UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Unidad de Ciclos Profesionales y de Posgrado

Colegio de Ciencias y Humanidades

Posgrado en Ciencias de la Tierra

(Geología)

Tectónica Extensional en el Occidente de la Faja Volcánica Trans-Mexicana: Frontera norte del bloque Jalisco

TESIS

Que para obtener el grado de

Doctor en Ciencias de la Tierra (Geología)

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José Rosas Elguera

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CONTENIDO

Resumen

Durante los últimos diez años varios modelos tectónicos han considerado al bloque Jalisco como una microplaca separándose de México desde el Plioceno debido al salto de la East Pacific Rise hacia el oriente. Esos modelos postulan un fallamiento normal y de transcurrencia a lo largo del graben Tepic-Zacoalco. En este estudio se presentan nuevos datos sobre la estructura, cinemática y tiempo de deformación a lo largo de los límites continentales del bloque Jalisco obtenidos a través de mapeo geológico y estructural integrados con los datos de perforación de pozos profundos (geotérmicos y petrolero).

El graben Tepic-Zacoalco (limite norte del bloque Jalisco) es una combinación de tres diferentes sistemas estructurales desarrollados durante el Mioceno tardío (12-9 Ma), Plioceno temprano (5.5-3.5 Ma) y, en menor extensión, en el Plioceno tardio-Cuaternario. Esas estructuras son agrupadas en tres sectores: (1) el sistema Pochotitan (12-9 Ma); (2) el sector central formado de grábenes *en echelon* (Mioceno tardio-Plioceno); (3) sector sur, formado por tres semi-grabenes (Plioceno-Cuaternario). El desplazamiento vertical en esas estructuras es de aproximadamente 1500 m. El desplazamiento de unidades fechadas sugiere que la tasa de deformación decreció de 0.75 mm/año para el Mioceno tardío a 0.1 mm/año para el Cuaternario.

La dirección de extensión promedio para el Mioceno tardío es de 72° mientras que para el Plioceno y Cuaternario esta entre 35° y 2°. Estos resultados confirman la ausencia de fallamiento transcurrente a lo largo del graben Tepic-Zacoalco durante el Plio-Cuaternario lo cual sugiere que el bloque Jalisco no se está separando de México.

El graben de Colima (limite oriental del bloque Jalisco), está formado por el graben de Colima norte y graben de Colima sur, los cuales están separados por el complejo volcánico Colima. El graben de Colima norte está constituido por el semi-graben Amacueca de dirección NE y por el graben de Sayula de dirección norte-sur. La extensión en el graben de Colima norte comenzó en el Plioceno con el emplazamiento de rocas volcánicas. Por su parte el volcán Cántaro fue emplazado en la falla occidental del graben Sayula hace 1.6 Ma. De esta manera los 2500 m de

desplazamiento vertical ocurrieron en aproximadamente 3.5 Ma dando una tasa de subsidencia de 0.7 mm/año.

De acuerdo con el tensor de paleo-esfuerzos estimado a partir del análisis de poblaciones de fallas en el graben de Colima norte, la dirección de extensión estimada es de 140° ± 19°, no obstante una extensión E-W puede observarse de acuerdo con el alineamiento de conos volcánicos del complejo volcánico Colima.

El graben de Colima sur se localiza al sur del volcán Colima. En esta región no se encontraron evidencias de fallamiento normal importante en las rocas del Plioceno y Cuaternario expuestas a lo largo de esta estructura y, en los últimos cinco años, la red sísmica de Colima casi no registró sismicidad. Sin embargo, cientos de eventos sísmicos (Ms=5.2) fueron registrados en una extensa área al oeste de la depresión. Algunos de esos eventos se agruparon en una dirección N-NE que se propagaban desde el área de Armeria hasta la parte sur del volcán Colima.

En este sentido se propone que la extensión Plio-Cuaternaria al sur del graben de Sayula es acomodada por una área triangular comprendida entre el complejo volcánico Colima y las ciudades de Manzanillo y Armería. El limite noroeste de esta area coincide con un sistema de transcurrencia antiguo de dirección noreste que afecta rocas cretácicas, este sistema puede ser considerado el límite neotectónico de la esquina sureste del bloque Jalisco.

En la región comprendida entre Guadalajara y la unión triple de las depresiones tectónicas Tepic-Zacoalco, Colima y Chapala, la Faja Volcánica Trans-Mexicana oculta los limites entre la Sierra Madre Occidental y los bloques Michoacán y Jalisco. A lo largo de ese límite se desarrollaron varios rasgos geológicos desde el Mioceno tardío. El vulcanismo comenzó con el emplazamiento de la Secuencia Máfica Basal de la Faja Volcánica Trans-Mexicana hacia los 13-8 Ma, que llenaron depresiones tectónicas, igualmente la sedimentación lacustre es un rasgo importante y notable para este tiempo. Ello sugiere que la extensión ocurrió antes de lo que previamente había sido sugerido. Por otra parte el registro volcano-sedimentario sugiere una probable unión entre las depresiones de Tepic-Zacoalco y Chapala a través de un sistema de cuencas. Además, desde el Mioceno tardío el vulcanismo silício ha dominado en el área de Guadalajara, pero en las regiones de Chapala y Zacoalco ha sido mas intermedio.

Como conclusión final, se propone que los limites continentales del bloque Jalisco se desarrollaron en repuesta a un levantamiento del batolito de Puerto Vallarta antes del Neogeno y que fue afectado por una deformación contractil antes del Plioceno. Con base en los resultados de este trabajo se propone que (1) los limites continentales del bloque Jalisco son estructuras antiguas reactivadas desde el Plioceno con una tasa de deformación baja (<1 mm/año) y (2) el fallamiento extensional en los bordes del bloque Jalisco es una deformación intrapalaca controlada por el basamento y relacionada con fuerzas en los limites de las placas mas que a un rifting continental activo. El movimiento E-SE del bloque Michoacán estaría inducido por el movimiento diferencial y subducción oblicua de la placa de Cocos. Por otra parte, se considera que la extensión Plio-Cuaternaria a lo largo del graben Tepic-Zacoalco es una respuesta a la baja tasa de convergencia y fuerte ángulo de subducción de la placa de Rivera

Abstract

In the last decade different 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 graben. We present a new picture of the structure, the kinematics and time of deformation along the continental boundaries of the Jalisco block, obtained by geological and structural mapping integrated with subsurface stratigraphic data provided by deep geothermal and oil wells.

The Tepic-Zacoalco graben (the northern boundary of the Jalisco block) is a combination of three 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 Pochotitán fault system (12-9 Ma); 2) a central branch made of *en echelon* grabens (Late Miocene-Pliocene; 3) a southern branch constituted by three half-grabens (Pliocene-Quaternary). Vertical displacement in these structures exceeds 1500 m. Displacement of dated geologic units constraints 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.

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 (ÕHmin) is 72° for the late Miocene extension in the Gulf area, whereas in Pliocene and Quaternary it ranges from 35° to 2°. These results confirm the absence of strike-slip deformation along the Tepic-Zacoalco graben in Plio-Quaternary times and indicate that the JB is not actively separating from the Mexican mainland.

The Colima graben (the eastern boundary of the Jalisco block), is formed by : the northern and southern Colima graben, which are separated by the Colima volcanic complex. The NE-trending Amacueca half graben and the N-S-trending Sayula graben form the Northern Colima graben.

Extension in the northern Colima graben started at the beginning of Pliocene time concurrently with the emplacement of alkaline volcanic rocks. The Cantaro volcanic complex was emplaced over the western bounding fault of the Sayula graben at about 1.6 Ma. Thus 2500 m of vertical offset must have occurred in ~3.5 m.y., giving a subsidence rate of 0.7 mm/yr. In the Sayula graben, however, a minimum of 300 m of vertical offset and a rate of deformation of 0.07 mm/yr can be estimated

Paleo-stress tensors computed from fault slip data measured at seven sites in the northern Colima graben indicate an average 140 °± 19° direction for the minimum principal stress, but east-west extension is supported by the north-south alignment of the parasitic cones of the Colima volcanic complex.

The southern Colima graben is a wide topographic depression, located south of Colima volcano. We did not find any evidence of large normal faulting in the Pliocene and Quaternary rocks exposed along this structure and, in the last five years, the Colima state seismic network recorded almost no seismicity in the so-called southern Colima graben. By contrast, thousands of crustal seismic events (mostly at 19 to 7 km depth) with magnitude up to M_s = 5.2 were recorded in a broad area west of it (G. Reyes-Davila, 1996, written commun.). Some of these events clustered in northeast- to north-northeast-trending swarms propagating from the Armeria area to the southern part of the Colima volcano (G. Reyes-Davila, written commun.)

We propose that Pliocene-Quaternary extension south of the Sayula graben is accommodated in a broad triangular area comprised between the Colima volcanic complex and the cities of Manzanillo and Armeria. The northwestern boundary of this area coincides with an older belt of northeast-trending strike-slip faults affecting Cretaceous rocks, which could be considered the neotectonic boundary of the southeastern corner of the Jalisco block (Tamazula-Manzanillo fault zone).

In the region between Guadalajara and the triple junction of the Tepic-Zacoalco, Chapala and Colima tectonic depressions the late Miocene to Quaternary volcanic rocks of the Mexican Volcanic Belt (MVB) largely conceal the boundaries between the basement domains of the Sierra Madre Occidental (SMO) to the north and the Jalisco and Michoacán blocks to the south.

Along the boundary between the SMO and the blocks located to the south (i.e the Tepic-Zacoalco and Chapala grabens), several geologic features have developed since late Miocene times. The succession of the MVB began with widespread mafic volcanism, and lacustrine sedimentation occurred at 13 to 8 Ma in several tectonic basins, suggesting that the extensional reactivation of the block boundaries took place earlier than previously suggested. The volcano-sedimentary record suggests a probable link between the Tepic-Zacoalco and Chapala grabens through a basin system developed in late Miocene and early Pliocene times. Furthermore, since latest Miocene time silicic volcanism has dominated in the Guadalajara area; more intermediate to mafic products have erupted in the Chapala and Zacoalco areas.

The Jalisco block boundaries first developed in response to the uplift of the Puerto Vallarta batholith in pre-Neogene time and underwent a complex contractile deformation before the Pliocene. On the basis of new structural and geophysical data, we propose that: (1) the continental boundaries of the Jalisco block are ancient structures reactivated since the Pliocene at a low (<1 mm/yr) rate of deformation, and (2) Pliocene-Quaternary extensional faulting at the edges of the Jalisco block is a basement-controlled intraplate deformation related to plate boundary forces rather than to active continental rifting. The parallelism between the subducted Rivera-Cocos plate boundary zone and the eastern neotectonic boundary of the Jalisco block supports east-southeastward motion of the southern Mexican blocks induced by the differential motion and oblique subduction of the Cocos and Rivera plates. On the other hand, we envisage Pliocene-Quaternary extension along the northern boundary as an upper-plate response to the low convergence rate and the steep subduction angle of the Rivera plate.

I INTRODUCCION

Durante los últimos años la cinemática del bloque Jalisco ha sido de particular interés ya que representaría un ejemplo interesante de fragmentación continental, con la posibilidad de que, al igual que Baja California, el bloque Jalisco sea transferido a una placa oceánica. No obstante, los resultados que se presentan en este trabajo parecen no soportar esta hipótesis que ha dominado el ambiente geológico durante los últimos 15 años. El bloque Jalisco, junto con los bloques Michoacán, Guerrero, Oaxaca y Chiapas, fueron términos acuñados por Mooser en 1972 para referirse a cinco bloques continentales ubicados al sur de la Faja Volcánica Trans-Mexicana (Fig. 1.1). Estos bloques estarían separados por elementos morfotectónicos importantes, por ejemplo el graben de Colima separa los bloques de Jalisco y Michoacán. Más recientemente, Mammerickx y Klitgord (1982), estudiando las lineaciones magnéticas y topografía de la East Pacific Rise, documentan una serie de reorganizaciones del centro de esparcimiento desde el Oligoceno tardío, estas reorganizaciones provocaron la transferencia de la East Pacific Rise hacia el oriente creando microplacas cuya vida fue de corta duración.

Estos dos conceptos, el bloque Jalisco y la transferencia de la East Pacific Rise hacia el oriente, fueron capitalizados por Luhr et al. (1985). Estos autores sugirieron que el último salto de la East Pacific Rise estaba representado por el graben de Colima lo que trajo como consecuencia la fragmentación continental y, en consecuencia, la "individualización" del bloque Jalisco. A partir de 1985 los modelos geodinámicos subsecuentes estaban fundamentados en el trabajo de Luhr y colaboradores. El modelo de Luhr et al. (1985) resultaba muy atractivo y novedoso dado que permitiría estudiar los

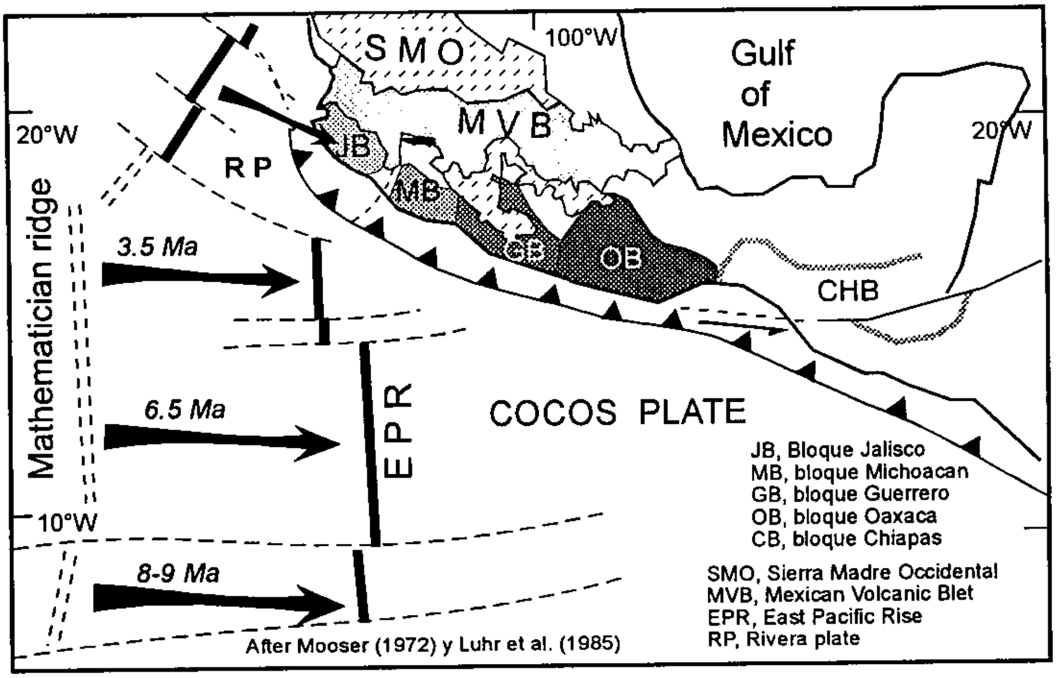

Fig. 1.1 Esquema en bloques sugerido para el occidente de México. Se incluyen los saltos de la Cresta del Pacifico Oriental (EPR). El último salto de la Cresta formaría el graben de Colima y el bloque Jalisco (JB) derivaría hacia el NW.

estados iniciales de una fragmentación continental y captura por una placa oceánica, tal como ocurrió con Baja California.

Intrínsecamente el modelo de Luhr et al. (1985) requería que el bloque Jalisco se desplazara a lo largo del graben Tepic-Zacoalco en un ambiente de fallamiento lateral derecho lo que provocaría la extensión requerida para que se formara el graben de Colima. El hecho de que el bloque Jalisco se estuviese moviendo a lo largo de un sistema dextral implicaría una convergencia oblicua entre las placas de Rivera y Norteamérica. Otros modelos, por ejemplo los que usan la tasa de convergencia entre la placa de Norteamérica y la placa de Rivera (Kostoglodov y Bandy, 1995) concluyen que el modelo que utiliza una convergencia alta se ajusta mejor a las relaciones sismotectónicas, las cuales relacionan las características sísmicas de las zonas de subducción (magnitudes y profundidades de los sismos) con los parámetros tectónicos (tasa de convergencia, edad de la placa en subducción, etc.). Esto implica que la componente lateral paralela a la trinchera se incremente de SE (casi a la altura del graben de Colima) a NW (al occidente de Bahía de Banderas), lo que provocaría un movimiento hacia el NW del bloque Jalisco y una extensión NW-SE, particularmente en la parte norte del bloque Jalisco.

Otros modelos (e.g. DeMets y Stein, 1990; este trabajo) consideran una convergencia de la Placa Rivera normal a la trinchera. En este sentido, DeMets y Stein (1990) sugieren que la formación del graben de Colima se relaciona con el movimiento hacia el SE, con relación a Norteamérica, del bloque Michoacán.

Adicionalmente a los resultados de la geología continental que se presentan en este trabajo, los datos que se tienen sobre el piso oceánico (tasas de esparcimiento a lo largo de la dorsal Rivera-Pacifico en la boca del Golfo de California) tampoco están de acuerdo con el modelo relacionado con el salto de la dorsal al continente. Lo que pude notarse de las anomalías magnéticas es que la tasa de dispersión entre las placas de Rivera y Pacífico se aproxima mas y mas a la tasa de esparcimiento Norteamérica-Pacífico. En este marco, la placa Rivera puede estar uniéndose poco a poco a Norteamérica, y no juntándose con la placa Pacífico (Stock, comunicación escrita).

En este estudio se presentan los resultados del trabajo de investigación que se realizó, en principio, en la frontera norte del bloque Jalisco y que, por los resultados que se fueron obteniendo durante su desarrollo, hubo necesidad de estudiar la parte norte del graben de Colima. Los capítulos que conforman la tesis son artículos publicados o en prensa. En el capitulo II, se presenta una compilación de regional sobre la estratigrafía y estructura del graben de Tepic-Zacoalco y se aportan algunos nuevos datos. La relevancia de este capítulo está en el hecho de que resalta varios puntos hasta entonces no cuestionados. (a) la simetría del graben Tepic-Zacoalco, (b) Se propone por vez primera una faja de semi-grábenes que formarían la frontera sur del graben, (c) También se cuestiona la transcurrencia activa a lo largo del graben, por el contrario, (d) Se sugiere, por vez primera, que si el bloque Jalisco se está moviendo lo debería de hacer hacia el SW con respecto a la placa de Norteamérica.

En el capitulo III, se estableció una estratigrafía regional del área de Guadalajara y punto triple. En este sentido, los aportes más importantes son: (a) A través de fechamientos K-Ar y Ar-Ar practicados a ignimbritas, se documenta la no-existencia de la Sierra Madre Occidental al sur del semi-graben de Zacoalco (es decir, en el bloque

Jalisco), (b) Se demuestra también que rocas pliocénicas descansan sobre las ignimbritas cretácicas (~80 Ma), (c) Se sugiere la posibilidad de que la ignimbrita San Gaspar (horizonte índice regional) haya fluido hasta el semigraben de Zacoalco. Por otra parte, se documenta la arquitectura del semigraben de Zacoalco. Se sugiere que (d) la falla principal de caracter lístrico esté ubicada al NE del semigraben de Zacoalco, (e) el sistema de fallas principales en la depresión de Zacoalco son de caracter normal sin componente lateral y planas (no lístricas), (f) se propone una flexura roll-over que explicaría la densidad de fallamiento normal en la Sierra de Atemajac.

En el capítulo IV se documenta la arquitectura del graben Tepic-Zacoalco. En esta sección se distinguen las estructuras relacionadas con la tectónica del Golfo de California (el sistema de fallamiento Pochotitán) de las que pertenecen a la tectónica asociada con el graben de Tepic-Zacoalco. En este último caso se documentan los grábenes de Compostela-Ceboruco y Plan de Barrancas-Santa Rosa. Otras aportaciones de este capítulo son: (a) Se confirma la ausencia de un fallamiento lateral para el Plio-Cuaternario, (b) la tasa de deformación decrese del Mioceno tardío al Cuaternario, (c) Se plantea la posibilidad de que la deformación observada esté relacionada a fuerzas en los límites de las placas y no a una transferencia de la East Pacific Rise.

El capitulo V, presenta un modelo donde se analizan y sintetizan los resultados obtenidos en el graben Tepic-Zacoaclo junto con los obtenidos para la parte norte del graben de Colima. Las aportaciones de este capitulo son: (a) las fronteras continentales del bloque Jalisco son límites antiguos desarrollados en respuesta al levantamiento del batolito de Puerto Vallarta y que (b) son zonas de debilidad que se han reactivado a través del tiempo; (c) Por último se propone que la extensión observada en los grábenes Tepic-Zacoalco y Colima se debe a un retroceso de la trinchera y al movimiento hacia el E-SE del bloque Michoacán con relación a Norteamérica. Finalmente, en el capitulo VI se propone un modelo donde las diferentes edades de las secuencias volcano-sedimentarias son explicadas en términos de una migración hacia el sur de un sistema de cuencas.

1.1 Limitaciones del Estudio

A pesar de que la región donde se desarrolló esta investigación ha sido motivo de al menos cuatro tesis doctorales, incluida ésta, los resultados aquí presentados solo permiten aclarar algunos puntos que permanecían obscuros. Otros continúan oscuros, por ejemplo:

1. Aunque se ha sugerido que el espesor cortical del bloque Jalisco es de ~39 km (Urrutia-Fucugauchi y Flores, 1996) queda aún por resolver el tipo de basamento.
2. El significado de las extensas áreas cubiertas por rocas ignimbríticas de composición riolítica y edad cretácica que se ubican al sur del graben Tepic-Zacoalco.
3. La edad y estilo de deformación hacia el interior del bloque Jalisco, problema que se complica debido a que solo hay rocas cretácicas cubiertas inmediatamente por rocas Plio-Cuaternarias.
4. Aunque Carmichael y sus estudiantes investigaron los campos volcánicos de Mascota, Talpa, Atenguillo, Amatlán y los basaltos que ocurren al norte de Guadalajara, aún queda por resolver la petrología del campo volcánico de Ayutla y su significado en el marco regional.

5. Durante el curso de la investigación pude detectar varias zonas de acomodo. En algunas regiones el vulcanismo estaba asociado a estas zonas, en otras el acomodo de la deformación se daba a través de un intenso fallamiento. Que factores influyen en cada caso ?
6. Las zonas de acomodo tienen una firma geoquímica en particular ?

Estas son solo algunas preguntas que quedan por resolver.

II AMBIENTE ESTRUCTURAL EN LA FRONTERA NORTE DEL BLOQUE JALISCO

Por

J. Rosas-Elguera, J. Nieto-Obregon y J. Urrutia-Fucugauchi

Resumen

El Bloque Jalisco (BJ) es una morfoestructura regional ubicada en el occidente de México. Aquí se sugiere que el límite norte del Bloque Jalisco está definido por una serie de depresiones tectónicas de dirección general NW-SE cuya traza tiene forma de Z alargada. Las principales características de estas depresiones son: a) al bloque hundido es siempre el bloque SW; b) el bloque hundido está basculado hacia el norte; c) el límite norte de estas cuencas tiene una dirección E-W la cual (hacia el oriente) cambia a NW-SE. La fase tectónica reciente que ha afectado a las depresiones está asociada con una dirección de extensión NE-SW. El análisis de la estructura de las cuencas tectónicas no apoyan la posibilidad de que el Bloque Jalisco esté derivando hacia el NW a lo largo de un sistema transcurrente diestro. Aquí se postula que las depresiones que constituyen la frontera norte del Bloque Jalisco se originaron como consecuencia de una fase extensional de dirección NE-SW provocada por el movimiento hacia el SW del Bloque Jalisco. Intrínsecamente, esta interpretación conlleva a dos observaciones: a) cuestiona la existencia del Graben de Tepic; aquí sugerimos que un sistema de medios grábenes explicaría mejor los rasgos observados y b) plantea un esquema donde las estructuras que conforman el Graben de Colima tendrían una componente lateral izquierda.

Abstract

Jalisco Block is major morphostructure located at west side of Mexico. Northern border of Jalisco Block is conformed by tectonic depressions running NW-SE. Fault-traces have a elongate Z pattern. Main characteristics of these depressions are: a) down-block is always SW-block; b) down-block is tilting northward; c) fault-traces trending E-W changing eastward to NW-SE trend. Earlier tectonic phase of the basins is associated with a NE-SW extension. The possibility that Jalisco Block is drifting to northwest along dextral fault system is not supported by the analysis of the structure of these depressions. We suggest that they are the response to an extensional phase trending NE-SW which has been provoked by the SW movement of the Jalisco Block. Intrinsically, two major conclusions rise up from this interpretation: a) controversy about existence of the Tepic Graben; we propose that our observations agree with a half-grabens system, and b) left-lateral component would be associated with the structures making up the Colima graben.

2.1 Introducción

La tectónica cenozóica del occidente de México se ha desarrollado en un ambiente muy dinámico a lo largo de su historia debido a: la continua subducción de la placa oceánica por debajo de la placa continental (Bourgois et al., 1988; Luhr et al., 1985; Atwater, 1970), los cambios de las direcciones de movimiento relativo entre placas, los saltos hacia el continente de la Cresta del Pacífico Oriental que han venido ocurriendo desde hace 12 Ma (Mammerickx y Klitgord, 1982) y a la apertura del Golfo de California (Gastil y Jensky, 1973). El marco geodinámico actual del occidente de México está influenciado por la interacción entre las placas de Rivera, de Cocos y de Norteamérica, la oblicuidad y los diferentes ángulos de la subducción a lo largo de la Trinchera Mesoamericana. En este ambiente se encuentra situado el Bloque de Jalisco (Fig. 2.1).

La región occidental de la Faja Volcánica Transmexicana está dominado por cuencas tectónicas y cadenas montañosas. Las orientaciones principales de las depresiones tectónicas mayores son E-W (graben de Chapala), N-S (graben de Colima) y NW-SE (graben de Tepic) (Fig. 2.1). Los orígenes de estos grábenes ha sido objeto de recientes discusiones (Serpa et al., 1992; Rosas-Elguera, 1991; Delgado-Granados, 1991; DeMets y Stein, 1990; Delgado-Granados y Urrutia-Fucugauchi, 1986; Luhr et al., 1985). En general, las depresiones tectónicas muestran expresiones morfológicas características tales como lagos elongados, colinas alineadas y es común encontrarlas asociadas con sedimentos recientes, actividad volcánica y geotérmica, y, en el caso del graben de Chapala, con manifestaciones de hidrocarburos.

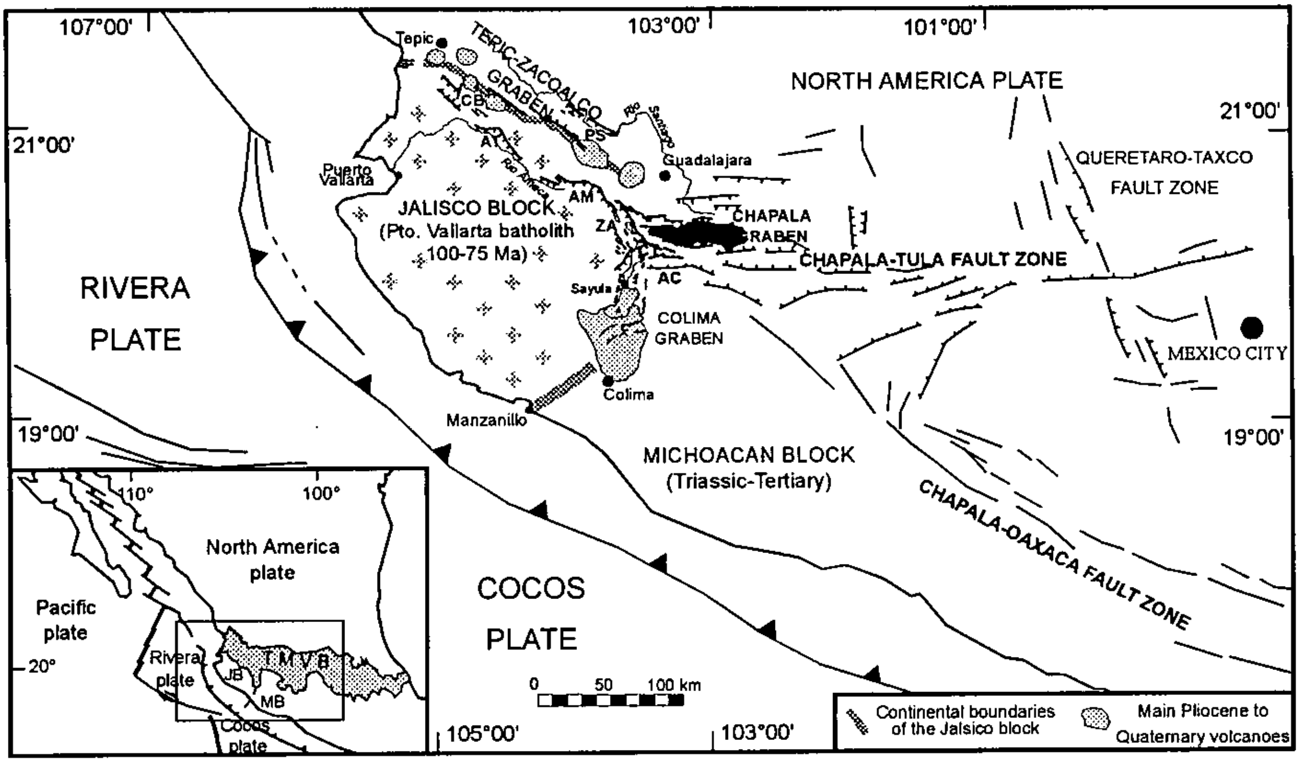

Fig. 2.1 Ambiente geodinámico del occidente de México. El bloque Jalisco está definido por el graben de Colima, la Trinchera Meso-Americana y el sistema Tepic-Zaoalco. Las zonas de falla Chapala-Oaxaca y Chapala-Tula tienen un sentido sinistral. TMVB, Faja Volcánica Trans-Mexicana. Adaptado de Harrison y Johnson (1988) y Rosas-Elguera et al. (1996).

Respecto al movimiento del Bloque Jalisco son dos las propuestas básicas: a) que el Bloque Jalisco deriva hacia el NW a lo largo de un sistema diestro (Allan et al., 1991; Garduño y Tibaldi, 1991; Garduño, 1988; Bourgois et al., 1988; Pasquaré et al., 1986; Luhr et al., 1985) y b) Nieto Obregón et al. (1985) y Harrison y Johnson (1988) postulan la posible existencia un sistema siniestro a lo largo del Río Grande de Santiago. En ambos casos el límite del Bloque Jalisco lo establecen a la altura del Río Grande de Santiago. Recientemente, se sugirió una dirección de extensión NE-SW en la Depresión de Amatlán de Cañas (Guzmán de la Campa,1989; Nieto Obregón et al., 1992).

Con el propósito de contribuir al conocimiento de la frontera norte del Bloque Jalisco y de su problemática, aquí se hace una síntesis de algunos de los resultados publicados que, en conjunto, con el análisis e interpretación de las depresiones que conforman el marco estructural de la porción NW de la Faja Volcánica Transmexicana, se discuten en términos de un mecanismo extensional que involucra el movimiento hacia el S-SW del Bloque Jalisco, originando las depresiones aquí descritas y discutidas. El análisis morfotectónico se llevó a cabo en mapas hipsográficos (escala 1:250 000) y en imágenes de satélite Landsat (escala 1:1 000 000 y 1: 500 000).

2.2 Los límites del bloque Jalisco

La zona central de México es una región tectónicamente activa que hacia el sur está dividida en varios bloques cuyos límites son discontinuidades tectónicas regionales (Fig. 2.1; Harrison y Johnson, 1988). La zona de Falla Chapala-Tula, que separa la Placa de Norteamérica de los bloques Michoacán y Guerrero (Fig. 2.1), tiene movimientos laterales izquierdos recientes que han sido documentados por Urrutia-Fucugauchi Böhnel (1988; 1987) y Harrison y Johnson (1988). Hacia el occidente, el Graben de Colima separa el Bloque Jalisco del Bloque Michoacán (Fig. 2.1). En la parte norte del graben de Colima el fallamiento normal tuvo un desplazamiento vertical es de 2.5 km y ocurrió en los últimos 4.9 millones de años (Allan, 1986). La prolongación hacia el mar del graben de Colima, junto con la Falla Barra de Navidad, constituyen el límite activo del Bloque Jalisco (Bourgois et al., 1988). DeMets y Stein (1990) sugirieron que el graben de Colima pudiera ser una cuenca tensional pasiva como respuesta al movimiento hacia el SE del Bloque Michoacán a lo largo de la zona de Falla Chapala-Oaxaca de carácter izquierdo (Fig. 2.1). La porción occidental y sur del Bloque Jalisco está limitada por la Trinchera Mesoamericana. Las características de esta frontera son su oblicuidad de 20° (Molnar y Sykes, 1969) con respecto a la Faja Volcánica Transmexicana y sus diferentes ángulos de subducción a lo largo de la fosa (Pardo y Suárez, 1992).

Los rasgos morfotectónicos principales del occidente de la Faja Volcánica Transmexicana, específicamente del sector norte del Bloque Jalisco, se muestran en la figura 2.2. Esta figura muestra que las trazas de las fallas de las depresiones tectónicas de Amátlan de Cañas, Ameca y Zacoalco, que constituyen el límite norte del Bloque Jalisco, tienen forma de Z alargada con una dirección general NW-SE. El basculamiento de estas depresiones es consistentemente hacia el N-NE lo que, en conjunto, provoca una estructura del tipo semi-grábenes más que un graben. Estas características estructurales, cuestionarían a priori la existencia del graben de Tepic.

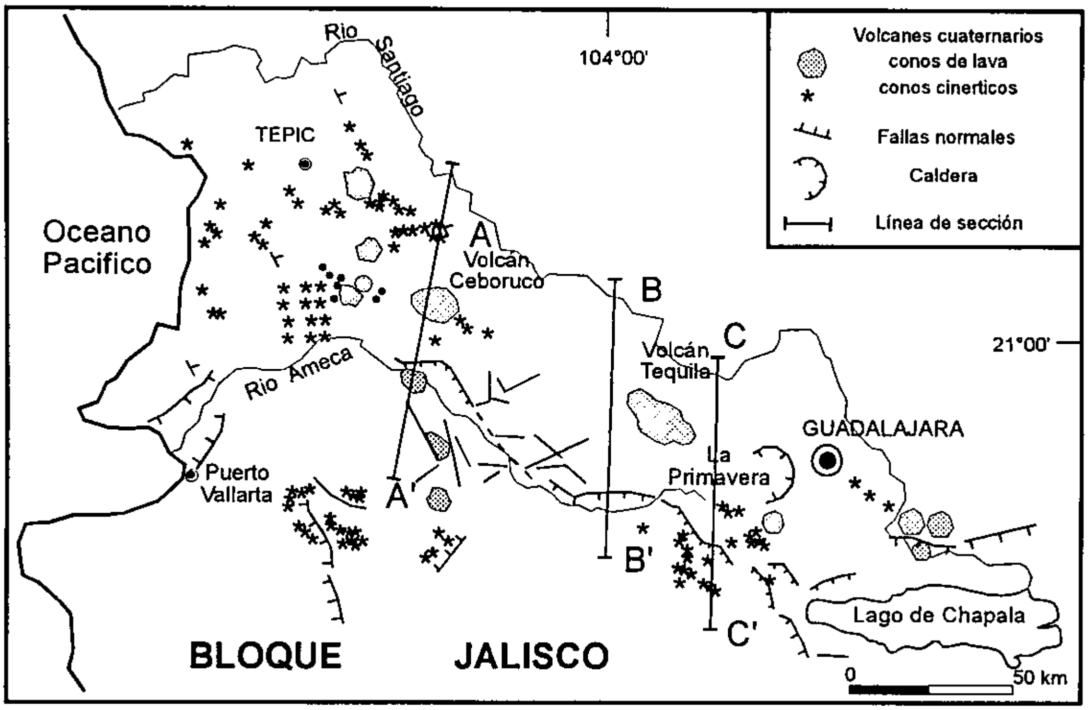

Fig. 2.2 Síntesis del ambiente volcano-tectónico de la frontera norte del bloque Jalisco. Nótese: (a) La dirección NW-SE y la forma de Z alargada de las fallas que conforman el limite norte del bloque Jalisco, (b) La gran similitud de los cauces de los rios Santiago y Ameca.

Las rocas volcánicas Plio-cuaternarias en la región de Tepic (Fig. 2.2) son de afinidad calcoalcalina y alcalina, las primeras son volumétricas predominantes y forman estratovolcanes mientras que las alcalinas, de menor volumen, están asociadas con fisuras profundas (Nelson y Carmichael, 1984; Nelson y Livieres, 1986). Existen varios grupos de volcanes y cráteres que forman cadenas cuya dirección es N45°W que indican un sistema de fracturas cuya dirección de extensión máxima sería NE-SW, ortogonal a la dirección de los volcanes (Gastil et al., 1979 a y b ; Suter, 1991) En la misma región de Tepic los estratos volcánicos pre-pliocénicos generalmente buzan 30°-40°NE (Gastil et al., 1979 a y b, Fig. 2.2).

Básicamente existen dos propuestas para explicar el movimiento del Bloque Jalisco: a) que el límite norte del Bloque Jalisco está controlado por un sistema transcurrente lateral derecho (Allan et al., 1991; Garduño y Tibaldi, 1991; Garduño, 1988; Bourgois et al., 1988, Pasquaré et al., 1986;) que controla el cauce del Río Grande de Santiago, por lo que el Bloque Jalisco estaría derivando hacia el NW y b) que los movimientos laterales izquierdos son los mayores y dominantes para este sector (Nieto et al., 1985; Harrison y Johnson, 1988). Garduño y Tibaldi (1990) reconocieron tres sistemas de fallamiento en el Río Grande de Santiago: uno normal de dirección N40°-75°, el otro sistema de tipo transcurrente, y que corta al anterior, tiene una dirección N110°-150°, en este sistema las fallas laterales izquierdas son miocénicas y las derechas del Plio-Cuaternario. Sin embargo, la fase tectónica más reciente para este sector está asociada con una distensión de dirección NE-SW (Michaud et al., 1991).

Los estudios de neotectónica sugieren que hacia el oriente del graben de Chapala, los movimientos izquierdos son los dominantes (Harrison y Johnson, 1988; Urrutia-Fucugauchi y Böhnel, 1988; 1987), mientras que hacia el occidente no se han identificado rotaciones de bloques como cabría esperar en un ambiente transcurrente (diestro o siniestro) (Urrutia-Fucugauchi y Rosas-Elguera, 1994; Mailloil y Bandy, 1994). Así, es posible que hacia el occidente del graben de Chapala esté actuando un mecanismo en el cual la participación de los movimientos trasncurrentes sea menor.

2.3 Depresiones Tectónicas

La Depresión de Amatlán de Cañas. En esta depresión (Fig. 2.3) las alturas máximas de la planicie son de 1000 msnm y está seccionada por el Río Ameca; hacia el norte la depresión está limitada por la Sierra del Guamuchil cuyas elevaciones mayores son de 1500 msnm. Lo bien preservado de las facetas triangulares del escarpe que limita la planicie evidencia lo reciente de la estructura.

Las rocas basales de la Sierra del Guamuchil consisten en dioritas, granodioritas, mozodioritas y gabros cuyas edades varían entre los 40.8 y 97.6 Ma (Gastil et al., 1979 a y b) que subyacen o intrusionan a ignimbritas riolíticas y tobas del Cretácivo tardío-Terciario. El vulcanismo en la Depresión de Amatlán de Cañas es de afinidad alcalina y calcoalcalina y se llegan a encontrar intercalados con conglomerados formados por fragmentos de rocas volcánicas y plutónicas. Los restos fósiles de mamut encontrados en los conglomerados que subyacen a los flujos máficos más antiguos ubican en el Pleistoceno a estas rocas volcánicas (Nieto-Obregón et el., 1992).

