

P and S readings, as well as polarization directions of first arrivals, were used to locate the events using the Seisan System of Lienart and Haskov (1995). Only events with readings from all four stations were located. All events have r.m.s. residuals smaller than 0.1 s. The resulting locations indicate two different sets of events. The first sequence of events, which occurred between April 28th and May 14th, is aligned with a mapped fault that strikes 120° from north and dips towards the SW. The second sequence of events occurred after May 15th and is located about 8 km to the NE of the first one. These events cluster, but show no linear trend (Fig. 3).

The first sequence is distributed between 1 and 5 km depth, with most of the events concentrated between 3 and 5 km depth. Earthquakes from the second group are located between 7 and 9 km depth. These two groups are clearly located on different faults.

5. Focal mechanisms

Focal mechanisms are generally obtained from first-motion polarities of P waves. P-wave first-motion mechanisms from only four stations will be poorly

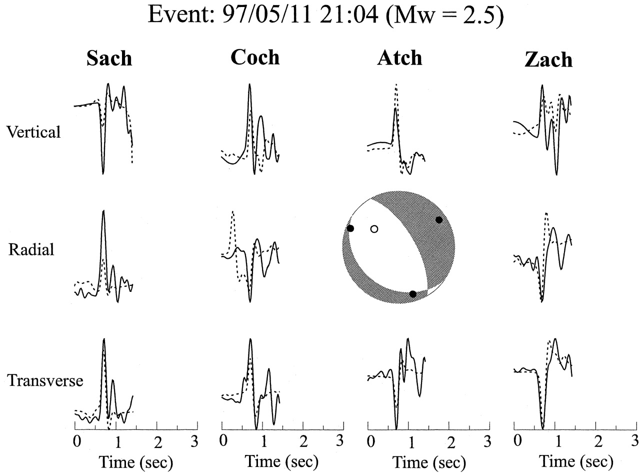

Fig. 5. Observed (solid) and synthetic (dashed) seismograms. Lower hemisphere projection focal mechanism is shown with the first motion polarities (dots: compressions and open circles: dilations).

constrained. Also, composite fault-plane solutions using many events may not be reliable since small earthquakes could have different mechanisms along the same fault, depending on preexisting fractures and local variations in the stress field. However, a waveform inversion, using both amplitude and phase, could provide a good estimate of the focal mechanism for individual earthquakes.

Modern broadband instruments allow for on-scale recording of high-quality data of small and moderate size earthquakes. These records are easily integrated to find the displacement. They contain information in a frequency band that allows for a fast inversion of the waveforms to obtain a reliable focal solution. As the events recorded are mostly below the array and near stations, the larger arrivals are P and S waves traveling directly to the stations. To perform the analysis, we used a 2-s window around the P and S waves after rotating the seismograms into vertical, radial and transverse components.

We used a linear inversion for the moment tensor (MT) elements of a double-couple mechanism adapted from a regional moment tensor algorithm (Randall et al., 1995). Deviations from a double couple were attributed to noise and errors in locations. Synthetic seismograms were computed with a reflectivity algorithm (Kennett, 1983). Because the earthquakes studied are smaller than magnitude 3.5, their source region can

