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Geological and structural study of the Chapala rift, State of Jalisco, Mexico

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RESUMEN

La estructura y morfología regional al sur y al oeste de Guadalajara están dominadas por un sistema Neogeneo de tres "rifts" que intersectan en una junta triple continental localizada a unos 50 km als SSW de la ciudad. Este sistema controla la actividad volcánica de la Faja Volcánica Trans-Mexicana (FVTM). La estratigrafía regional se define de estudios de campo. Las unidades más antiguas en el "rift" de Chapala son una sucesión gruesa de brechas heterogéneas cubiertas por una secuencia de flujos andesíticos con fechamiento entre 12 y 8.8 Ma. Esta secuencia forma una meseta amplia disectada por fallas asociadas al proceso de "rifting". Localmente está cubierta por sedimentos lacustres del Mioceno tardío al Plioceno temprano. El proceso de "rifting" se inició durante el hiatus en volcanismo después del ciclo volcánico del Mioceno tardío. Para el Plioceno medio se inicia el volcanismo efusivo de la FVTM, que continua con menor intensidad en el Cuaternario. La apertura del "rift" de Chapala se inició a fines del Mioceno tardío a lo largo de lineamientos N90°E, presentando al principio movimientos laterales izquierdos y luego normales. La mayoría de estos lineamientos han permanecido inactivos desde el Pleistoceno y la deformación en la zona es en lineamientos N135°E a N180°E. Estos lineamientos controlan las 2 ramas del sistema triple. El "rift" de Chapala constituye un aulacogeno. Las deformaciones extensionales E-W afectan al Graben de Citala, cuyo extremo sur puede considerarse como el moderno punto triple.

PALABRAS CLAVE: Geología, geología estructural, rift de Chapala, Estado de Jalisco, México.

ABSTRACT

The regional structure and the morphology south and west of Guadalajara are dominated by a Neogene system of three rifts intersecting in a continental triple junction situated about 50 km SSW of the city. This system controls Mexican Volcanic Belt (M.V.B.) volcanism. Field studies define the regional stratigraphy. The oldest rocks outcropping in Chapala Rift are a thick succession of heterogeneous breccias unconformably covered by a sequence of extensive andesitic lava flows dated between 12 and 8.8 m.y. This sequence forms a broad plateau dissected by the faults associated with rifting. Locally it is overlapped by lacustrine sediments of Late Miocene/Early Pliocene age. Rifting started during the volcanic hiatus after the end of the Late Miocene volcanic cycle. In Mid-Pliocene the essentially effusive volcanism of M.V.B. begins and continues with decreasing intensity into the Quaternary. The opening of Chapala Rift began at the end of the Late Miocene along N90°E trending lineaments, presenting at first left-lateral and then normal motion. Almost all the N90° lineaments of Chapala Rift have been inactive since the Pleistocene and the region is now being deformed by lineaments of orientation ranging from N135°E to N180°E. These lineaments control the other two branches of the triple system. The Chapala Rift can thus be considered as an aulacogen of the incipient crustal fracturation process in west-central Mexico. In contrast, extensional deformations along and E-W directed axis are now affecting the southern Citala Graben, whose western end may be regarded as the site of a new triple point.

KEY WORDS: Geology, structural geology, Chapala rift, Jalisco State, Mexico.

INTRODUCTION

The volcanic activity of the western part of the Pliocene and Quaternary Mexican Volcanic Belt (M.V.B.) is controlled by a system of three rifts intersecting in a junction zone about 50 km SSW of Guadalajara. This triple system is composed of a N-trending branch, the Colima Rift, a NW-trending branch, the Tepic-Chapala Rift and an E-trending branch, the Chapala Rift (Figure 1).

Numerous authors (*e.g.* Allan, 1986, Allan *et al.*, 1987; Barrier *et al.*, 1989; Demant, 1981; Luhr *et al.*, 1985; Nixon *et al.*, 1987; Pasquaré *et al.*, 1986) have investigated the geological significance of this structural configuration; most of them link it with the Tertiary geodynamic evolution of the Mexican Pacific Margin as outlined by Atwater (1970), and later by Mammerickx and Klitgord (1982) and Ness *et al.*, 1985). As geological field studies of this region have been until now poorly developed, most previous work has largely depended on the interpretation of satellite images and airphotos. The main contributions towards a better understanding of west-central Mexico geology are the regional studies of Demant (1978, 1979,1981) and of Gastil *et al.* (1978, 1979). The works of Luhr and Carmichael (1980, 1981, 1982), Mahood (1980), Nelson (1980), Nelson and Carmichael (1984), Thorpe and Francis (1975) are devoted to single volcanic centres within the Tepic-Chapala or Colima Rifts. More recently the papers of Allan (1984, 1985, 1986), based on field studies, broadened the knowledge of the northern Colima Rift and of the Zacoalco Graben, a fault basin that links the