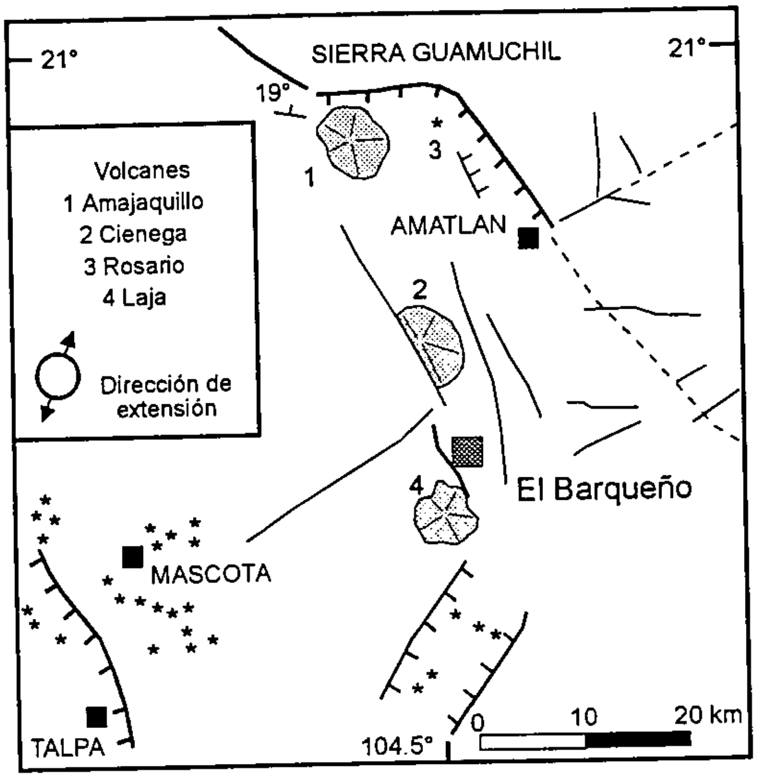

Fig. 2.3 Mapa tectónico simplificado de las depresiones Amatlán de Cañas, Mascota-Talpa y Atenguillo. El estereograma indica la dirección de extensión encontrada por Guzmán de la Campa (1989). El resto de los símbolos como en la figura 2.2

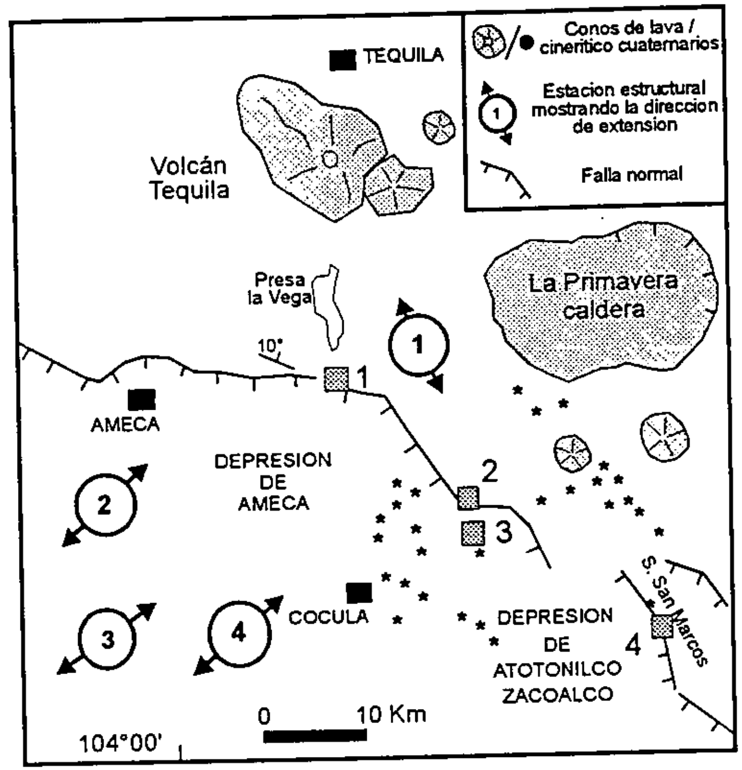

Fig. 2.4 Mapa tectónico simplificado de las depresiones Ameca y Zacoalco. Estereogramas:1-2, este trabajo; 4, Barrier et al. (1990); en 3, la dirección es estimada a partir de fracturas (n=85). El resto de los simbolos como en la figura 2.2

El tramo E-W de la falla que constituye la frontera norte de la Depresión de Amatlán de Cañas tiene longitud de 15 km, hacia el oriente el rumbo de la falla cambia a N35°-40°W por aproximadamente 40 km (Fig. 2.2). Esta falla es continua y puede ser muy reciente según se desprende de lo bien conservado de sus facetas triangulares en la traza del escarpe de falla y del hecho de que esté cortando los conglomerados donde se encontraron los fósiles de mamut (Nieto-Obregón et al., 1992). Hacia el SW de Amatlán de Cañas se localiza la falla Atenguillo de dirección N25°-30°W que es subparalela a otras dos ubicadas inmediatamente al NE de ella (Fig. 2.2). En el bloque levantado de la Depresión de Amatlán de Cañas se puede apreciar un sistema conjugado de estructuras que posiblemente estén asociadas a las fallas regionales, las direcciones principales de este sistema de fallas son N60°E y N45°-60°W (Fig. 2.3).

Debido al basculamiento de unidad conglomerática de 10°a 20° hacia el escarpe de la falla principal (hacia el NE) que limita la Depresión de Amatlán de Cañas y de sus resultados paleomagnéticos, Nieto-Obregón et al. (1992) interpretaron un fallamiento lístrico regional. La dirección de la inclinación de los estratos es consistente con la encontrada por Gastil et al. (1979 a y b) para las rocas volcánicas pre-pliocénicas de la región de Tepic, aunque en esta región el buzamiento varía de 30° a 40°.

Las morfoestructuras volcánicas más relevantes en la Depresión de Amatlán de Cañas son los volcanes Amajaquillo, Ciénega y Laja (Fig. 2.3). Los volcanes Amajaquillo y La Ciénega son de carácter calcoalcalino mientras que La Laja, El Vigia y las mesas de basaltos entre los ríos Ameca y Atenguillo son de carácter alcalino (Righter y Carmichael, 1992; Nieto Obregón et al.,1992). Las edades radiométricas por K-Ar indican edades entre

0.64 y 3.6 para el vulcanismo reciente del Campo Volcánico de Amatlán de Cañas Ma (Righter y Carmichael, 1992). Debido a que el volcán Ciénega (2.2 Ma) está cortado por la falla Atenguillo, pero el volcán Laja (0.66 Ma) no, se deduce que la falla estuvo activa entre la formación de esos volcanes.

La Depresión de Ameca. La Depresión de Ameca es una planicie con una altura menor de 1300 msnm (Fig. 2.4). El límite norte de esta depresión lo forma la Sierra de la Laja cuya base está constituida por un intrusivo granítico de 76 ± 6 Ma (Grajales-Nishimura y López-Infanzón, 1983) sobre el que descansan, discordantemente, conglomerados y areniscas del Cretácico Tardío (Ramírez, 1981). Hacia el SW de Ameca aflora un intrusivo cuarzomonzonítico de 54.3 ± 4.9 Ma (González-Partida y Martínez-Serrano, 1989). Al oriente, la Depresión de Ameca está limitada por rocas riolíticas y andesíticas del Plioceno tardío sobre las que fluyeron andesitas y basaltos del Cuaternario (ver capitulo III). Finalmente, en la Depresión de Ameca también aflora una secuencia volcanosedimentaria basculada 10°NE (Fig. 2.4).

El límite norte de la Depresión de Ameca es un escarpe de dirección E-W cuya longitud es de 30 km, que hacia el oriente cambia a una dirección N35°W (Fig. 2.4). El espesor de lo sedimentos es de unos 1000 m (Alatorre, 1996, comunicación personal). En nuestro trabajo estructural preliminar hemos considerado el buzamiento y la dirección del buzamiento del plano de falla así como el plunge y la dirección de las estrias. Para establecer el sentido de las fallas se consideraron los criterios de Petit (1987) y Petit et al. (1983). Se usó el método de Aleksandrowski (1985) para determinar la dirección de los paleo-esfuerzos en los sitios evaluados. El estudio de la Sierra de la Laja ha evidenciado fallamiento inverso (N5°E 20°SE y pitch de 60°SE), mientras que para el sitio ubicado al sur de la Presa de la Vega se estimó una dirección de NW-SE para s3 (Fig. 2.4).

Depresión Atotonilco-Zacoalco. La Depresión de Atotonilco-Zacoalco cuya altura promedio es de 1400 msnm constituye el extremo SE del graben de Tepic (Fig. 2.4). Esta depresión está conformada por dos pequeñas cuencas que contienen a las lagunas de Atotonilco, Zacoalco y San Marcos cuyos ejes mayores tienen una dirección NW-SE (Fig. 2.4). Al igual que en las anteriores depresiones, en estas dos cuencas el límite norte lo constituye un escarpe cuya dirección es casi E-W. En ambos casos las dimensiones son considerablemente menores que en las anteriores depresiones; sin embargo, también hacia el oriente, el escarpe cambia de E-W a una dirección NW-SE. La traza de la falla San Marcos sirve como conducto a las manifestaciones termales cuyas temperaturas alcanzan hasta 90°C. En este sector el espesor de los sedimentos lacustres y vulcano-sedimentarios es de al menos 750 m (Gutiérrez-Negrín, 1984), aunque pudieran llegar a 900 m o más como ocurre al norte del graben de Colima (Allan, 1985).

Hacia el norte, la característica principal de la Depresión Atotonilco-Zacoalco es la naturaleza bimodal de su vulcanismo calco-alcalino cuyas edades varían entre 2.0 y 0.65 Ma (Delgado-Granados, 1991; Allan 1986). Hacia el norte de la depresión se desarrolló el complejo volcánico La Primavera, cuyas rocas hiperalcalinas son del Pleistoceno (Mahood, 1977; Demant y Vincent, 1978).

La Sierra de San Marcos limita hacia el oriente la Depresión Atotonilco-Zacoalco. La porción sur de la sierra está formada por una secuencia de rocas volcánicas del Mioceno tardío-Plioceno temprano cuyo espesor es de unos 750 m y en cuya base afloran tobas riodacíticas, hacia la cima las rocas son andesitas separadas (en diferentes niveles) por dos flujos ignimbríticos. En su porción norte los fechamientos reportados por Allan (1986), varían entre 0.65 (andesitas) y 1.44 Ma (dacita).

Los lineamientos mayores interpretados para la Depresión Atotonilco-Zacoalco, tienen una dirección general N35°W que es paralela a la tendencia principal de los volcanes monogenéticos lo cual implica que la dirección de compresión mínima es NE-SW (Fig. 2.4). El volcanismo presente en la Depresión de Atotonilco-Zacoalco constituye la diferencia principal con respecto a las otras dos depresiones ya que en la Depresión de Ameca los volcanes monogéneticos están prácticamente ausentes. Por su parte, en la Depresión de Amatlán de Cañas el vulcanismo es de afinidad alcalina y calco-alcalina (Nieto Obregón et al., 1992; Righter y Carmichael, 1992) mientras que en la Depresión de Atotonilco-Zacoalco es de carácter calco-alcalino (Delgado-Granados, 1991).

Los bloques hundidos en la Depresión de Atotonilco-Zacoalco son los ubicados en el SW. Es común encontrar manantiales termales asociados con estas fallas (e.g. San Marcos, Villa Corona, Aguacaliente) cuyas temperaturas varían entre 40° y 90°C. El límite norte de la Depresión de Atotonilco-Zacoalco es una falla normal cuya dirección de máxima extensión es de NE-SW (Fig. 2.4). Por su parte, el fracturamiento distensivo en la parte suroccidental de la Depresión de Atotonilco-Zacoalco tiene una actitud N25-30°W por lo que se asume que la dirección de s3 es N60°E que es casi paralela a la encontrada por Barrier et al. (1990) para la región de Zacoalco (Fig. 2.4), a la estimada para el Río Santiago (Michaud et al., 1991) y a la asumida según la distribución de los volcanes en los límites entre las depresiones de Ameca y Atotonilco-Zacoalco (Fig. 2.4).

Las secciones Morfoestructurales. En la figura 2.5 se presentan las secciones morfoestructurales de las depresiones de Amatlán de Cañas, de Ameca y de Atotonilco-Zacoalco. Los bloques ubicados al norte de las depresiones muestran diferentes grados de disección vertical. En el Bloque Ceboruco, el Río Grande de Santiago ha profundizado su cauce hasta los 200 msnm, lo que contrasta notablemente con la Sierra del Guamuchil, donde la disección vertical alcanza sólo los 1000 msnm, y con la Depresión de Amatlán de Cañas donde el cauce del Río Ameca está a 600 msnm (Fig. 2.5a). En el Bloque Laja el cauce del Río Grande de Santiago está a 500 msnm, mientras que el del Río Ameca está a 1300 msnm; finalmente en el Bloque Primavera el cauce del Río Grande de Santiago está a 750 msnm. Al comparar los niveles bases de erosión (Fig. 2.5) puede notarse que en el extremo más occidental de la zona de estudio (Fig. 2.5a) el nivel alcanza una elevación considerablemente menor que en las dos zonas restantes (Figs. 2.5b y 2.5c). Ello implica, a priori, que la erosión fluvial ha alcanzado a afectar rocas más antiguas en el occidente que hacia el oriente. El hecho de que la Sierra del Guamuchil, donde afloran rocas intrusivas (Gastil et al., 1979 a y b), esté profundamente disectada (Fig. 2.5a) soporta la idea anterior. Con estos argumentos y considerando que los cauces de los ríos Grande de Santiago y Ameca están controlados por fallas, entonces es posible que estas características pudieran interpretarse en términos de sus edades relativas y sugerirse que

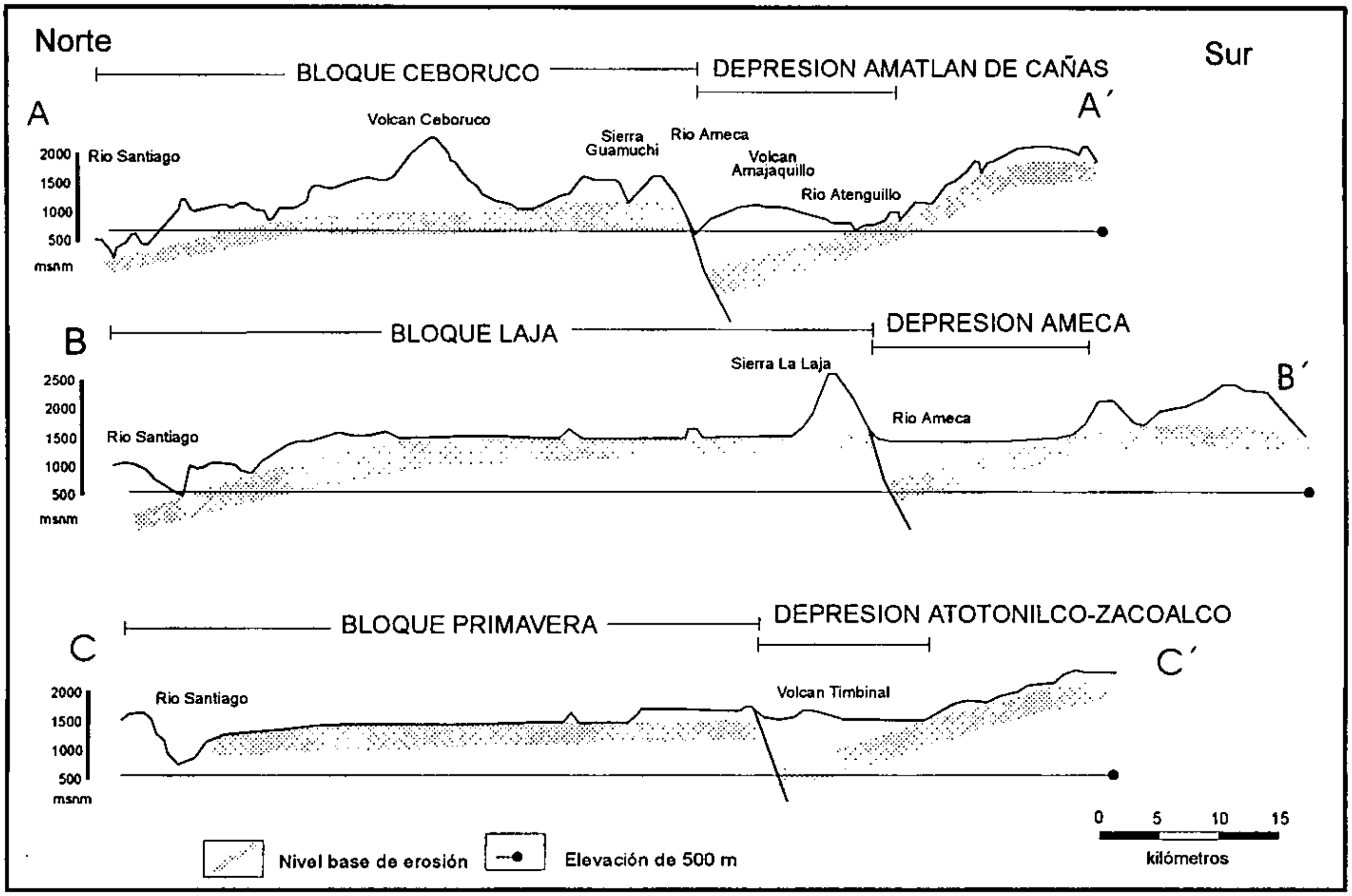

Fig. 2.5 Secciones morfoestructurales de las depresiones Amatlán, Ameca y Zacoalco, su localización se muestra en la figura 3.2. Nótese (a) la diferencia de alturas entre los cauces de los rios Santiago y Ameca; (b) el basculamiento hacia el norte del macizo montañoso. Ver el texto para la discusión

la actividad tectónica que las originó se inició en el occidente haciéndose más joven hacia el oriente.

De las premisas anteriores se desprenden básicamente dos observaciones: a) que el fallamiento que controla los cauces de los ríos Grande de Santiago y Ameca es más reciente hacia el sur. Este fallamiento sería de carácter lístrico con el bloque basculado hacia el norte (Fig. 2.5); b) que los procesos erosivos han actuado con mayor intensidad de occidente a oriente, debido en gran medida a la participación de la actividad tectónica.

2.4 Discusión

La continua subducción de la placa océanica por debajo de la placa continental (Atwater, 1970), los cambios de las direcciones de movimiento relativo entre placas, los saltos de la Cresta del Pacífico Oriental hacia el continente (Mammerickx y Klitgord, 1982) y la apertura del Golfo de California han influenciado grandemente la geología del occidente de México. Actualmente esa influencia está relacionada con la interacción entre las placas de Rivera, de Cocos y de Norteamérica, la oblicuidad y los diferentes ángulos de la subducción a lo largo de la Trinchera Mesoamericana. La región suroccidental de México esta dividida en varios bloques cuyos límites son discontinuidades tectónicas regionales de reciente actividad (Fig. 1, Harrison y Johnson, 1988). Estudios recientes indican que hacia el oriente del graben de Chapala los movimientos con una componente lateral izquierda son los dominantes (Harrison y Johnson, 1988; Urrutia-Fucugauchi y Böhnel, 1988), mientras que hacia el occidente no se han identificado rotaciones de bloques como cabría esperar en una ambiente transcurrente (diestro o siniestro) (Mailloil y

Bandy, 1994; Bohnel et al., 1991)). Así, es posible que hacia el occidente de Chapala esté actuando un mecanismo en el cual la participación de los movimientos laterales sea menor.

Las premisas en esta discusión son las siguientes: a) la expresión morfotectónica de la frontera norte del Bloque Jalisco está dominada por una serie de depresiones tectónicas (semi-grábenes) cuyo bloque hundido es consistentemente el bloque SW; c) la dirección general de estas estructuras es NW-SE, y presentan una forma de Z alargada b) las depresiones tectónicas son penecontemporáneas y se deben a un evento tectónico extensional; c) la consistencia del basculamiento hacia el NE de las rocas neógenas y cuaternarias; d) el carácter alcalino de las rocas volcánicas en la Depresión de Amatlán de Cañas. El problema fundamental es explicar el origen de la geometría de las trazas de las fallas que limitan las depresiones estructurales que caracterizan la frontera norte del Bloque Jalisco.

Gastil y Jensky (1973) propusieron una falla regional de carácter dextral por debajo de donde ahora se instala la Faja Volcánica Transmexicana. Recientemente, también se ha sugerido que los movimientos mayores en el límite norte del Bloque Jalisco, desde la región de Tepic hasta Guadalajara están controlados por fallas laterales derechas debido al movimiento del Bloque Jalisco hacia el NW (Allan et al., 1991; Garduño y Tibaldi, 1991; Garduño, 1988; Bourgois et al., 1988, Pasquaré et al., 1986). Varios argumentos no apoyan esta hipótesis. a) La traza de las depresiones estudiadas tiene forma de Z alargada, por lo que en un sistema diestro, se esperaría que en las fronteras septentrionales (de dirección E-W) de la traza hubiesen estructuras compresivas recientes lo cual no se ha observado, sino que, por el contrario, lo que se han desarrollado son depresiones tectónicas cuyo bloque hundido es consistentemente el bloque sur respecto a la traza E-W de los escarpes; b) la dirección NW-SE de los volcanes que van desde Guadalajara hasta la región de Tepic, así como los descritos para la Depresión de Atotonilco-Zacoalco, sugieren una dirección NE-SW de máxima extensión; c) se ha documentado que la última fase de deformación en el Río Grande de Santiago (Michaud et al., 1990) y en la Depresión de Amatlán de Cañas (Guzmán de la Campa, 1989) está relacionada con un régimen distensivo de dirección NE-SW.

En un intento por conciliar de manera simplificada las premisas de esta discusión, se plantea la posibilidad de explicar estas características a través de una fase extensional que ocasiona que el movimiento del Bloque Jalisco sea hacia el S-SW. Esta actividad sería progresivamente más joven de norte a sur y ocasionaría la fragmentación en bloques a lo largo de fallas lístricas y fallas planas rotadas (fallamiento tipo dominó).

Además, con este tipo de tectónica se explicarían las estructuras de semi-grábenes, cuyos basculamientos dan la gran consistencia del buzamiento hacia el NE de las rocas volcánicas y vulcanosedimentarias neógenas en las regiones de Tepic y al sur de la Depresión Atotonilco-Zacoalco y de los conglomerados en la Depresión de Amatlán de Cañas. Debido a que los cauces de los ríos Grande de Santiago y Ameca están controlados por fallas, a que la traza de su cauce es prácticamente idéntica y a que morfológicamente el Río Ameca es el más joven es posible sugerir una migración de la actividad tectónica hacia el sur la cual también esta sustentada en el hecho de que las rocas basculadas hacia el norte de la Depresión de Amatlán de Cañas son del Cenozoico

Medio (Gastil et al., 1979 a y b) mientras que las de esta depresión son del Cuaternario (Nieto-Obregón et al., 1992). Por otra parte, lo bien conservado de las facetas triangulares del escarpe que limita al norte de la Depresión de Ameca, se puede sugerir lo reciente de su formación (Nieto-Obregón et al., 1992). Interpretar un movimiento hacia el S-SW del Bloque Jalisco plantea, intrínsicamente, un esquema donde las estructuras que conforman el Graben de Colima tendrían una componente lateral de izquierda. DeMets y Stein (1990) sugirieron que el graben de Colima es una cuenca tensional pasiva en respuesta al movimiento hacia el SE del Bloque Michoacán a lo largo de la zona de falla Chapala-Oaxaca de carácter siniestro. Finalmente, nuestra interpretación sería congruente con el hecho de que las direcciones de máxima extensión recientes en el Río Grande de Santiago (Michaud et al., 1990), en la Depresión de Amatlán de Cañas (Guzmán de la Campa, 1989), en el semi-graben de Zacoalco (Barrier et al., 1990).

2.5 Conclusiones

Aquí se sugiere que el límite norte del Bloque Jalisco (sur del "graben de Tepic") está definido por una serie de depresiones tectónicas de dirección general NW-SE cuya traza tiene forma de Z alargada. El bloque hundido de estas depresiones está consistentemente basculado hacia el N-NE lo que cuestionaría la existencia del graben de Tepic. Por ello, se sugiere que las estructuras al norte del Bloque Jalisco corresponden a un sistema de semi-grábenes los cuales se originaron como consecuencia de un mecanismo de extensión que involucra un movimiento hacia el S-SW del Bloque Jalisco. En esta interpretación el graben de Colima correspondería a una estructura asociada con una extensión oblicua-siniestra. Finalmente, es necesario enfatizar la necesidad de llevar a cabo un intenso trabajo estructural y estratigráfico, particularmente en las fronteras del Bloque Jalisco, que aporte un mayor número de datos. Hasta ahora se ha considerado al Bloque Jalisco como un macizo coherente; sin embargo las fosas de Los Volcanes, Mascota y Talpa, así como lo reciente de su vulcanismo, pueden considerarse como evidencias de su fragmentación interna.

III STRATIGRAPHY AND TECTONICS OF THE GUADALAJARA REGION AND THE TRIPLE JUNCTION AREA, WESTERN MEXICO

by

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ABSTRACT

In the region comprised between Guadalajara and the triple junction of the Tepic-Zacoalco, Chapala and Colima rifts the late Miocene to Quaternary volcanics of the Mexican Volcanic Belt (MVB) largely conceals the boundaries between the basement domains of the Sierra Madre Occidental (SMO) to the north and the Jalisco and Michoacán blocks to the south. Integrating previous works with new geologic mappings and isotopic age determinations we propose a comprehensive regional stratigraphy for the Guadalajara and the triple junction area and attempt to define the boundaries between these basement domains. In the study area the silicic succession of the SMO is restricted to the north of the Santa Rosa-Cinco Minas fault and the northern boundary faults of Lake Chapala. The succession of the MVB began with a widespread mafic volcanism and lacustrine sedimentation occurred at 11 to 8 Ma in several tectonic basins developed along the Tepic-Zacoalco and the Chapala rifts, suggesting that the extensional reactivation of the block boundaries took place earlier than previously suggested. Since latest Miocene time, volcanism has been dominated by silicic products in the north (Guadalajara area) and by more intermediate to mafic products in the south (Chapala and Zacoalco areas).

We also present a new interpretation of the structural geometry of the Zacoalco half-graben, in which the Bola del Viejo fault is considered the main detachment structure responsible for the NE tilting of the Sierra de San Marcos and Sierra de Tapalpa blocks. Furthermore, because of the almost identical tilting of the Sierra de San Marcos block and other blocks to the SE we propose that the San Marcos fault has a planar surface. Finally, we have confirmed that the Santa Rosa fault had a normal motion in post late Miocene times and that it is probably inactive since Middle Pleistocene.

3.1 Introduction

The structure of west-central México is dominated by a complex assemblage of crustal blocks bounded by major tectonic structures (Fig. 3.1). These are the Tepic-Zacoalco, Colima, and Chapala rifts, which separate the Jalisco block JB) and the Michoacán block from the stable North American plate (Fig. 3.1). The three rifts join south of Guadalajara to form what has been long interpreted as an active of the rigde-rigde-rigde (RRR) type triple junction (Luhr et al., 1985 Allan et al., 1991) (Fig. 3.1).

Although the region has received the attention of many workers in the past, contributions to its geologic mapping were limited to small areas (Demant, 1979; Mahood, 1980; Gilbert et al., 1985; Nieto-Obregon et al., 1985; Allan, 1986; Nixon et al., 1987; Quintero-Legorreta et al., 1992; Garduño et al., 1993; Moore et al., 1994; Ferrari and Rosas-Elguera, in press) or to regional synthesis (Ortega-Gutierrez et al. 1991; López-Ramos, 1995; Ferrari et al., in press). Nevertheless, a geologic and stratigraphic framework for this region is needed to address two main problems: (1) to determine the relative extension of the Sierra Madre Occidental (SMO), the Jalisco block (JB) and the Michoacán block and (2) to reconstruct properly the structure and the tectonic evolution of the triple junction area.

The continuation of the Eocene-early Miocene ignimbrite arc of the SMO south of the Mexican Volcanic Belt (MVB) has been suggested in the geologic maps of western México until recent times (Ortega-Gutierrez et al. 1991; López-Ramos, 1995). Nevertheless, several works indicate that the ignimbrites within the JB are all Cretaceous to early Paleocene in age (Gastil et al., 1978; Wallace and Carmichael, 1989; Lange and

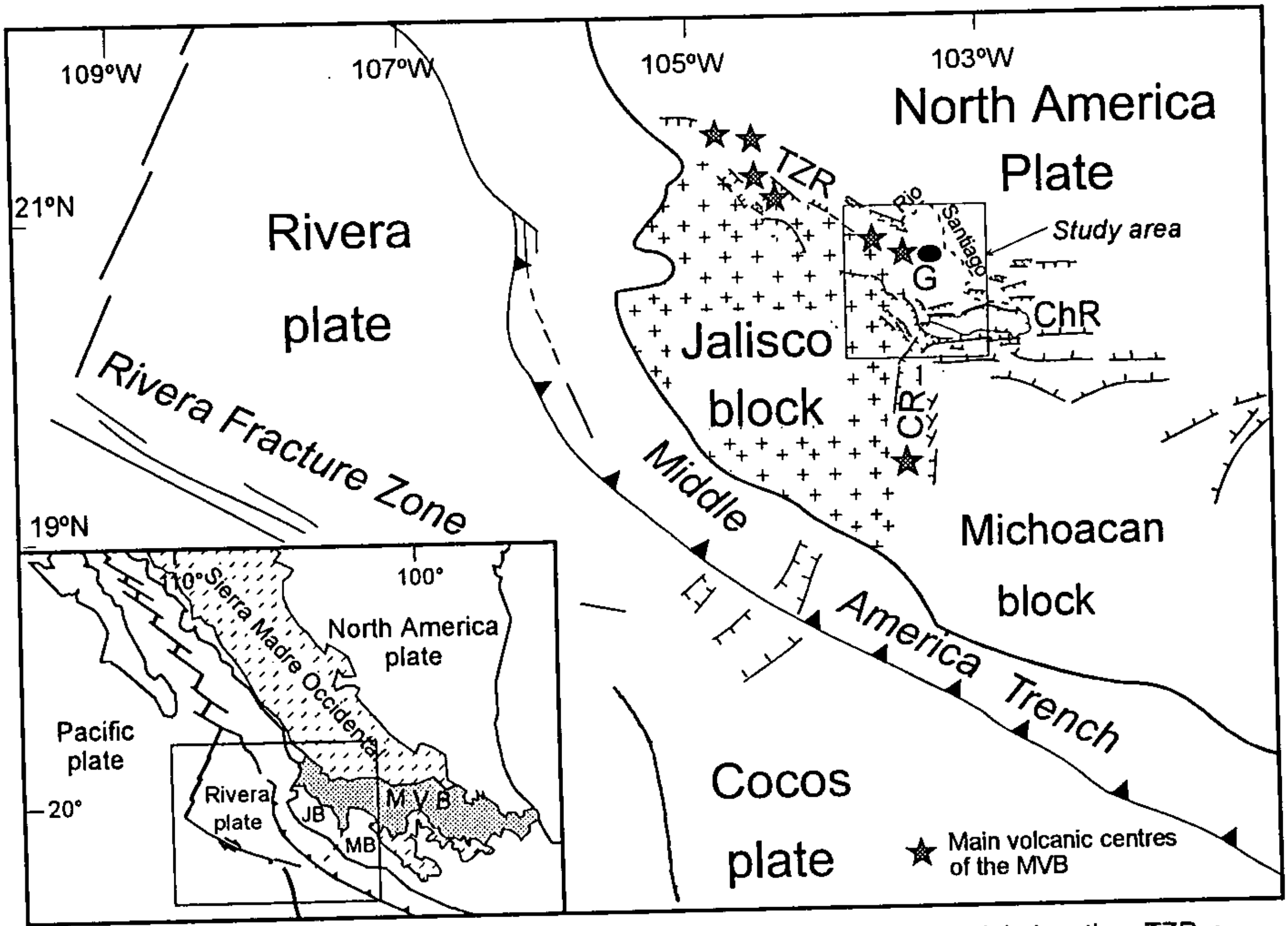

Fig. 3.1 Geodynamic framework of western Mexico and of the Guadalajara triple junction. TZR = Tepic-Zacoalco rift, CR = Colima rift, ChR = Chapala rift, G = Guadalajara. Inset show the extension of the Mexican Volcanic Belt (MVB), which cover the boundary among the Jalisco block (JB), the Michoacan block (MB) and the Sierra Madre Occidental.

Carmichael, 1991; Righter et al., 1995) and suggest that the SMO was not emplaced in this area. Furthermore, the basement of the southern SMO appears to be different, in both age and composition, from that in the JB and Michoacán block (Ferrari, 1995; Rosas-Elguera et al., 1996), although the location of the boundaries between these basement domains are not clearly defined under the MVB.

The nature, the age and the relations between the Tepic-Zacoalco, Colima and Chapala rifts also has been controversial. Whereas some workers consider the three rifts to be an active triple junction separating the JB microplate from the Mexican mainland (Luhr et al., 1985; Michaud et al., 1991; Allan et al., 1991; Moore et al., 1994) others maintain that the rifts are ancient structures, partially reactivated during late Miocene to Quaternary times in response to plate boundary forces rather than to a mantle plume (Ferrari et al., 1994a; Rosas-Elguera et al. 1996; Ferrari and Rosas-Elguera, in press).

In this paper we contribute to the knowledge of the Guadalajara triple junction area providing: (1) an updated regional stratigraphy based on new isotopic ages of selected geologic units and an interpretation of the subsurface geology constrained by deep geothermal and oil wells; (2) a definition of the boundaries between the SMO, the JB and the Michoacán block; and (3) a reconstruction of the structural geometry and of the kinematics of the south-eastern Tepic-Zacoalco rift.

3.2 Regional stratigraphy and geochronology

The area studied is comprised between 21° and 19° 45' N Lat. and 103° and 104° W Long. and includes the Guadalajara region and the triple junction area (Figs. 3.1 and 3.2).

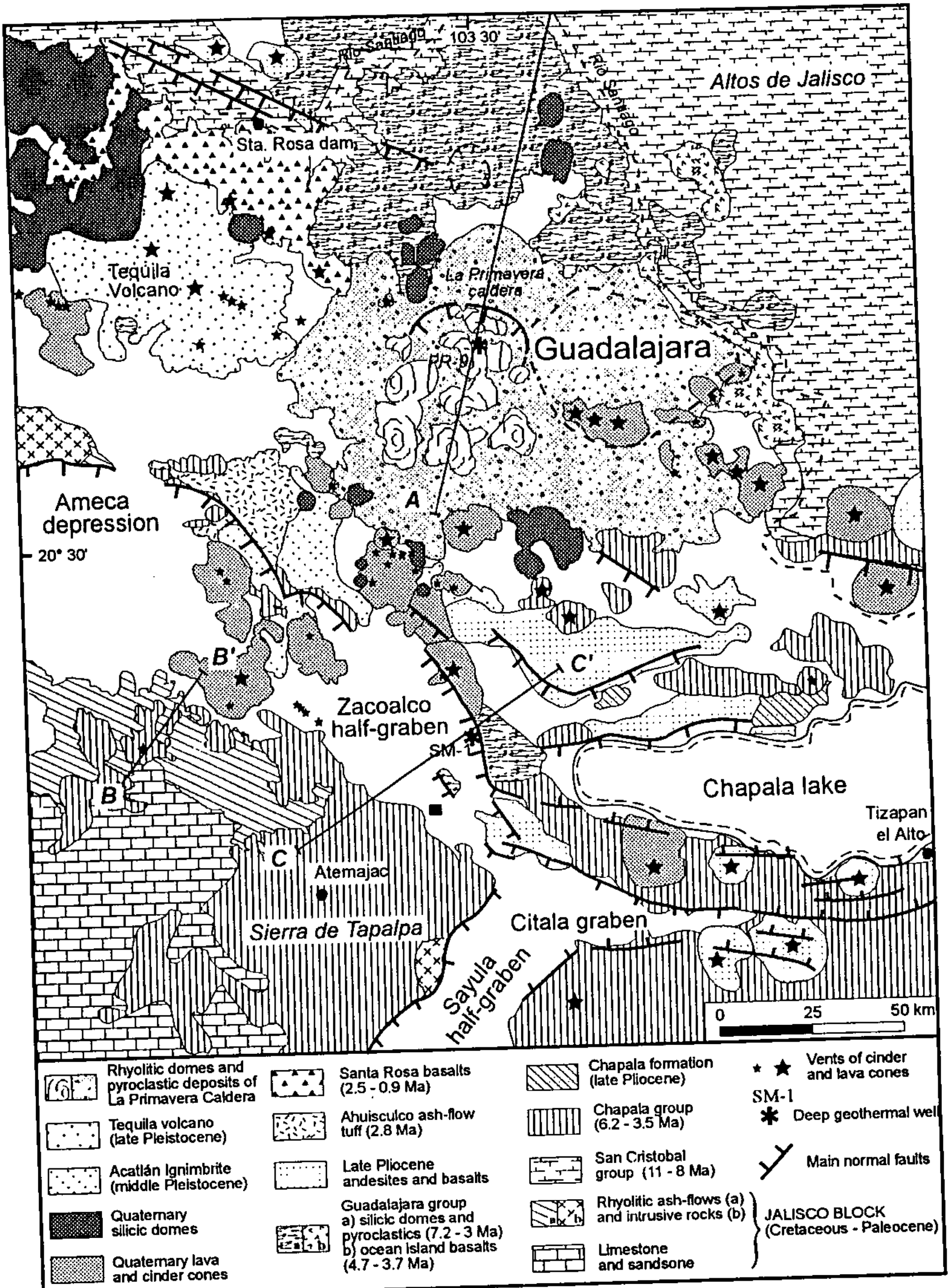

Fig. 3.2 Geologic map of the triple junction and Guadalajara areas. Solid lines indicate the traces of the geologic cross-sections of Figure 6. After Ferrai et al. (in press) and this study

Three basement domains can be distinguished: the SMO, the JB and the Michoacán block (Fig. 3.1). The late Miocene to Quaternary volcanics of the MVB obscure the boundaries between these domains. Based on new geologic mapping and a revision of published maps and ages we have elaborated a new regional stratigraphy. In addition, we have dated some key stratigraphic units to better constrain the regional stratigraphy. In this section we summarize the stratigraphy of each geologic assemblage and discuss the implications of our new isotopic ages. All the isotopic analyses were performed by M. López Martínez at Centro de Investigación Científica y de Educación Superior de Ensenada. The methodology for the K-Ar analyses is that described by Dalrymple and Lanphere (1969). The samples were fused in the double-wall tantalum furnace, similar to that described in MacDougall and Harrison (1984). The isotopic analysis was performed using a MS-10 mass spectrometer (see Farrar et al., 1966 for details). The methodology for $^{40}Ar/^{39}Ar$ analysis is described in detail by López Martínez (1984), from whom complete analytical data can be obtained upon request.

Sierra Madre Occidental

The SMO is a massive, middle Tertiary, volcanic province composed of silicic ash-flow tuffs and rhyolitic lavas and subordinated andesitic and basaltic lavas. Their average thickness exceeds 1.5 km (McDowell and Clabaugh, 1979) and the ages cluster in three discrete periods of Eocene, Oligocene and early Miocene age (Nieto-Obregon et al., 1981, 1985; Montigny et al. 1987 and references therein; Aguirre-Diaz and McDowell, 1991 and references therein; Moore et al., 1994). In the study area the SMO is exposed about 50 km north of Guadalajara north of Rio Santiago, where it is composed by 23 to 22 Ma silicic ash-flows (Moore et al., 1994) overlain highly altered ignimbrites and andesites of Eocene age (Webber et al., 1994; Ferrari et al., in press) (Fig. 3.3). The southernmost exposition of the SMO succession is at the bottom of the Rio Santiago canyon at the Santa Rosa dam (Fig. 3.2). Here, a rhyodacitic ash-flow yielded ages of 16.9 Ma (Nieto-Obregon et al., 1985) and ~15 Ma (Moore et al., 1994). The volcanic succession of the SMO is underlain by subvolcanic stocks of granitic to dioritic composition with Oligocene to early Miocene ages (Gastil et al., 1978; Nieto-Obregon et al., 1981, 1985).