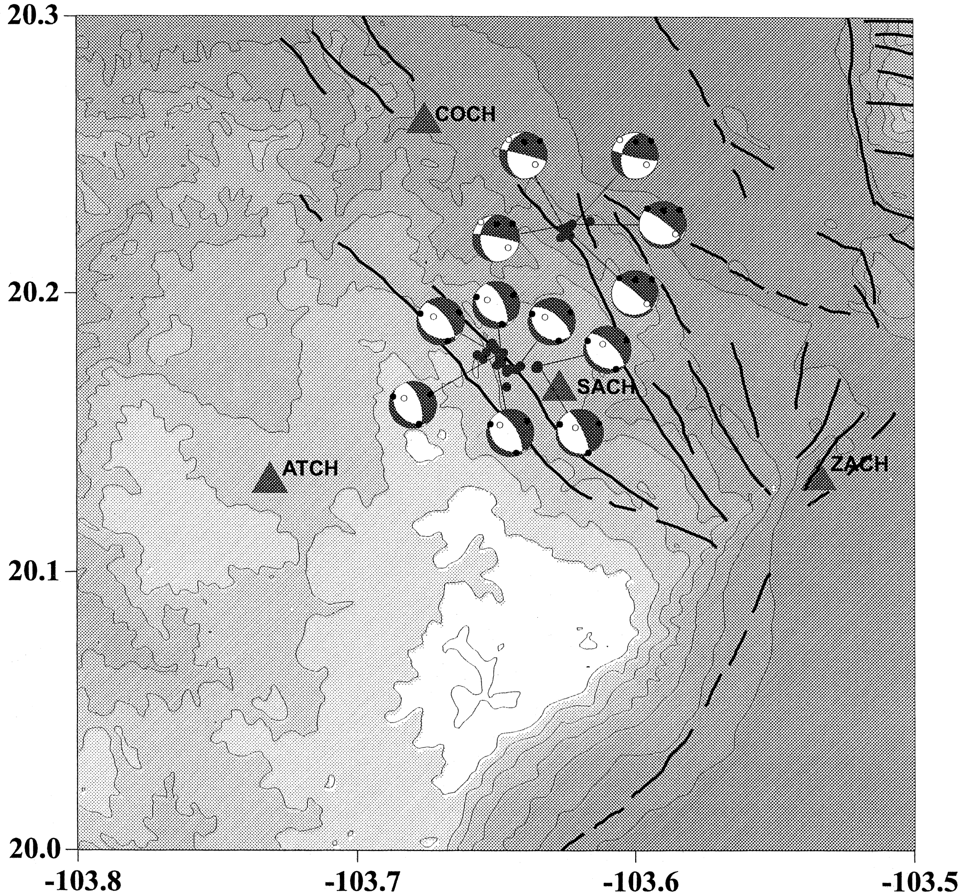

Fig. 6. Topographic map and lower hemisphere projections of earthquake focal mechanisms.

Table 2
Source parameters

Date	H:M	Latitude ()	Longitude ()	Depth (km)	Strike ()	Dip ()	Rake ()	M_w
970428	1723	20.174	−103.542	4.3	126	28	−92	2.4
970505	1923	20.174	−103.635	3.9	121	23	−102	2.5
970506	0010	20.174	−103.643	4.1	109	29	−120	1.6
970506	0242	20.175	−103.635	3.9	120	16	−124	1.9
970511	1659	20.178	−103.650	4.5	134	30	−115	2.6
970511	1705	20.176	−103.648	4.6	121	31	−120	1.6
970511	2104	20.182	−103.651	4.1	124	26	−113	2.6
970516	0241	20.223	−103.625	8.8	284	86	−122	1.9
970516	0616	20.224	−103.623	8.7	286	89	−123	1.8
970516	1031	20.222	−103.623	8.5	311	84	−79	1.9
970516	1233	20.225	−103.623	8.5	308	77	−78	1.8
970516	1240	20.224	−103.624	8.6	280	84	−124	2.2

be considered as a point source located at the hypocenter.

The displacement seismograms were band-pass filtered between 0.2 and 5 Hz. The band-pass was applied in order to remove shallow-crustal reverberations, which vary from one station to another, and to reduce the microseismic noise that peaks at 7 s (e.g. Aki and Richards, 1980). Synthetic P and S waves were aligned with the observed arrivals in order to minimize errors in location, crustal heterogeneities, and local anisotropy.

Fig. 5 shows an example of fitting P, SV, and SH waves at the four stations for an event of $M_w = 2.5$. Generally the amplitude and the phase are well modeled by the mechanism shown in the figure. The mechanism does not violate the first-motion polarities (shown in the figure) and the uncertainties are considerably reduced. Statistical errors are estimated to be within ±5 degrees for the azimuth, dip, and rake angles.

From the 33 events located in this study, we chose 12 with high signal-to-noise ratios at all stations to perform an MT inversion. Focal mechanisms present different patterns for each sequence (Fig. 6). Table 2 summarizes the parameters for each solution obtained in this study. The fault plane was taken as the nodal plane with an orientation parallel to mapped faults. Events belonging to the first sequence agree with a shallow angle (between 20° and 30°) normal fault dipping towards the SW and striking parallel to the mapped faults in the area. The focal mechanisms for the second sequence of events showed greater diversity, but they are consistent with a steeply-dipping normal fault with different degrees of strike-slip component dipping towards the NE and striking in a similar direction as the previous earthquake sequence. However, the other plane, a near horizontal normal fault dipping to the SW, could equally well be the fault plane.

6. Discussion and conclusions

A correct evaluation of the seismic hazard in towns and large cities around the triple junction must take into account the complex interaction between faults and the potential generation of earthquake ruptures in the area. The largest intensity reported during the 1568 earthquake occurred in the town of Zacoalco (Suárez et al., 1994). This maximum intensity coincides with the area of recent seismic activity during the period of April–May, 1997. The large number of fault escarpments mapped near the earthquake swarm show a complex geometry (Fig. 3). This complexity is expected at the intersection of three fault systems with trends differing by about 120° from each other. It is conceivable that large earthquakes rupture in a complex way in this region. Ferrari and Rosas-Elguera (1998) reported that most faults mapped in the area are shorter than 40 km. None of these could accommodate an earthquake larger than about M 6.5 since the width of the faults is close to 10 km. Thus several faults must be involved to generate a large earthquake.

The sequence of events indicates that there were at least two faults activated in less than a month (Fig. 6). The first, and larger, earthquake swarm occurred at depths shallower than 5 km, at the foot of the Sierra de Tapalpa, which is considered by Ferrari and Rosas-Elguera (1998) to be the southwestern block of the fault system that forms the Zacoalco half-graben. Fault plane solutions obtained in this study for the first sequence of events show a shallow-dipping normal fault striking to the SE and dipping to the SW, in agreement with mapped faults in the area.