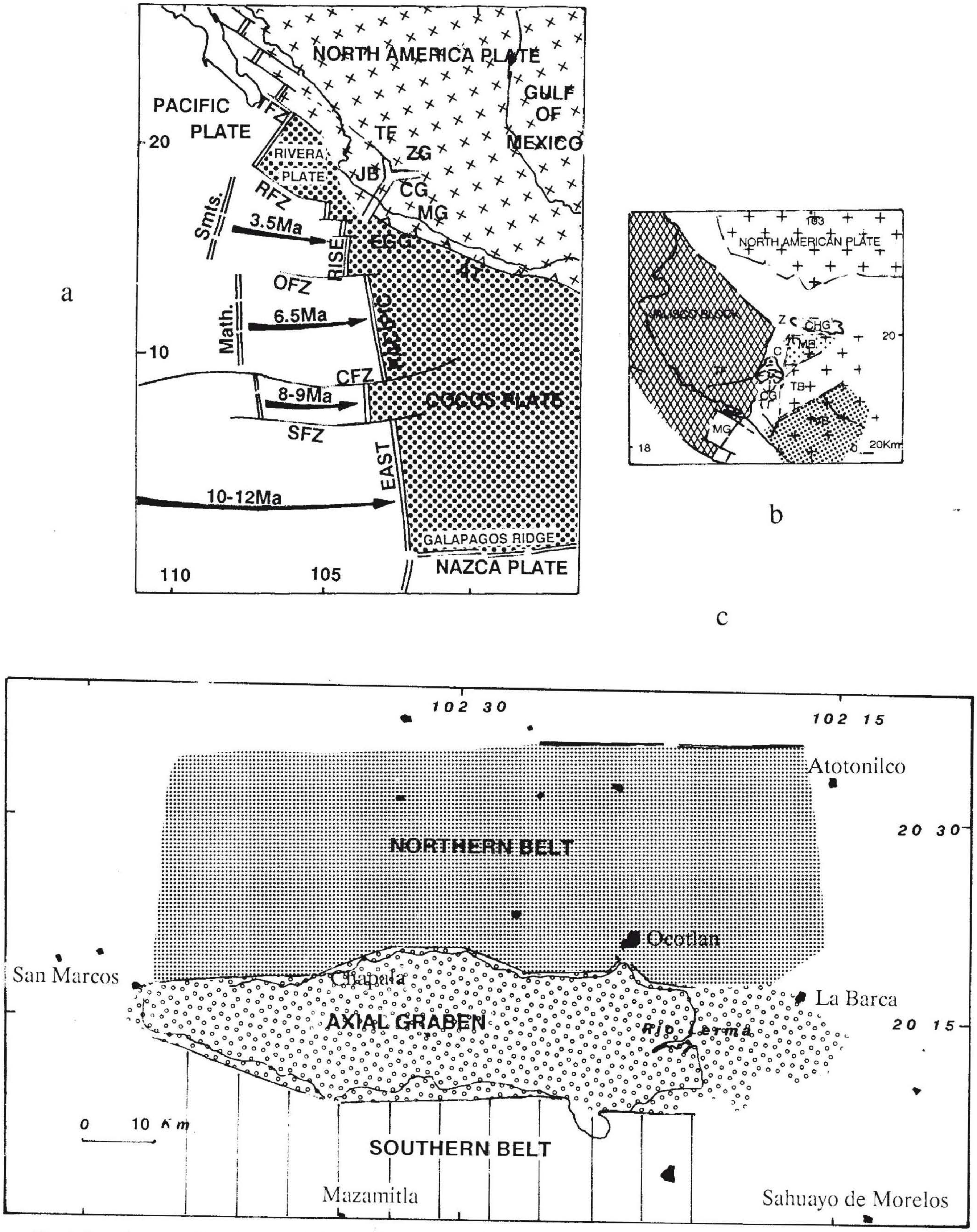

Fig. 1. Locality map of study area. a) Tectonic sketch of the East Pacific Ocean (modified from Bourgois and Michaud, 1991). b) Tectonic map of the triple junction (Garduño and Tibaldi, 1991). c) Morpho-structural map of study area.

Colima Rift with the Tepic-Chapala Rift. We also note the contribution of Nieto-Obregon *et al.*, (1985) whose study is fundamental to the understanding of the stratigraphy and tectonics of the Tepic-Chapala Rift.

Few geologists have focused their attention on the Chapala Rift. As a result, precise field data concerning the Chapala Rift is lacking. Geological knowledge of this branch of the Jalisco Triple Junction started with the outline of Diaz and Mooser (1972) who recognized a faulted anticline in the rift's structure. More recently Delgado-Granados and Urrutia-Fucugauchi (1986) published a note on the area, without providing convincing field evidence for their conclusions. The recent paper by Rosas-Elguera *et al.*, (1989), although not concerning the entire rift, contains some valuable data. The regional syntheses of Allan *et al.*, (1987) and of Barrier *et al.*, (1989) are also marginally concerned with the Chapala Rift. The aim of our paper is to establish the geological evolution of this region based on stratigraphic and structural data collected in the field.

We define the Chapala Rift as a belt-shaped region affected by distensive deformation along N90°E trending faults, stretching from 102° 20' W to 103° 30' W and limited by 20° N and 20° 40' N. Its length is about 120 km, its width about 60 km. We separate the rift into three main parts, each part being morphologically and structurally distinct (Figure 1):

1) Axial Graben: this contains the shallow Lake Chapala, at an elevation of 1510 m a.s.l. The Axial Graben is located slightly south of the median axis of the rift.

2) Northern Belt: here the rift's deformation is strong and widespread, creating a series of minor graben and half-graben basins between the northern side of the Axial Graben and 20°35' lat. N.

3) Southern Belt: its most distinctive morpho-structural element is a broad plateau, intensively deformed only on its northern margin, where it is truncated by the bounding faults of the Axial Graben. Many coalescent Pliocene volcanoes are recognizable on the plateau.

At the south-western margin of Chapala Rift, the Citala Graben opens. It is a small, deep fault basin structurally controlled by N90°E trending normal faults. The bottom of this depression is covered with a thick series of sediments which conceals its true geometry. The floor of the graben is at the same altitude as the floor of the northernmost segment of the Colima Rift (Northern Colima Graben, Allan 1985), almost 150 m below the level of Lake Chapala.

AIRPHOTOS AND SATELLITE IMAGES INTERPRETATION

From interpretation of airphotos at a scale of 1:50,000 and of LANDSTAT (band 7) images, we may point out the presence of four sets of lineaments in the Chapala Rift area:

1) E-W system. Chapala Rift is controlled by N90° E trending fractures that condition the region's morphostructure; their abundance and importance is easily seen on the topographic maps of CETENAL (Centro de Estudios del Territorio Nacional) (scale 1:50.000), as they create high linear scarps of great lateral continuity. The M.V.B. volcanoes are often aligned with these lineaments. The western boundary of this system is extremely sharp, as it is truncated by the N140°E/N180°E trending lineaments controlling the southern part of the Zacoalco Graben and the Northern Colima Graben (Figure 1). To the east the E-W system can easily be followed as far as 102° 25' W. Here the alluvial plain of Rio Lerma (Ciénaga de Chapala) tends to hide its morphological expression. Near Ixtlán de los Hervores, N110°E trending faults apparently cutting the N90°E lineaments of the rift have been reported (Rosas-Elguera *et al.*, 1989). Between Tototlán and Atotonilco N50°E trending minor fractures are linked to (and intersect) important E-W directed lineaments (Figure 1).