Jalisco block

The Jalisco block is formed by a distinctive stratigraphic assemblage consisting of late Cretaceous to early Tertiary rhyolitic ash-flow tuffs and subordinate andesites, volcaniclastic deposits and turbiditic sequences intruded by granitoid plutons (Gastil et al., 1978; Allan, 1986; Köhler et al., 1988; Zimmermann et al., 1988; Lange and Carmichael, 1991; Rigther et al., 1995). This succession is only exposed west of the Sayula half-graben, which clearly constitutes the eastern boundary of the JB in the study area. The northern boundary of the JB, however, has been poorly defined in previous studies. Silicic ash-flow tuffs exposed to the west of Lake Chapala in the Sierra de Tapalpa were previously mapped as belonging to the SMO (Ortega-Gutiérrez et al., 1991; López-Ramos, 1995). We have dated a biotite concentrate from the uppermost unit of a NE tilted succession of rhyolitic ash-flows exposed north-west of Atemajac (Fig. 3.2). Duplicate K-Ar analyses yielded 77 and 78 Ma ages in agreement with the integrated age of 78 ± 2 Ma obtained for the $^{39}Ar/^{40}Ar$ experiment. The age spectra obtained is shown in Figure 3.4. A well defined plateau was obtained for 83 % of the ^{39}Ar released yielding an age of 79 ± 2 Ma which we take as the best age estimate for this unit sample (ZHG JRE-90, Table 1). This date agrees with previously published isotopic ages for silicic volcanics in the JB (Gastil et al. 1978; Wallace and Carmichael, 1989; Lange and Carmichael, 1991; Righter et al., 1995).

The PR-9 geothermal well drilled in the La Primavera Caldera encountered the JB succession directly beneath late Miocene to Quaternary rocks of the MVB. At PR-9 the JB is composed by ~200 m of granitic rocks underlying ~800 m of andesitic rocks dated at 51 Ma (Ferrari et al., in press) (Fig. 3.3). The SM-1 geothermal well, located in the Zacoalco half-graben, cut ~200 m of arkosic sandstone which correlate with the late Cretaceous succession exposed in the Sierra de Tapalpa (Venegas et al., 1985) (Fig. 3.3). These data indicate that the distinctive succession of the SMO does not continue south of Guadalajara and suggest that the JB can be traced as far north as the alignment of the La Primavera caldera and the Volcán Tequila, which is in agreement with Ferrari et al. in press).

Michoacán block

The Michoacán block, exposed south of Lake Chapala, consists mostly of a late Cretaceous (68 ± 12 Ma) tonalitic to Qz-monzonitic batholith (López-Ramos, 1995; Schaaf et al., 1995) which intruded a Triassic to Cretaceous marine volcanic and sedimentary succession. The geologic map of México (Ortega-Gutierrez et al., 1991) shows Cretaceous limestone east of Tizapán el Alto Fig. 3.2), on the southern shore of Lake Chapala. However, Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI) indicate that this

Table 3.1. New isotopic ages for the Triple junction and Guadalajara areas

K-Ar Results

Sample	Rock	Material dated	% K	40Ar* mol/gr (10 exp -11)	% 40Ar*	% 40Ar atm	Age (Ma)	Latitude	Longitude
ACATLAN	Ignimbrite	w.r.	2.6255	0.30015	10		0.66 ± 0.06	20.43	103.61
PR 7	Ignimbrite	w.r.	0.308	0.0866	18		1.6 ± 0.4	20.63	103.53
ZHG/JRE-2	Ignimbite	w.r.	4.17 ± 0.02	1.9057	26.5	73.5	2.6 ± 0.2	20.58	103.85
		plag	3.68 ± 0.04	1.7840	46.4	53.6	2.8 ± 0.1		
ZHG/JRE-6	Andesite	w.r.	0.94 ± 0.01	0.70384	18.6	81.4	4.3 ± 0.4	20.22	103.69
				0.72938	43.6	56.4	4.4 ± 0.2		
ZHG/JRE-8	Andesite	w.r.	1.13 ± 0.02	0.86737	49.3	50.7	4.4 ± 0.2	20.32	103.90
				0.87379	48.9	51.0	4.5 ± 0.2		
ZGH/JRE-9	Ignimbrite	biotite	6.13 ± 0.11	5.2612	29.7	70.3	4.9 ± 0.3	20.25	103.56
		matrix	3.27 ± 0.04	2.8318	34.8	65.2	5.0 ± 0.3		
		hornblende	0.62 ± 0.04	0.60625	25.6	74.4	5.6 ± 0.4		
ZHG/JRE-5	Andesite	w.r.	1.20 ± 0.01	1.1022	32.1	67.9	5.3 ± 0.3	20.20	103.70
				1.1016	41.2	58.8	5.3 ± 0.6		
ZHG/JRE-7	Basalt	matrix	0.76 ± 0.03	1.3243	41.2	58.8	10.0 ± 0.5	20.25	103.67
					57.3	42.7	10.2 ± 0.5		
ZHG/JRE-90	Ignimbrite	biotite	5.60 ± 0.07	76.500	91.3	8.70	77 ± 3	20.31	103.90
				77.571	91.8	8.20	78 ± 3		

40Ar/39Ar Results

			% 40Ar*	%39Ar	40Ar*/39Ark	Integrated age (Ma)	Plateau age (Ma)		
ZHG/JRE-90	ignimbrite	biotite	96.1	83.0	20.78 ± 0.18	78 ± 2	79 ± 2	20.31	103.9

40Ar* is the radiogenic 40Ar, 40Aratm is the 40Ar of atmospheric composition, %39Ar is the percent of 39Ar used for the plateau age calculation.
All errors are reported at the 1 Õ level. Decay constants are those of Steiger and Jägar, 1977.

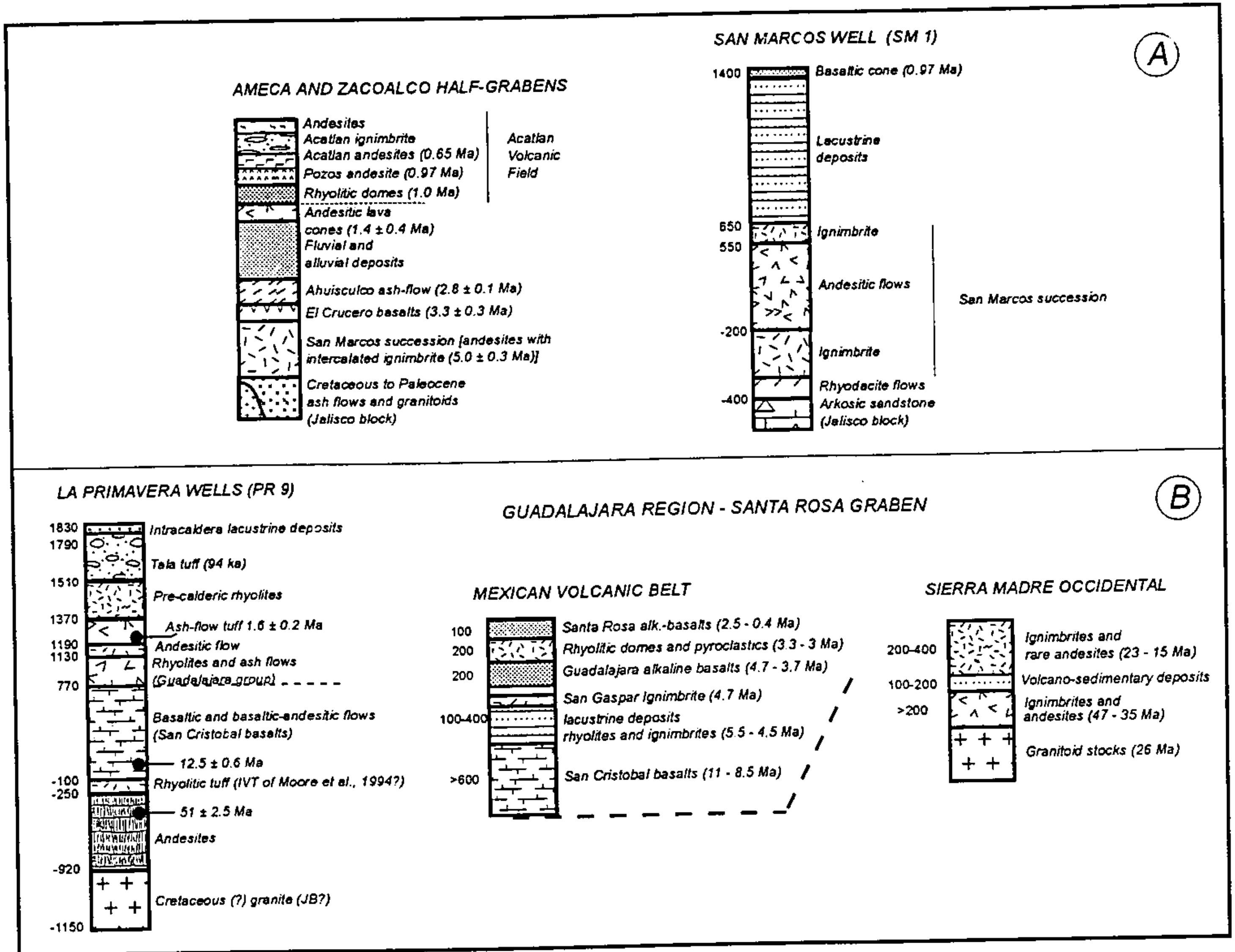

Fig. 3.3 Esratigrafía regional del área de estudio. (A) Estratigrafía simplificada de kis semigrabenes de Ameca y Zacoalco El pozo San Marcos no esta a escala. (B) Las columnas estratigráficas a lo largo del rio Santiago entre San Cristobal y la presa de Santa Rosa son comparadas con la SMO, al norte, y el pozo Primavera, al sur. En San Cristobal, solo la suce-sión de la MVB esta expuesta; ella llena una cuenca (representada por la linea punteada), formada entre la SMO, cuya cima esta expuesta en la presa de Santa Rosa. Los números a la izquierda de las columnas son espesores en metros o elevaciones Las edades absolutas son referidas en el texto. (Ferrari et al., en prensa; este trabajo)

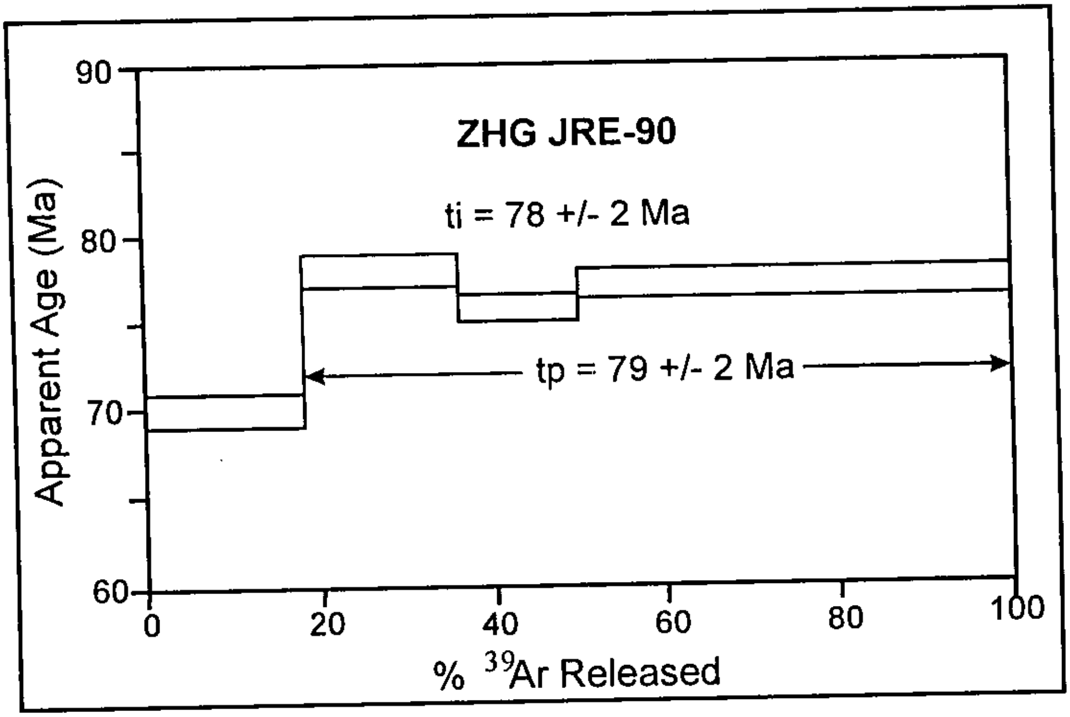

Figure 3.4.- Age spectra obteined on sample ZHG-JRE 90. ti is the integrated age. The arrows indicate the fractions used in the plateau age (tp) calculation. The width of the boxes represent 1 sigma errors. The error of the integrated and plateau age include the analitical error of J.

sequence consists of lacustrine limestone and overlies a thick andesitic succession of early Pliocene age. East of Guadalajara the boundary between the SMO and the Michoacán block is poorly defined. Ash-flows tuffs belonging to the SMO with a reported age of 24 Ma (Castillo an Romero, 1991) crop out locally as south as the latitude of Guadalajara in the Sierra de Pénjamo, ~75 km east of the study area. The Chapala 1 well drilled by Petroleos Mexicanos in the eastern part of Lake Chapala encountered ~500 m of Pliocene andesites (López-Ramos, 1979) whereas two wells drilled by the (Comisión Federal de Electricidad) at Ixtlán de Los Hervores and Los Negritos, at the eastern end of Lake Chapala -cut more than 1020 m of late Pliocene to Quaternary volcanic rocks of the MVB (Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). On the basis of these data we believe that the limit between the SMO and the Michoacán block east of Guadalajara correspond to the broad extensional belt of Lake Chapala, which was largely filled by volcanic rocks and lacustrine sediments since late Miocene times (Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI).

Mexican Volcanic Belt

San Cristobal group. The oldest unit within to the MVB is the San Cristobal group whose dominant member is a widespread succession of alkali-olivine basalts and basaltic andesites with ages between 11 and 9 Ma (Watkins et al. 1971; Damon et al., 1979; Moore et al., 1994). A distinctive silicic welded ash-flow (the inversely welded tuff of Moore et al., 1994) is interbedded with the basalts in the lowest part of the exposed succession whereas a heterogeneous silicic succession, consisting of pumice flows, welded ash-flows, ash falls and reworked pyroclastics (Los Caballos tuff of Moore et al., 1994) is present in the uppermost part of the sequence. In the Rio Santiago canyon the San Cristobal basalts reach a maximum thickness of 600 m (Fig. 3.3). However, they thin up to ~250-200 m toward the east, in the Los Altos de Jalisco plateau (Fig. 3.2) (Ferrari et al., 1994b), where they were dated at 13-9 Ma Nieto et al., 1981; Verma et al., 1985; Nixon et al., 1987; Castillo and Romero, 1991). In the southern part of the Los Altos plateau, the basalts gave slightly younger ages of 8.8 to 8.7 Ma and overlie a lacustrine succession (Rosas-Elguera et al. 1989; Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). The San Cristobal group was also cut by the La Primavera geothermal wells, where a basaltic andesite in the basal part of the succession yielded a K/Ar whole-rock age of 12.5 ± 0.6 Ma (Ferrari et al., in press) (Fig. 3.3). The southernmost exposures of the late Miocene basalts are in the Sierra de Tapalpa. We have dated a basaltic flow near the village of Atemajac, a 10.1 ± 0.5 Ma age was obtained sample (ZHG JRE-7, Table 1). This unit underlies alkaline basalts of early Pliocene age (Allan, 1986; this work). This age agrees very well with the 10.1 ± 0.4 Ma age obtained by Allan (1986) for an andesite collected in the eastern lake Sayula and suggests that the extension in the northern Colima rift area alredy could have initiated before the Pliocene.

Guadalajara group. The late Miocene basalts of the San Cristobal group are overlain by the Guadalajara group (Ferrari et al., in press), which is composed of a succession of rhyolitic flows and minor ignimbrites and basaltic lavas emplaced between 7.15 and 3.1 Ma (Gilbert et al., 1985). The Guadalajara group is exposed in an elongated N-S area covering more than 900 km^2. A preliminary estimate of the volume is ~350 km^3 (Rossotti et al., 1997). The oldest units are extensive rhyolitic domes and flows and associated pyroclastic flows and air-fall deposits with K/Ar ages comprised between 7.15 and 5.0 Ma (Gilbert et al., 1985). These are followed by oceanic-island-basalts (OIB)-type megacrysts-bearing basalts dated 4.7 and 3.3 Ma (Watkins et al., 1971; Gilbert et al., 1985; Moore et al. 1994) and by other early Pliocene silicic domes and associated pyroclastics. There are two regional pyroclastic markers intercalated in this succession: the 4.7 Ma San Gaspar and the 3.3 Ma Guadalajara ignimbrites (Gilbert et al., 1985). Both ignimbrites show evidence of mingling between two types of chemically distinct magma Gilbert et al. 1985). The source of these ignimbrites is unknown but it is probably buried beneath the late Pleistocene pyroclastic deposits coming from the La Primavera caldera (Fig. 3.2).

An ignimbrite with a very similar petrographic composition to the San Gaspar outcrops ~50 km south of Guadalajara. This unit has an average thickness of 3 m and is well exposed in the hanging wall of the Zacoalco half-graben. We have dated the phenocrysts and the groundmass of a sample from this ignimbrite (sample ZHG JRE-9, Table 3.1). The groundmass sample yielded an age of 5.0 ± 0.3 Ma, which is compatible with the age of the San Gaspar ignimbrite. If this site really represents the southernmost exposure of the San Gaspar ignimbrite, then the source of this tuff should be located somewhere in the Guadalajara area, buried beneath the younger volcanics.

The age of the San Gaspar mingled-ignimbrite corresponds to the first occurrence of alkaline basalts (Guadalajara basalts of Moore et al., 1994) and to a major episode of extensional faulting in the region (Ferrari and Rosas-Elguera, in press). It can be speculated that a major silicic magma chamber emplaced in the Guadalajara region at ~7 Ma and was rejuvenated periodically through injection of mafic magmas during the main extensional pulses. In this context, the La Primavera caldera could represent the last episode of a 7-Ma- long volcanic history of this chamber. A complete discussion of this model will be present in a later paper Ferrari et al, in preparation).

Chapala group. An andesitic to basaltic succession named Chapala group (Ferrari et al., in press) is exposed south of Lake Chapala on both sides of the Sayula half-graben. The succession is composed by calc-alkaline and alkaline rocks with ages of 6.2 to 3.5 Ma (Allan, 1986; Delgado et al., 1995). On the southern shore of Lake Chapala the rocks are mostly andesites with a thickness of at least 500 m according to the sequence cut by the Chapala-1 oil-well drilled near Tizapán El Alto by Petroleos Mexicanos (López-Ramos, 1981). To the west of Lake Chapala, in the Sierra de Tapalpa, andesitic lava flows overlie the late Cretaceous JB succession and late Miocene basalts (Fig. 3.2). We have dated three samples of andesitic rocks in this area at 4.3 ± 0.4, 4.5 ± 0.2, and 5.3 ± 0.3 Ma samples ZHG JRE-6, ZHG JRE-8 and ZHG JRE-5, Table 3.1). These ages agree with those obtained by Allan (1986) some km to the west for an alkaline and calc-alkaline mafic succession emplaced on the western shoulder of the Sayula half-graben, and are mostly contemporaneous with the OIB-type basalts of the Guadalajara group.

Late Pliocene units. During the late Pliocene, shield and lava cones developed on the shoulders of the present-day Chapala Lake basin (Fig. 3.2). These volcanoes are mainly composed of basaltic lavas with calc-alkaline affinity (Rosas-Elguera et al., 1989; Delgado, 1992). During the late Pliocene, extension concentrated along the axial zone of the present Lake Chapala (Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). The volcano sedimentary deposit related to this process is represented by the Chapala Formation (Fig. 3.2) composed by an alternance of lacustrine sediments and pyroclastic ash and pumice deposits Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). Palmer (1926) referred to the volcano sedimentary sequence in Lake Chapala as the Chapala beds. The sequence was subsequently studied by Downs (1958) and Clemens (1959, 1962). Downs (1958) named the volcano sedimentary sequence the Chapala Formation and reported that the fossil fauna in the lake bottom is characteristic of the late Pleistocene. A sample of an andesitic lava which underlies the Chapala Formation near the village of Chapala yield a K/Ar age of 3.4 ± 0.2 Ma Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). Thus we propose to retain the name of Chapala Formation only for the NE-tilted volcano-sedimentary sequence younger than 3.4 Ma exposed on the northern side of Lake Chapala (Fig. 3.2).

A welded ash-flow tuff with phenocrysts of plagioclase is exposed in the Sierra de Ahuisculco, south-west of the La Primavera caldera (Fig. 3.2). Because a sample of this unit has yielded a K/Ar age of 2.8 Ma (Table 3.1) we prefer to separate the Ahuisculco ash-flow from the Guadalajara group, which is entirely late Miocene to early Pliocene in age.

Quaternary units. Early to middle Pleistocene volcanism is represented by calc-alkaline alignments of basaltic cinder and lava cones, alkaline basaltic plateaux and silicic domes and flows Figs. 3.2 and 3.5). Some of these cones have been dated at 1.4 to 1.8 Ma (Gilbert et al., 1985; Allan, 1986; Delgado, 1992). A sample of an ash-flow tuff from the La Primavera wells yielded a K-Ar age of 1.6 0.2 Ma Table 3.1, Fig. 3.3) which is correlative with the rhyolitic domes dated at 1.4 Ma (Ferrari et al., in press). Alkaline basalts with OIB affinities are exposed along Rio Santiago, north of Volcán Tequila (Fig. 3.2). Although Moore et al. (1994) report several Quaternary ages for these rocks Nieto-Obregón et al. (1985) dated one of the lowermost flows of Mesa de Santa Rosa at 2.5 Ma. Most of the calc-alkaline volcanism, however, is concentrated south west of Guadalajara, in the Acatlán Volcanic Field -a name we propose for a group of dacitic and rhyolitic domes, andesitic cone and lava flows located between the tips of two major segments of the Zacoalco half-graben (Fig. 3.2). The Acatlán Volcanic Field also is the source of the widely known Acatlán Ignimbrite, which show evidence of mingling between a silicic and an andesitic magma Wright and Walker, 1981). A sample of this ignimbrite gave an age of 0.66 ± 0.02 Ma by K-Ar method (Table 3.1).

The youngest stratigraphic units of the region are the andesitic-dacitic calc-alkaline Tequila volcanic complex (Nixon et al., 1987; Wallace and Carmichael, 1994) and the alkaline silicic domes and pyroclastics of La Primavera caldera (Mahood, 1980), both are late Pleistocene in age.

3.3 Tectonics

In this section we review the structure of the western arm of the triple junction area (the Tepic Zacoalco rift) and briefly compare it with the Chapala and northern Colima rift. A more detailed description of the tectonics of these latter structures will be given in forthcoming papers Rosas-Elguera and Urrutia-Fucugauchi, ver capitulo VI). In the study area the Tepic Zacoalco rift is composed by the eastern part of the Plan de Barrancas-Santa Rosa graben and by the Ameca and Zacoalco half-grabens (Fig. 3.5).

Plan de Barrancas-Santa Rosa graben. According to Ferrari and Rosas-Elguera in press) the Plan de Barrancas-Santa Rosa graben is a structural depression developed along the boundary between the SMO and JB. It consists of a 20-km-wide graben formed by the Santa Rosa-Cinco Minas fault to the north and the Plan de Barrancas fault system and its buried extension to the south (Fig. 3.5). In fact, gravimetric modeling indicate that the Plan de Barrancas fault system could be continued southeastward under the Volcán Tequila up to the southern limit of the La Primavera caldera (Alatorre-Zamora and Campos-Enriquez, 1992) (Fig 3.5). The surface expression of this fault system is represented by the vent alignments of the Tequila area (Fig. 3.5). At the Santa Rosa dam, the stratigraphy of the two sides of the fault zone indicate that ~450 m of vertical offset occurred in Pliocene time (Ferrari and Rosas-Elguera, in press) with an average NNE direction of minimum principal stress (s3) (Fig. 3.5).

The sense of motion and the Quaternary activity of the Santa Rosa fault has long been matter of discussion. Nieto-Obregon et al. (1985) interpreted this structure as an active right-lateral strike-slip fault on the basis of geodetic data obtained at Santa Rosa dam and on a complex array of left-stepping en-echelon riedels and conjugate antithetic faults. This interpretation has been strongly supported by Allan et al. (1991), Garduño and

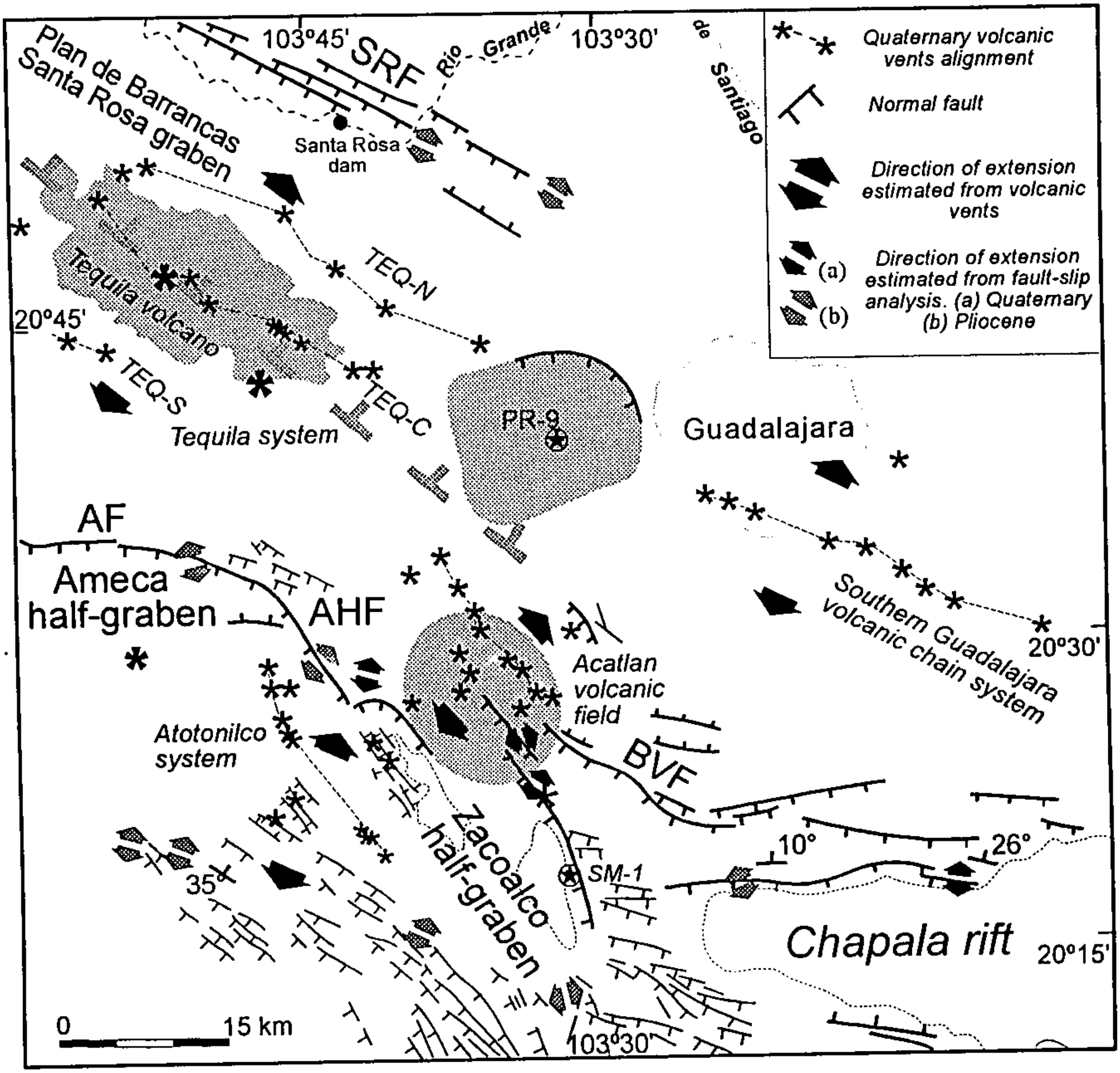

Figure 3.5.- Structural stress and map of the triple junction area. Direction of extension from the volcanic vent alignment and fault slip data inversion after Ferrari and Rosas-Elguera (in press) and Rosas-Elguera (unpublished data). The prolongation of the Plan de Barrancas fault system below the Tequila volcanic complex and La Primavera caldera is based on the gravimetric and aeromagnetic modelling of Alatorre-Zamora and Campos-Enriquez (1992).

Tibaldi (1991) and Moore et al. (1994) although no additional evidences were presented. However Michaud et al. (1991), Quintero-Legorreta et al. (1992), Ferrari et al. (1994a) and Ferrari and Rosas-Elguera (in press), based on detailed stratigraphic and structural studies in the dam area, demonstrate that strike-slip faulting affects only rocks as young as middle Miocene in age and is post-dated by normal faulting between early and late Pliocene. They further indicate that the fault is presently inactive. Quintero-Legorreta et al. (1992) explained that the hydraulic load at the dam site has provoked a right-lateral, normal reactivation of some blocks close to the dam site. Ferrari and Rosas-Elguera in press) note that the slip rate reported by Nieto-Obregon et al. (1985) are inconsistent with the length of the fault. Furthermore, they pointed out that the fault is covered by a thick alkaline lava flow, dated at 1 Ma (Moore et al., 1994) about 20 km north of Volcán Tequila, which is not affected by the fault. In addition to the above arguments, we note that the Santa Rosa dam, which was built in 1964 on the trace of the fault, does not display any sign of deformation. If the fault has a right lateral motion ranging from 0.5 to 2 cm/yr as suggested by Nieto-Obregon et al. (1985), a displacement of 16 to 60 cm should have ocurred in the last 32 years, which would have been catastrophic for the dam. Instead, continuous monitoring of the dam by Comisión Federal de Electricidad indicate no motion, except in the rainy season (Burgueño, personal communication). In conclusion, we consider that the Cinco Minas-Santa Rosa fault is substantially inactive or, if any motion took place in the Quaternary, was at a rate undetectable by geological means.

However a Quaternary reactivation of the Plan d Barrancas fault is indicated by a system of normal faults that cut a rhyolitic and dacitic domes and flows between Magdalena and the Volcán Tequila (Ferrari and Rosas-Elguera, in press). Particularly, 50 to 100-m-deep normal faults are cut into a dacitic flow dated 0.63 Ma (Nixon et al., 1987) just northwest of Volcán Tequila.

Using the geothermal well data of Comisión Federal de Electricidad and our field observations we interpretate the subsurface geology of this area. Figure 6a depicts a cross section through the southeastern part of the Plan de Barrancas-Santa Rosa graben. This figure shows several important features: (1) the succession cut by PR 9 well and dated at 51 Ma could be correlative with similar although undated) rocks exposed north of Rio Santiago which constitute the base of the SMO; (2) the thickness of the San Cristóbal basalts along the Rio Grande de Santiago canyon is ~600 m, but according to the stratigraphy of well PR-9 it becomes ~800 to the south, implying a deep basin developed in late Miocene time in the Guadalajara area; (3) the late Miocene basaltic lava flows are thinner to both sides of the Plan de Barrancas-Santa Rosa graben, suggesting an early development of this structure. We conclude that the northern boundary of the JB is an old line of weakness that concentrated tectonic activity through time.

Ameca and Zacoalco half-grabens. These two structures are part of a belt of tectonic depressions called the Southern half-grabens of the Tepic-Zacoalco rift by Rosas-Elguera et al. (1993), which cut inside the northern JB. The Ameca half-graben is bounded to the north by the Ameca-Ahuisculco fault, which can be divided into two segments (Fig. 3.5). The first the Ameca segment, 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 1400 m. The second

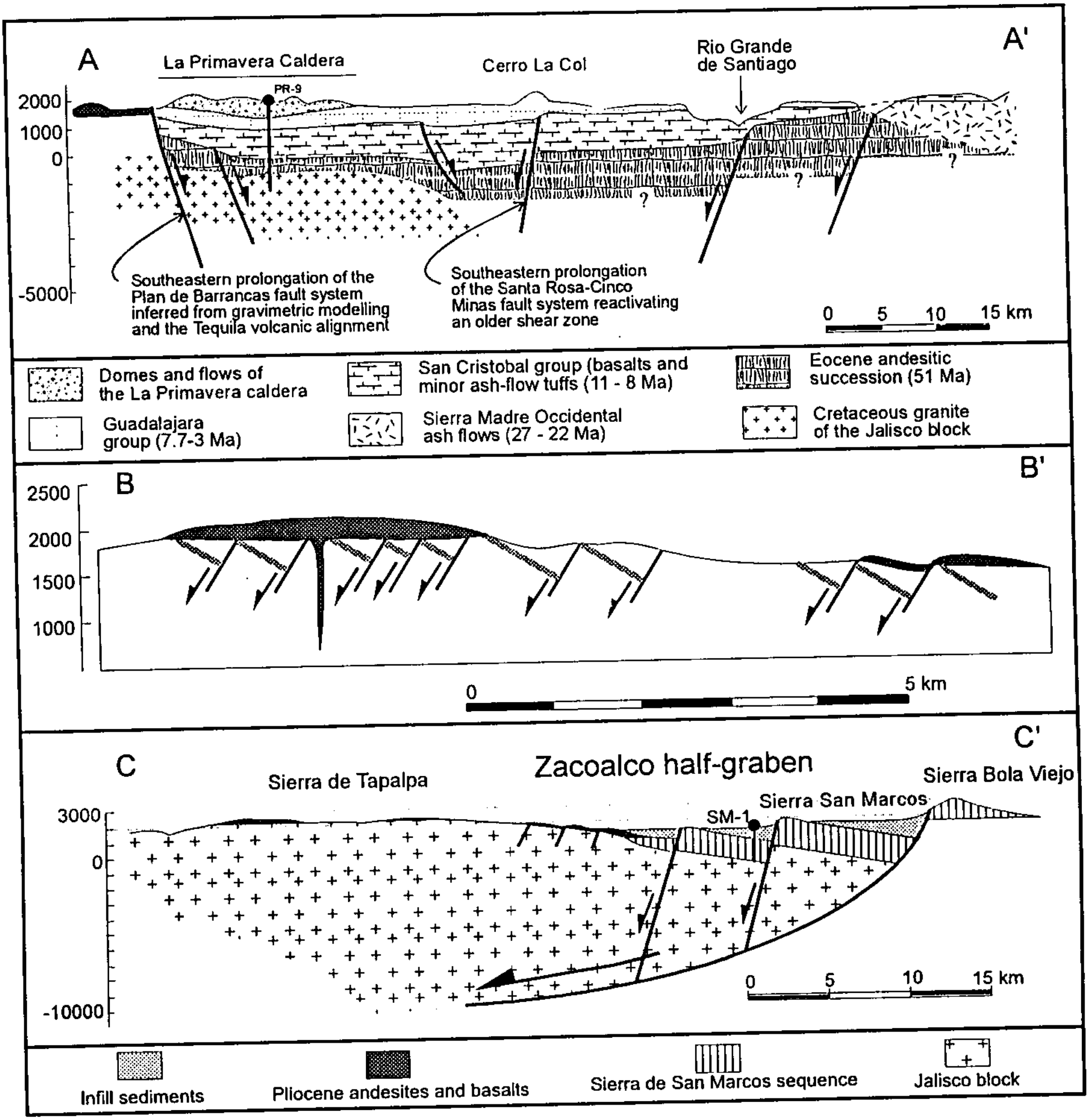

Fig. 3.6 Secciones geológicas de la parte oriental del graben Teipc-Zacoalco. (A) Sistema Plan de Barrancas-Santa Rosa. Observe que la cuenca es llenada por los basaltos San Cristobal y la forma lisrica de la pequeña falla del sistema Santa Rosa-Cinco Minas, la cual bascula los depósitos lacustres del Plioceno temprano en la presa de Santa Rosa. (B) Semigraben de Ameca. La línea gruesa representa una ingnimbrita cretacica que muestra el basculameitno de la sucesión. (C) Interpretacion propuesta del semigraber de Zacoalco. Observe la actitud diferente de la sucesión volcánica en el área de Guadalajara la cual no está basculada después del Plioceno tardío. Ver texto para discusión

segment, the Ahuisculco fault, is 22 km long and strike 145°-155° (Fig. 3.5). Here the fault cut a rhyolitic ignimbrite of 2.8 Ma Fig 3.2 and Table 3.1) and show a minimum vertical offset of 450 m. However, ~900 to 1000 m of infilling sediments can be estimated from gravimetric modeling (Alatorre-Zamora, personal communication, 1996). Thus, ~1350 m of vertical offset can be assumed for this structure as well. Secondary conjugated faults cut also Pleistocene volcanoes as well as the Acatlán ignimbrite with vertical offset not exceeding 100 m.

The Zacoalco half-graben is bounded by the 20 km long, San Marcos fault, a structure striking 160°-170° which downfaults early Pliocene as well as early Pleistocene rocks (Allan, 1986; Delgado-Granados, 1992) up to 1500 m (Ferrari and Rosas-Elguera, in press). Based on dated geologic units we distinguish two episodes of normal faulting: the first occurring between 5.0 Ma and 1.4 Ma, and the second between 1.4 and the present. During the first episode the San Marcos fault acted as a feeding system for the La Lima volcano, dated by (Allan 1986) at 1.4 Ma. Next the fault system was reactivated cutting the La Lima volcano and producing the rest of the 1500 m of the total vertical offset. Fault slip analysis and volcanic alignments indicate a s3 direction ranging from ~N-S to NE-SW for the Ameca, Ahuisculco and San Marcos fault segments (Fig. 3.5).

Many faults sub-parallel to the San Marcos and Ahuisculco faults affect a 15-km-wide zone in the Sierra de Tapalpa, where pre-late Pliocene rocks are tilted ~35° toward the NE (Fig. 3.5). Figure 3.6b depicts the structure of this extensional belt as a "domino style" geometry, suggestive of a listric nature for the normal fault system above. Nevertheless the succession in the footwall of the San Marcos fault (Sierra de San Marcos) is also tilted to the NE, indicating that the main listric fault must be located to the northeast. Therefore we propose that the Bola del Viejo fault sould be the main detachment structure which tilt the Sierra de San Marcos and Sierra de Tapalpa sequence (Fig. 3.6c). In addition we propose that the San Marcos fault would have a planar surface, because the tilting of the south western downfaulted blocks is the same (~20°) (Fig. 3.6c). The down faulted blocks to the southwest become smaller. Therefore we suggest a flexural (roll-over) zone bordering the half-grabens (Fig. 3.6c). Finally, we assume that the maximum depth of the listric detachment fault should be located at ~10 km depth and should correspond to the depth of the microseismic activity reported by Suárez et al. (1994).

Tectonic control of the Quaternary volcanism. The Quaternary volcanic activity is strongly controlled by the tectonics. Two main features illustrate this situation: the Acatlán Volcanic Field (AVF) and the volcanic vent alignments.

The AVF developed along an accommodation zone between two left-stepping segments of the Zacoalco and Ahuisculco fault (Fig. 3.5) and represents a zone of magma-focusing through a significant part of Pleistocene time. Several papers have shown that relay ramps, formed between the approaching tips of two normal faults, may act as structural traps for oil reservoir (Morely et al., 1990; McClay et al., 1995). We speculate that the AVF is a magmatic equivalent of just such situations. A relay ramp, formed in the first phase of extension, favored magma emplacement at depth, and its subsequent differentiation. Progressive deformation of the relay ramp, due to the continuation of regional extension, allowed the injection of mafic magma into this silicic magma chamber, triggering the eruption of the bimodal Acatlán Ignimbrite and the emplacement of several dacitic to rhyolitic domes.

Four system of Quaternary volcanic-vent alignments are present in the study area: Tequila (TEQ), Southern Guadalajara Volcanic Chain (Luhr and Lazaar, 1985) (SGVC), Acatlán (ACA), and Atotonilco (ATO). The Tequila system, located at the NW portion of the area is formed by three WNW-trending alignments -TEQ-N, TEQ-C, and TEQ-S (Fig. 3.5)- with K-Ar ages ranging between 1.8 and 0.2 Ma (Gilbert et al., 1985; Nixon et al. 1987). The TEQ-C alignment is built on the buried extension of the Plan de Barrancas fault (see section 3.1) and contain the Volcán Tequila which also shows a notable elongation in the same WNW-ESE direction (Fig. 3.5). The Pleistocene La Primavera Caldera (Mahood, 1980) separate the TEQ-N alignments from the SGVC. If one considers the two alignments together the overall length of the chain would be ~62 km. The Acatlán and Atotonilco systems are located in the accommodation area between the overstepping Ahuisculco and San Marcos faults (Fig. 3.5). Volcanic vents are more scattered but depict a clear NW orientation parallel to the nearby normal fault. Particularly, the ACA alignment constitute the northwestern prolongation of the Bola del Viejo fault (Fig. 3.5).