The second, and smaller, sequence of events occurred at a greater depth (between 7 and 9 km) than the first one and about 8 km towards the center of the graben. Their fault plane solutions show two styles of faulting. One set of solutions shows a vertical normal fault with a large right-lateral strike-slip component, while the other solution presents an almost pure verti-

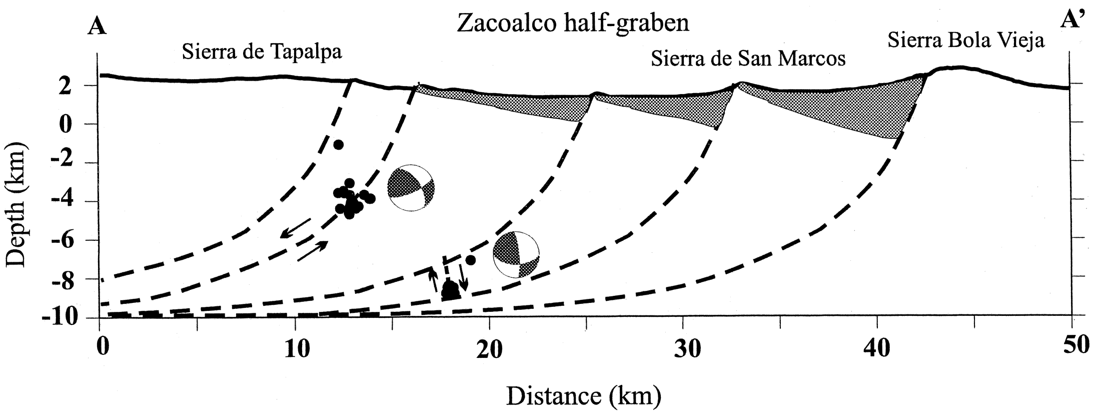

Fig. 7. Cross section and interpretation of the seismic sequence. See Fig. 1 for cross section location.

cal dip-slip motion. Both solutions indicate motion on a nearly vertical normal-fault plane (or on a nearly horizontal one), trending to the northwest.

Right-lateral motion on the Zacoalco half-graben is in agreement with Garduño and Tibaldi (1991), who found evidence for an active right-lateral pull-apart basin in the Zacoalco half-graben. Dextral motion is expected from the configuration of the triple-junction.

The earthquake sequence and their fault-plane solutions provide constraints on the proposed models of the deeper structure across the Zacoalco half-graben (i.e. Allan, 1986; Michaud et al., 1994; Rosas-Elguera et al., 1997). Barrier et al. (1990) suggested that the observed main faults at the rift edges form deep-detachment faults in the triple junction and reach depths near the brittle-ductile transition in the continental crust. Allan (1986) interpreted the structure across the Zacoalco half-graben as formed by rotated blocks at the surface, bounded by normal faults dipping to the SW. The tips of these rotated blocks at the surface confine sediment-filled basins, suggesting that crustal extension across the graben is limited to shallow depths and that normal escarpments form part of listric faults (Jackson and McKenzie, 1983). From satellite images, Michaud et al. (1994) proposed that fault structure across the Zacoalco half-graben is formed by a main detachment listric-normal fault (dipping NE) and a series of secondary listric, normal faults (dipping SW). They suggest that the detachment fault crops out at Sierra de Tapalpa and becomes near horizontal at the base of Sierra Bola del Viejo. On the other hand, Rosas-Elguera et al. (1997), incorporating more field data, proposed that the main detachment fault in the Zacoalco half-graben is formed by a listric fault that surfaces at the base of the Sierra Bola del Viejo, and dips towards the SW. A series of normal-faults, dipping SW, bounds the tilted blocks in the interior of the half-graben. Furthermore, they suggested that the maximum depth for the detachment fault should not exceed 10 km, as was reported by Suárez et al. (1994) in the region of the Sayula half-graben. Our fault-plane solutions agree better with the Rosas-Elguera et al. (1997) interpretation.

We propose a modified cross-section from the Rosas-Elguera et al. (1997) model (Fig. 7), in which we substitute the non-rotational normal faults for rotational ones in order to accommodate the shallow-angle normal faults that we obtained from the focal-mechanism solutions. Rotational normal faults start at a steep angle (in agreement with the observations) and become less steep with increasing depth, forming a series of secondary listric-normal faults. Rosas-Elguera et al. (1997) proposed the Bola del Viejo fault, part of La Lima fault system, as the main detachment structure. Other faults form a system of rotated blocks that slide as the graben opens. At the base of the detachment a set of antithetic faults are created to accommodate the motion. We infer from the seismicity that the initial brittle rupture initiated at an intermediate segment (about 5 km deep) of a listric-normal fault that dips to the SW, at the base of the Sierra de Tapalpa. A few days later, the second sequence of events occurred at a greater depth (between 7 and 9 km) either on an antithetic nearly-vertical fault or in a deeper segment along the detachment, triggered by motion of the blocks to the SW.

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