2) N-S / NNW-SSE system. Lineaments of this trend were recognized only in the south-western quadrant of the rift. They are genetically related to the structurally dominating systems of the Northern Colima Graben and of the southern part of the Zacoalco Graben, the southeasternmost fault basin of the Tepic-Chapala Rift. East of Zacoalco village, faults of this system clearly truncate older N90°E trending lineaments of the Chapala Rift (Figure 1).

3) NW-SE system. Lineaments of this trend are present only in the north-western margin of the rift (Figure 1). These are the cause of the downfaulting of the Zapotitán de Hidalgo-San Marcos area. We consider them as the southernmost expressions of the deformation system prevailing in the Tepic-Chapala Rift.

4) WNW-ESE system. Lineaments of this system affect only slightly the south-eastern margin of the rift (Figure 1). WNW-ESE trending lineaments represent the westernmost expressions of a system already recognized in the contiguous central part of M.V.B. by Pasquaré *et al.*, (1987,1988). Therefore this system, unlike the others, is not directly linked with the Neogene tectonics of Jalisco Triple Junction.

STRATIGRAPHY

The region of the Chapala Rift is shown in its entirety on the sheet F13-12 "Guadalajara" of the Mexican geological map, edited in 1988 by the Instituto Nacional de Estadística, Geografía e Informática. In this document an outcrop of a Cretaceous limestone is reported near the village of Sahuayo (La Calera). This would constitute the ancient marine basement of the rift's stratigraphic column. However, accurate geological mapping of Chapala Rift suggests that all the rocks outcropping inside the rift are of Tertiary age, most of them Neogene volcanics. In fact the Chapala rocks are essentially andesitic and basaltic lavas, forming extended sheets of smaller flows related to preserved central volcanoes (Figures 2 and 3).

The oldest unit is well exposed along the road from Chapala to Jocotepec and forms the block of Sierra el Travesaño-Sierra las Vigas, as well as the coastal horst of C. Grande, C. San Miguel, next to Chapala village (Figure 3). It is a heterogeneous breccia made up of decimetric to metric lava blocks ranging from andesite to dacite. In some outcrops the single blocks are embedded in a muddy to sandy matrix; elsewhere they are in close contact and the rock is strongly consolidated. These "Chapala breccias" are usually severely tectonized and deeply altered by hydrothermal processes, so that it becomes difficult to define the original volcanic facies tof the rock. No attempt at dating this unit is reported in the literature.

An erosional unconformity separates the "Chapala breccias" from a succession of andesitic to basaltic tabular lava flows up to 10 m thick (Figure 2 and 3). They form a broad plateau, of not less than 300 m in thickness, which was the dominant morphological feature of the rift before its dislocation into rotated blocks by the action of N90°E trending faults. The deformation is particularly strong between the southern wall of the Axial Graben and the aligment Atotonilco-Tototlán (Figure 4). Outside this belt the plateau is only weakly affected by faulting and its form is largely conserved. Attempts at dating the plateau lavas in the region of Arandas-Atotonilco yield ages of 10\12 m.y. (Verma *et al.*, 1985) and of 8.8 m.y. in the surroundings of Villa Chavinda (Rosas-Elguera *et al.*, 1989). This sequence was named "Intermediate Volcanic Sequence" (I. V. S.) by Pasquaré and Zanchi (1985) and Pasquaré *et al.*, (1988).

The petrographic analysis of I.V.S. lavas revealed predominant intersertal microlithic fabrics, but flow and doleritic fabrics are also present. The plagioclase (Labradoreite-Oligoclase) is more sodic towards the top of the sequence. Olivine is the most abundant mafic mineral. It is present in phenocrysts as well as in the groundmass. Also clinopyroxene (augite) and orthopyroxene are observed. From this preliminary modal analysis, I.V.S. lavas are defined as basalts in the bottom part of the sequence, grading into a series of andesites upwards.

Intercalations of fluvial and lacustrine facies rocks are frequently observed between lava flows (Figure 2). They are arranged into small bodies of lenticular shape. Their

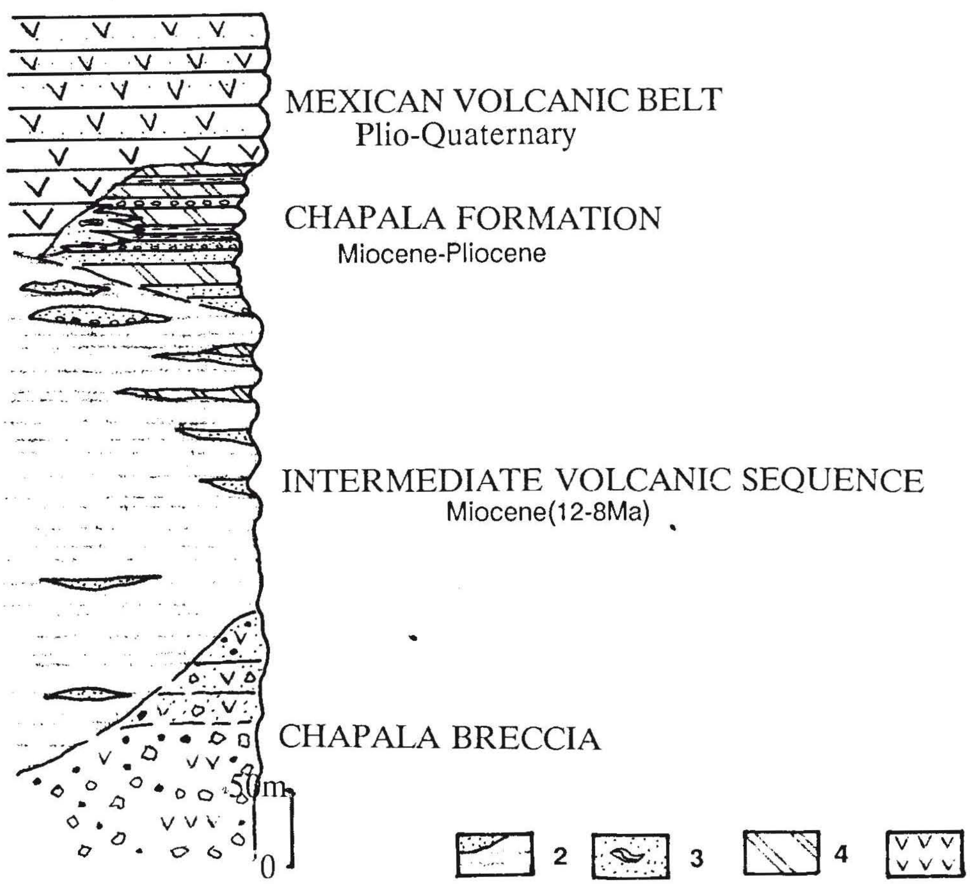

Fig. 2 Schematic stratigraphic column of the Chapala Rift: 1)Heterogeneous "Chapala breccias" (Palaeogene?). 2) Late Miocene volcanics of the "Intermediate Volcanic Sequence". 3) Lacustrine sediments of the "Chapala Formation" (Late Miocene-Pliocene) 4) Pliocene-volcanics. 5) Quaternary volcanics.