Since the proposal of Nakamura (1977) the alignment of volcanic vents has been generally accepted to be an indicator of the state of stress in the upper crust, being the sHmin orthogonal to the averaged direction of the vent alignment (Zoback, 1992). Suter (1991) calculated a mean, 30°-trending, minimum horizontal principal stress (sHmin) for the SGVC alignment. The sHmin obtained for the others alignments is very similar (Fig. 3.5). However, in the study area, many of the volcanic-vent alignments follow major faults which are older than Quaternary in age. This can explain the different direction of sHmin obtained by fault-slip data inversion and volcanic-vent alignments for the Quaternary (Fig. 3.5). In conclusion, the development of the AVF and the location of the volcanic-vent alignments illustrate the importance of pre-existing crustal weakness zones in determining the distribution and the style of the volcanic activity in the western MVB.

3.4 Conclusions

We have proposed a comprehensive regional stratigraphy for the Guadalajara and the triple junction area by integrating previuos studies (Watkins et al., 1971; Gilbert et al. 1985; Moore et al., 1994; Ferrari et al., in press) with new geologic mappings and isotopic-age determinations. We also attempted to define the boundaries between the basement domains of the SMO, the JB and the Michoacán block, which presently are covered by the late Miocene to Quaternary MVB. In the study area the silicic succession of the SMO is restricted to the north of the Santa Rosa-Cinco Minas fault and of the northern boundary faults of Lake Chapala. We have also shown that widespread mafic volcanism and lacustrine sedimentation occurred at 11-8 Ma in several tectonic basins developed along the Tepic-Zacoalco and the Chapala rifts. This indicates that extensional reactivation of the block boundaries took place earlier than previously suggested, in accordance with the model of (Ferrari 1995) who postulated a late Miocene extension in the Guadalajara area in response to the initial opening of the southern Gulf of California.

We have also presented a new interpretation of the structural geometry of the Zacoalco half-graben, in which the Bola del Viejo fault is considered the main detachment structure responsible for the northeast tilting of the Sierra de San Marcos and Sierra de Tapalpa blocks. Furthermore, because of the almost identical tilting of the Sierra de San Marcos block and other blocks to the southeast we consider that the San Marcos fault has a planar surface. Finally, we have confirmed that the Santa Rosa fault had a normal motion in post-late Miocene times and that it probably has been inactive since middle Pleistocene.

UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Unidad de Ciclos Profesionales y de Posgrado

Colegio de Ciencias y Humanidades

Posgrado en Ciencias de la Tierra

(Geología)

Tectónica Extensional en el Occidente de la Faja Volcánica Trans-Mexicana: Frontera norte del bloque Jalisco

TESIS

(Resumen)

Que para obtener el grado de

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José Rosas Elguera

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Resumen

Durante los últimos diez años varios modelos tectónicos han considerado al bloque Jalisco como una microplaca separándose de México desde el Plioceno debido al salto de la East Pacific Rise hacia el oriente. Esos modelos postulan un fallamiento normal y de transcurrencia a lo largo del graben Tepic-Zacoalco. En este estudio se presentan nuevos datos sobre la estructura, cinemática y tiempo de deformación a lo largo de los límites continentales del bloque Jalisco obtenidos a través de mapeo geológico y estructural integrados con los datos de perforación de pozos profundos (geotérmicos y petrolero).

El graben Tepic-Zacoalco (limite norte del bloque Jalisco) es una combinación de tres diferentes sistemas estructurales desarrollados durante el Mioceno tardío (12-9 Ma), Plioceno temprano (5.5-3.5 Ma) y, en menor extensión, en el Plioceno tardio-Cuaternario. Esas estructuras son agrupadas en tres sectores: (1) el sistema Pochotitan (12-9 Ma); (2) el sector central formado de grábenes *en echelon* (Mioceno tardio-Plioceno); (3) sector sur, formado por tres semi-grabenes (Plioceno-Cuaternario). El desplazamiento vertical en esas estructuras es de aproximadamente 1500 m. El desplazamiento de unidades fechadas sugiere que la tasa de deformación decreció de 0.75 mm/año para el Mioceno tardío a 0.1 mm/año para el Cuaternario.

La dirección de extensión promedio para el Mioceno tardío es de 72° mientras que para el Plioceno y Cuaternario esta entre 35° y 2°. Estos resultados confirman la ausencia de fallamiento transcurrente a lo largo del graben Tepic-Zacoalco durante el Plio-Cuaternario lo cual sugiere que el bloque Jalisco no se está separando de México.

El graben de Colima (limite oriental del bloque Jalisco), está formado por el graben de Colima norte y graben de Colima sur, los cuales están separados por el complejo volcánico Colima. El graben de Colima norte está constituido por el semi-graben Amacueca de dirección NE y por el graben de Sayula de dirección norte-sur. La extensión en el graben de Colima norte comenzó en el Plioceno con el emplazamiento de rocas volcánicas. Por su parte el volcán Cántaro fue emplazado en la falla occidental del graben Sayula hace 1.6 Ma. De esta manera los 2500 m de

desplazamiento vertical ocurrieron en aproximadamente 3.5 Ma dando una tasa de subsidencia de 0.7 mm/año.

De acuerdo con el tensor de paleo-esfuerzos estimado a partir del análisis de poblaciones de fallas en el graben de Colima norte, la dirección de extensión estimada es de 140° ± 19°, no obstante una extensión E-W puede observarse de acuerdo con el alineamiento de conos volcánicos del complejo volcánico Colima.

El graben de Colima sur se localiza al sur del volcán Colima. En esta región no se encontraron evidencias de fallamiento normal importante en las rocas del Plioceno y Cuaternario expuestas a lo largo de esta estructura y, en los últimos cinco años, la red sísmica de Colima casi no registró sismicidad. Sin embargo, cientos de eventos sísmicos (Ms=5.2) fueron registrados en una extensa área al oeste de la depresión. Algunos de esos eventos se agruparon en una dirección N-NE que se propagaban desde el área de Armeria hasta la parte sur del volcán Colima.

En este sentido se propone que la extensión Plio-Cuaternaria al sur del graben de Sayula es acomodada por una área triangular comprendida entre el complejo volcánico Colima y las ciudades de Manzanillo y Armería. El limite noroeste de esta area coincide con un sistema de transcurrencia antiguo de dirección noreste que afecta rocas cretácicas, este sistema puede ser considerado el límite neotectónico de la esquina sureste del bloque Jalisco.

En la región comprendida entre Guadalajara y la unión triple de las depresiones tectónicas Tepic-Zacoalco, Colima y Chapala, la Faja Volcánica Trans-Mexicana oculta los limites entre la Sierra Madre Occidental y los bloques Michoacán y Jalisco. A lo largo de ese límite se desarrollaron varios rasgos geológicos desde el Mioceno tardío. El vulcanismo comenzó con el emplazamiento de la Secuencia Máfica Basal de la Faja Volcánica Trans-Mexicana hacia los 13-8 Ma, que llenaron depresiones tectónicas, igualmente la sedimentación lacustre es un rasgo importante y notable para este tiempo. Ello sugiere que la extensión ocurrió antes de lo que previamente había sido sugerido. Por otra parte el registro volcano-sedimentario sugiere una probable unión entre las depresiones de Tepic-Zacoalco y Chapala a través de un sistema de cuencas. Además, desde el Mioceno tardío el vulcanismo silício ha dominado en el área de Guadalajara, pero en las regiones de Chapala y Zacoalco ha sido mas intermedio.

Como conclusión final, se propone que los limites continentales del bloque Jalisco se desarrollaron en repuesta a un levantamiento del batolito de Puerto Vallarta antes del Neogeno y que fue afectado por una deformación contractil antes del Plioceno. Con base en los resultados de este trabajo se propone que (1) los limites continentales del bloque Jalisco son estructuras antiguas reactivadas desde el Plioceno con una tasa de deformación baja (<1 mm/año) y (2) el fallamiento extensional en los bordes del bloque Jalisco es una deformación intrapalaca controlada por el basamento y relacionada con fuerzas en los limites de las placas mas que a un rifting continental activo. El movimiento E-SE del bloque Michoacán estaría inducido por el movimiento diferencial y subducción oblicua de la placa de Cocos. Por otra parte, se considera que la extensión Plio-Cuaternaria a lo largo del graben Tepic-Zacoalco es una respuesta a la baja tasa de convergencia y fuerte ángulo de subducción de la placa de Rivera

Abstract

In the last decade different 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 graben. We present a new picture of the structure, the kinematics and time of deformation along the continental boundaries of the Jalisco block, obtained by geological and structural mapping integrated with subsurface stratigraphic data provided by deep geothermal and oil wells.

The Tepic-Zacoalco graben (the northern boundary of the Jalisco block) is a combination of three 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 Pochotitán fault system (12-9 Ma); 2) a central branch made of *en echelon* grabens (Late Miocene-Pliocene; 3) a southern branch constituted by three half-grabens (Pliocene-Quaternary). Vertical displacement in these structures exceeds 1500 m. Displacement of dated geologic units constraints 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.

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 (ŐHmin) is 72° for the late Miocene extension in the Gulf area, whereas in Pliocene and Quaternary it ranges from 35° to 2°. These results confirm the absence of strike-slip deformation along the Tepic-Zacoalco graben in Plio-Quaternary times and indicate that the JB is not actively separating from the Mexican mainland.

The Colima graben (the eastern boundary of the Jalisco block), is formed by : the northern and southern Colima graben, which are separated by the Colima volcanic complex. The NE-trending Amacueca half graben and the N-S-trending Sayula graben form the Northern Colima graben.

Extension in the northern Colima graben started at the beginning of Pliocene time concurrently with the emplacement of alkaline volcanic rocks. The Cantaro volcanic complex was emplaced over the western bounding fault of the Sayula graben at about 1.6 Ma. Thus 2500 m of vertical offset must have occurred in ~3.5 m.y., giving a subsidence rate of 0.7 mm/yr. In the Sayula graben, however, a minimum of 300 m of vertical offset and a rate of deformation of 0.07 mm/yr can be estimated

Paleo-stress tensors computed from fault slip data measured at seven sites in the northern Colima graben indicate an average 140 °± 19° direction for the minimum principal stress, but east-west extension is supported by the north-south alignment of the parasitic cones of the Colima volcanic complex.

The southern Colima graben is a wide topographic depression, located south of Colima volcano. We did not find any evidence of large normal faulting in the Pliocene and Quaternary rocks exposed along this structure and, in the last five years, the Colima state seismic network recorded almost no seismicity in the so-called southern Colima graben. By contrast, thousands of crustal seismic events (mostly at 19 to 7 km depth) with magnitude up to M_s = 5.2 were recorded in a broad area west of it (G. Reyes-Davila, 1996, written commun.). Some of these events clustered in northeast- to north-northeast-trending swarms propagating from the Armeria area to the southern part of the Colima volcano (G. Reyes-Davila, written commun.)

We propose that Pliocene-Quaternary extension south of the Sayula graben is accommodated in a broad triangular area comprised between the Colima volcanic complex and the cities of Manzanillo and Armeria. The northwestern boundary of this area coincides with an older belt of northeast-trending strike-slip faults affecting Cretaceous rocks, which could be considered the neotectonic boundary of the southeastern corner of the Jalisco block (Tamazula-Manzanillo fault zone).

In the region between Guadalajara and the triple junction of the Tepic-Zacoalco, Chapala and Colima tectonic depressions the late Miocene to Quaternary volcanic rocks of the Mexican Volcanic Belt (MVB) largely conceal the boundaries between the basement domains of the Sierra Madre Occidental (SMO) to the north and the Jalisco and Michoacán blocks to the south.

Along the boundary between the SMO and the blocks located to the south (i.e the Tepic-Zacoalco and Chapala grabens), several geologic features have developed since late Miocene times. The succession of the MVB began with widespread mafic volcanism, and lacustrine sedimentation occurred at 13 to 8 Ma in several tectonic basins, suggesting that the extensional reactivation of the block boundaries took place earlier than previously suggested. The volcano-sedimentary record suggests a probable link between the Tepic-Zacoalco and Chapala grabens through a basin system developed in late Miocene and early Pliocene times. Furthermore, since latest Miocene time silicic volcanism has dominated in the Guadalajara area; more intermediate to mafic products have erupted in the Chapala and Zacoalco areas.

The Jalisco block boundaries first developed in response to the uplift of the Puerto Vallarta batholith in pre-Neogene time and underwent a complex contractile deformation before the Pliocene. On the basis of new structural and geophysical data, we propose that: (1) the continental boundaries of the Jalisco block are ancient structures reactivated since the Pliocene at a low (<1 mm/yr) rate of deformation, and (2) Pliocene-Quaternary extensional faulting at the edges of the Jalisco block is a basement-controlled intraplate deformation related to plate boundary forces rather than to active continental rifting. The parallelism between the subducted Rivera-Cocos plate boundary zone and the eastern neotectonic boundary of the Jalisco block supports east-southeastward motion of the southern Mexican blocks induced by the differential motion and oblique subduction of the Cocos and Rivera plates. On the other hand, we envisage Pliocene-Quaternary extension along the northern boundary as an upper-plate response to the low convergence rate and the steep subduction angle of the Rivera plate.

VoBo

DR. JAIME URRUTIA-FUCUGAUCHI

IV LATE MIOCENE TO QUATERNARY EXTENSION AT THE NORTHERN BOUNDARY OF THE JALISCO BLOCK, WESTERN MEXICO: THE TEPIC-ZACOALCO RIFT REVISED

by

L. FERRARI AND J. ROSAS-ELGUERA

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 NNW trending, high angle normal faults which tilt up to 35° towards ENE blocks of the Sierra Madre Occidental succession. These faults accommodate at least 2000 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 2000 m. Toward the east is the Plan de Barrancas-Santa Rosa graben, a WSW 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 S to SW dipping listric normal fault systems with a minimum of 1400 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 (σ_{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.

4.1 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. 4.1). 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;

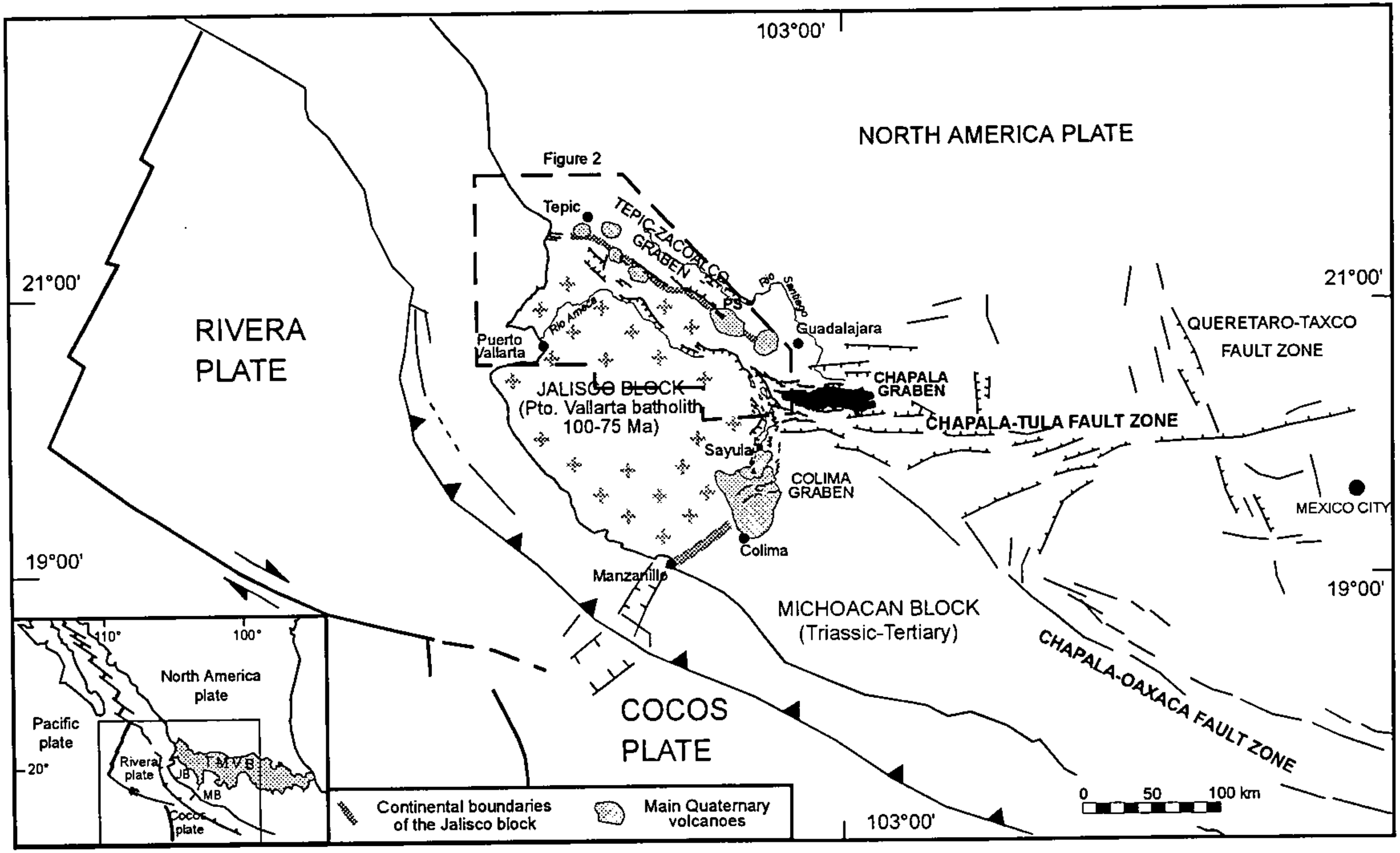


Fig. 4.1 Ubicación de la zona de estudio en relación con el marco tectónico regional. TMVB, Trans-Mexican Volcanic Belt

Lonsdale, 1991; Lyle and Ness, 1991). Southeast of the Gulf, however, subduction did not stop and since ~ 5 Ma the Rivera plate behaved independently from the Cocos plate (Atwater, 1970; Mammerickx 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. 4.1)(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. 4.1). 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. 4.1) 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 ~E-W 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-Obregon 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-Obregon 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. 4.1) . 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.

4.2 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, pag. 432).

The Mazatán fault system was originally mapped by Gastil et al. (1978) as a NW-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. 4.2) and claimed that it cut Pliocene rocks. The same authors depicted the Pochotitán fault system as a NW-trending fault with both strike-slip and normal motion which runs approximately along the Rio Santiago from the Aguamilpa area to the Santa Rosa dam (Fig. 4.2).

4.3 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. 4.2). 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

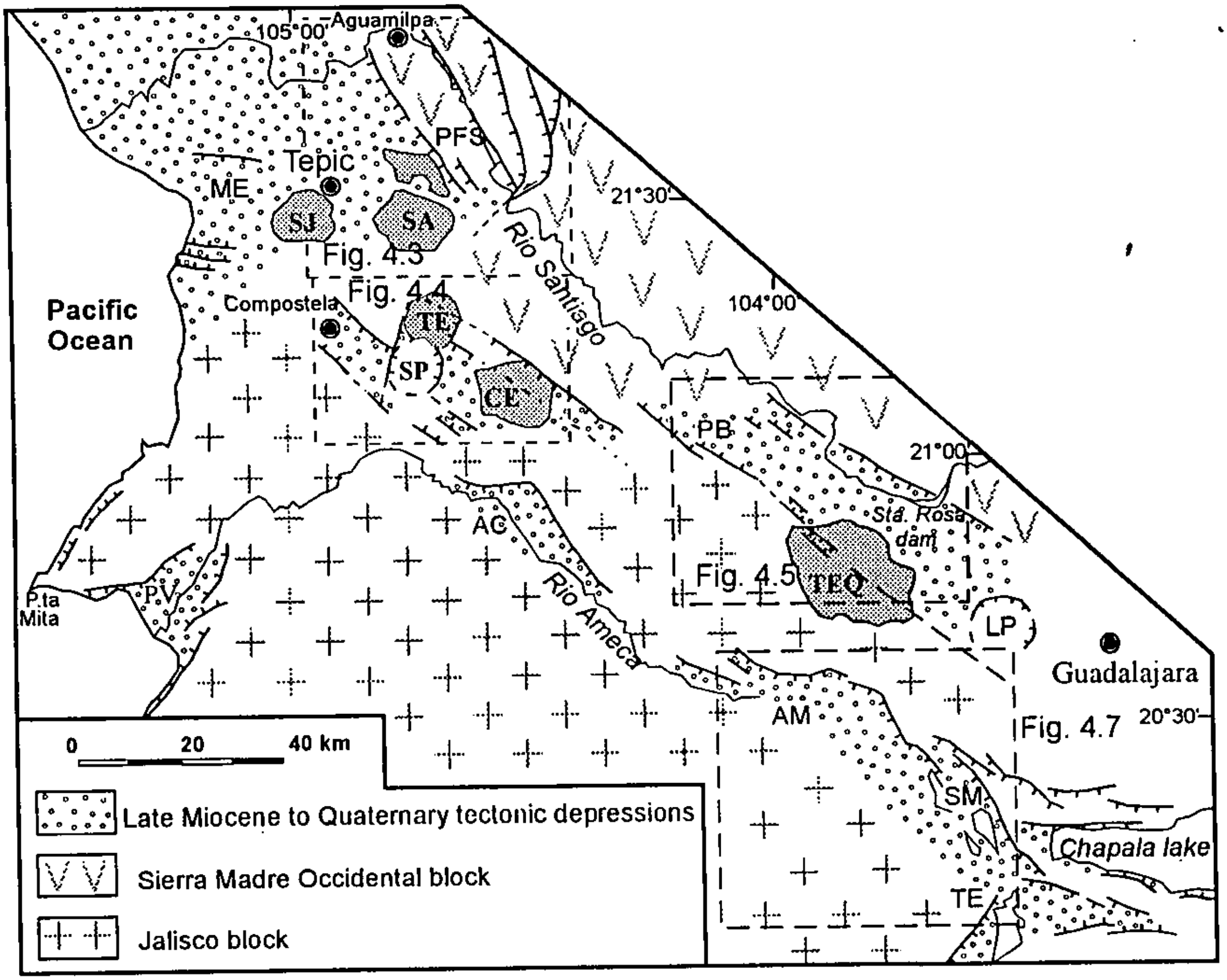


Fig. 4.2 Mapa tectónico del área de estudio mostrando las principlaes cuencas tectónicas del rift Tepic-Zacoalco y el límite entre el bloque Jalisco y la sierra Madre Occidental (Ferrari et al., en prensa. PFS=Sistema de Fallas Pocotitlán; ME=graben Mecatan; PV=graben Puerto Vallarta AC=Semigraben Amatlán de Cañas; PB=Falla Plan de Barrancas; AM=Falla Ameca; SM=Falla San Marcos; TE=Falla Techalutla (semigraben Sayula). VOLCANES: SJ=San Juan; SA=Sanganguey; TE=Tepetiltic; CE=Ceboruco; TEQ=Tequil<a. CALDERAS: SP=San Pedro; LP=La Primavera.

previously included in the TZR can be divided into three types according to their structure, kinematics and tectonic location (Fig. 4.2):

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-Obregón et al., 1992).

In the next section we describe the structure and the age of these fault systems. Table 4.1 summarizes the features of each fault system.

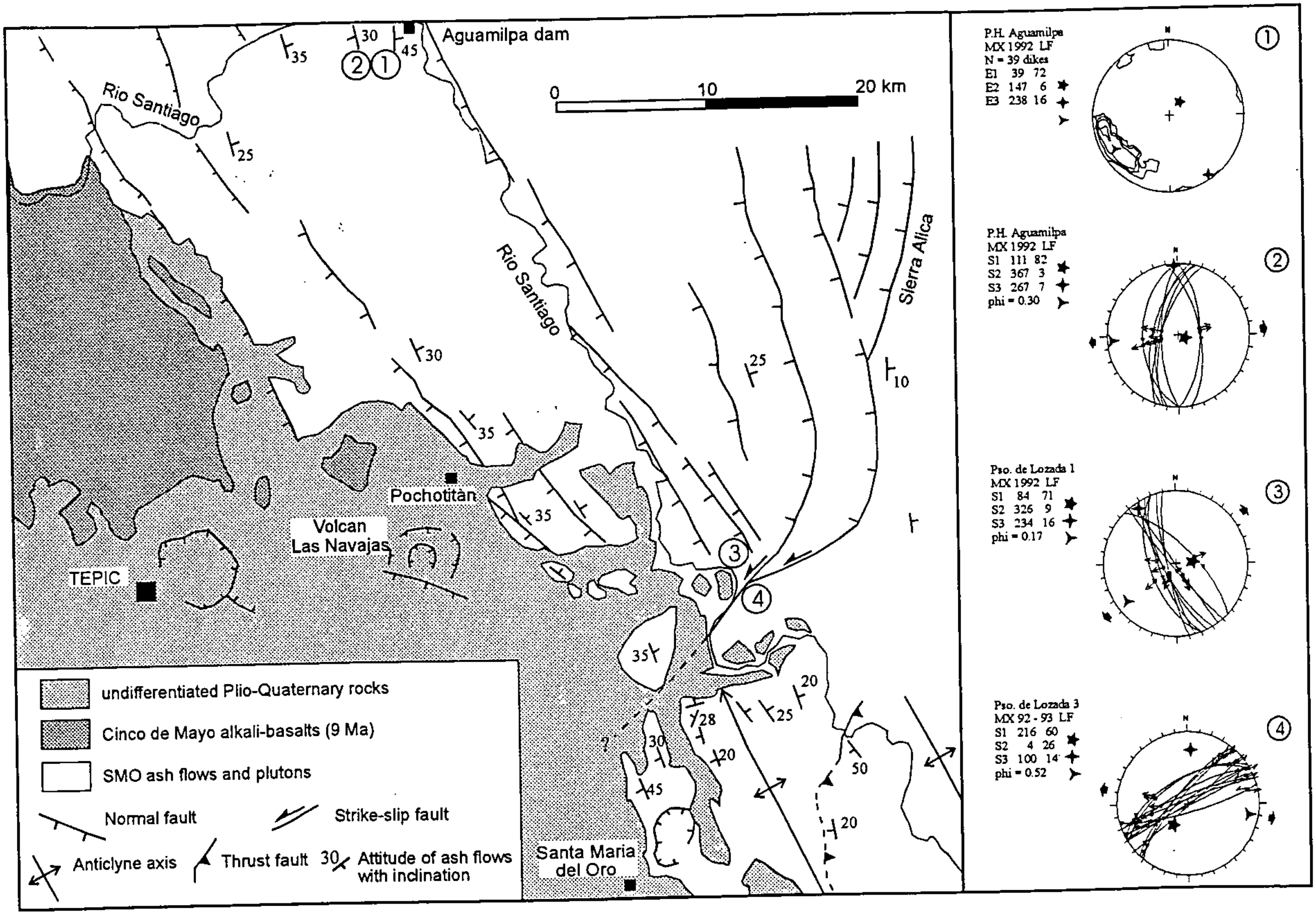
The Gulf extensional province

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. 4.2 and 4.3). These faults are grouped in a 30-km-wide belt between Volcán Las Navajas and Sierra Alica (Fig. 4.3), where ash-flows as young as 19 Ma old crop out in faulted blocks, tilted up to 35° towards ENE in a step-like structure. Individual faults strike 140° to 180°, dip toward the SW and show a dominant dip-slip motion produced by E-W to ENE-WSW trending extension (Fig. 4.3, Table 4.2). The eastward tilting of the volcanic rocks increases toward the west, which suggests that the master fault has a listric geometry at depth.

TABLE 4.1 SUMMARY OF THE LATE MIOCENE TO PRESENT EXTENSIONAL FAULT SYSTEMS OF WESTERN MEXICO

Fault system	Strike	Fault lenght (km)(1)	Inclination of hangingwall blocks	Minimum vertical offset (m)	σ3 azimuth (2)	Age of faulting (Ma) (3)	Min. rate of displacement (mm/year)
GULF EXTENSIONAL PROVINCE							
Pochotitán fault system	140° - 155°	35	20°- 35° ENE	>2000	45° - 85°	11.5 - 9	0.8
COASTAL NAYARIT							
Mecatan graben	0° - 10°	5	0°	300	0° ?	< 3.1	0.1
TEPIC-ZACOALCO RIFT							
Central branch							
Compostela graben	125°	30	0°	600 500	35°	4.5 - 2.3 2.3 - 1.1	0.27 0.41
Ceboruco graben	120°	35	20°- 40° NNE	1800 900	? 30° ?	11.5 - 9? 4.5 - 2.3	0.72 0.45
Plan de Barranca - La Primavera	120°	>17	20° SSW	500 ? 100	15° - 35°	> 3.5 < 0.66	0.5 0.15
Cinco Minas fault	130°	15	0°	400 100	40° ?	5.5 - 3.9 3.2 - 1	0.25 0.05
Santa Rosa fault	120° - 130°	37	0°	450	30° ?	5.5 - 4.5	0.45
Southern branch							
Amatlan de Cañas half graben	80°-100° 150°	20 25	10° - 25° NNW 0°	1500 40	20° - 60°	5.5 - 3.5? < 0.66	0.75? 0.06
Ameca fault	80° - 110°	34	<10° NNE	1400	35°-60°	?	?
San Marcos fault system	140° - 170°	45	10°- 45° NNE 0°	1550 100	15° - 70°	3.3? - 1 < 1	0.4 0.1
Puerto Vallarta graben	20° - 80°	25	0°	1000 50	135° 20° - 40°	latest Miocene? Pliocene?	
COLIMA RIFT Sayula half graben	10° - 30°	40 ?	?	2500 (4)	90°-110° (5)	5-3.4	0.51

(1) Length of the major fault within the fault system.
(2) Range of minimum principal stress direction from Table 4.2; question mark when inferred from fault orientation assuming a pure extensional deformation.
(3) Time of fault activity constrained by dated stratigraphic unit on both side of the fault; question mark indicates values only partly constrained by isotopic ages or geologic data. See text for details.
(4) According to Allan (1986). (5) According to this work and to Barrier et al. (1991)



Aguamilpa dam
0
10
20 km
Rio Santiago
Rio Santiago
Sierra Alica
Pochotitàn
Volcan
Las Navajas
TEPIC
Santa Maria
del Oro
undifferentiated Plio-Quaternary rocks
Cinco de Mayo alkali-basalts (9 Ma)
SMO ash flows and plutons
Normal fault
Strike-slip fault
Anticlyne axis
Thrust fault
Attitude of ash flows
with inclination
P.H. Aguamilpa
MX 1992 LF
N = 39 dikes
E1 39 72
E2 147 6
E3 238 16
P.H. Aguamilpa
MX 1992 LF
S1 111 82
S2 367 3
S3 267 7
phi = 0.30
Pso. de Lozada 1
MX 1992 LF
S1 84 71
S2 326 9
S3 234 16
phi = 0.17
Pso. de Lozada 3
MX 92 - 93 LF
S1 216 60
S2 4 26
S3 100 14
phi = 0.52

Fig. 4.3a

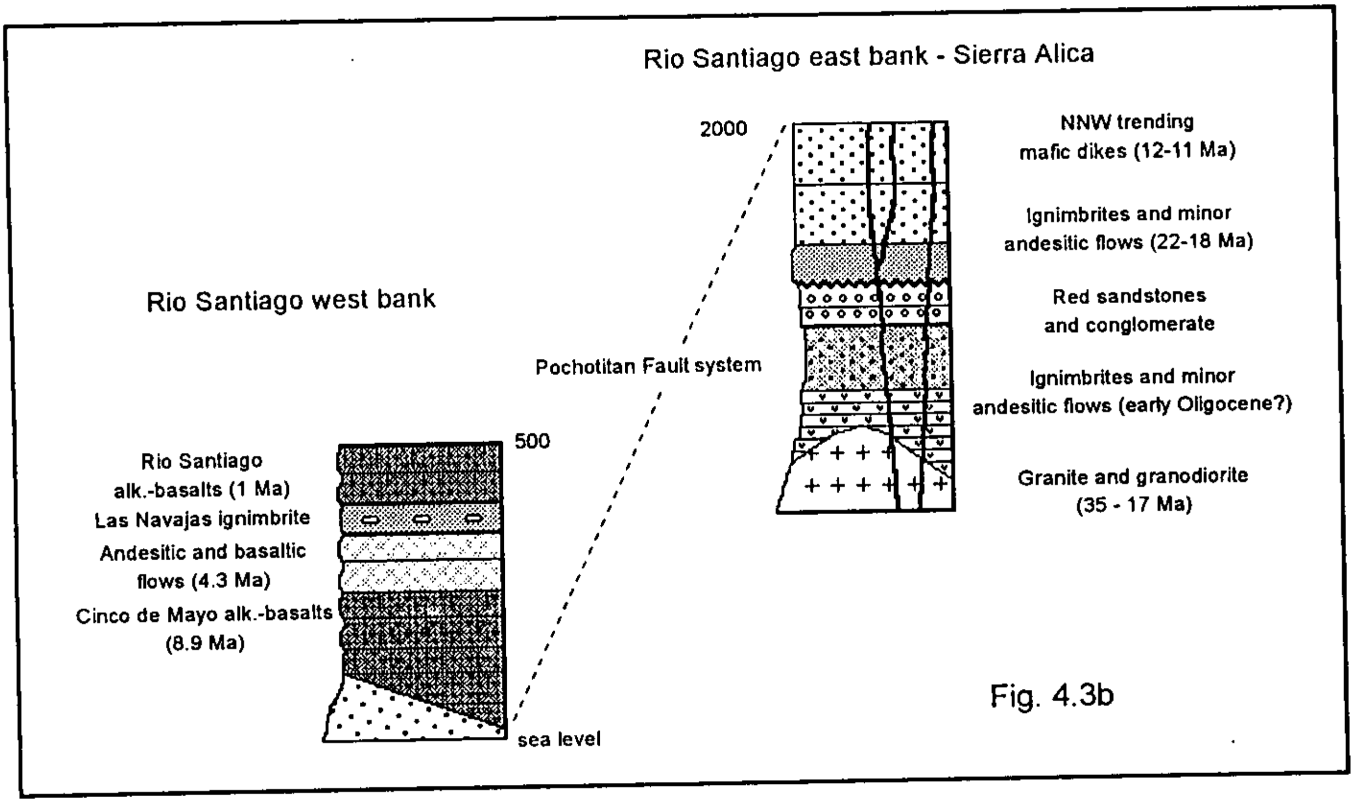


Fig. 4.3 (a) Geo-structural map of the Tepic region. The Pochotitlán fault system (PFS) comprises the NW to N-S trending normal faults between the homonymous village and Sierra Alica and is separated by the folds of the Santa Maria del Oro area by left-lateral normal transfer fault system that is inferred to continue south-westward. Also shown are stereograms (Schmidt projection, lower hemisphere) of meso-faults measured at sites numbered as in Fig. 4.10 and Table 4.2. The stress tensor was calculated with the direct 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 stria direction measured on the fault plane of the footwall block. Small triangles on great circles indicate calculated stria for the obtained tensor. The angle between measured and calculated stria is always less than 20°. Stereogram of site 1 represent poles to 39 dikes contourned at 2, 5, 10, 20 points per 1 % area. (b) Generalized stratigraphy to the east and to the west of the PFS. Elevation asl in meters. Radiometric ages from compilation in Ferrari et al. (in press).

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. 4.3). But 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 2000 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 fig. 4.3 (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. 4.3). 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 extensional faulting. Toward the west the SMO ash-flows are covered unconformably by alkali-basaltic lava flows (Cinco de Mayo plateau, Fig. 4.3) 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 systems 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 ENE-WSW left-lateral normal faults (Fig. 4.3). These faults act as a transfer system between the region which underwent ENE-

WSW extension to the north and the Santa Maria del Oro area (Fig. 4.3), which seems to have suffered only a middle Miocene folding phase (Ferrari, 1995). Thus the PFS represents the southern termination of the "Gulf Extensional Province" (Gastil et al., 1975; Fenby and Gastil., 1991) which accompanied the initial opening of the Gulf of California in late Miocene time (Stock and Hodges, 1989).

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 E-W orientation (Fig. 4.2). 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 NW trending normal faults affecting lavas dated at 1 Ma in the Jumatan area, about 25 km west-nothwest 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 WSW-ENE 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.

4.4 The fault systems along the boundary between SMO and JB

Between Compostela and the Santa Rosa dam several WNW-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. 4.2). Based on the en-echelon pattern of these faults and on oblique right-lateral striations found in the oldest rocks, Ferrari (1995) suggest 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. 4.4). 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. 4.4, site 5) which indicate NNE 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. 4.4). A rhyolitic dome

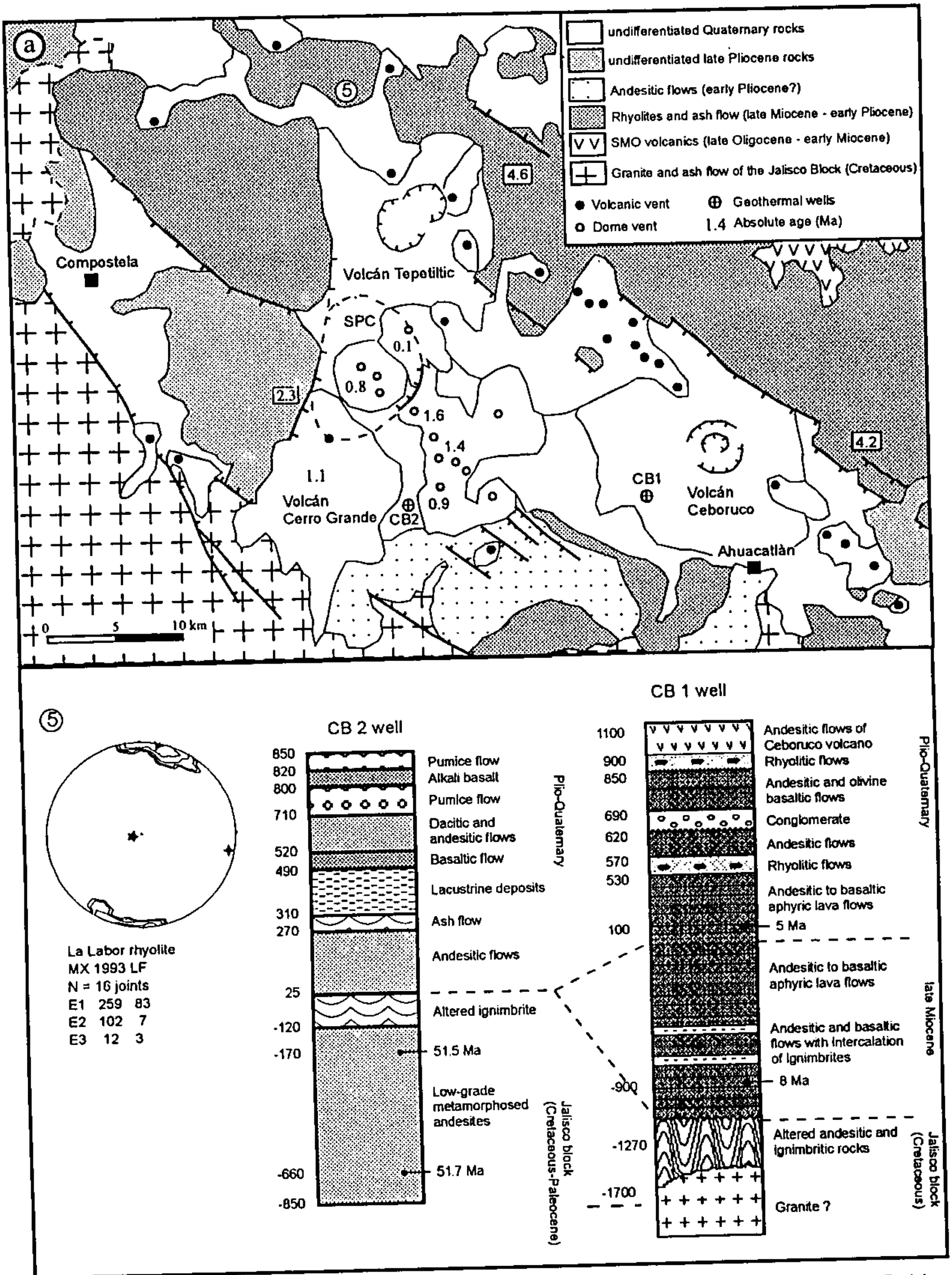


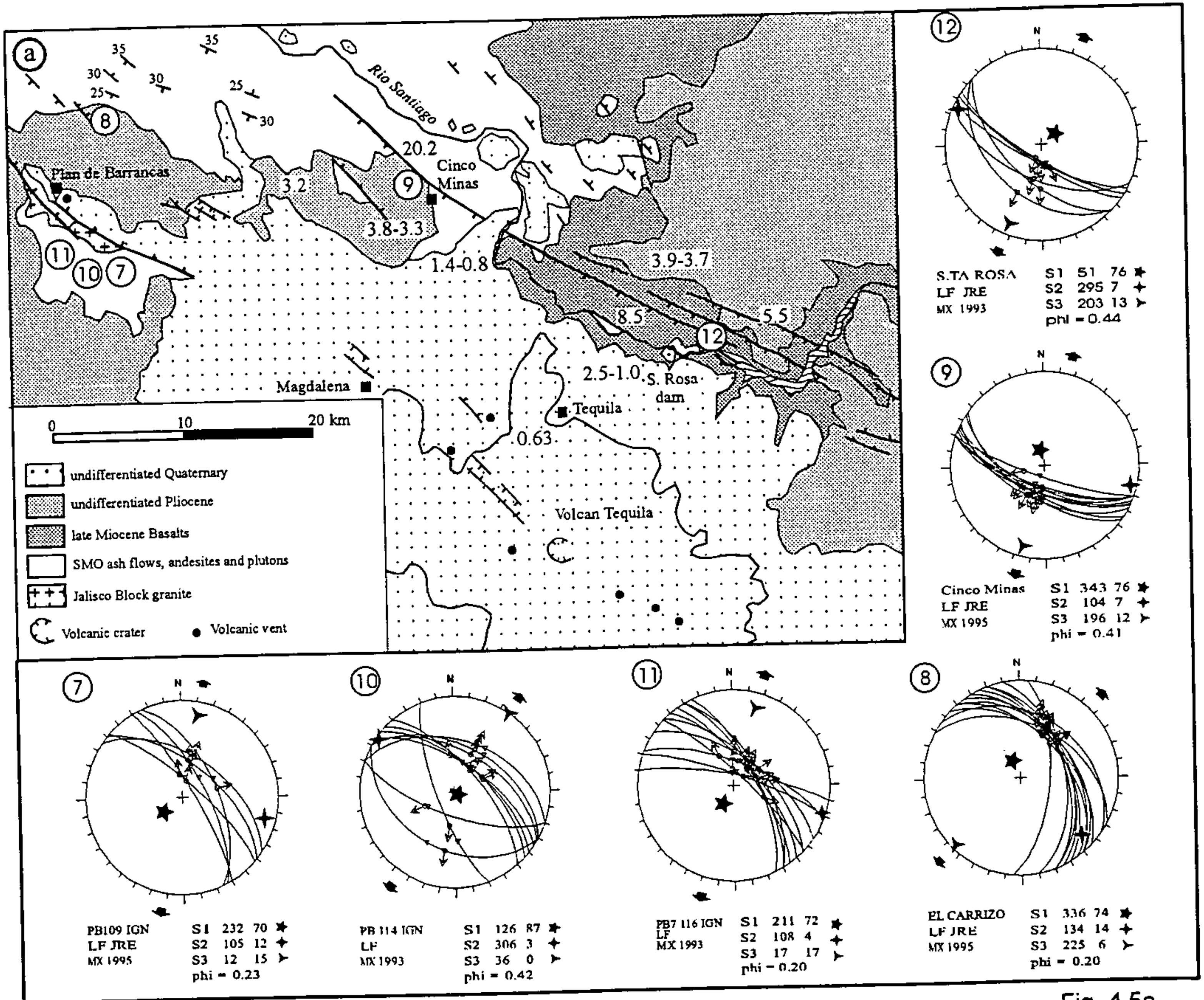
Fig. 4.4 (a) Geo-structural map of the Compostela-Ceboruco area. SPC=San Pedro Caldera Fault and geologic limits dashed when inferred. Ages are refered in the text. (b) stereogram of poles to extensional joints contoured at 2, 5, 10, 20 pints per 1% area. (c) Generalizad stratigraphy of two deep exploratory wells drilled by CFE with elevation in meters (not to scale).

complex of 2.3 Ma (Gastil et al., 1978), located inside the graben, is not affected by these faults but is cut by NNE-SSW and NE-SW striking normal faults which downthrow the eastern part of the graben and form the depression where the San Pedro caldera developed (Fig. 4.4). 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. 4.4). 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. 4.4). Surprisingly, the well encountered rocks correlative with the JB succession at a depth of 2400 m without crossing the SMO succession. The succession above the JB is composed of 1800 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. 4.4). 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 but if this correlation is confirmed then a depression of about 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, SW dipping normal faults, exposed north of Ceboruco volcano are related to a younger extensional phase which is responsible for another 900 m of vertical offset (Fig. 4.4). 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 Pliocene rocks lie at the base of the depression beneath the Ceboruco 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. 4.2 and 4.5). 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. 4.5, 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



a
Rio Santiago
Plan de Barrancas
Cinco Minas
Magdalena
Tequila
S. Rosa dam
Volcan Tequila
20.2
3.2
3.8-3.3
1.4-0.8
3.9-3.7
8.5
5.5
2.5-1.0
0.63
0 10 20 km
undifferentiated Quaternary
undifferentiated Pliocene
late Miocene Basalts
SMO ash flows, andesites and plutons
Jalisco Block granite
Volcanic crater
Volcanic vent
S.TA ROSA LF JRE MX 1993
S1 51 76
S2 295 7
S3 203 13
phi = 0.44
Cinco Minas LF JRE MX 1995
S1 343 76
S2 104 7
S3 196 12
phi = 0.41
PB109 IGN LF JRE MX 1995
S1 232 70
S2 105 12
S3 12 15
phi = 0.23
PB 114 IGN LF MX 1993
S1 126 87
S2 306 3
S3 36 0
phi = 0.42
PB7 116 IGN LF MX 1993
S1 211 72
S2 108 4
S3 17 17
phi = 0.20
EL CARRIZO LF JRE MX 1995
S1 336 74
S2 134 14
S3 225 6
phi = 0.20

Fig. 4.5a

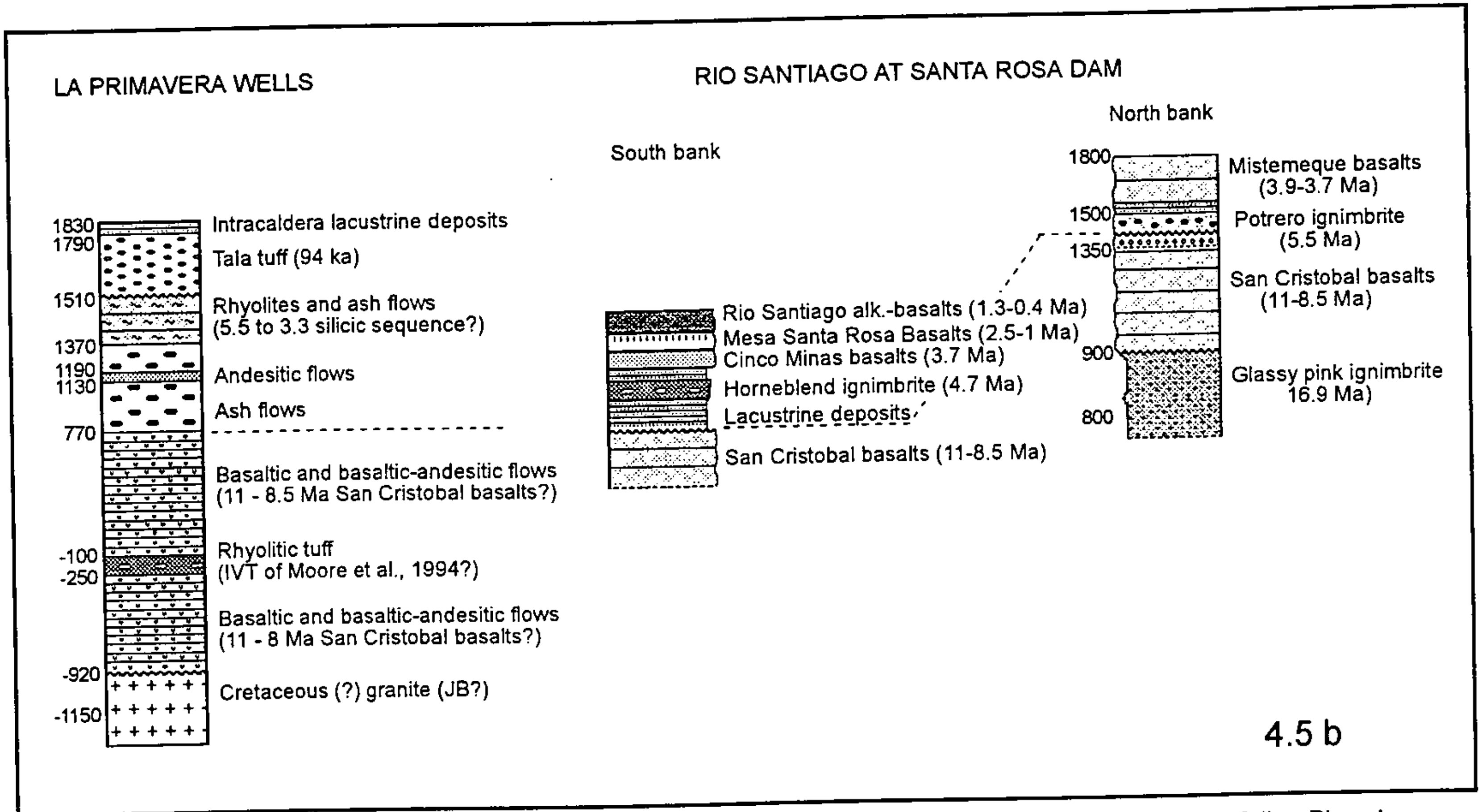


Fig. 4.5 (a) Mapa geoestructural del graben Plan de Barrancas-Santa Rosa. Se infiere que el sistema de fallas Plan de Barrancas continua por debajo del volcán Tequila y sus volcanes monogenéticos asociados, lo cual lo hace paralelo a la falla de Santa Rosa. Las edades estan referidas en el texto. Los estereogramas de las mesofallas son como en la figura 4.3. (b) Estratigrafía generalizada de las márgenes norte y sur del Río Santiago a la altura de la presa de Santa Rosa. Elevaciones en metros

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. 4.5b). In fact a 5.5 Ma ignimbrite (Nieto-Obregon et al., 1985) is downfaulted about 450 m on the northern bank of the Rio Santiago whereas about 100 m of lacustrine sediments with a 4.6 Ma ignimbrite (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. 4.5, site 9). Alkaline basalts dated at 3.8 Ma old (Nieto-Obregón 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. 4.5a). 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 SE of Cinco Minas (Fig. 4.5).

On the other side of the graben the Plan de Barrancas fault system consists of several 120° striking and NE dipping normal faults (Fig. 4.5) which downfault by at least 400 m a granite of the JB and the SMO ash flows, that are found tilted up to 25°. Slickensides on the fault planes show dip-slip motion (Fig. 4.5, 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

SSW and faulted for a maximum of 30 m (Fig. 4.5, 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 silicic flows are horizontal. These structural relations indicate that the Plan de Barrancas faults started to be active in the early Pliocene (or earlier) and that most of the motion took place before the late Pliocene. In addition aeromagnetic and gravimetric modelling 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-Enriquez, 1992) (Fig. 4.2). The trace of this fault coincides with a prominent alignment of vents of the Tequila volcano and other minor cinder cones (Fig. 4.5). The stratigraphy of the geothermal wells drilled in the La Primavera caldera (where resurgence equals or exceeds the collapse) confirm 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. 4.5b). 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 Saavedra, a dacitic dome dated at 0.63 Ma (Nixon et al., 1987) just northwest of Volcán Tequila (Fig. 4.5).

In summary, both the time of faulting and amount of displacement appears to match on the two sides of the Plan de Barrancas-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.

4.5 The fault systems along the northern Jalisco block

The southern part of the TZR consists of three large depressions developed entirely within the JB which control the course of Rio Ameca (Fig. 4.2). These depressions, also named the Ameca tectonic depression (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. 4.2). The fault is a single entity and its curvature is probably due to reactivation of an older basement structure. Early Paleocene pyroclastic flow deposits and granite of the JB exposed at an elevation of 2000 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 1500 m (Fig. 4.6). The western part of the depression is filled by an undated granitic conglomerate tilted up to 24° toward the NNW 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 no tilting is appreciable in the conglomeratic sequence underlying the 0.66 Ma old El Rosario basalts, about 10 km NW of Amatlán. These basalts are downfaulted not more than 50 m by a normal fault parallel with the eastern

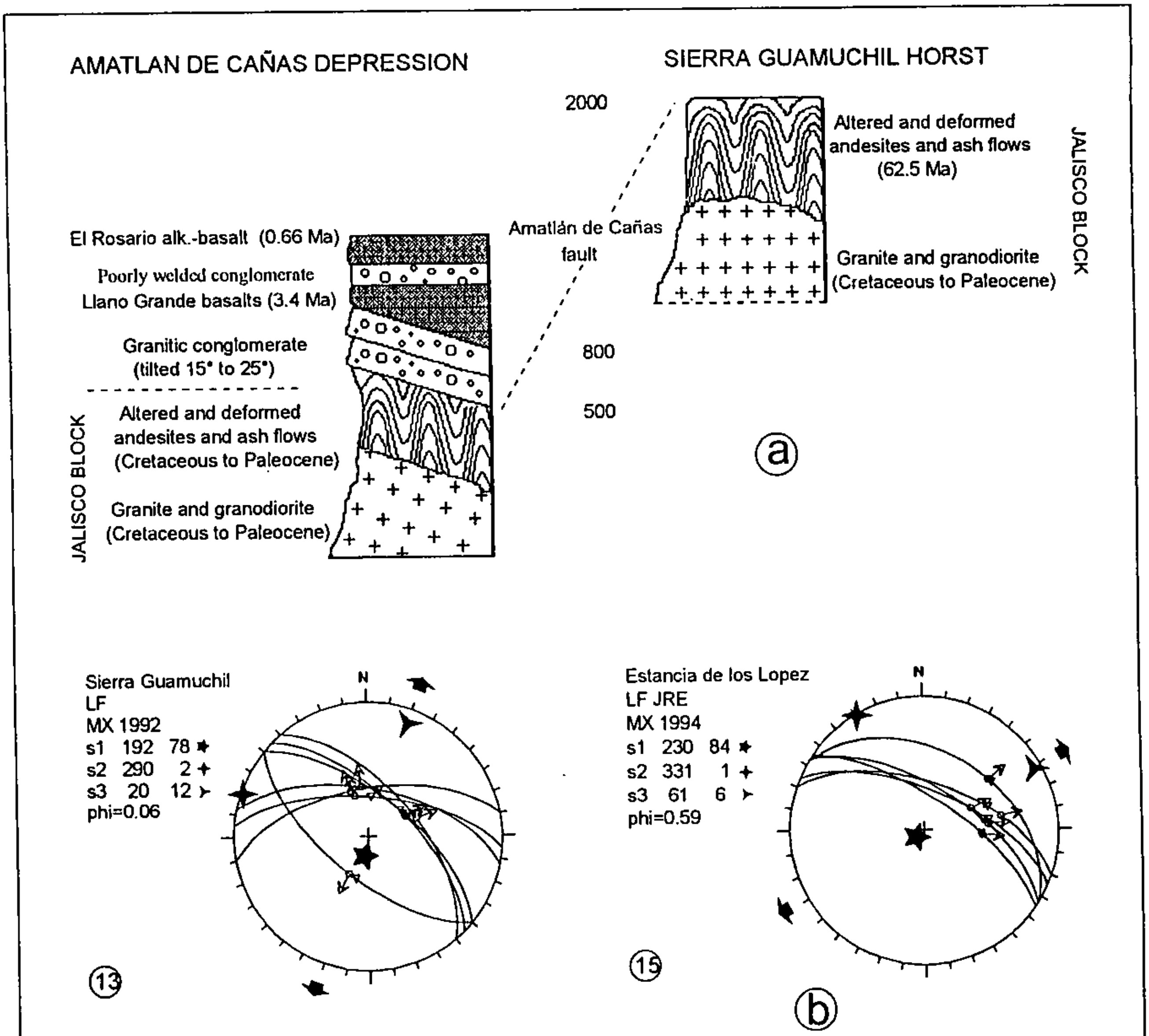
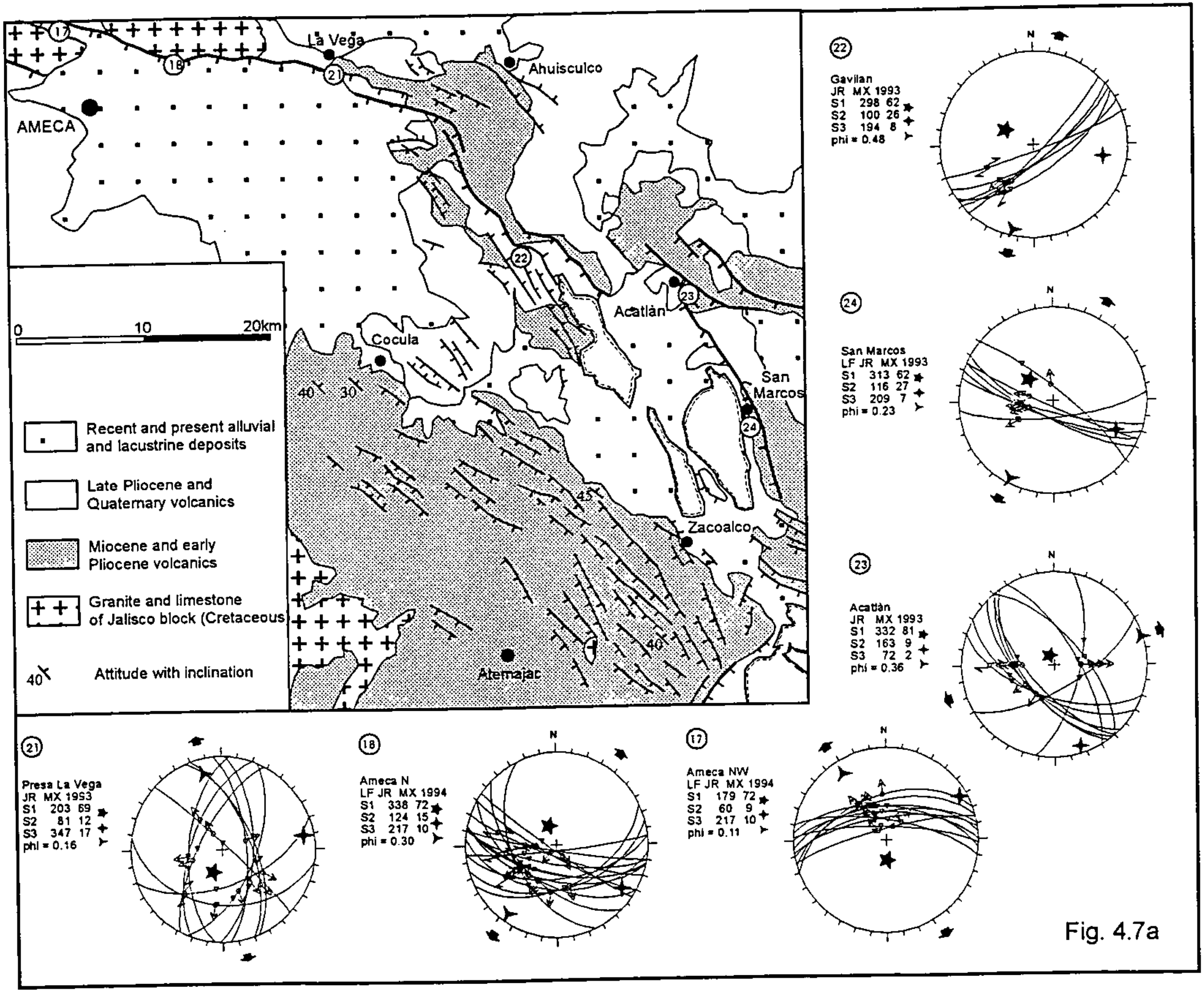


Fig. 4.6 (a) Estratigrafía generalizada del semigraben Amatlan de Cañas con elevaciones en metros (b) Estereogramas de las mesofallas en los sitios a lo largo de la falla Amatlán (ver - Fig. 4.3 para la explicación y la figura 10 y Tabla 2 para localización

segment of the Guamuchil fault but dipping to the NE. 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 S to SW which bound to the north the Ameca and the Zacoalco depressions (Fig. 4.7). 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 1400 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 NNE. The central segment, between Ahuisculco and Acatlán, is 20 km long and strike 145°-155° (Fig. 4.7). Here the fault cuts an ash flow succession attributed to the latest Miocene-early Pliocene (Ferrari et al., this issue) and secondary conjugated faults cut also Pleistocene volcanoes as well as the Acatlán ignimbrite (Walker and Wright, 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 NE (Fig. 4.7). This "domino style" geometry suggests that the San Marcos fault is a SW dipping listric detachment structure, as already hypothesized by Allan (1986). Nevertheless the lack of a geologic



AMECA
La Vega
Ahuisculco
Cocula
Acatlàn
San Marcos
Zacoalco
Atemajac
0 10 20km
Recent and present alluvial and lacustrine deposits
Late Pliocene and Quaternary volcanics
Miocene and early Pliocene volcanics
Granite and limestone of Jalisco block (Cretaceous)
Attitude with inclination
22
Gavilan
JR MX 1993
S1 298 62
S2 100 26
S3 194 8
phi = 0.48
24
San Marcos
LF JR MX 1993
S1 313 62
S2 116 27
S3 209 7
phi = 0.23
23
Acatlàn
JR MX 1993
S1 332 81
S2 163 9
S3 72 2
phi = 0.36
21
Presa La Vega
JR MX 1993
S1 203 69
S2 81 12
S3 347 17
phi = 0.16
18
Ameca N
LF JR MX 1994
S1 338 72
S2 124 15
S3 217 10
phi = 0.30
17
Ameca NW
LF JR MX 1994
S1 179 72
S2 60 9
S3 217 10
phi = 0.11

Fig. 4.7a

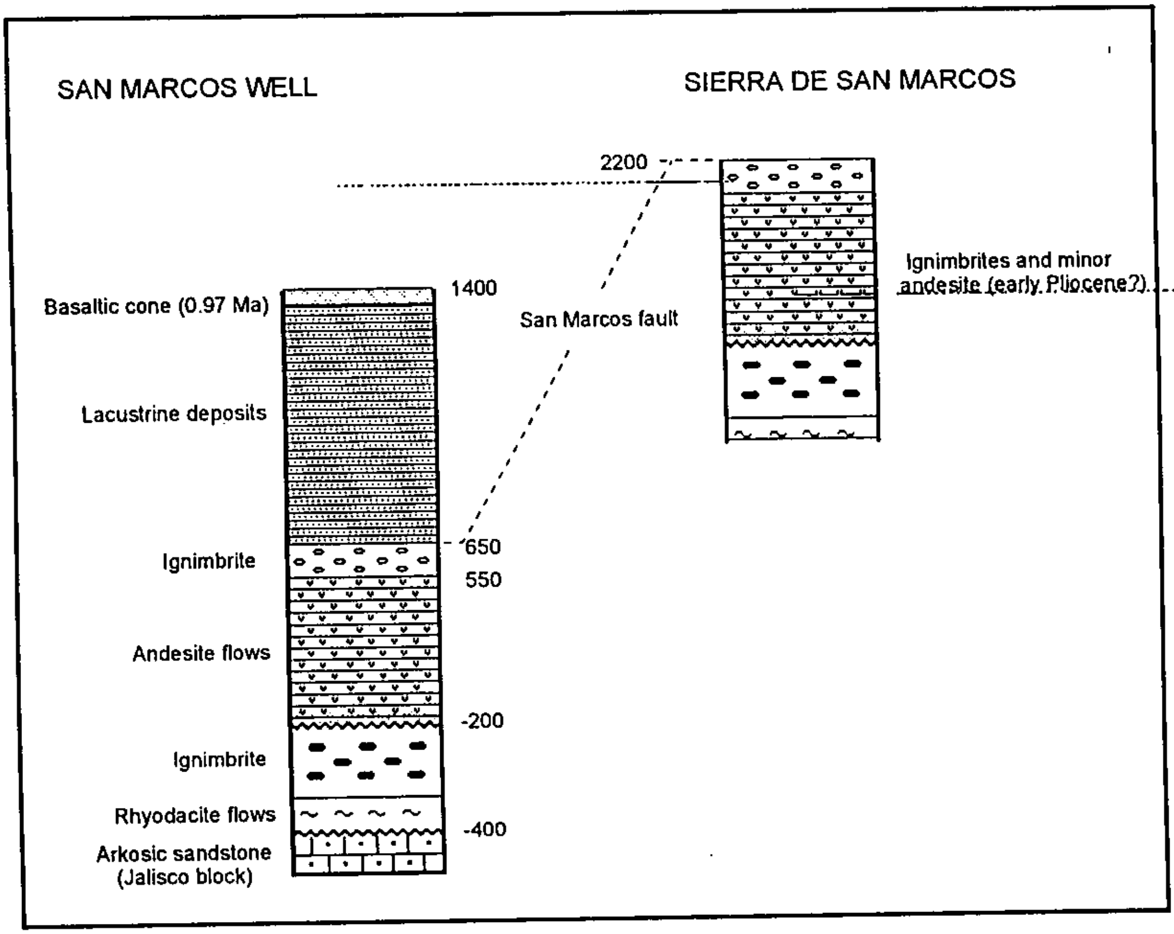


Fig. 4.7 (a) Mapa geoestructural del sistema de fallas Ameca-San Marcos. Estereogramas de las mesofallas como en la figura 3. (b) Estratigrafía generalizada de la Sierra de San Marcos y del pozo geotérmico SM-2 (según Venegas et al., 1985). Elevaciones en metros (no están a escala)

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. 4.7b). 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°. Anyway 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. Suarez 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. 4.2) 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 ~E-W 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. 4.2). 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 and produced by NE trending extension (Fig. 4.9b, site 20). The age of formation of the Puerto Vallarta graben is difficult to establish because rocks affected by the 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 indicates 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).

4.6 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. 4.3, 4.4, 4.5, 4.7, 4.8 and 4.9. 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. 4.10 and listed in Table 4.2. The orientation of

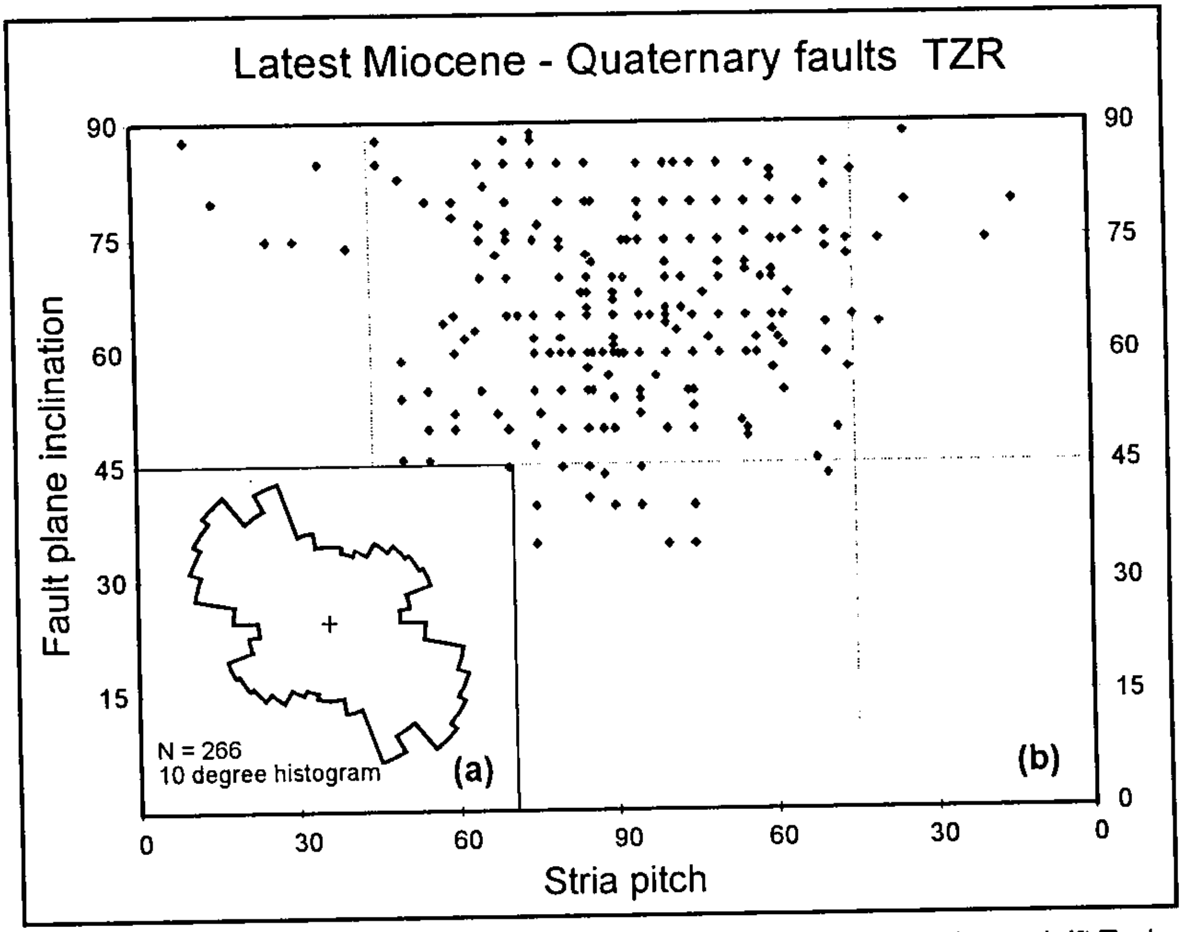


Fig. 4.8 Estadistica de las mesofallas del Mioceno tardío al Cuaternario en el rift Tepic-Zacoalco mostradas en los estereogramas de las figuras 4.4 a 4.9. (a) Diagrama de Rosa de la dirección de las fallas, (b) Diagrama de la inclinación de la falla contra el pitch

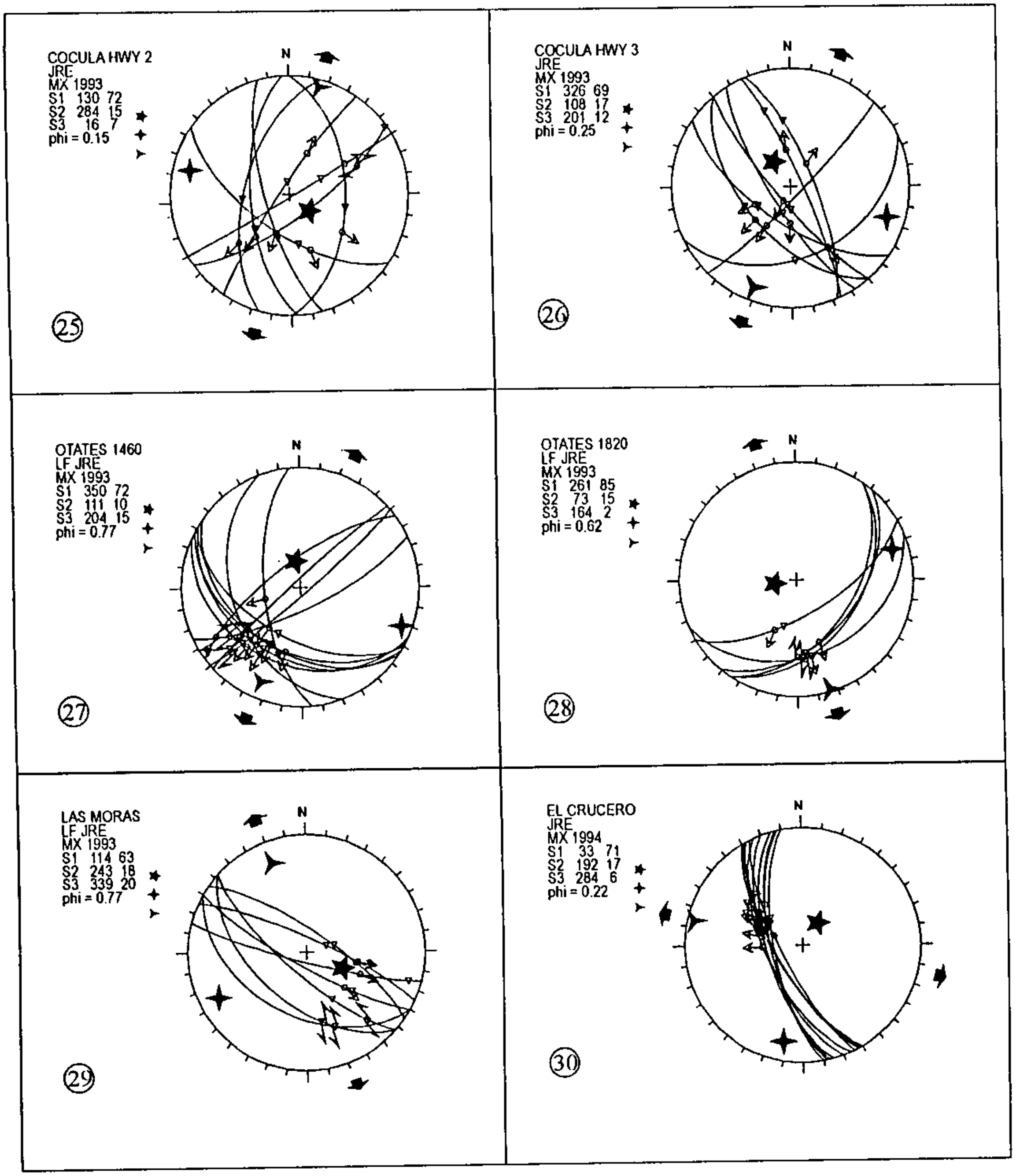


Fig. 4.9 Estereogramas de las mesofallas en los sitios no mostrados en las figuras 4.3 a 4.7 (para explicación ver figura 4.3 y la figura 4.10 y Tabla 4.2 para localización). (a) Sierra de Tapalpa. (b) Sitios dentro del BJ en el límite entre la Sierra Madre Occidental y el BJ con extensión ESE

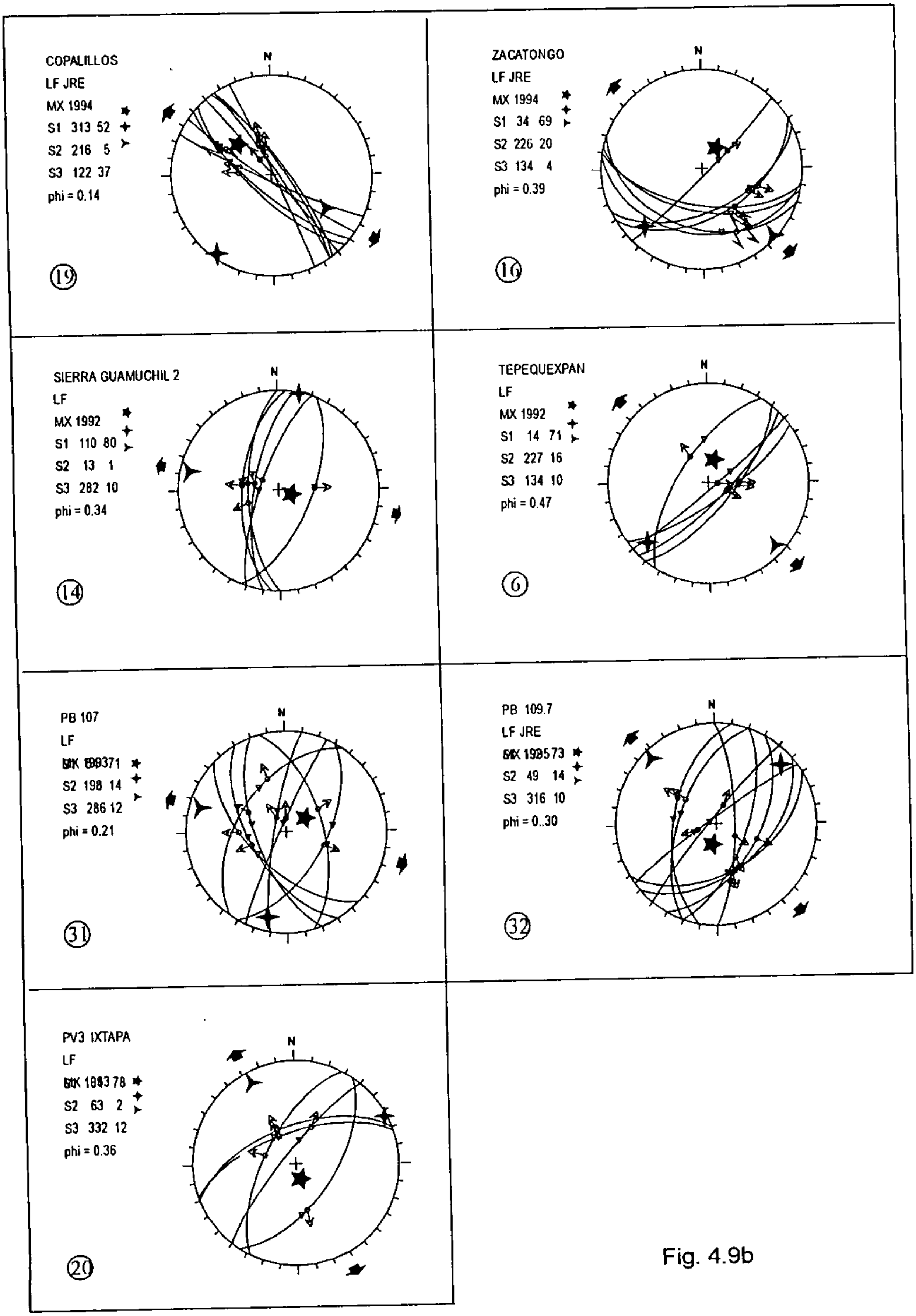

COPALILLOS
LF JRE
MX 1994
S1 313 52
S2 216 5
S3 122 37
phi = 0.14
19
ZACATONGO
LF JRE
MX 1994
S1 34 69
S2 226 20
S3 134 4
phi = 0.39
16
SIERRA GUAMUCHIL 2
LF
MX 1992
S1 110 80
S2 13 1
S3 282 10
phi = 0.34
14
TEPEQUEXPAN
LF
MX 1992
S1 14 71
S2 227 16
S3 134 10
phi = 0.47
6
PB 107
LF
S2 198 14
S3 286 12
phi = 0.21
31
PB 109.7
LF JRE
S2 49 14
S3 316 10
phi = 0..30
32
PV3 IXTAPA
LF
S2 63 2
S3 332 12
phi = 0.36
20

Fig. 4.9b

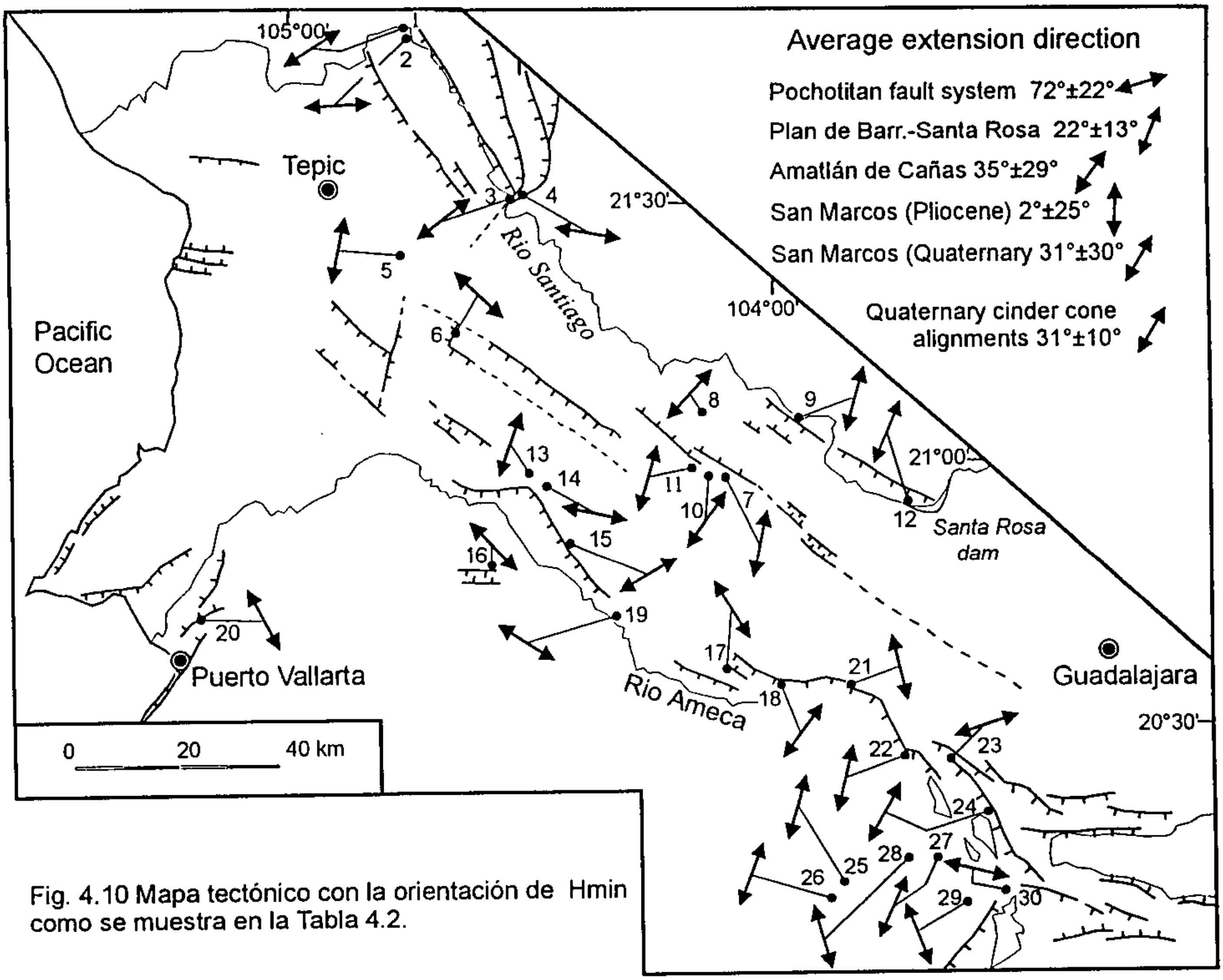


Fig. 4.10 Mapa tectónico con la orientación de Hmin como se muestra en la Tabla 4.2.