stratification served as a geometric reference which allows us to identify angular unconformities of up to 5/10 inside the I.V.S. succession (*e.g.* Tarengo Massif, near La Barca). In the upper part of the sequence lacustrine. diatomitic facies tend to dominate, as shown by the well-exposed outcrops in the half-graben structure of Potrerillos, north of Jocotepec (Figure 3).

In the region of Tototlán-Zapotlanejo on top of the Late Miocene sequence the ignimbrite mentioned by Demant (1981) and Gilbert *et al.*, (1985) is observed. Best outcrops are found along the C.F. 80 main road, between Puente Grande and Zapotlanejo (La Providencia), near the village of Tecomatlán, north-west and west of Tototlán (Potrero de Gomez), and east of Santa Fe village, under the lavas of the C. Grande, a Pliocene stratovolcano (Figure 3). The most obvious feature of this unit is the presence of fiamme of dark glass ranging up to about 10 centimeters; these are particularly well developed in the outcrops near Tecomatlán. This unit represents the only significant variation from the dominantly basic and effusive volcanic activity observed in the rift.

Locally the I.V.S. lavas are unconformably covered by sedimentary lacustrine and deltaic deposits, including diatomitic and terrigenous facies, which have a grainsize ranging from clay to fine-grained conglomerate (Figure 2). Diatomic samples from the Villa Chavinda area have been dated as Mid Pliocene in age (Rosas-Elguera *et al.*, 1989). The notes to the Mexican geological map attribute samples collected near Jocotepec to the Late Miocene. The outcrops of this unit are confined within the Axial Graben and the adjacent tectonic depressions. In the fault basin north of Chapala village the sediments attain their maximum thickness of about 100 m (Figure 2). Dip angles of up to 40° were measured on strata of varying strike, as an effect of strong rotation on listric N-E trending normal faults.

In this same area, near Sta. Cruz dam, the contact between the sediments and the overlying lavas of C. Chihué, a volcano of the M.V.B. cycle, is well exposed. Following Pasquaré *et al.*, (1986,1987) we consider the M.V.B. volcanic cycle as Pliocene and Quaternary. The products of M.V.B. centres are essentially lava flows and scoriae of basaltic to andesitic composition, connected with recognizable volcanic centres. Their morphology and composition suggest a monotonous, essentially effusive activity of Hawaiian-Strombolian type.

The petrographic analysis of Pliocene lavas shows them to be dominated by microlithic intersertal as well as flow or pyroclastic fabrics. Commonly the fabric is porphyritic with a vitreous groundmass. Plagioclase is calcic and is abundant in the groundmass as well as among phenocrysts. Olivine is the prevailing mafic phenocryst, but augite is also present. On the whole, the modal composition allows the definition of M.V.B. lavas as andesitic basalts.

The M.V.B. sequence in the region of Chapala Rift is a sheet of irregular thickness overlying the Late Miocene plateaux. This sheet is continuous only in the Axial and Southern Belt of the rift. On the northern highlands of the Atotonilco-Tepatitlán region, Pliocene centres are more widely spaced, giving the volcanic cover an episodic aspect (Figure 3).

Pliocene volcanoes are dissected by N90°E trending faults of the Chapala Rift which also tend to control their alignment (Figure 4), so that they often form elongated Sierras (*e.g.* Sierra de Poncitlán, Sierra de Pajacuarán). In contrast, those identified as Quaternary according to the rare age determinations (Rosas-Elguera *et al.*, 1989) and by the state of conservation of primary volcanic morphology (Kieffer, 1971), are nearly undeformed. However, east of Sahuayo, some Quaternary monogenetic scoria cones of less than 2 km^3 are slightly affected by N110°E trending faults also controlling their alignment (Figure 4).

STRUCTURAL DATA

The N90°E trending faults of the Chapala Rift have essentially accomodated normal dip-slip movements. This led to the present structure of the region of the rift, which features downfaulted and tilted blocks descending like steps towards Lake Chapala (Figure 4). In the Northern Belt, next to the Axial Graben, half-grabens created by the northwards tilting of the lowered blocks are recognized (*e.g.* half-graben of Potrerillos) (Figure 5). Towards the Atotonilco -Tototlán latitude the tilting decreases and finally stops north of Atotonilco (about 25 km from the northern lake shore), where the landscape is dominated by wide mesas. In contrast, within the Southern Belt this conformation is reached already 5 to 8 km from the southern lake shore (Figure 5). Thus, with respect to the median axis of the Axial Graben, the extensional system of the Chapala Rift is strongly asymmetric.

In order to understand the displacement for each system and to calculate the stress tensors (Reches, 1987), a microtectonic analysis of 89 fault surfaces was conducted in 11 structural stations. The results are summarized in Figure 4.