TABLE 4.2 STRESS FIELD DETERMINATIONS

Site number and location (1)	Longitude (W)	Latitude (N)	Lithology	Age	Tectonic phase	σ1 (2)	σ2 (2)	σ3 (2)	N (3)	(4)
1 Aguamilpa dam	104° 45' 00"	21° 51' 00"	Basaltic dikes	late Miocene	late Miocene	39/72	147/6	238/16	39	
2 Aguamilpa dam	104° 45' 00"	21° 51' 00"	Ignimbrite	early Miocene	late Miocene	111/82	357/3	267/7	8	0.30
3 Paso de Lozada 1	104° 31' 30"	21° 30' 30"	Andesite	late Oligocene	late Miocene	84/71	326/9	234/16	9	0.17
4 Paso de Lozada 3	104° 31' 10"	21° 30' 30"	Granite	early Miocene	late Miocene	216/60	4/26	100/14	13	0.52
5 La Labor	104° 47' 20"	21° 22' 00"	Rhyolite	early Pliocene	Pliocene	259/83	102/7	12/3	16	
6 Tequepexpan	104 33' 00"	21° 13' 10"	Rhyolite	early Pliocene	late Pliocene	14/71	227/16	134/10	5	0.47
7 Plan de Barrancas Hwy	104° 11' 30"	21° 01' 00"	Ignimbrite	early Miocene ?	late Mio-Pliocene	232/70	105/12	12/15	6	0.23
8 El Carrizo	104° 08' 00"	21° 05' 15"	Ignimbrite	early Pliocene ?	Pliocene	336/70	134/14	196/12	12	0.20
9 Cinco Minas fault	103° 55' 00"	21° 02' 00"	Granitic breccia	early Miocene	late Mio-Pliocene	343/76	104/7	196/12	10	0.41
10 Plan de Barrancas Hwy	104° 13' 00"	21° 01' 00"	Ignimbrite	early Miocene ?	late Mio-Pliocene	126/87	306/3	36/0	11	0.42
11 Plan de Barrancas Hwy	104° 14' 00"	21° 01' 30"	Ignimbrite	early Miocene ?	late Mio-Pliocene	211/72	108/4	17/17	11	0.20
12 Santa Rosa Dam	103° 42' 15"	20° 54' 30"	Ignimbrite	middle Miocene	late Mio-Pliocene	51/76	295/7	203/13	7	0.44
13 Sierra Guamuchil 1	104° 27' 40"	20° 59' 30"	Andesite	early Paleocene	early Pliocene?	192/78	290/2	20/12	7	0.06
14 Sierra Guamuchil 2	104° 27' 40"	20° 59' 30"	Andesite	early Paleocene	late Miocene?	110/80	13/1	282/10	5	0.34
15 Estancia de los Lopez	104° 24' 30"	20° 51' 00"	Granite	early Paleocene	Pliocene ?	230/84	331/1	61/6	5	0.59
16 Zacatongo	104° 34' 30"	20° 48' 30"	Conglomerate	Pliocene ?	Pliocene ?	34/69	226/21	135/4	9	0.34
17 El Arco	104° 03' 30"	20° 35' 55"	Granite	late Cretaceous	Pliocene ?	179/72	60/9	328/15	10	0.11
18 Portezuelo	104° 02' 20"	20° 36' 20"	Granite	late Cretaceous	Pliocene ?	338/72	124/15	217/10	16	0.30
19 Copalillo	104° 20' 50"	20° 43' 30"	Basaltic andesite	early Pliocene ?	Pliocene	313/52	216/5	122/37	10	0.14
20 Ixtapa	105° 13' 00"	20° 42' 10"	Conglomerate	Pliocene ?	Pliocene?	164/78	63/2	332/12	6	0.36
21 Presa La Vega	103° 51' 00"	20° 34' 40"	Ignimbrite	late Miocene ?	Pliocene	203/69	81/12	347/17	11	0.16
22 Cerro Gavilán	103° 43' 00"	20° 26' 30"	Andesite	late Pliocene	Quaternary	298/62	100/26	194/8	6	0.48
23 Acatlán	103° 35' 10"	20° 55' 30"	Ignimbrite	early Pleistocene	Quaternary	332/81	163/9	72/9	10	0.36
24 San Marcos	103° 33' 40"	20° 51' 45"	Basaltic breccia	mid. Pleistocene	Quaternary	313/62	116/27	209/7	7	0.23
25 Cocula-Autlán Hwy	103° 53' 30"	20° 19' 52"	Ignimbrite	early Miocene?	Pliocene	130/73	284/15	16/7	8	0.15
26 Cocula-Autlán Hwy	103° 53' 30"	20° 20' 30"	Ignimbrite	early Miocene?	Pliocene	326/69	108/17	201/12	8	0.25
27 Barr. de Otates 1460	103° 40' 30"	20° 17' 15"	Basaltic breccia	late Miocene	Pliocene	350/72	111/10	204/15	11	0.77
28 Barr. de Otates 1820	103° 40' 30"	20° 15' 00"	Basaltic breccia	late Miocene	Pliocene	261/75	73/15	164/2	5	0.62
29 Las Moras	103° 35' 00"	20° 09' 00"	Basaltic breccia	late Miocene	Pliocene	114/63	243/18	339/20	7	0.14
30 El Crucero	103° 31' 30"	20° 13' 30"	Basaltic andesite	early Pliocene	Pliocene	33/71	192/17	284/6	10	0.22
31 Plan de Barrancas Hwy	104° 11' 20"	21° 01' 15"	Ignimbrite	early Miocene	Pliocene ?	54/71	193/14	286/12	8	0.21
32 Plan de Barrancas Hwy	104° 11' 30"	21° 01' 00"	Ignimbrite	early Miocene	Pliocene ?	192/73	49/14	316/10	9	0.30

(1) Number of site as in fig. 3 to 7, 9 and 10. (2) Trend and plunge of stress tensor axes determined by fault slip data inversion according to the method of Angelier (1990) except at site 1 and 5, where they are eigenvectors of pole extensional joints, respectively, obtained by density analysis with the program Orient (Charlesworth et al., 1988). (3) Number of planes used in the computation. (4) Tensor shape = $(\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$.

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 4.3 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, in press). 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 all the 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. 4.8). 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. 4.8). In addition all the 32 stress tensors computed are characterized by a vertical maximum principal stress (Table 4.2).

As a whole, paleostress determinations for sites within the same fault system show a good consistency (Fig. 4.10). 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 Amatlán 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 4.3). Therefore these results indicate a consistent ~NNE direction of extension for the whole Pliocene and Quaternary in the TZR.

Site 30, adjacent to the NNE-trending bounding fault of the Sayula half-graben (Techaluta fault, Michaud et al., 1994) shows a ESE to SE direction of extension which is compatible with the orientation of the structure (Figs. 4.9a and 4.10). 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 ENE striking

TABLE 4.3 STRESS ORIENTATION INFERRED BY ALIGNMENTS OF QUATERNARY VOLCANIC VENTS

Alignment	Number of vents	Length (km)	Trend (azimuth)	Regression coefficient	Quality	σHmin (azimuth)	Reference
Southern Guadalajara	9	31	116	-0.971	A	24	this work
Tequila region							
TEQ-N	4	21	135	-0.976	A	36	this work
TEQ-C	16	30	127	-0.885	B	37	this work
TEQ-S	16	31	120	-0.799	C	30	this work
Acatlan region							
ACA-C	15	18	138	-0.907	A	48	this work
ACA-NE	7	7	118	-0.801	B	28	this work
Atotonilco region							
ATO-N	9	25	115	-0.857	B	25	this work
ATO-S	6	13	112	-0.966	A	22	this work
Central Nayarit							
NA-01	9	12	131		B	41	1
NA-02	20	34	130		A	40	1
NA-03	7	3	106		A	16	1
Average			**122.5**			**31.5**	

Quality ranking according to Suter, 1991. (1) Suter, 1991.

planes, as observed at site 29 (Fig. 4.9a). Other sites displaying a roughly SE 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. 4.4a and 4.10). However, NNE-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 ESE stretching of the JB during the final separation of Baja California and the formation of the Puerto Vallarta graben.

4.7 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), WNW-ENE 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, ~NNE 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 4.1) (Fig. 4.11a). Although these data are in a few cases not well constrained,

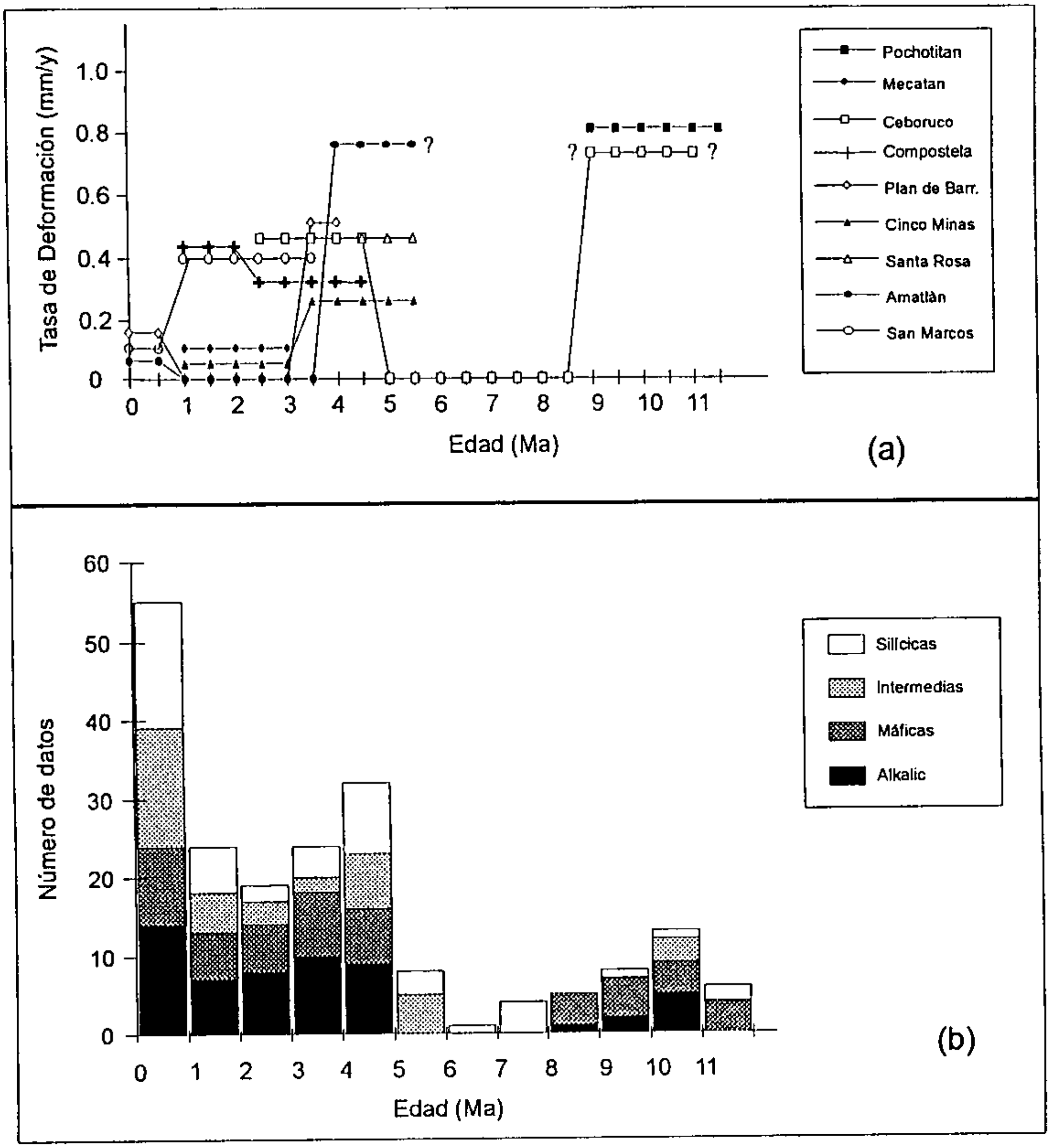


Fig. 4.11 (a) Tasa de deformación mínima para los istemas de fallas del rift Tepic-Zacoalco. Ver Tabla 4.1 para detalles. Los signos de interrogación indican valores solo parcialmente cotejados con datos radiométricos o geológicos. (b) Frecuencia y composición de rocas volcánicas datadas del Mioceno tardío al Presente en el área de estudio (datos de Ferrari et al., en prensa, Tablas 1 y 2). Silícicas=riolitas a dacitas; Intermedias=andesitas; Máfica=basaltos.

they show that the extensional tectonics has diminished in intensity with time. The higher rate of 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 volcanic rate (Fig. 4.11b). 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.

4.8 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 NW-trending strike-slip fault (Tequila fault of Bourgouis 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 km (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 NW 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; 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.

V THE CONTINENTAL BOUNDARIES OF THE JALISCO BLOCK AND THEIR INFLUENCE IN THE PLIOCENE-QUATERNARY KINEMATICS OF WESTERN MEXICO

by

ROSAS-ELGUERA, J., L. FERRARI, V.H. GARDUÑO, AND J. URRUTIA-FUCUGAUCHI

Abstract

Extensional faulting observed in southwestern Mexico has been related to the incipient rifting of the Jalisco block from the Mexican mainland since the Pliocene. On the basis of new structural and geophysical data, we propose that: (1) the continental boundaries of the Jalisco block are ancient structures reactivated since the Pliocene at a low (<1 mm/yr) rate of deformation, and (2) Pliocene-Quaternary extensional faulting at the edges of Jalisco block is a basement-controlled intraplate deformation related to plate boundary forces rather than to active continental rifting.

The Jalisco block boundaries first developed in response to a the uplift of the Puerto Vallarta batholith in pre-Neogene time and underwent a complex contractile deformation before the Pliocene. During Pliocene-Quaternary times north-northeast extension reactivated the northern boundary forming the Tepic-Zacoalco rift, whereas east-southeast extension formed the northern Colima rift. South of the Colima volcano, active extension is found only west of the so-called southern Colima rift, and partly reactivates old northeast-trending basement faults. The parallelism between the

subducted Rivera-Cocos plate boundary zone and the eastern neotectonic boundary of the Jalisco block support east-southeastward motion of the southern Mexican blocks induced by the differential motion and oblique subduction of the Cocos and Rivera plates. On the other hand, we envisage Pliocene-Quaternary extension along the northern boundary as an upper-plate response to the low convergence rate and the steep subduction angle of the Rivera plate.

5.1 Introduction

A precise definition of the continental deformation in western Mexico is crucial to distinguish between models describing the interaction among Cocos, Rivera, and North American plates (Fig. 5.1a). In the past decade, the complex tectonics of western Mexico has been related to (1) an active rifting induced by a relocation of the East Pacific Rise (Luhr et al., 1985), or by the presence of a hotspot (Moore et al., 1994), beneath the continent; (2) a passive rifting produced by the differential motion and oblique subduction of the Rivera and Cocos plates (DeMets and Stein, 1990; Bandy, 1992; Ferrari et al., 1994a; Bandy et al., 1995). Most of the Pliocene-Quaternary deformation and volcanism in western Mexico occurred along the Tepic-Zacoalco and Colima rifts (Fig. 5.1a), which have been proposed as the continental boundaries of the Jalisco block. Several workers visualized the Tepic-Zacoalco rift as a series of pull-apart basins linked by right-lateral faults, and the Colima rift as a roughly north-south graben, both developed in Pliocene-Quaternary times due to a west-northwestward motion of the Jalisco block (Luhr et al., 1985; Allan et al., 1991; Bourgois and Michaud, 1991). Although field structural studies

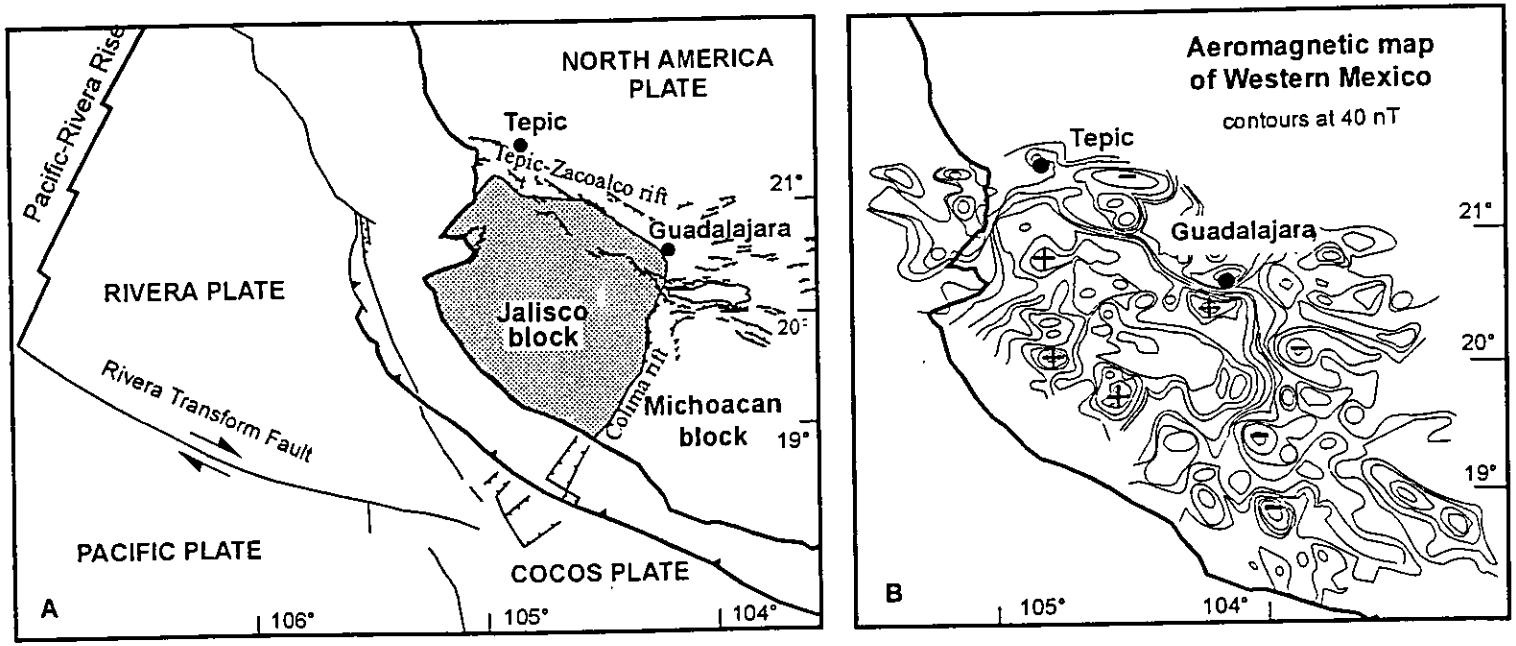


Figure 5.1.- Geodynamic setting of western Mexico. Note coincidence between Jalisco block deduced by surface geology (gray area in A) and distribution of maxima in aeromagnetic map of western Mexico (B).

began to question these assumptions (Michaud et al., 1991; Serpa et al., 1992; Rosas-Elguera et al., 1993; Ferrari et al., 1994a; Ferrari and Rosas-Elguera, 1995) a unifying view of the structure and the tectonic evolution of the Jalisco block boundaries is still lacking. Linking our structural field studies with previous works and subsurface data, we redefine here the structure of the Jalisco block boundaries and advance two main conclusions: (1) the Tepic-Zacoalco rift and the Colima rift are ancient tectonic structures partly reactivated in Pliocene-Quaternary times with purely extensional deformation and (2) the eastern neotectonic boundary of the Jalisco block does not coincide entirely with the Colima rift.

5.2 The Jalisco block and its boundaries

Most of the Jalisco block is composed by the Puerto Vallarta batholith, emplaced in late Cretaceous time (100-75 Ma, Schaaf et al., 1995). North of the Jalisco block is the Eocene to early Miocene volcanic succession of the Sierra Madre Occidental, whereas to the east is the Triassic to early Tertiary succession of the Michoacan block (Fig. 5.2). The Puerto Vallarta batholith is geochemically and isotopically distinct from the late Cretaceous to Tertiary plutons exposed in the Michoacan block and Nd model ages suggest that it could be underlain by an older (Precambrian?) basement (Schaaf et al., 1995). The uniqueness of the Jalisco block is clearly observable also in the aeromagnetic map of western Mexico (Fig. 5.1b), which shows a remarkably different anomaly pattern with steep gradients at its boundaries.

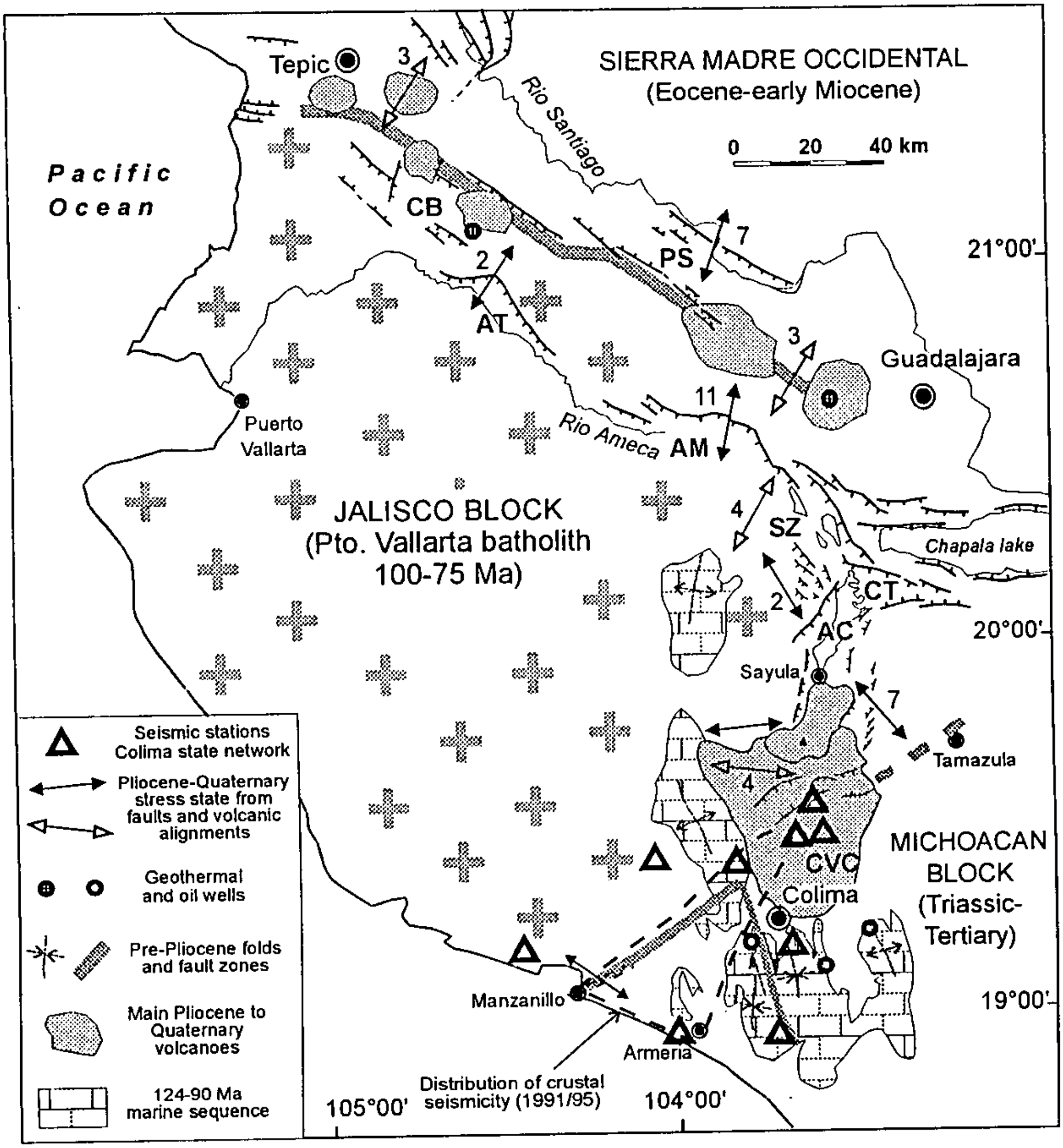


Figure 5.2.- Tectonic and stress map of Jalisco block and ist boundaries. Latest Miocene to Quaternary faults in black. Double arrows are minimum horizontal stress orientations averaged for number of sites reported (after Rosas-Elguera, 1995). Main extensional structures mentioned in text: CB-Ceboruco, PS-Plan de Barrancas-Sata Rosa, AT-Amatan de Cañas, AM-Ameca, SZ-San Marcos-Zacoalco, AC-Amacueca, CT-Citala. CVC is Colima volcanic complex.

The midcrustal rock assemblage of the Puerto Vallarta batholith are presently exposed at 1000 to 2500 m of elevation indicating a substantial uplift since its emplacement. The absence of the Sierra Madre Occidental ash flow tuffs within the stratigraphic succession of the Jalisco block (Ferrari et al., 1996b) and the finding of a pre-late Miocene subaerial conglomerate resting over the Puerto Vallarta batholith in the inner trench off Manzanillo (Michaud et al., 1995) indicate that most of the uplift occurred in Paleogene. Indeed, on the basis of apatite fission track ages, Calmus et al. (1995) established that the batholith was at <1 km of depth by Eocene times. Geothermal wells drilled along the Tepic-Zacoalco rift found plutonic rocks correlative with the Puerto Vallarta batholith only at a depth of 1.1 to 1.8 km below sea level (Ferrari et al., 1994b), whereas oil wells drilled up to a depth of 4 km south of Colima City (Fig. 5.2) did not encounter any plutonic rocks (Grajales-Nishimura and López-Infanzón, 1983). This suggests that the boundaries of the Jalisco block developed first as a consequence of the uplift of the Puerto Vallarta batholith in pre-Neogene times.

Northern Boundary

During the middle to late Miocene this structure was reactivated by a shear tectonics related to the initial opening of the Gulf of California (Ferrari, 1995), which was replaced, since the end of Miocene, by the extension responsible for the formation of the Tepic-Zacoalco rift. This is composed of several independent fault systems, which can be grouped in two branches: a northern branch made up of two grabens developed at the boundary between the Jalisco block and the Sierra Madre Occidental, and a southern branch made up of half-graben located inside the Jalisco block.

Northern Branch. This is formed by two en echelon basins, striking 125° on average (Fig. 5.2). The Ceboruco graben is a 2700-m-deep, composite asymmetrical depression developed in two stages in late Miocene and early Pliocene times. The Plan de Barrancas-Santa Rosa graben is a 70-km-long and 20-km-wide depression with about 550 m of vertical displacement, mainly attained during the Pliocene. The faults bounding these depressions show a dominant dip-slip motion. The Paleo-stress field computed by fault-slip data inversion with the method of Angelier (1990) at seven sites depicts an average 20° ± 13° trending minimum principal stress (Fig. 5.2). Small normal faults affect Quaternary rocks only in the southeastern part of the Plan de Barrancas-Santa Rosa graben.

Southern Branch. This branch consists of three half grabens, with an average 125° trend, located inside the Jalisco block and parallel to the northern branch of the Tepic-Zacoalco rift (Fig. 5.2). The footwalls of the Amatlan de Cañas and Ameca half grabens are made of Cretaceous granitic rocks (Schaaf et al., 1995 and reference therein) cut by south- to southwest-dipping normal faults. Inside the Amatlan de Cañas half graben Pliocene-Quaternary alkaline and calc-alkaline volcanoes (Righter and Carmichael, 1992) overlie a granitic conglomerate over 100 m thick, indicating that by the early Pliocene most of the basin had been developed. The easternmost depression, the Zacoalco half graben, is formed by a south- to southwest-dipping detachment fault with a minimum of 1400 m of vertical displacement. Most of this extension occurred during the Pliocene, but normal fault scarps, 50 to 100 m high, found in Quaternary rocks, suggest active tectonic activity. This is confirmed by the historical seismicity and the moderate level of microseismic activity recorded in the region (Suarez et al., 1994). The minimum principal stress direction computed from fault slip data inversion is 35° ± 29° for the Amatlan de Cañas half graben (2 sites) and 12° ± 30° for the Ameca and Zacoalco half grabens (11 sites)(Fig. 5.2). This agrees with the 31° ± 10° minimum horizontal principal stress direction inferred from the alignment of 11 Quaternary volcanic vents (Ferrari and Rosas-Elguera, 1994). Therefore, these results indicate a consistent north-northeast direction of extension for the whole Pliocene and Quaternary in the Tepic-Zacoalco rift, although the rate of extension along the main faults decreased from ~0.45 mm/yr in the Pliocene to ~0.1 mm/yr in the Quaternary (Ferrari and Rosas-Elguera, 1994).

Eastern Boundary

The Colima rift has been considered the eastern boundary of the Jalisco block, developed since the Pliocene in three sectors (Allan et al., 1991). According to its structure, we found more appropriate to divide the Colima rift in two main sectors separated by the Colima volcanic complex: the northern and southern Colima rift.

Northern Colima Rift. This is composed of the northeast-trending Amacueca half graben and the north-south-trending Sayula graben (Fig. 5.2). The Amacueca half-graben is formed by a 25° trending, 25-km-long, detachment fault on the west and by small northwest-dipping normal faults, progressively joining with the Citala graben, to the east (Fig. 5.2). Gravimetric modeling indicates a vertical offset of about 2500 m (Allan et al., 1991). Composite focal mechanism solutions computed from microseisms recorded immediately north of Amacueca graben indicate active east-west extension in the area (Suarez et al., 1994). South of Amacueca, the rift continues into the north-south-trending Sayula graben. The western bounding fault is 18 km long but can be traced southward along the alignment of the Cantaro, Nevado de Colima, and Colima volcanoes for a total length of 53 km (Fig. 5.2). To the east, the Sayula graben is bounded by 35° striking, northwest-dipping normal faults showing a left-stepping en echelon arrangement (Fig. 5.2). These faults cut lamprophyres dated at 4.2 Ma (Allan, 1986) overlain by brown ash-flows tuffs. Taking this contact as a marker, a minimum of 300 m of vertical offset and a rate of deformation of 0.07 mm/yr can be estimated. Paleo-stress tensors computed from fault slip data measured at seven sites in the northern Colima rift indicate an average 140 °± 19° direction for the minimum principal stress (Rosas-Elguera, 1995), but east-west extension is reported as well for one site in the Sayula graben (Barrier et al., 1990) and is supported by the north-south alignment of the parasitic cones of the Colima volcanic complex.

Extension in the northern Colima rift started at the beginning of Pliocene time concurrently with the emplacement of alkaline volcanic rocks (Allan, 1986). The Cantaro volcanic complex was emplaced over the western bounding fault of the Sayula graben at about 1.6 Ma. Thus 2500 m of vertical offset must have occurred in ~3.5 m.y., giving a subsidence rate of 0.7 mm/yr.

Southern Colima Rift. The southern Colima rift is a wide topographic depression, located south of Colima volcano. Allan et. al. (1991) considered this depression the result of Pliocene to Quaternary normal faulting, but geologic and geophysical works by Serpa et al. (1992) questioned this interpretation. Inside the depression, marine sedimentary sequences and intermediate to felsic intrusive and volcanic rocks of Cretaceous age are partly covered by Pliocene-Pleistocene gravel, volcanic debris, and alluvium (Sloan, 1989). The Cretaceous rocks are involved in north-northwest-trending decakilometric folds, which were later transected by a right-lateral transpressional fault zone in pre-Pliocene times (Serpa et al., 1992; Fig. 2). However, we did not find any evidences of large normal faulting in the Pliocene and Quaternary rocks exposed south of Colima city and, in the last five years, the Colima state seismic network recorded almost no seismicity in the so-called southern Colima rift. By contrast, thousands of crustal seismic events (mostly at 19 to 7 km of depth) with magnitude up to M_s = 5.2 were recorded in a broad area west of it (G. Reyes-Davila, 1996, written commun.; Fig. 2). Some of these events clustered in northeast- to north-northeast-trending swarms propagating from the Armeria area to the southern part of the Colima volcano (G. Reyes-Davila, written commun.). A number of geologic observations indicate the existence of similarly oriented Quaternary faulting in this area: (1) a northeast trending, 100-m-deep, normal fault affects the northeastern flank of Nevado de Colima volcano, and on its southwestward prolongation are aligned the present crater of Colima volcano as well as the large 1869 parasitic cone (Rodriguez-Elizarrarás, 1995); (2) a caldera opened toward the northeast is cut in the Nevado de Colima volcano; (3) small northeast-trending normal faults affect poorly consolidated slope debris southwest of Colima volcano (Garduño et al., 1996); (4) outcrop-scale normal faults have been observed in Quaternary rocks ~10 km southwest of Colima city (Sloan, 1989); (5) the dominant trend of the surface faulting produced in the Manzanillo bay after the 9 October 1995 earthquake strike 30°-50° (Garduño et al., 1996).

We propose that Pliocene-Quaternary extension south of the Sayula graben is accommodated in a broad triangular area comprised between the Colima volcanic complex and the cities of Manzanillo and Armeria (Fig. 5.2). The northwestern boundary of this area coincides with an older belt of northeast trending strike-slip faults affecting Cretaceous rocks, which could be considered the neotectonic boundary of the southeastern corner of the Jalisco block (Tamazula-Manzanillo fault zone, Garduño-Monroy et al., 1996; Fig. 2).

5.3 Implications for the large-scale kinematics of western Mexico

We showed that neotectonic deformations along both boundaries of the Jalisco block are characterized by low-rate extension orthogonal to the average trend of the fault systems (Fig. 5.2). This deformation cannot be produced by a west-northwestward motion of the Jalisco block. To explain the apparent contrast posed by concurrent perpendicular extension at the Jalisco block boundaries we propose that the eastern boundary is the product of a slow southeast motion of the Michoacan block relative to North America along the Chapala-Tula fault system, an active extensional deformation zone with a minor left-lateral component of motion (Suter et al., 1992; Suter, 1995; Fig. 3). In our view the

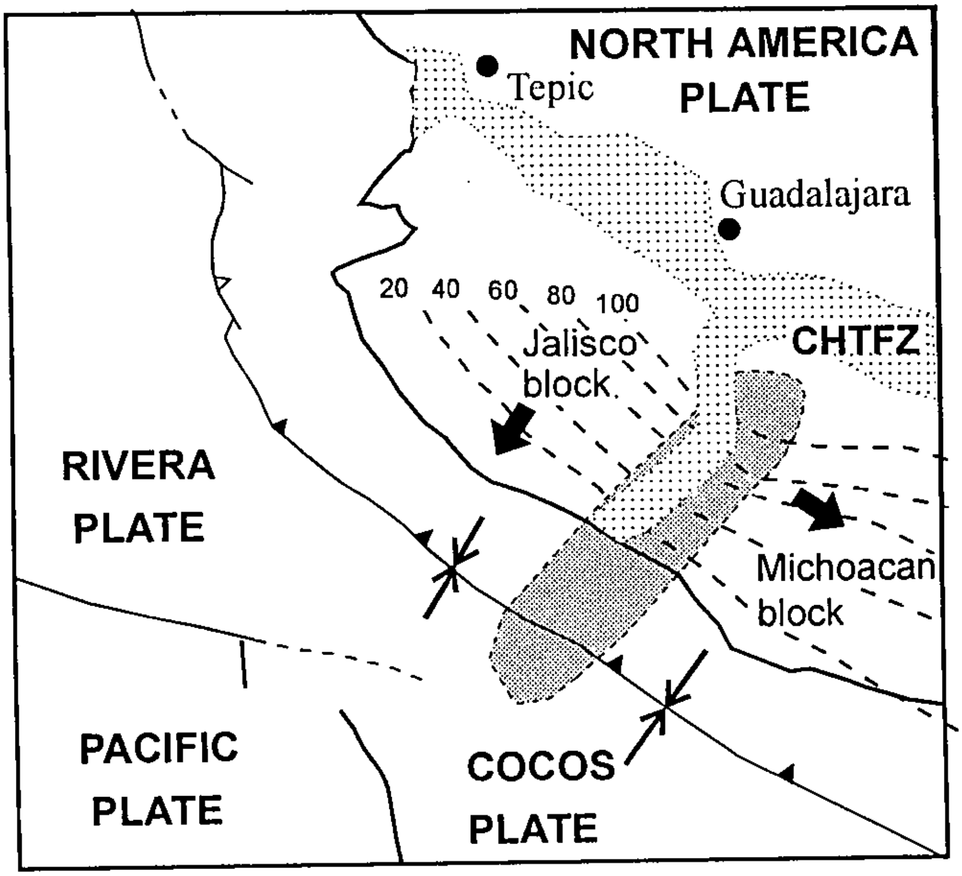


Figure 5.3.- Proposed Pliocene-Quaternary motions of the Jalisco and Michoacan blocks relative to North America and their relation with coeval extensional deformation zones (dotted areas) and the subducted Rivera-Cocos plate boundary (in gray, from Bandy et al., 1995). Small arrows at the trench are Rivera-North America and Cocos-North America relative convergence vectors according to DeMets and Stein, 1990. Dashed lines represent depth (in kilometers) of the Benioff plane according to Pardo and Suarez (1995). CHTFZ-Chapala-Tula fault zone.

neotectonics of the eastern boundary of the Jalisco block is controlled by partial reactivation of basement structures with partitioning of a regional east-southeast extension in locally east-west- and north-east-trending extension. According to Bandy et al. (1995), the subducted Rivera-Cocos plate boundary is a relatively wide zone, with a northeast trend, passing roughly under the Colima volcano (Fig. 5.3). The parallelism between the subducted Rivera-Cocos plates and the neotectonic eastern boundary of the Jalisco block suggests a direct relation between plate tectonic forces and continental deformation. Our results thus support the prediction of DeMets and Stein (1990) and Bandy et al. (1995) that differential motion and oblique subduction of the Rivera and Cocos plates could be responsible for extension at the eastern boundary of the Jalisco block.

On the other hand, we explain trench-normal extension in the Tepic-Zacoalco rift as an upper-plate response to the low convergence rate and the steep subduction angle of the Rivera plate (Pardo and Suarez, 1995; Fig. 5.3), as it is observed worldwide in the plates overriding retreating plate boundaries (Royden, 1993). Consequently, the Pliocene-Quaternary structures developed at the edges of Jalisco block are basement-controlled intraplate deformations, related to plate boundary forces rather than to a relocation of the East Pacific Rise under continental Mexico.

VI THE TECTONIC CONTROL ON THE VOLCANO-SEDIMENTARY SEQUENCE OF THE CHAPALA GRABEN, WESTERN MEXICO

by

J. ROSAS ELGUERA AND J. URRUTIA-FUCUGAUCHI

Abstract

The Chapala graben forms part of a regional system of intra-arc and half-grabens located along the western and central part of the Mexican Volcanic Belt. Results of a stratigraphic and tectonic study of the thick and widespread volcano-sedimentary sequence around the Chapala graben are reported. The study has concentrated on the distribution of the lacustrine deposits, and on the stratigraphy, the geochronology, and the deformation of the sequence. The volcano-sedimentary record suggests a probable link between the Tepic-Zacoalco and Chapala grabens through a basin system developed in late Miocene and early Pliocene times. The stratigraphic sections show a southward spatial migration of the basin (and lake) system. The main unit of the volcano-sedimentary succession is the Chapala Formation, which has been affected by NE-tilting, in contrast with the lacustrine deposits to the east, in the Chapala plain (e.g. Ixtlan area) where the sequence is essentially flat-lying. Two distinct units with different structural attitudes and separated by an angular unconformity can be distinguished in the Chapala Formation. Based on the differences between the stratigraphic sections, and structural attitudes, we propose a model for development of the Chapala graben in which a combination of left-lateral and extensional deformation together with volcanic and erosional processes contributed to shape the basin. Furthermore, we suggest that the Lake Chapala is a remnant of a large Jalisco paleo-lake in western-central Mexico.

6.1 Introduction

Intense and widespread Late Cenozoic tectonic and volcanic activity in central Mexico has produced numerous grabens and crater lakes. Many of these tectonic and volcanic depressions have been or are still occupied by lakes. At present, the largest lake is Lake Chapala, which partly fills an east-west elongated basin some 115 km long and up to ~37 km wide (Fig. 6.1). The lake itself is about 80 km long and 20-30 km wide, and occupies the western two thirds of the topographic depression. In historic times the lake has remained relatively shallow. Lake Chapala has an average water depth of 10 m. Fluvial and lacustrine sediments, interbedded with volcanic units, have been deposited in the Chapala graben, and represent a potentially important and unique record of the paleoenvironmental, volcanic and tectonic history of western and central Mexico (Rosas-Elguera et al., 1993a).

West of Lake Chapala, is the NW-trending Tepic-Zacoalco graben which is formed by two en-echelon Plio-Quaternary tectonic depressions in the north (e.g. the Plan de Barrancas-Santa Rosa system), and by various half-grabens in the southern portion (e.g. Amatlán de Cañas and Zacoalco) (Fig. 6.1) (Rosas-Elguera et al., 1993b; Ferrari and Rosas-Elguera, in press). Several Quaternary strato-volcanoes (e.g. Tequila and Ceboruco) are located along the Tepic-Zacoalco graben (Fig. 6.1) where the thickness of the volcanic rocks filling the depression is > 1000 m in places (Ferrari et al., in press). Along the Plan de Barrancas-Santa Rosa system, however, the thickness of the lacustrine deposits is ~100 m (Nieto-Obregón et al., 1985; Quintero Legorreta et al., 1992) which represents ~10-13 % of the thickness of the younger infill sediments of the

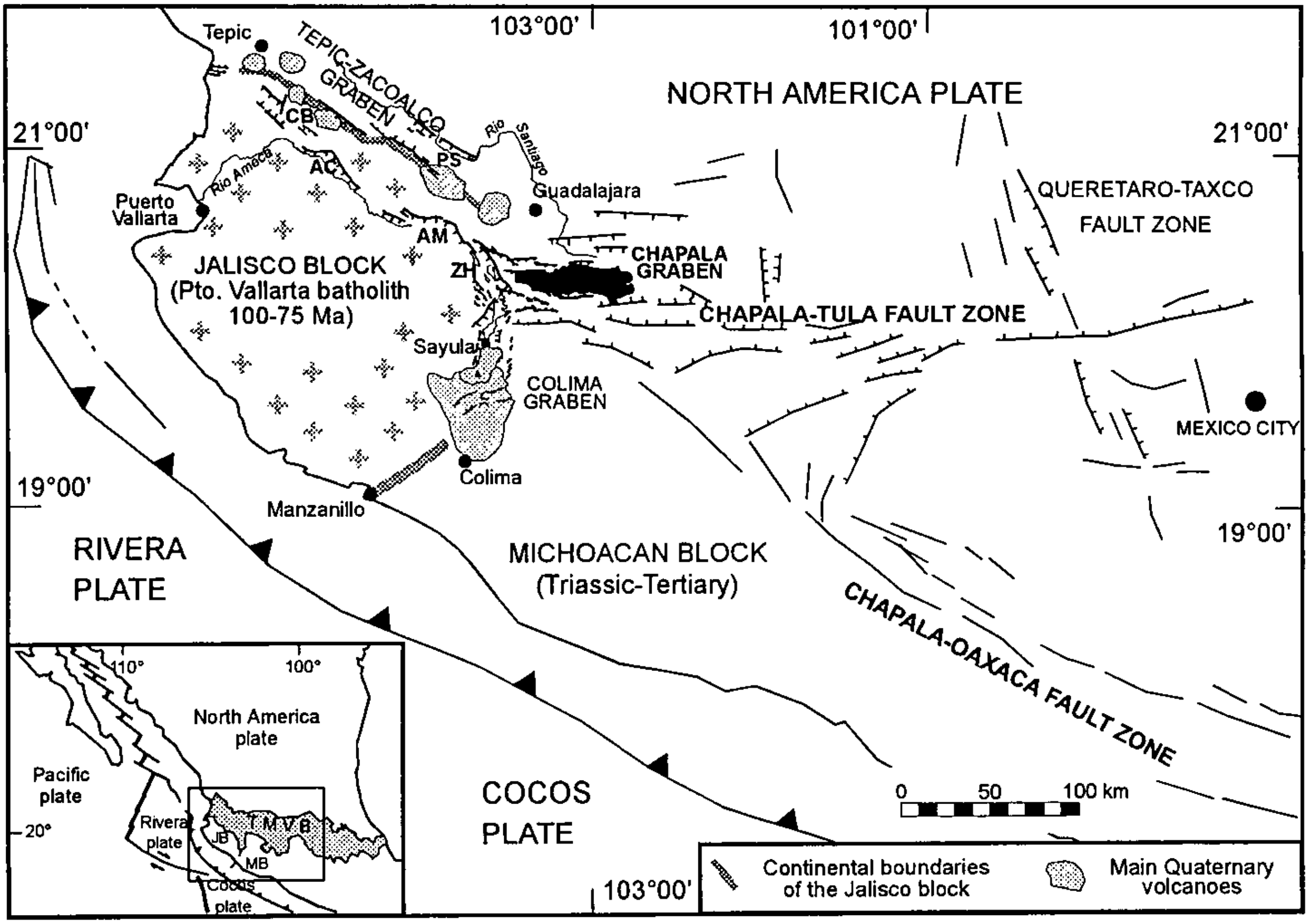


Fig. 6.1 Mapa tectonico para el occidente de la Faja Volcanica Trans-Mexicana donde se muestra el area de estudio en el marco regional. Depresiones tectonicas: PS, graben Plan de Barrancas-Santa Rosa; AC, AM y ZH son los semigrabenes de Amatlan, Ameca y Zacoalco, respectivamente. Modificado de Johnson y Harrison (1990), Rosas-Elguera et al., (1996) y Ferrari y Rosas-Elguera (en prensa)

southern half-grabens (Venegas et al., 1985; Rosas-Elguera et al., in press; Ferrari and Rosas-Elguera, in press). The volcanic activity and sedimentary units were developed from late Miocene to Present time (Nieto-Obregón et al., 1985; Quintero-Legorreta et al., 1992; Moore et al., 1994).

The Chapala graben forms part of a regional system of grabens and half-grabens that extend roughly E-W across central Mexico, within the magmatic arc of the Trans-Mexican Volcanic Belt (TMVB) (Fig. 6.1). This system of grabens and horsts has been related to a regional structure, referred to as the Chapala-Tula fault zone (Johnson and Harrison, 1990). In the western-central TMVB, these tectonic depressions have been interpreted in terms of a continental triple junction (Luhr et al., 1985; Allan et al., 1991). The depressions have favored the development of an extensive lake system that include Lake Sayula in the northern Colima graben, Lake San Marcos in the Zacoalco half-graben and Lake Chapala in the Chapala graben (Fig. 6.1). There are topographic differences between the basins, and Lake Chapala lies at a higher elevation (some 200 m) than lakes within the triple junction area. Regional tectonic stress patterns have evolved during the late Cenozoic, and have since changed from dominant left-lateral strike-slip to normal faulting (e.g., Pasquaré et al., 1988; Johnson and Harrison, 1990; Garduño-Monroy et al., 1993; Ferrari et al., 1994a; Urrutia-Fucugauchi and Rosas-Elguera, 1994). At the western end, the Chapala graben joins a group of large structures of the N-S Colima graben, the NW-SE Tepic-Zacoalco graben, and the Chapala-Oaxaca fault zone (Fig. 6.1). These structures seem to limit a series of large crustal blocks that comprise southern and central Mexico (Fig. 6.1) (Mosser, 1972; Rosas-Elguera et al., 1997), and have been interpreted in terms of active rifting or intra-plate extension and lateral displacements (Luhr et al., 1985; DeMets and Stein, 1991; Nieto-Obregón et al., 1992; Ferrari et al., 1994; Rosas-Elguera et al., 1996; Ferrari and Rosas-Elguera, in press).

In this paper, we report the results of a study of the volcano-sedimentary sequence of the Chapala basin. We compare our results with those reported for the Tepic-Zacoalco graben and propose an evolutionary model of the Chapala tectonic depression since the late Miocene. Furthermore, we propose that the Lake Chapala is a remnant of a larger paleo-lake which we name the Jalisco paleo-lake. This study forms part of a long-term collaborative project directed to investigate the tectonic evolution of western Mexico.

6.2 Geological setting

The Chapala graben represents a major topographic depression surrounded by broad volcanic-capped plateaus. To the east, and separated by a zone of WNW-ESE normal faults, the plateaus widen into the Michoacan-Guanajuato volcanic field (Hasenaka and Carmichael, 1985). To the north, large late Miocene basaltic plateaus form a relatively undisturbed extended large high area (Fig. 6.2). East-west faults decrease in number and in offset to the north, away from the deformation zone of Chapala.

Southwest of Lake Chapala, is the Citala graben, which is separated from the Chapala graben by a volcanic range made of tilted fault blocks (Fig. 6.2). The Chapala graben extends eastward from the triple junction zone and narrows within some 30 km

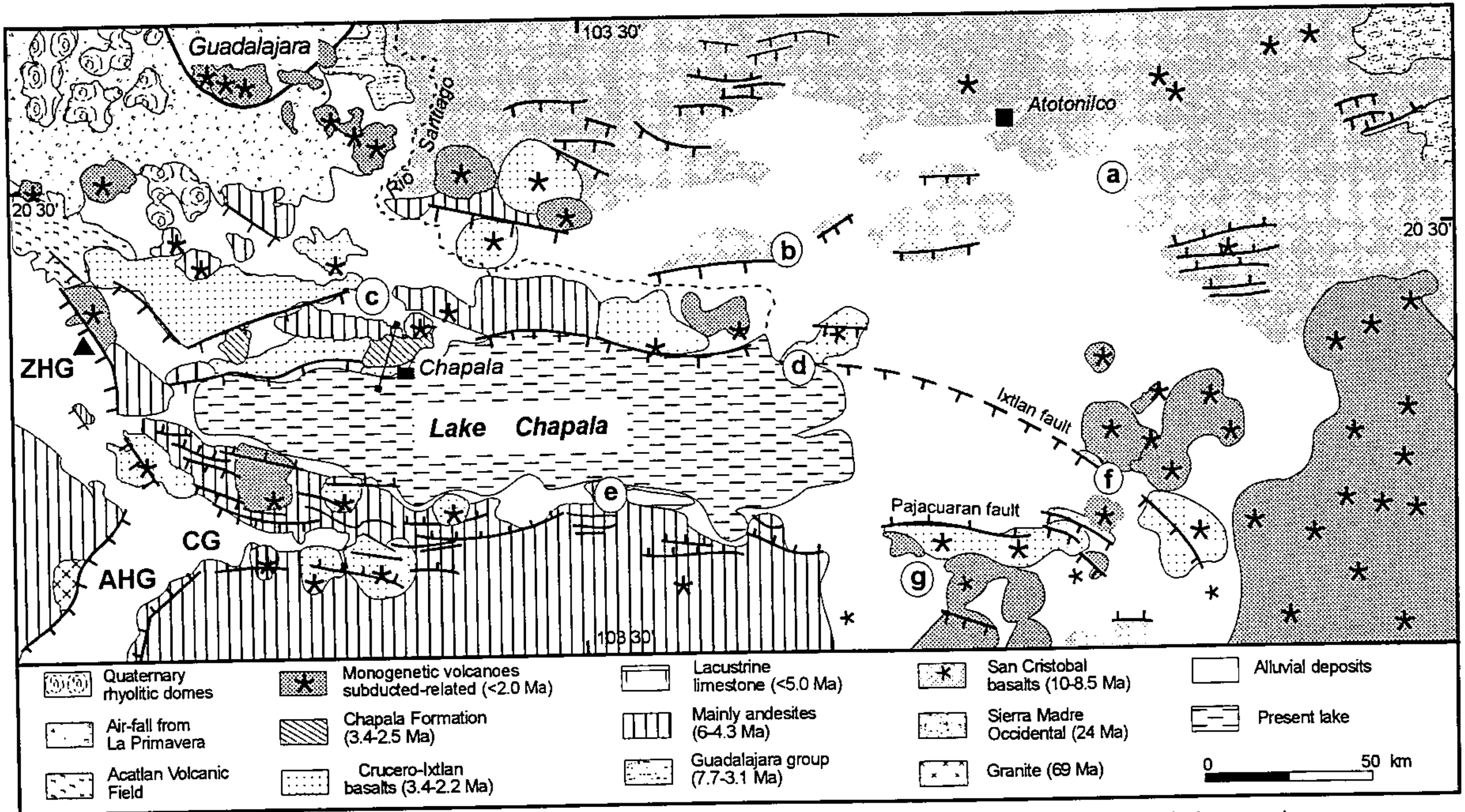


Fig. 6.2 Mapa geológico simplificado del graben de Chapala. Las letras en los círculos son los sitios de las secciones mostradas en la figura 3. El triángulo es el pozo geotérmico SM-1. La línea gruesa al norte del poblado de Chapala, es la localización de la sección estructural mostrada en la figura 4c. Las depresiones tectónicas actuales incluyen el graben de Citala (CG), y el semigraben de Amacueca (AHG). Adaptado de Ferrari et al., (in press); Allan (1986); este trabajo.

(Delgado-Granados and Urrutia-Fucugauchi, 1986). It is characterized by recent faulting and may represent the most active structure in the region (Urrutia-Fucugauchi, 1986).

The Chapala graben is bounded to the north by southward-dipping normal faults that form a 50 km wide deformation zone, composed of large blocks. The large Ixtlan fault, that runs along the Lake Chapala shore, extends into the eastern lacustrine plain. On the southern edge of the graben, the Pajacuaran fault also extends into the eastern lacustrine plain, converging with the Ixtlan fault (Fig. 6.2). Johnson and Harrison (1990) estimated more than 1000 meters of downward fault displacements, from an analysis of Landsat Thematic Mapper images. Campos-Enriquez et al. (1990) estimated 1000 meters of normal faulting from spectral analysis of an aeromagnetic profile oriented NNE-SSW across the Lake Chapala. These authors also analyzed the shallow crustal structure in the southern Zacoalco half-graben and along the Chapala-Tula fault zone. Their models document a series of large tilted blocks with vertical displacements in the order of hundreds of meters, that provide evidence for the structural interpretation of the Zacoalco depression as a large half-graben, in agreement with the field structural studies of Rosas-Elguera et al. (1997) and Ferrari and Rosas-Elguera (in press).

6.3 Geologic evolution of the Chapala graben: The volcano-sedimentary record

Volcano-sedimentary deposits are exposed over a large area in and around the Tepic-Zacoalco, Chapala, and Colima tectonic depressions. Along the Tepic-Zacoalco graben the volcano-sedimentary sequence is exposed in the Plan de Barrancas-Santa Rosa graben where it is ~100 m thick and contains an ignimbrite dated at 4.7 Ma (Nieto-

Obregón et al., 1985; Quintero-Legorreta et al., 1992). Moore et al. (1994) report, to the north of Guadalajara City, a succession over 600 m thick of exposed late Miocene basalts capped by a 100 m thick sequence of white silicic ash and pumice flows with reworked pumice beds and fluvial deposits. In the Zacoalco half-graben, about 750 m of a lacustrine sequence were cut by geothermal exploration wells at the base of the San Marcos volcanic range (Venegas et al., 1985). This represents a minimum estimate for the thickness of the sequence which probably thickens towards the center of the basin, away from the San Marcos area.

Based on gravimetric modelling, Allan (1985) estimated a thickness of about 900 m for sedimentary fill of the northern basin of the Colima graben. Delgado-Granados (1992) estimated the thickness of the lacustrine sequence of the Chapala Formation at ~600 m. From our reconnaissance studies and the structural attitude of the sequence in the Chapala area we have inferred a thickness for the volcano-lacustrine deposits of about 900-1000 m, which is particularly well exposed in the northern sector of the Lake Chapala.

In the Chapala area, the volcano-sedimentary sequence has a broad distribution around the Lake Chapala (Fig. 6.2) and constitutes a mappable unit that can be easily distinguished from the volcanic units in the region. We dated two fresh andesitic lava flows. The isotopic analyses were performed by M. López Martínez at Centro de Investigación Científica y de Educación Superior de Ensenada. The methodology for the K-Ar analyses is that described by Dalrymple and Lanphere (1969). The samples were fused in the double-wall tantalum furnace, like that described in MacDougall and Harrison

(1984). The isotopic analysis was done using a MS-10 mass spectrometer (see Farrar et al., 1966 for details).

The youngest unit forms the substrate to a ~900-1000 m thick sequence of volcano-sedimentary strata located to the north of Chapala City; at this site the K-Ar age was 3.4 Ma. The second oldest unit, overlying a lacustrine sequence to the southwest of Atotonilco, gives 8.7 Ma (site b, Fig. 6.2). Table 6.1 shows these results and those reported for the Chapala graben. Geological mapping (Fig. 6.2) is based on these data and our field work. Stratigraphic relationships of the volcano-sedimentary succession with the radiometrically dated volcanic rocks, document different stages of evolution of the Chapala basin. In an attempt to document the development of the basin (and paleo-lake) and possible relationships with tectonic and volcanic events, we have investigated the distribution of lacustrine sediments and their stratigraphy in seven sections (Fig. 6.3).

Field observations through the volcano-sedimentary sequence show that the ancient coastline of a paleo-lake can be found as far as Atotonilco, in the northeastern sector of present-day Lake Chapala (Fig. 6.2, site a). At this site, the geologic section is composed of late Miocene basalts underlying a lacustrine sequence with intercalated rhyolitic ash-flow tuffs. A pumice from this ash-flow tuff was dated by the K-Ar method at 10 Ma (Fig. 6.3a). We propose that this unit correlates with that reported from north of Guadalajara City by Moore et al. (1994). To the southeast of Atotonilco (Fig. 6.2, site b) a sequence of about 50 m of lacustrine sediments and ash underlies a ~400 of andesitic rocks dated at 8.7 Ma (Fig. 6.3b, Table 6.1). Garduño-Monroy et al. (1993) documented a transtensional tectonics in this area.

Table 6.1. New and compiled K/Ar ages for the Chapala graben

Sample	Rock	Material dated	% K	40Ar* mol/gr (10 exp -11)	% 40Ar*	% 40Ar atm	Latitude	Longitude	Age (Ma)	Reference
N-3	Andesite	w.r.	1.8957	0.0801	3.0	97.0	20.01	103.64	0.224 ± 0.02	1
N-5	Andesite	w.r.	1.784	0.6333	38.0	62.0	20.06	103.55	2.00 ± 0.20	1
N-2	Andesite	w.r.	1.192	0.6733	33.0	67.0	20.11	102.57	3.00 ± 0.30	1
ROE-144	Andesite	w.r.	1.78	1.0488	0.1		20.14	102.36	3.30 ± 0.30	1
ROE-23	Basalt	w.r	1.80 ± 0.01	1.0742	31.4	68.6	20.30	103.23	3.40 ± 0.20	This study
P. Damon	Andesite						20.78	102.78	3.29 ± 0.26	2
CHP-601B	Andesite	w.r.	1.85 ± 0.04	2.78 *			20.40	103.35	3.85 ± 0.42	3
P. Damon	Ash-flow						20.35	103.17	4.20 ± 0.11	2
CHP-092	Andesite	w.r.					20.45	103.44	4.19 ± 0.69	3
PED-JAL-26	Basalt	w.r.					20.34	103.19	4.33	4
CHP-169	Basalt	w.r.					20.13	103.19	4.48 ± 0.69	3
CHP-705	Basalt	w.r.	0.79 ± 0.08	1.29 *			20.01	103.24	4.60 ± 1.07	3
CHP-106	Andesite	w.r.	1.52 ± 0.004	2.53*			20.33	103.53	4.64 ± 0.68	3
MGN-4379	Andesite	w.r.	1.3126			92	20.16	102.90	5.00 ± 0.40	5
CHP-113	Andesite	w.r.					20.20	103.56	5.17 ± 0.82	2
CHP-552	Basalt	w.r.	1.71 ± 0.1	3.34*			20.11	103.77	5.45 ± 0.85	2
ROE-24	Andesite	w.r.	2.52 ± 0.13	2.4115	35.8	64.2	20.31	103.27	5.50 ± 0.30	This study
CHP-555	Basalt	w.r.	0.71 ± 0.04	1.60 *			20.06	102.69	6.26 ± 1.21	2
ROE-25	Basalt	w.r	0.73 ± 0.02	1.1	8.5	91.5	20.42	103.75	8.70 ± 1.0	This study
ROE-142	Andesite	w.r	0.913	1.434	0.1		20.03	102.39	8.80 ± 0.8	1
S8	Basalt	w.r.	0.71	1.26		43.9	20.78	102.44	10.00 ± 20	6
1131	Basalt	w.r.	1.14	0.202	58.4		20.70	102.34	10.20 ± 0.30	7
S6	Basalt	w.r.	1.51	2.9		39.8	20.69	102.54	11.00 ± 2.00	6
S1	Basalt	w.r.	1.06	2.17		78.9	20.68	102.21	12.00 ± 2.00	6

1, Rosas-Elguera et al. (1989); 2, P.E. Damon [Refered in Allan et al. (1991)]; 3, Delgado-Granados, et al. (1995); 4, Nieto-Obregón et al. (1981); 5, Grajales-Nishimura and López-Infanzón, 1983; 6, Verma et al. (1985); 7, Nixon et al. (1987); *, exp-7. w.r., whole rock. White spaces where no data exist.

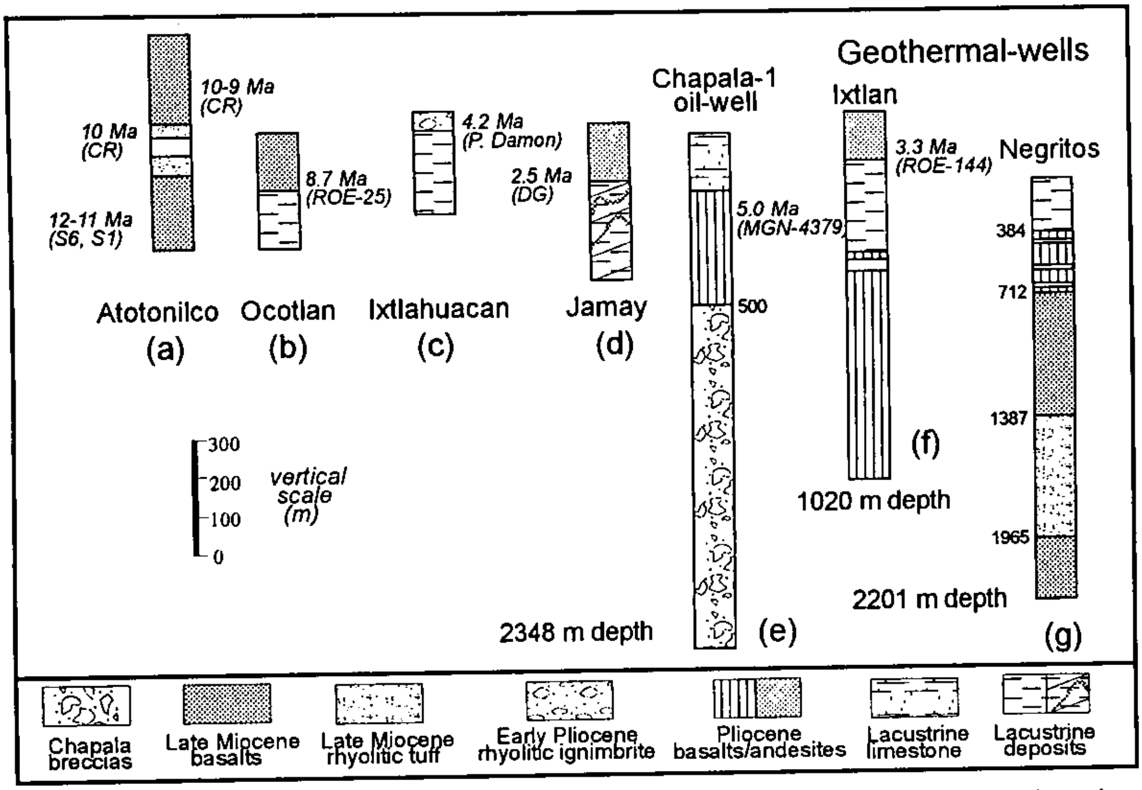


Fig. 6.3 Secciones estratigráficas de los sitios estudiados. La geología del subsuelo en los sitios (e) y (f)-(g) es de acuerdo con los pozos para geotermia y petróleo, respectivamente. CR son edades no publicadas de Castillo y Romero (1991); DG es una edad de Delgado-Granados et al. (1995). El resto se indican en la Tabla 6.1.

To the north of Chapala village the lacustrine sediments underlie a 4.2 Ma rhyolitic welded ash-flow tuff (unpublished data by P.E. Damon reported in Allan et al., 1991) (Fig. 6.3c). There, the sequence is represented by a horizontal exposed section ~30 m thick, with a conspicuous silicified conglomerate at its top which overlies unconsolidated claystone with intercalated fine-grained sandstones in thin horizons or filling paleo-channels. In a quarry at the northeastern corner of Lake Chapala, the lacustrine sequence rests on top of columnar basalts intercalated with ashes of basaltic composition (Fig. 6.3d). The whole sedimentary sequence shows a notable gravity-related intraformational deformation.

To the east of Tizapan el Alto there is a sequence of lacustrine limestones previously mapped as Cretaceous (Ortega-Gutiérrez et al., 1992). However they overlie 5.0 Ma old andesitic rocks (Grajales-Nishimura and López-Infanzón, 1983). The andesitic sequence can be 500 m thick according to the oil-well drilled at this site by Petroleos Mexicanos (Fig. 6.3e). Exposures along the No. 15 highway show the limestones, with individual strata 0.20 to 0.30 m thick overlying an unconsolidated green-sandy unit affected by hydrothermal solutions.

The geothermal fields of Ixtlan and Negritos are located within the eastern sector of the lacustrine plain, indicating that volcanic and hydrothermal activity has been a dominant process in the region (Fig. 6.2, sites f and g). The Ixtlan and Negritos sections are located in these geothermal fields (Fig. 6.3f and 6.3g). The geothermal wells show that the lacustrine section is some 300 to 450 m thick resting on more than 1500 m of a similar late Miocene volcanic succession to that found in the Atotonilco area, to the north of the Chapala basin (Fig. 6.3a). In the geothermal area, the lacustrine sediments are overlain by ~250 m of andesitic rocks dated at 3.3 Ma (Rosas-Elguera et al., 1989) (Fig. 6.3e). The exposed lacustrine sediments are flat-lying beds 0.05-0.25 m thick, of diatomite and argillaceous claystones.

Chapala Formation. Palmer (1926) referred to the volcano-sedimentary succession in the Lake Chapala as the Chapala beds. The sequence was subsequently studied by Downs (1958) and Clements (1959, 1962). Downs (1958) called the volcano-sedimentary sequence the Chapala Formation and reported that the fossil fauna in the lake bottom is characteristic of the late Pleistocene.

The Chapala Formation is a NE-tilted succession composed of an alternation of lacustrine sediments and pyroclastic units of ash and pumice. The sediments include conglomerates with fragments of andesites (<3 cm) and quartz, sandstones, siltstones, claystones and diatomite. Although some parts of the conglomeratic unit are silicified they are different from those of the sequence exposed to the north. Exposure events are recorded throughout the sequence as indicated by desiccation cracks filled with travertine. We consider that the silicified horizons and travertine deposits are evidence of hydrothermal activity which occurred within the basin, up to the present time (e.g. Ixtlan area). Diatomite horizons are usually thin (< 0.4 m) and are whitish in color, with low densities and porous textures.

To the northwest of Chapala village the section is ~50 m thick, and is characterized by a north-tilted sequence of volcanic ashes, lacustrine sediments and several diatomite horizons. The sequence rests on top of Pliocene andesitic flows. Individual sedimentary units are less than 4 m thick. Ash horizons are 0.8 m to 12 m thick. The pyroclastic material is non-welded and contains 0.02-0.22 m diameter pumice lapilli within a fine-grained glassy matrix. In the upper part of the section there is a horizon some 0.8 m thick composed solely of pumice, which was likely deposited in the lake. Air-fall ashes deposited subaerially are intercalated with the lacustrine horizons, indicating changes in the lake level conditions.

Our K-Ar date for the andesitic-substratum of the Chapala Formation gives an age of 3.4 Ma (Table 6.1). Delgado-Granados et al. (1995) reported a K-Ar age of 2.5 Ma for a volcano which is correlative with the volcanic rocks on the top of the volcano-sedimentary sequence at the northeastern corner of Lake Chapala (Fig. 6.3d). Thus we conclude that the age range for the Chapala Formation is about 3.4 to 2.5 Ma. Thus we retain the name of Chapala Formation for a NE-tilted volcano-sedimentary sequence younger than 3.4 Ma with the areal distribution shown by figure 6.2. Considering a thickness of 900 m, a subsidence rate of ~1.0 mm/yr can be assumed. Similar subsidence rates have been calculated for the Tepic-Zacoalco and northern-Colima grabens (Rosas-Elguera et al., 1996; Ferrari and Rosas-Elguera, in press).

6.4 Structure and tectonics

The present-day Lake Chapala is a small remnant of a large basin. To the north the late Miocene basaltic flows form extensive plateaus (~1900 m above sea level) (Fig. 6.2) with coeval ignimbritic and rhyolitic flows (Urrutia-Fucugauchi, 1981; Verma et al., 1985; Ferrari et al., 1994b). The basaltic plateau exhibits a calc-alkaline affinity (Verma et al., 1985) and could represent the first widespread and uniform volcanic event in the Trans-Mexican Volcanic Belt history (Ferrari et al., 1994b). We show that the geology of the Atotonilco section is similar to the subsurface geology of the geothermal well located at Los Negritos (Figs. 6.3a and 6.3g). Considering the elevation of the upper contact of the late Miocene rhyolitic tuff in the Atotonilco and Negritos sections (Figs. 6.3a and 6.3g), we can suppose ~2000 of vertical offset. The subsidence could be associated with a left transtensional phase in late Miocene times (Garduño-Monroy et al., 1993) which should leave a morphology characterized by a lacustrine basin system. Later, however, this displacement could have been influenced by the purely extensional Pliocene tectonics.

As the regional stress changed to a dominantly extensional tectonics, the basin continued to evolve. According to the Ixtlahuacan site (Fig. 6.3c), around the early Pliocene the area to the north of the actual Lake Chapala was experiencing subaerial conditions and an extensional tectonics concentrated to the south forming the present-day basin in late Pliocene-Pleistocene times. At this time the lacustrine sediments of the Chapala Formation were deposited in this new depression (Fig. 6.4a).

The Chapala Formation shows different structural attitudes indicating a subsidence and tilting of the volcano-sedimentary succession (Fig. 6.4). The lower and older unit is characterized by an average 33° to the NE along a N83°W strike but the upper deposits strikes and dip N75°W, 19°NE. The upper unit oversteps various members of the lower unit and this overlap suggests that subsidence and tilting of the basin was ongoing during deposition of the lacustrine sequence (Figs. 6.4a-b).

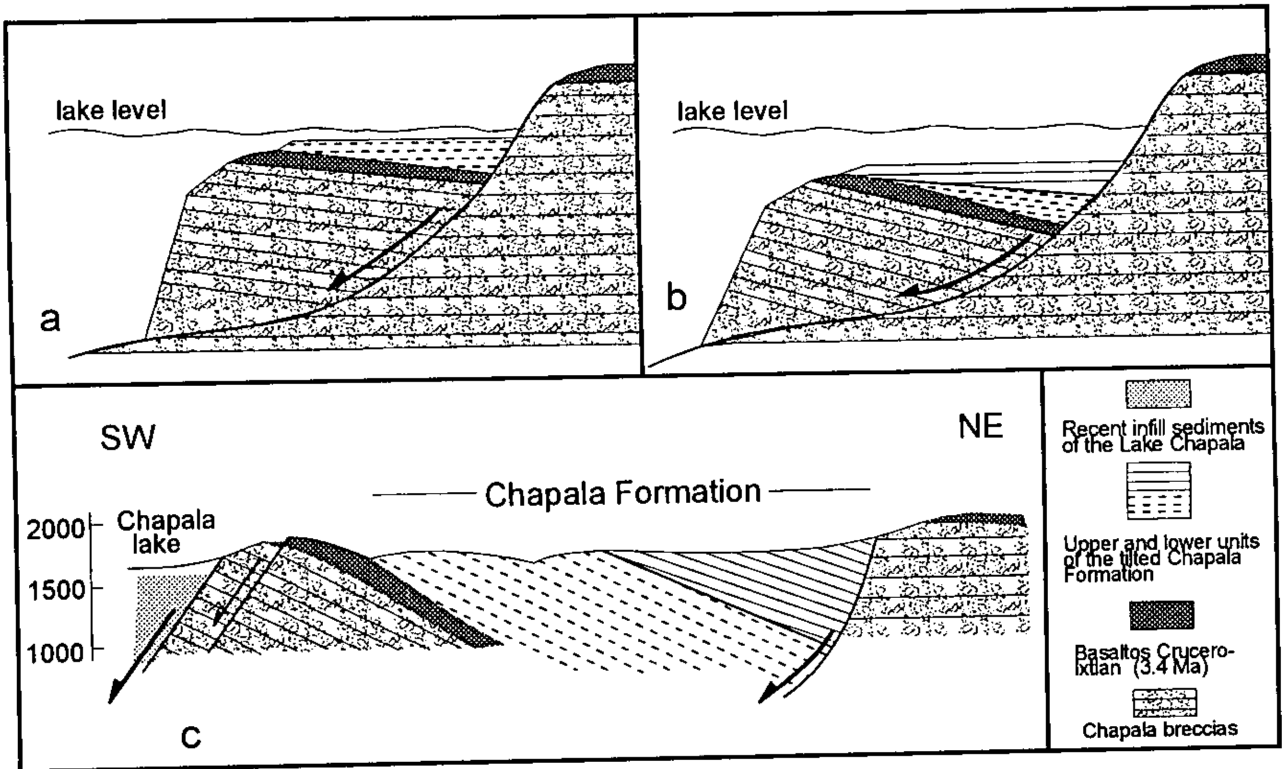


Fig. 6.4 Modelo propuesto para la evolución de la formación Chapala. (a) y (b) esquematizan los estados tempranos de la sedimentación de las unidades inferior y superior de la Formación Chapala. Observe el carácter lístrico de la falla que controla la actitud estructral de los sedimentos. (c) Sección estructural mostrando la discordancia principal en la Formación Chapala.

A model for the development of the basin since late Pliocene time, based on the distribution and characteristics of the Chapala formation, is summarized in Figure 6.4. During the early stages, post-3.4 Ma, the region underwent tectonic extension that resulted in the formation of a depression, which began to be filled with detrital and pyroclastic sediments (Fig. 6.4a). As the basin subsided and tilted the older units, erosion and renewed deposition of sediments and volcanic ashes continued filling the basin, forming the onlap structure (Fig. 6.4b). Finally, the region underwent normal which tilted the whole succession (Fig. 6.4c). Although our model explains one unconformity, due to the subsidence and tilting process provoked by active faulting, two or more unconformities can be expected.

The above data suggest the former existence of a large lacustrine basin which is here named the Jalisco paleo-lake. According to the radiometric ages, the geological sections presented, and the distribution of the volcano-sedimentary sequence in time and space, we infer the evolution of the Lake Chapala. At the early stages of development we assume that the Jalisco paleo-lake was located to the north of the present-day Lake Chapala (Fig. 6.5a). The Tepic-Zacoalco and Colima grabens were developed due to a reactivation of older structures during early Pliocene times (Rosas-Elguera et al., 1996). The influence of this tectonic activity in the Chapala area could have resulted in the enlargement of the Jalisco paleo-lake toward the west (Fig. 6.5b) and probably changed the environmental conditions of the lake. After 3.4 Ma the extensional tectonic activity migrated to the south to form a complex lake system which extended also to the west of the present Lake Chapala (Fig. 6.5c). During the Pleistocene the Chapala basins became

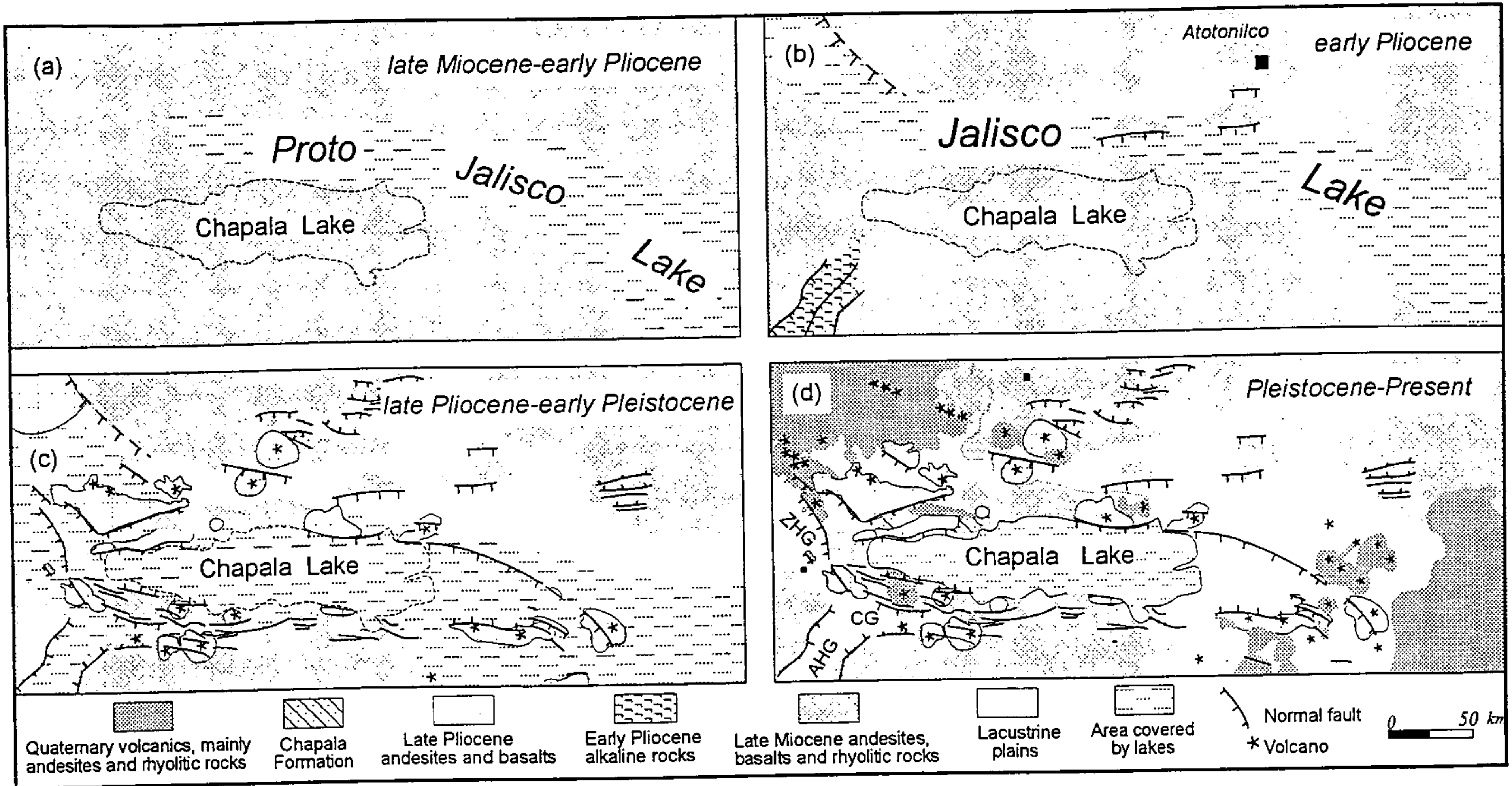


Fig. 6.5 Modelo sugerido para el desarrllo de un sistema de cuancas en la región del graben de Chapala. Observe la influencia de la actividad volcánica y tectónica en la ampliación del paleo-lago hacia el oeste y sur (b-c) y el progresivo aislamiento del sistema de cuencas en las fases posteriores debido a la actividad volcánica (d).

isolated by volcanic and tectonic activity which closed the communication between the depressions (Fig. 6.5)

6.5 Conclusions

Previous works considered the Chapala graben as a central down-faulted block in an anticline structure (Palmer, 1926; Diaz and Mooser, 1972). Recent structural data suggest that the development of the graben is associated with a transtensional system which changed to an extensional tectonics (Rosas-Elguera and Urrutia-Fucugauchi, 1993; Garduño-Monroy et al., 1993).