1) E-W system. We obtained data for surfaces of this trend in structural stations in different positions inside the rift. A gradual variation of the fault mechanisms is evident. On both sides of the Axial Graben (stereograms 5 and 11, Figure 4) the striae pitch angles range from 70° to 90°, which indicate normal dip-slip displacements with a very small component of left-lateral strike-slip. In the Northern Belt of the rift (stereograms 7,4 and 3, Figure 4) left-lateral strike-slip movements dominate over normal dip-slip displacements; striae pitch angles in the range 0°/20° are common. In stations 4 and 3 (Figure 4) fault surfaces bearing striations belonging to both sets were observed: the high pitch angle striae are always better conserved and superimposed on the others. The microtectonic data collected in each of the structural station were used to calculate the corresponding stress tensors. For the first phaseof deformation, featuring left-lateral movement, the resulting tensor has subhorizontal

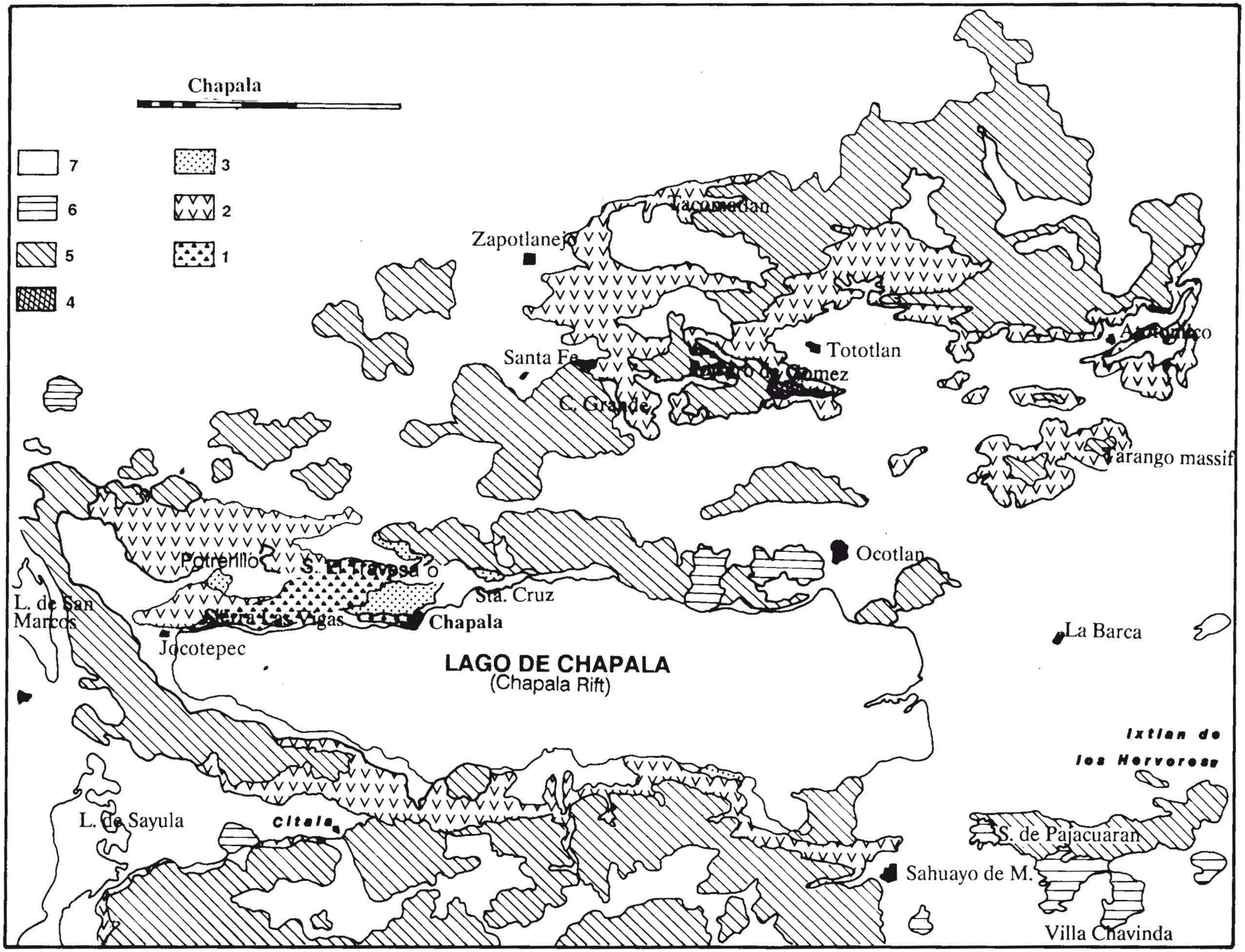

Fig. 3. Geological sketch map of the Chapala Rift: 1) Heterogeneous "Chapala breccias" (Palaeogene?). 2) Late Miocene volcanics of the "Intermediate Volcanic Sequence". 3) Lacustrine sediments of the "Chapala Formation" (Late Miocene-Pliocene). 4) Zapotlanejo Ignimbrite. 5) Pliocene volcanics. 6) Quaternary volcanics. 7) Undifferentiated superficial deposits-lacustrine areas.