The volcano-sedimentary sequence is not completely exposed at any given locality and no correlatable geological horizons were found in the seven sections of the volcano-sedimentary sequence studied in the Chapala region. However, their stratigraphic relationships with the dated volcanic rocks (see Fig. 6.3) show that each section represents a particular stage in the evolution of the Chapala basin supplying evidence for a basin system developed between late Miocene and early Pliocene. Furthermore, our stratigraphic data (Fig. 6.3) permit correlation of these units with those described to the north of Guadalajara City and we can infer that a major lake system (i.e., our proposed Jalisco paleo-lake) developed to the north of the present Lake Chapala. Thus, a link between the basin systems developed along the southeastern end of the Tepic-Zacoalco graben and the evolution of the Chapala graben can be reasonably established.

The lacustrine sediments in the Atotonilco area (Fig. 6.2, site a; Fig. 6.3a) suggest that the Chapala tectonic basin (and the Jalisco paleo-lake) commenced its development

~10 Ma ago due to a transtensional tectonic phase which could be the southeastern-end of the transcurrent regime documented in the middle Miocene along the Tepic-Zacoalco graben (Ferrari, 1995; Ferrari and Rosas-Elguera, in press). Later, the extensional tectonics took over and migrated progressively to the south to form the present tectonic depression during the past 3.4 Ma (Figs. 6.2 and 6.3). Thus the distribution, stratigraphic relationships with the dated volcanic rocks and the subsurface geology of the volcano-sedimentary sequence in the Chapala graben area suggest the existence of a large Jalisco paleo-lake which evolved to the present-day Lake Chapala.

VII CONCLUSIONES

El trabajo apenas se inicia. Durante mucho tiempo se han escrito numerosos artículos relacionados con el bloque Jalisco, sin embargo, los estudios geológicos detallados que sustenten los modelos propuestos para el occidente de México son escasos y dispersos. Considero que los resultados de este trabajo contribuyen notablemente al conocimiento de esta parte de México, de tal manera que los datos aquí presentados deben ser considerados para sugerir cualquier modelo relacionado con el bloque Jalisco. Las conclusiones que se presentan son de carácter estratigráfico con implicaciones volcánicas y/o tectónicas y de carácter tectónico (arquitectura de las depresiones, tasas de deformación, direcciones de extensión y modelo tectónico).

7.1 Estratigrafía Regional

a) Basamento mesozoico: La formación de los límites continentales del bloque Jalisco

El suroeste de México se distingue por una zona de rocas plutónicas del Cretácico-Terciario de afinidad calco-alcalina expuestas desde Puerto Vallarta hasta el Golfo de Tehuantepec. Esos plutones intrusionan unidades mesozoicas las cuales incluyen una secuencia meta-sedimentaria y otra volcano-sedimentaria no metamorfizada (Ortega-Gutiérrez, 1981; Campa y Coney, 1983; Macias y Solis, 1985; González y Torres, 1988). Uno de los plutones más grandes localizado a lo largo del margen continental de México es el batolito de Puerto Vallarta el cual cubre una superficie de ~9000 km^2 (Schaaf et al., 1995). De acuerdo con los modelos gravimétricos, el espesor cortical en el bloque Jalisco es de aproximadamente 39 km (Urrutia-Fucugauchi y Flores-Ruiz, 1996). Este cinturón de rocas plutónicas puede ser continuado hacia el norte para formar la cordillera plutónica de Baja California y Golfo de California (Gastil, 1983). La edad del batolito de Puerto Vallarta está entre 100 y 75 Ma (Schaaf et al., 1995). A partir de los análisis de los elementos traza, es posible demostrar que este batolito tiene una afinidad tectónica correspondiente a los granitos desarrollados en un arco volcánico de tal manera que representa las raíces de un arco volcánico Cretácico (Schaaf et al., 1995).

El batolito de Puerto Vallarta y los cuerpos intrusivos del bloque Michoacán son geoquímica e isotópicamente diferentes. El bloque Michoacán, expuesto al oriente del graben de Colima en buena parte está conformado por un batolito tonalítico a cuarzomonzonítico del Cretácico tardío (68 ± 12 Ma) (Pantoja, 1983; Schaaf et al., 1995; López-Ramos, 1995) el cual intrusiona una sucesión marina volcánica y sedimentaria de edad Triásico a Cretácico. Aunque los bajos cocientes de $^{87}Sr/^{86}Sr$ de los plutones expuestos en el bloque Michoacán sugieren una fuente del manto sin contaminación cortical (Pantoja, 1983), las edades modelo de neodimio sugieren que el batolito de Puerto Vallarta pudiera estar subyacido por un basamento más antiguo (Paleozoico-Proterozoico) (Khöler et al., 1988; Schaaf et al., 1993). Adicionalmente, en la parte oriental del batolito de Puerto Vallarta, la presencia de granitos de dos micas junto con granitos tipo S sugiere que la contaminación cortical jugó un papel más importante que en la parte occidental.

En la figura 7.1 se muestra el área afectada por la influencia térmica de los

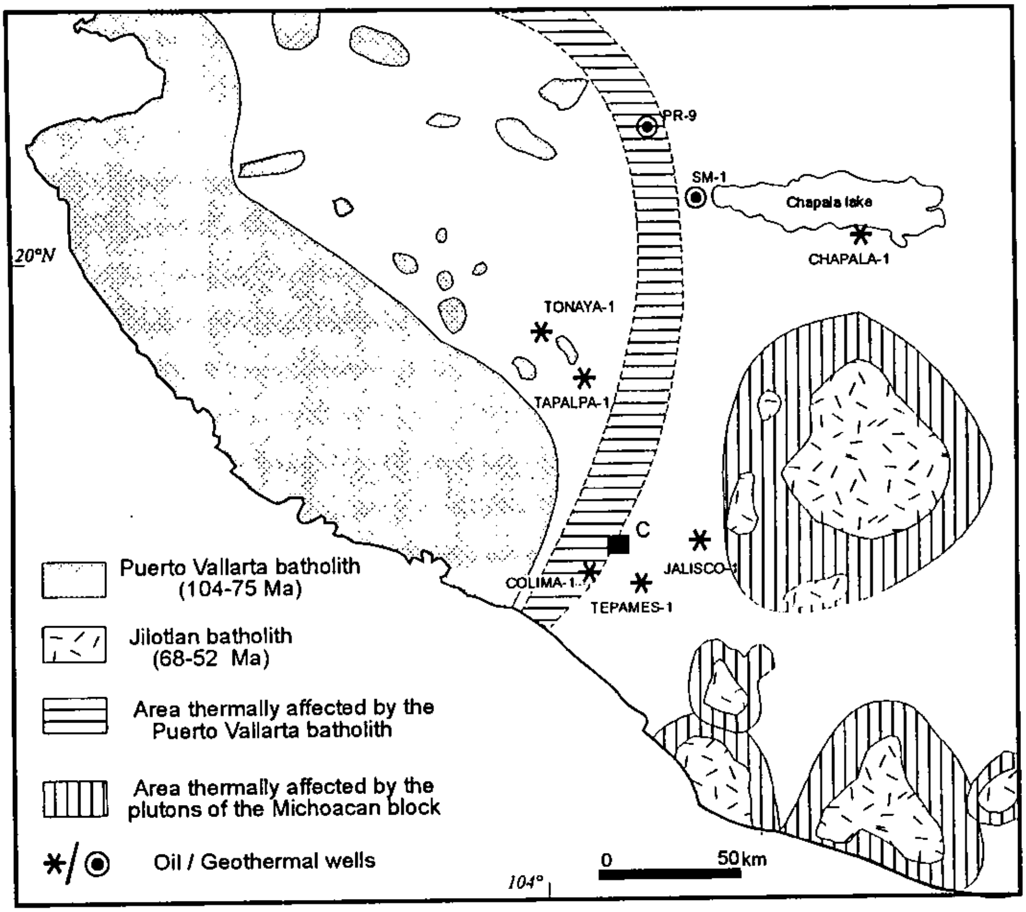


Fig. 7.1 Distribución aproximada de los batolitos Puerto Vallarta y Jilotlán Nótese que el area de influencia térmica de los plutones sugiere que no hubo interacción entre ellos formándose un límite natural (Tomado de Grajales-Nishimura y López-Infanzón, 1983)

plutones de Puerto Vallarta y Jilotlán durante su emplazamiento. De esta figura, resulta obvio que esos cuerpos intrusivos no tuvieron influencia entre si de tal manera que se formó un límite natural entre ellos. El mapa aeromagnético de la figura 5.1b delinea perfectamente el bloque Jalisco dando una idea de su singularidad.

Sin que ninguno de los tres argumentos anteriores (geoquímico, térmico y magnético) sean sólidos por si mismos, si son elementos de juicio dentro del contexto geológico regional. Conjuntando estos argumentos uno puede intuir claramente que, al menos el límite continental oriental del bloque Jalisco es una zona de debilidad, anterior al desarrollo del graben de Colima, que jugaría posteriormente un papel importante.

b) Sierra Madre Occidental versus Sierra Madre Suroccidental

La Sierra Madre Occidental es una provincia volcánica del Terciario medio formada por ignimbritas y lavas de composición riolítica con andesitas y basaltos subordinados expuesta al norte del graben Tepic-Zacoalco. Hacia el NE de Guadalajara la secuencia piroclástica sobreyace a andesitas e ignimbritas de edad eocénica (Webber et al., 1994).

Por otra parte, en el bloque Jalisco, tanto el batolito de Puerto Vallarta como las ignimbritas riolíticas son el tipo de roca dominante. Esta unidad piroclástica ha sido considerada como parte de la Sierra Madre Occidental (Sánchez, 1956; Ortega-Gutiérrez et al., 1992; López-Ramos, 1995).

De manera informal denominaré como Sierra Madre Suroccidental al relieve montañoso formado por rocas piroclásticas de composición predominantemente riolítica que cubren una amplia región del bloque Jalisco. (A reserva de los resultados radiométricos, esta nomenclatura se podría extender para rocas similares que afloran en el bloque Michoacán, particularmente en su parte norte). Esta distinción con la Sierra Madre Occidental se debe a que entre las regiones de San Sebastian y Puerto Vallarta, las edades radiométricas de las rocas piroclásticas están en el rango de 91 a 71 Ma (Gastil et al., 1978). Hacia el norte, en la Sierra del Guamuchil, y en el valle del río Ameca, dos muestras de flujos de cenizas dieron una edad K/Ar de 61 y 75 Ma (Righter et al., 1995). Además, el basamento de las rocas Plio-Cuaternarias a lo largo de la depresión de Atenguillo está formado por ash-flows silícicos con edades entre 83 y 65 Ma (Wallace and Carmichael, 1989; Righter et al., 1995). Finalmente, en el borde nor-oriental del bloque Jalisco, la cima de una sucesión ignimbrítica tiene 79 Ma por Ar-Ar (este trabajo). Esas doce edades radiométricas, que cubren una amplia región, se muestran en la tabla 7.1.

La conclusión inmediata es que las rocas piroclásticas (Sierra Madre Occidental) expuestas hacia el norte del graben Tepic-Zacoalco y las que afloran en el borde norte del bloque Jalisco (Sierra Madre Suroccidental) son unidades volcánicas diferentes en tiempo y espacio por lo que representan, evidentemente, differentes eventos tectono-magmáticos. Adicionalmente a esto, la Sierra Madre Occidental tiene un estilo de deformación relacionado solo a una tectónica extensional en tanto que la Sierra Madre Suroccidental muestra, al menos dos fases de deformación. Una de carácter compresivo (o transpresivo) y otra, sobrepuesta de carácter extensional.

TABLA 7.1 Edades radiométricas para las ignimbritas del bloque Jalisco

Sample	Rock type	Latitude	Longitude	Material	Age (Ma)	Reference
MAS - 808	ash-flow	20.90	105.13	sanidine	74.87	Righter et al., 1995
MAS - 607	ash-flow	20.19	104.38	biotite	70.64	Righter et al., 1995
MAS - 433	ash-flow	20.99	104.47	plagioclase	60.9	Righter et al., 1995
MAS - 427	ash-flow	20.75	104.49	sanidine	65.3	Righter et al., 1995
1154 - F	welded tuff				91.5 ± 2.3	Gastil et al., 1978
1169 -B	welded tuff				80.5 ± 4.0	Gastil et al., 1978
1168 - F	welded tuff				88 ± 1.8	Gastil et al., 1978
1170 - F	welded tuff				71.2 ± 1.4	Gastil et al., 1978
LV - 237	ash-flow	20.44	104.41	biotite	80.7 ± 0.4	Wallace and Carmichael, 1983
LV - 250	ash-flow	20.43	104.48	biotite	80.3 ± 0.3	Wallace and Carmichael, 1983
ZHG ROE - 1	ash-flow	20.31	103.9	biotite	79 ± 2.0	Este trabajo

No se tienen datos de latitud y longitud para las muestras de Gastil et al. (1978)

c) Secuencia Máfica Basal de la Faja Volcánica Transmexicana

El volcanismo del Mioceno tardío está caracterizado por una unidad basáltica ampliamente distribuida desde la región de Tepic hasta el Estado de Hidalgo (Ferrari et al., 1994). Las edades isotópicas publicadas sugieren que el desarollo de este vulcanismo basáltico ocurrió entre 13 y 9 Ma (Gastil et al., 1979; Moore et al., 1994; Ferrari et al., en prensa; este trabajo; Rosas-Elguera et al, en preparación). En toda su extensión estos basaltos han sido denominados de diferente manera. Basaltos Cinco de Mayo, en Tepic (Ferrari et al. en prensa), Basaltos San Cristobal, alrededor de Guadalajara (Moore et al., 1994); Secuencia Máfica del Río Santiago, en Los Altos de Jalisco (Ferrari et al., 1994). Aqui sugiero el nombre de **Secuencia Máfica Basal de la Faja Volcánica Transmexicana** para referirme a este vulcanismo del Mioceno tardío.

En la tabla 7.2 se resumen las características generales de la Secuencia Máfica Basal de la Faja Volcánica Transmexicana. Como puede apreciarse las edades están en el rango de 8.7 a 13 Ma y su espesor decrese hacia el oriente. Gastil et al. (1979) y Ferrari et al. (1996) sugirieron que este volcanismo representa un importante evento tectónico relacionado con la apertura del Golfo de California.

Cuál es el significado de la Secuencia Máfica Basal ? Recientemente DeMets y Traylen (sometido) revisaron las lineaciones de los centros de esparcimiento creadas a lo largo de la cresta del Pacífico-Rivera y el norte de los Matemáticos desde hace 10 Ma. Un rasgo notable es que entre 9.92 Ma y 7.86 Ma la tasa de esparcimiento a lo largo de la cresta de los Matemáticos decreció de 95±3 mm/año a 64±13 mm/año, pero pudo haber comenzado antes de 9.92 Ma (DeMets and Traylen, sometido). Adicionalmente,

Tabla 7.2 Características temporales de la Secuencia Máfica Basal de la Faja Volcánica Trans-Mexicana

Región	Espesor (m)	Edad (Ma)	Observaciones	Referencias
Tepic	600	9.9 - 8.9	flujos de lava alcalinos	1, 10
Punta Mita		13 - 10	basaltos almohadillados	1
Aguamilpa		11-12	diques	2, 4
Ceboruco	800	8.5	lavas	11
Guadalajara	800	12.5 - 8.5	flujos de lava alcalinos	3, 5, 9
Los Altos	200 - 300	13 - 8.7		6
Punto Triple	< 100	10.2		7, 12
Chapala	200	8.8 - 8.7		8, 12

1, Gastil et al. (1979); 2, Damon et al. (1979); 3, Damon et al. (1981); 4,Clark et al. (1981), 5, Nieto-Obregon et al. (1985); 6, Verma et al. (1985) 7, Allan (1986); 8, Rosas-Elguera et al. (1989); 9, Moore et al. (1994); 10, Righter et al. (1995); 11, Ferrari et al. (en prensa); 12, Este trabajo

DeLépinay et al. (1995) han sugerido un proceso de erosión tectónica ocasionado por un retroceso de la trinchera Mesoamericana para explicar el hundimiento de una porción del bloque Jalisco. De acuerdo a esos autores esto ocurrió en el Mioceno tardío.

Aquí se propone que el decremento en la tasa de esparcimiento pudo haber sido provocado por un decremento en la tasa de subducción ocasionando un retroceso de la trinchera lo que pudo haber provocado extensión en la placa sobreyacente a lo lago del límite, previamente desarrollado, entre la Sierra Madre Occidental y el bloque Jalisco reactivando estructuras antiguas (nótese que la Secuencia Máfica Basal es paralela al limite entre la Sierra Madre Occidental y los bloques ubicado al sur). Este mecanismo pudo haber contribuido para el emplazamiénto de la Secuencia Máfica Basal.

d) Rocas volcánicas del Mioceno tardío-Plioceno

Grupo Guadalajara. El grupo Guadalajara está compuesto por una sucesión de domos riolíticos y depósitos piroclásticos asociados cuyas edades radiométricas están entre 7.15 y 3.1 Ma (Gilbert et al., 1985). En menor proporción, el grupo Guadalajara incluye lavas basálticas tipo OIB datados en 4.7 a 3.3 Ma (Watkins et al., 1971; Gilbert et al., 1985; Moore et al. 1994). Contemporáneamente a estos basaltos se emplazaron dos marcadores regionales: la ignimbrita San Gaspar de 4.7 Ma y la ignimbrita Guadalajara de 3.3 Ma. De acuerdo con los resultados de este trabajo se sugiere que la ignimbrita San Gaspar fluyó hasta el área que corresponde al semi-graben de Zacoalco lo cual, implicitamente da una idea del carácter peniplano de la región. El grupo Guadalajara está expuesto en un área elongada de dirección ~N-S que cubre una superficie de 900 km^2

con un volumen estimado de 350 km^3 (Rossotti et al., 1997). Es interesante notar que la primera aparición de los basaltos alcalinos corresponde con la edad de la ignimbrita San Gaspar y con el episodio principal de extensión en la región.

Recientemente obtuvimos edades de 6.0 y 5.0 Ma por huellas de fisión para dos domos riolíticos ubicados en la parte norte de la región de estudio y que sobreyacen extensos derrames riolíticos. De acuerdo con estos datos se puede plantear una migración del vulcanismo riolítico hacia el sur a partir del Mioceno superior. Con estos datos, es posible especuar que una cámara magmática se emplazó en la región de Guadalajara hace unos 8 Ma y que fue periodicamente rejuvenecida a través de la inyección de magmas máficos durante las fases de extensión principales. En este contexto, la Caldera La Primavera pudiera representar el último episodio de una historia vulcano-tectónica que inició hace 7 Ma.

Basaltos Crucero-Ixtlán. Este vulcanismo calco-alcalino se desarrolló en el Plioceno tardío (3.4 - 2.5 Ma) (Rosas-Elguera et al., 1989; Delgado, 1992). Durante este periodo la extensión se concentró en la zona axial del actual Lago de Chapala (ver capitulo VI). En la parte occidental del lago de Chapala, los basaltos Crucero-Ixtlán sobreyacen a las brechas Chapala e infrayacen a la Formación Chapala de aproximadamente 900 m de espesor, en tanto que hacia el oriente, sobreyacen a basaltos miocénicos que en conjunto forman la Sierra de Pajacuarán. También en la parte oriental, en la zona geotérmica de Ixtlán, los basaltos sobreyacen a sedimentos lacustres. Lo relevante de los basaltos Crucero-Ixtlán es que al separar dos secuencias lacustres están marcando una edad Plioceno tardío para una de las últimas fases de extensión del graben de Chapala.

La secuencia vulcano-sedimentaria

Generalmente los depósitos lacustres de la depresión tectónica de Chapala habían sido considerados como del Plio-Cuaternario (Delgado, 1992) y las calizas lacustres del Cretácico (Ortega-Gutiérrez et al., 1992; López-Ramos, 1995). Sin embargo, de acuerdo con los resultados (estratigráficos y radiométricos) presentados en este trabajo, concluimos que la secuencia volcanosedimentaria tiene diferentes edades. Las más antiguas: del Mioceno tardío y las más jóvenes menos de 3.4 Ma. En este sentido el nombre de Formación Chapala se restringe al periodo comprendido entre 3.4 y 2.5 Ma.

Conjuntando los resultados de este trabajo y los obtenidos por Moore et al. (1994) para la porción norte de la región de Guadalajara, puede interpretarse que éstas sean las evidencias de la existencia de un sistema de lagos (paleo-lago Jalisco) ubicados hacia el norte del actual lago de Chapala. La migración hacia el sur de las cuencas está sustentada por la Formación Chapala (3.4 a 2.5 Ma) cuya subsidencia, de acuerdo con los argumentos anteriores debió ocurrir a una tasa de aproximadamente 1 mm/año durante el Plioceno tardío.

La conclusión anterior es importante porque, al igual que la depresión de Chapala, dentro del bloque Jalisco se han desarrollado otras cuencas del Mioceno tardío como las reportadas por Carranza (1997) para la región de Tecolotlán donde se han encontrado fragmentos de *Neohipparion eurystyle*, *Dinohippus mexicanus*, *Nanippus minor*, y *Astrohippus stockii*. Este registro fósil es similar al reportado al norte del graben de Tepic-Zacoalco, a lo largo del área de Colotlán. Esto significaría que desde el Mioceno tardío se ha desarrollado una tectónica extensional (?) en una amplia región del occidente de México y que ha sido poco documentada.

7.2 Tectónica

a) Control tectónico del vulcanismo en las fronteras del bloque Jalisco. A lo largo del graben de Tepic-Zacoalco se han desarrollado las principales estructuras volcánicas de la región. Paralelamente a su desarrollo, también fueron formados una gran cantidad de conos cineríticos cuaternarios. Los grandes volcanes y los conos menores se desarrollaron alineados a lo largo de una dirección de ~315°± 15°. Por lo que estarían relacionados a una dirección de extensión de 45°°± 15°. Por su parte, el complejo volcánico Colima estaría vinculado con estructuras N-S al igual que nueve conos cineríticos, por lo que la dirección del esfuerzo horizontal compresivo mínimo es E-W.

b) Zonas de Acomodo y Vulcanismo. En el capítulo II se planteó la existencia de un campo volcánico asociado con la evolución de una zona de acomodo. En dicho capítulo se dió la definición del Campo Volcánico de Acatlán, en términos generales, tiene un vulcanismo de caracter bimodal calco-alcalino desarrollado en una zona de acomodo entre las fallas de Zacoalco y Ahuisculco. En la figura 7.3, se presenta un mapa detallado

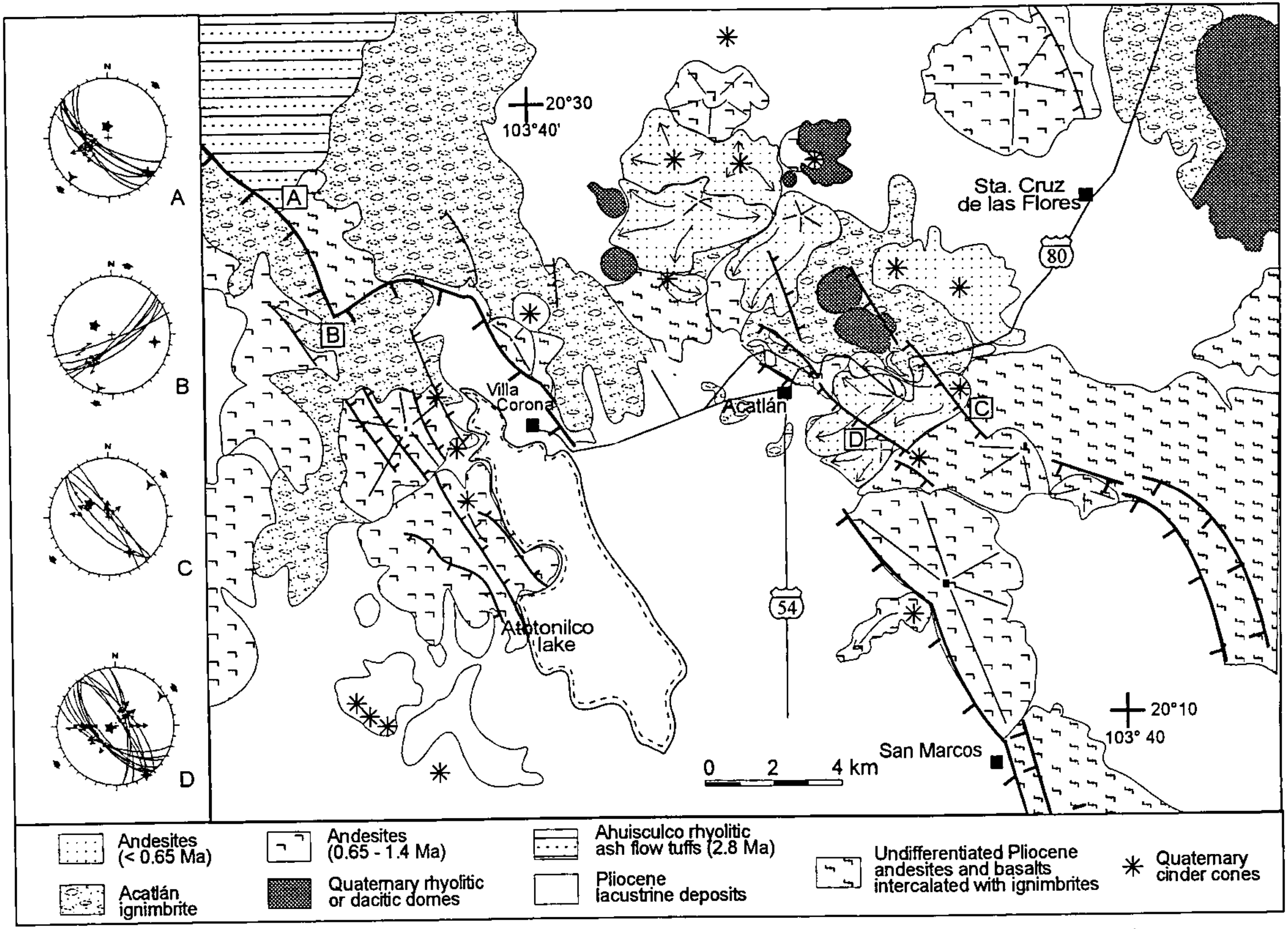


Fig. 7.3 Geología y tectónica del Campo Volcánico Acatlán. Nótese que las rocas mas jóvenes del campo están cortadas por fallas normales de ~ 50 m de desplazamiento vertical. Ello es evidencia de que la tectónica en este campo es activa.

del Campo Volcánico Acatlán, en tanto que en la figura 3.5 (ver capítulo III) se mostró que los principlaes conductos volcánicos están alineados a lo largo de fracturas NW-SE y NE-SW. En la figura 7.4, se muestra un esquema evolutivo del Campo Volcánico Acatlán.

Las relaciones en tiempo y espacio entre el Campo Volcánico Acatlán y el sistema de fracturamiento proporciona elementos geométricos y cinemáticos relacionados con el desarrollo de la zona de acomodo. Los fechamientos isotópicos permiten bosquejar la evolución de este campo en términos de la evolución de la cuenca tectónica. Así. en la figura 7.5a se muestra el primer estadío de la evolución. En este punto, la extensión regional de dirección NE produce las principales estructuras que conforman la arquitectura de los semi-grábenes de Ameca y Zacoalco. El sistema de fallas Bola Viejo-Zacoalco está separado de la falla Ameca-Auhisulco por una estructura tipo relay ramp. En el Pleistoceno (~1.4-1.0 Ma) se desarrolla un vulcanismo bimodal consitutido por volcanes andesíticos monogenéticos y domos riolíticos, desarrollados a lo largo de las fracturas principales. La Ignimbrita Acatlán es la unidad más notable en el Campo Volcánico Acatlán, hacia su base, la ignimbrita es de composición riolítica en tanto que su cima es de carácter andesítica (Wright y Walker, 1981). En sus miembros intermedios, la ignimbrita muestra claras evidencias de mezcla de magmas (e.g. pomez de dos composiciones: andesítica y riolítica). La erupción de esta ignimbrita ocurrió hace ~0.65 Ma (Fig. 7.4c). Posteriormente hubo la construcción de pequeños volcanes andesíticos (Fig. 7.4d). El trabajo estructural detallado indica que aún las unidades volcánicas más jóvenes están afectadas por fallas normales (Fig. 7.3).

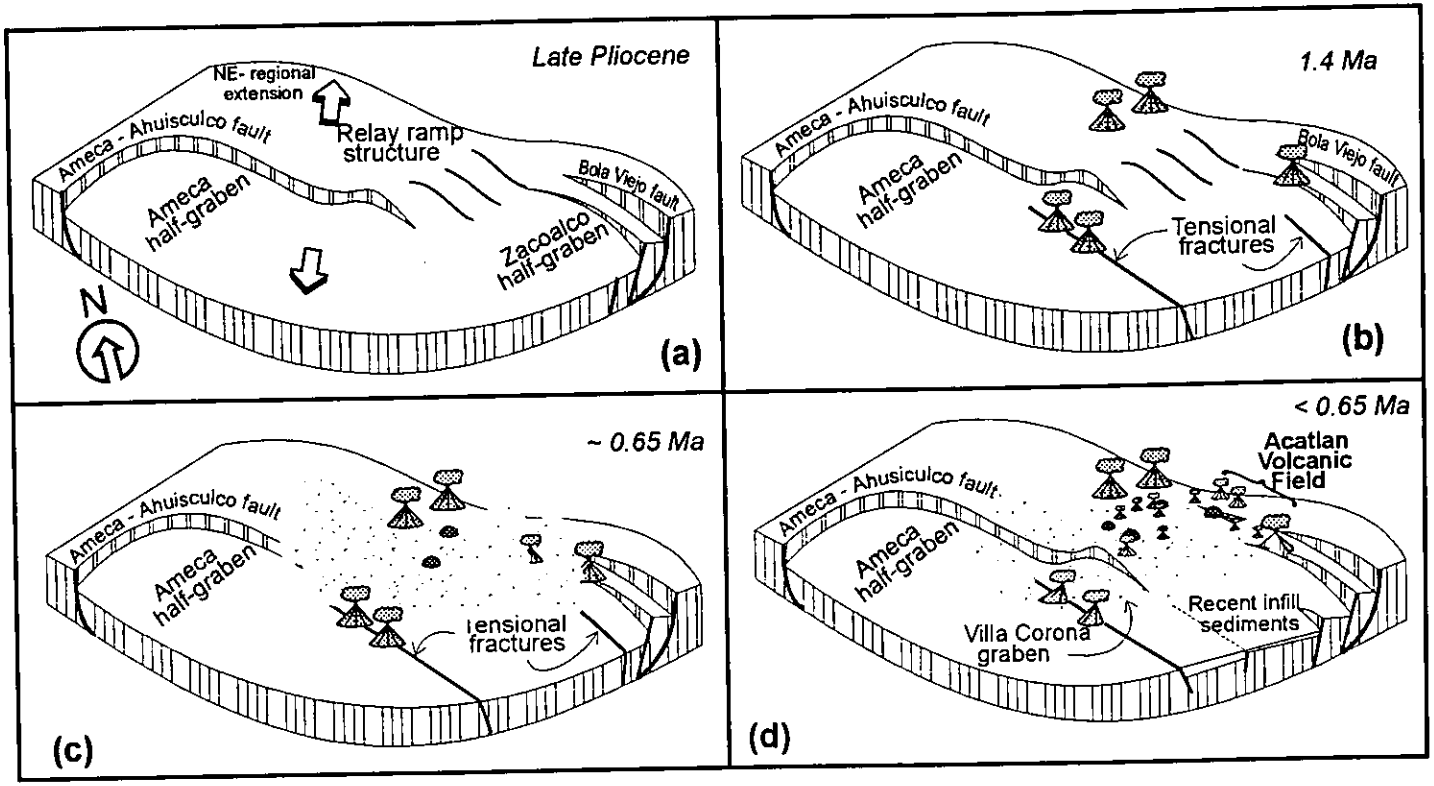


Fig. 7.4 Evolución del Campo Volcánico Acatlán. En este esquema, los sistemas de fallas Bola Viejo y Ameca-Ahuisculco están separados por un relay ramp. Donde posteriomente de emplazaría el Campo Volcánico Acatlán

El esquema anteriormente planteado puede explicarse si se considera una cámara magmática estratificada y con una íntima relación con la tectónica extensional de la región. En este sentido, se plantea que las fracturas tensionales permitieron la inyección de magma máfico en la base de la cámara magmática, lo que ocasionaría que se cambiarán las condiciones de presión y temperatura, mezclándose de esta manera los magmas y acelerando la erupción.

c) Arquitectura de las estructuras en las fronteras continentales del bloque Jalisco

El graben de Tepic-Zacoalco. Durante mucho tiempo el graben Tepic-Zacoalco se había concebido como una estructura simétrica (graben) limitada por las fallas de Mazatán y Pochotitlán (Demant, 1978; Allan et al., 1991). En nuestro trabajo (Ferrari y Rosas-Elguera, ver capitulo III) se presenta un esquema donde el graben está compuesto por varios sistemas de fallas independientes que pueden visualizarse en dos sistemas el norte y sur. El sistema norte está formado por los grábenes de Compostela-Ceboruco y Plan de Barrancas-Santa Rosa. Este sistema tiene una dirección 120°-130°; asociado, de acuerdo a las determinaciones de paleo-esfuerzos, a una dirección de extensión de 22°±13°. Por su parte el sistema sur constituido por los semi-grábenes de Amatlán, Ameca y Zacoalco (ubicados dentro del bloque Jalisco) tiene una dirección es de 150° a 110°. El semi-graben de Amatlán estaría asociado a una dirección de extensión 35°±29° en tanto que en el sistema Ameca-Zacoalco dirección de extensión es de 2°±25°, en ambos casos se ha estimado para el Plioceno.

Los desplazamientos verticales en el sistema sur son de ~1500 m en tanto que en el sistema norte varían de 550 a 2700 m. A partir de esto, se estimó que la tasa de hundimiento, a lo largo del sistema de fallas principal, decreció de ~0.45 mm/año en el Plioceno a ~0.1 mm/año en el Cuaternario.

Falla Zacoalco versus Falla Bola Viejo. Varias fallas sub-paralelas a las fallas de San Marcos y Ahuisculco afectan una zona de 15 km de ancho en la Sierra de Tapalpa, donde las rocas pre-Plioceno están basculadas ~35° hacia el NE. En la figura 3.5 se mostró la estructura de esta faja extensional como un geometría "estilo domino", sugiriendo una naturaleza lístrica de la falla principal. Sin embargo, debido a que la Sierra de San Marcos también está basculada unos 16°-20° hacia el NE, entonces la falla lístrica principal debe estar localizada más al noreste. Por ello, se propone la falla Bola Viejo como la estuctura principal de detachment la cual basculó las secuencias de las sierras de San Marcos y Tapalpa. Adicionalmente se propone que la falla de San Marcos es de naturaleza plana debido a que el basculamiento del bloque ubicado al SW también es de 16°-20°. También debido a que los bloques fallados de la sierra de Tapalpa son más pequeños, se sugiere una zona de flexura (roll-over) que bordea los grábenes.

El graben de Colima. El graben de Colima ha sido considerado como el límite oriental del bloque Jalisco desarrollado desde el Plioceno y dividido en tres sectores (Allan et al., 1991). Sin embargo, de acuerdo a los datos presentados en el capítulo IV es más conveniente dividir en dos sectores al graben de Colima: su parte norte y su parte sur. La parte norte del graben de Colima está compuesta por dos depresiones menores: el semigraben de Amacueca y el graben de Sayula. El desplazamiento vertical de la parte norte del graben de Colima es de 2500 m (Allan, 1985), lo cual proporciona una tasa de deformación de 0.7 mm/año. En tanto que en el sistema de fallas que bordea la porción oriente de la cuenca de Zapotlán, la tasa de deformación que se estimó es de 0.07 mm/año. La dirección de extensión promedio, estimada a partir de la inversión de estrías es de 140° ± 19°. No obstante una dirección de extensión E-W puede deducirse a partir del alineamiento de centros volcánicos y del análisis de poblaciones de fallas reportadas en la literatura (e.g. Barrier et al., 1990; este estudio) o del análisis de alineamiento de conos volcánicos.

La parte sur del graben de Colima. En este sector del graben de Colima el fallamiento es menos evidente que en la parte norte. De hecho en esta región no se realizaron estudios de microtectónica con detalle. No obstante, las observaciones más importantes son las siguientes. Aunque no se han realizado mecanismos focales, la red sismológica de Colima ha registrado decenas de sismos corticales (7-19 km de profundidad) con magnitudes Ms < 5.2 alineados a lo largo de una dirección de norte a nor-noreste. Además, debido a que (1) Una falla de dirección noreste de aproximadamente 100 m de desplazamiento vertical afecta el flanco noreste del Nevado de Colima y su prolongación hacia el SW está alineada con el actual volcán Colima; (2) Pequeñas fallas normales cortan los materiales poco consolidados de la porción SW del volcán Colima (Garduño et al., 1996); (3) Pequeñas fallas normales asociadas a una extensión E-W, han sido reportadas a ~10 km al SW de Colima (Sloan, 1989); (4) La dirección dominante del fallamiento, producido después del sismo de 1995 en

Manzanillo, es de 30°-50° (Garduño et al., 1996) se sugiere que la extensión, al sur del volcán Colima es acomodada en un área triangular tal como se mostró en la figura 5.2.

d) Modelo Tectónico

Para explicar la extensión perpendicular en ambos límites continentales del bloque Jalisco se propone un modelo tectónico donde el movimiento del bloque Michoacán hacia el sureste, con relación a Norte América, a lo largo del sistema Chapala-Tula explicaría la extensión en la frontera oriental del bloque Jalisco. Por otra parte, la extensión a lo largo del graben Tepic-Zacoalco se explicaría por una lenta tasa de convergencia con el consecuente retroceso de la trinchera. En ambos casos, el fallamiento reciente en las fronteras continentales del bloque Jalisco estaría controlado por la reactivación de límites antiguos. Así, la extensión a lo largo de los grábenes Tepic-Zacoalco y Colima estaría relacionada con fuerzas en los límites de placas más que con la relocalización de la Cresta del Pacífico Oriental por debajo de México.

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