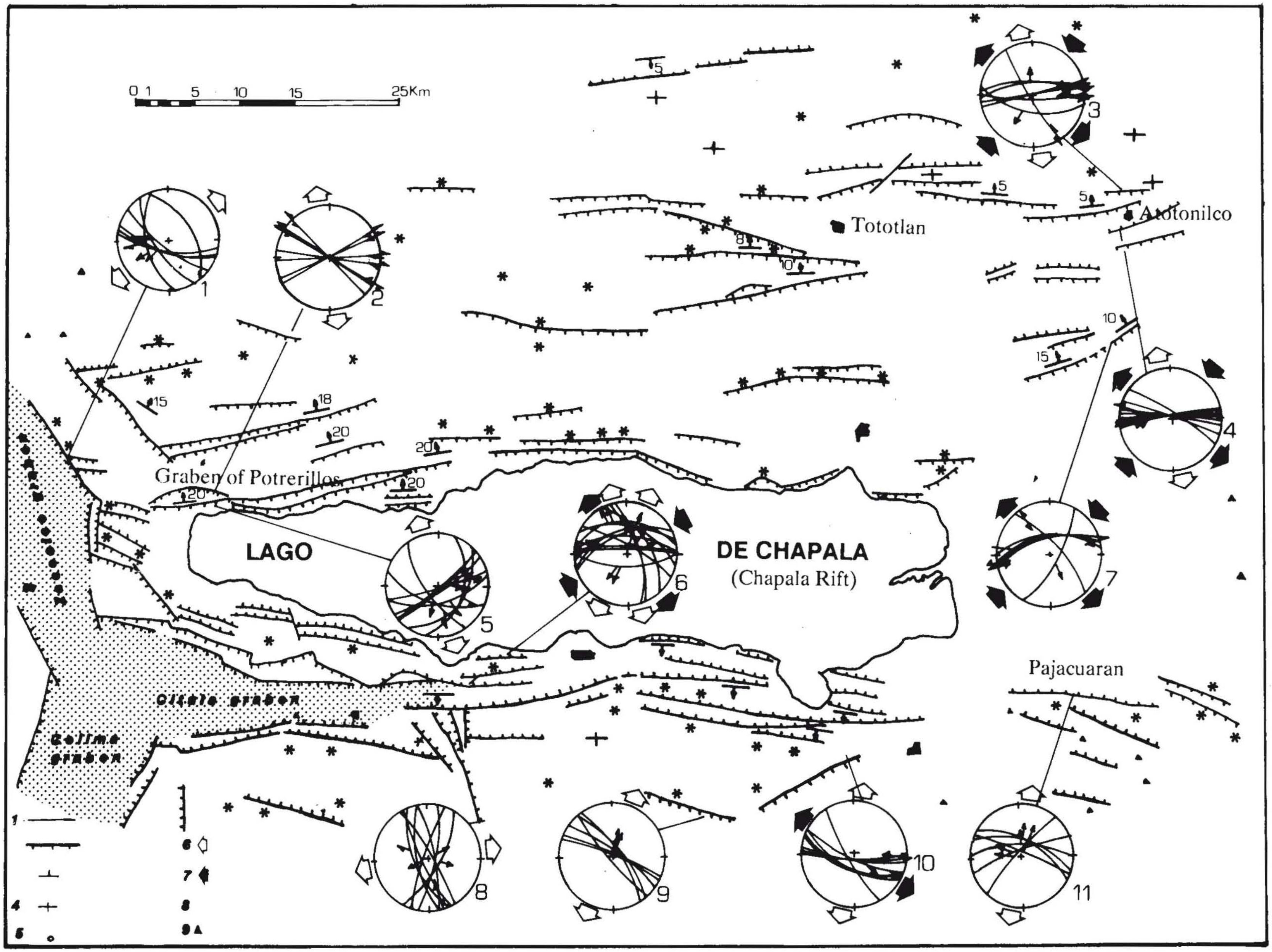

Fig. 4. Structural map of the Chapala Rift: 1) Fracture lineament. 2) Normal fault: bars are on the down-dropped block. 3) Tilted block: arrow is parallel to the dip, figure expresses dip-angle. 4) Sub-horizontal block. 5) Structural stations. 6) Orientation of σ3. 7) Orientation of σ1 and σ3; where lacking it must be considered sub-vertical. 8) Pliocene volcanic centres. 9) Quaternary major and minor volcanic centres. The little arrows on the stereographic traces of fault planes indicate the pitch of the striae and the mechanism of the fault.

N35°E trending σ1, sub-vertical σ2, and N125°E trending σ3. The second phase, featuring normal movements, shows sub-vertical σ1 and N170°E trending σ3 (Figure 4). The major N90°E trending rift faults show no evidence of recent activity, with the exception of the Pajacuarán Fault which forms the southern boundary of the Axial Graben to the south-east. Detailed field study of the steep fault scarp cutting the Sierra de Pajacuarán shows that faulting affects the recent slope deposits.

2) NNW-SSE/N-S system. In station 6 and 8 (Figure 4) normal dip-slip movements with small left-lateral components are recognized on faults of this system. Pitch angles are between 70° and 90°. The faults displace the N90°E trending Chapala Rift surfaces and affect the recent superficial deposits. The calculated tensor has sub-vertical σ1, and sub-horizontal N70°E oriented σ3 (Figure 4).

3) NW-SE system. Microtectonic data about this system were collected in station 1 (Figure 4), on the San Marcos fault. This is normal dip-slip fault with a minor (but significant) right-lateral component, sharply truncating the N90°E trending lineaments of the Chapala Rift. Pitch angles range between 50° and 70°. The related tensor has sub-vertical σ1 and sub-horizontal N45°E oriented σ3 (Figure 4).

4) WNW-ESE system. Structural station 9, just north of Mazamitla (Figure 4), indicates that faults of this system have accomodated only normal dip-slip displacements. The stress tensor has sub-vertical σ1 and sub-horizontal N20°E oriented σ3 (Figure 4).

INTERPRETATION AND DISCUSSION

The name of the "Chapala breccias" remains a matter of debate because of the extreme variability of its lithological, structural and textural characteristics, wich are often obliterated by pervasive jointing and alteration in most outcrops. Most probably the "Chapala breccias" belong to the Sierra Madre Occidental (S.M.O) volcanic cycle defined by Mc Dowell and Clabaugh (1979). Clark *et al.*, (1981) and Lemish (1955) described similar breccia facies of great thickness intercalated in the S.M.O. stratigraphic succession. If our correlation is correct, the "Chapala breccias" would be Palaeogene in age.

The geological evolution of the region can be outlined with precision only after Late Miocene times. In that period, volcanism of the "Intermediate Volcanic Sequence" was taking place in the region of the future Chapala Rift. This phase of activity led to the building of a thick extended basaltic and andesitic plateau. The S.M.O. volcanic cycle is Palaeogene to Early Miocene in age (Damon *et al.* 1979, Mc Dowell and Clabaugh, 1979, Nieto *et al.*, 1981), while age determinations of I.V.S. place the sequence in the Late Miocene (Rosas-Elguera *et al.*, 1989, Verma *et al.*, 1985). The unconformity recognized between Chapala breccias and I.V.S. lavas thus corresponds to a gap in the volcanic activity, of regional significance. It is clear that during this gap a profound geodynamic reorganization must take place, whose effect was the transition from the NW-SE directed S.M.O. to the E-W trending I.V.S and M.V.B.

Late Miocene volcanism has been recognized in several parts of west-central Mexico. Allan *et al.*, (1987) report that Late Miocene lavas are exposed on the fault scarps bounding the Northern Colima Graben, with thicknesses increasing to the north. Gastil *et al.*, (1978,1979) have recognized Late Miocene basalts in the Tepic-Chapala Rift, and Watkins *et al.*, (1971) recognized similar rocks outcropping just north of Guadalajara. The northern, E-W trending, boundary of this unit has been mapped by us north and north-east of Guadalajara where (at about 21° lat. N) the "Intermediate Volcanic Sequence" overlaps the Palaeogene units of the Sierra Madre Occidental. The "Intermediate Volcanic Sequence" at the scale of the whole of Mexico, forms an E-W belt which can be considered as the Late Miocene equivalent of the Pliocene and Quaternary M.V.B. The geometry and the extension of Late Miocene plateaux have led Demant (1981) to propose a mechanism of fissure eruption for their emplacement.

The geological meaning of the Zapotlanejo ignimbrite, observed on top of the I.V.S., is still unclear. On the one hand its stratigraphic position and its petrographic facies suggest a strong linkage with the Pliocene ignimbritic activity in the Guadalajara region (Gilbert *et al.*, 1985). On the other hand the only available age determination of 7.73 m.y. (Gilbert *et al.*, 1985), would place it in the final phases of the Late Miocene volcanic cycle.

In the study area it was not possible to define deformation trends older than the Chapala Rift system based on the N90°E trending faults. Thus Miocene volcanic activity cannot be placed in a detailed structural context. The increasing abundance towards the top of the "Intermediate Volcanic Sequence" of lacustrine sedimentary intercalations, and the observed angular unconformities inside the sequence, suggest that the downfaulting connected with the rift's extension had already begun by the end of the Late Miocene. This is corroborated by the few available age determinations for the oldest lacustrine sediments of the Axial Graben.

Structural data prove that the early development of Chapala Rift featured left-lateral movements along N90° faults. The N50°E trending kilometric fracture lineaments of the Tototlán-Atotonilco region, associated with major E-W faults (Figure 4), can therefore be considered as synthetic "Riedel" shears formed during this early phase of rifting. Striae from left-lateral displacements are preserved on the fault surfaces active at the beginning of the rifting process and now situated at great lateral distance from the Axial Graben. It is only on such faults that the oldest low-pitch striae have not been fully obliterated by more recent high-pitch striae, that dominate on fault surfaces of the Axial Graben belt and its surroundings. The progressive migration of the distensive movements from a peripheral position towards the rift axis is consistent with current

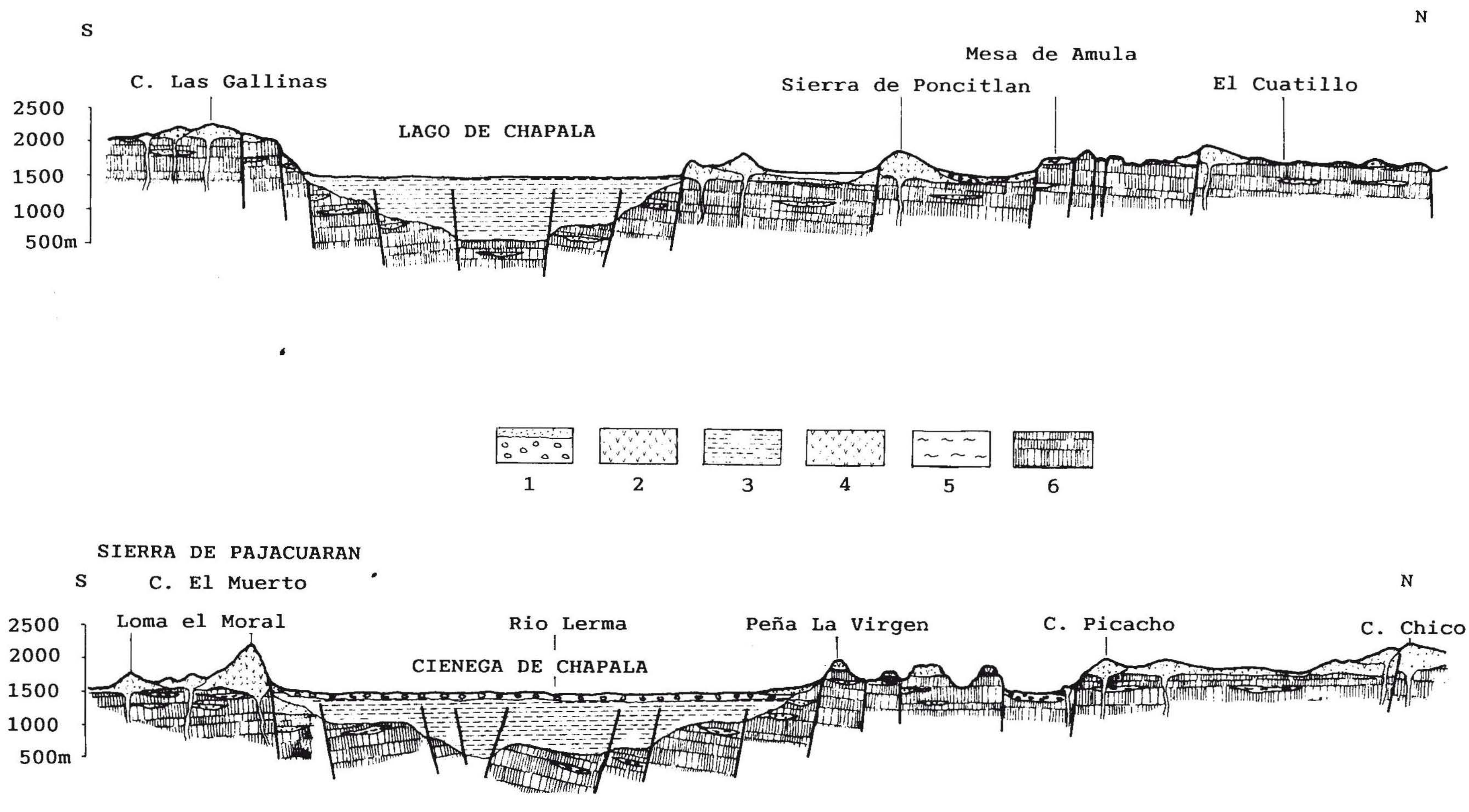

Fig. 5. Geological section across the Chapala Rift: 1) Lacustrine sediments and superficial deposits (Quaternary). 2) Basaltic-andesitic lavas, scoriae and volcanic breccias (Late to Mid Pliocene). 3) Lacustrine sediments, including silt, diatomite, clay and fine-grained conglomerates (Late Miocene-Pliocene). 4) Basaltic and andesitic lavas with sedimentary intercalations (Late Miocene). 5) Zapotlanejo ignimbrite. 6) Pliocene and Miocene volcanics rocks.

models for regions affected by brittle extension (Jackson and McKenzie, 1983).

The strong tilt of the downfaulted blocks is due to rotation. This implies that most Chapala faults have listric shape, and therefore extension occurs at relatively shallow depth (Jackson and Mc Kenzie, 1983). We may now reject, from solid evidence, those hypotheses (Diaz and Mooser, 1972) that postulated a large faulted anticline in the structure of the Chapala Rift. This kind of hypothesis is also in obvious contrast with experimental results and theoretical models for the rheology of rocks at upper crustal levels.

The oldest M.V.B. volcanoes, rising unconformably over the Late Miocene plateau of the "Intermediate Volcanic Sequence", were referred to the Mid-Pliocene (Allan *et al.*, 1987, Rosas-Elguera *et al.*, 1989). Thus it is possible to identify a gap between I.V.S. and M.V.B. volcanic cycles, recognized and studied at the scale of the whole M.V.B. by Garduño-Monroy and Gutiérrez-Negrín (1992). The two Neogene volcanic cycles are also different with respect to the chemical composition of their products, which is subalkaline in the Miocene and alkaline in the Pliocene (Rosas-Elguera *et al.*, 1989).

During the gap in the volcanic activity, lacustrine sedimentation took place in young fault basins which were eventually to become the major tectonic depressions in the present Chapala Rift. In the course of rift evolution the progressive downfaulting usually had the effect of lowering these sediments, which are now covered by Pliocene and Quaternary sedimentary sequences in most of the Axial Graben. However, in some cases elongated marginal basins were separated from the main subsiding basin by the formation of structurally elevated blocks of the volcanic substratum. The suggested scheme of tectonic evolution can be recognized in the small marginal graben situated north of Chapala village, filled by lacustrine sediments (Figure 3 and 4). The mechanism explains the presence of Late Miocene/Early Pliocene lacustrine sediments well above the bottom of the rift's downfaulted basins. Delgado-Granados and Urrutia-Fucugauchi (1986) proposed a new "Chapala Formation" which would comprise the small and scattered outcrops of old lacustrine sediments. However, only approximatelly isochronous sediments would be referred to this Formation, since the strata outcropping around Lake Chapala have probably never been laterally continuous as they belong to different basins arrising at different times during the rifting process. The sediments of the proposed Formation represent only the lowest part of the sedimentary succession deposited from the end of Late Miocene to Present in the Axial Graben of the Chapala Rift.

During Pliocene times the Chapala Rift reaches its present structural configuration. From the Mid-Pliocene on volcanism accompanies deformation. Very few volcanoes of the Chapala Rift reach large dimensions (*e.g.* the C. Grande, a stratovolcano situated north of Chapala, formed by about 32 km^3 of lava and scoriae). The upwelling of lava is controlled by the Pliocene stress field characterized by an average N160°E to N20°E trending $\sigma3$. Consequently M.V.B. volcanic centres are aligned along an E-W trend.

In the Pleistocene, movements along N-E faults gradually come to an end, and the Chapala Rift begins to be passively deformed by the N-S/NNW-SSE, NW-SE and WNW-ESE fault systems, active throughout the Quaternary. In the same period the floors of the Northern Colima Graben and the Zacoalco Graben were lowered by more than 150 m with respect to Lake Chapala.

The recent activity of the Pajacuarán Fault is important in the south-eastern quadrant of the rift. Note that this fault is approximately aligned with the lineament that forms the southern boundary of the Citala Graben. The Citala Graben is younger than the Axial Graben of the Chapala Rift. This is suggested by the youthful morphology of the bounding fault-scarps, the presence of significant Plio-Quaternary volcanism on its sides and the relatively low altitude of its floor, nearly 150 metres below the level of Lake Chapala.

The end of major rifting is quickly followed by the end of volcanic activity, whose last manifestations can be divided into two geographically separated groups. The first group is situated near Villa Chavinda and west of Ocotlán (Figure 4) and is controlled by the WNW-ESE fault system. This eastern group of volcanoes may be the westernmost expression of the intensive Quaternary activity of the Tarascan Plateau, and is probably unrelated to the Pliocene volcanism of Chapala Rift. Most of these volcanoes are small monogenetic scoria cones, different from Pliocene centres both in morphology and size. The second group occupies the extreme north-western margin of the rift. Here the NW-SE fault system is clearly dominant over the older E-W Chapala Rift system, and controls the alignment of the volcanic centres (Figure 4) Reconnaissance mapping of this area revealed an abundance of Quaternary andesitic and dacitic domes. The structural setting of these centres and the type of activity suggests also that this group is not related with the Pliocene volcanism of Chapala Rift.

Sedimentation inside the Axial Graben continued throughout the Quaternary. The thickness of the present sedimentary fill of the basin is about 800 m (Rosas-Elguera *et al.*, 1989). If we add the elevation above Lake Chapala of the I.V.S. undeformed plateaux of the Atotonilco area (about 350 m), the total vertical offset of the Axial Graben would be about 1100/1300 m. It is interesting to compare these figures with the results of Allan (1985) on the adjacent Northern Colima Graben. He estimated the thickness of the sedimentary infill at about 900 m, but the total vertical offset of the bounding faults at up to 2500 m.

CONCLUSIONS

The Chapala Rift, active since the end of the Miocene, is now dead. It can be considered as an aulacogen of the

Neogene rift system of west-central Mexico, which is still active along the N-S (Colima Rift) and NNW-SSE (Tepic-Chapala Rift) branches (Allan *et al.*, 1987). Let us summarize the main evidence supporting this conclusion:

a) The proven inactivity of the N-E trending normal faults of the rift and the temporal relations between this system and the NW-SE, N-S/NNW-SSE and WNW-ESE systems.

b) The difference of elevation between Lake Chapala and the bottom of the adjacent fault basins, due to different vertical offsets which correspond to different degrees of stretching.

c) The absence of Quaternary to Present volcanism directly linked with the rift's E-W lineaments, comparable to the volcanism recognized in the Tepic-Chapala and Colima Rifts.

Tectonic activity along the Axial Graben has now ceased. However, note the probably still active structure of Citala Graben. Our data suggest that in the course of rifting, the E-W directed axis of distension migrated southwards leaving behind numerous graben and half-graben structures. From the end of the Pliocene, the E-W axis is probably located inside the Citala Graben. If these conclusions are correct, the Quaternary and Present triple junction of west-central Mexico is located at the intersection between Citala Graben and Northern Colima Graben.

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