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Late Cenozoic tectonics offshore western Mexico and its relation to the structure and volcanic activity in the western Trans-Mexican Volcanic Belt

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RESUMEN

La tasa de convergencia calculada indica que la tectónica del occidente de México ha sido tensional durante los últimos 3 Ma. Este estilo de deformación se ve reflejado en la formación de estructuras rift en la parte occidental de la Faja Volcánica Trans-Mexicana [FVTM]. Los valores obtenidos para la tasa de convergencia predicen que, a través del tiempo, se verifica una tectónica menos tensional (con tendencia a la neutralidad) en la parte sureste de la zona de interacción de las placas de Rivera y Norteamérica, mientras que en la parte noroccidental se vuelve más tensional. Por otra parte, un análisis cualitativo de las tasas de esparcimiento muestra que éstas fueron más rápidas antes de los 6.5 Ma de lo que fueron posteriormente. Después de analizar diferentes parámetros cinemáticos, se concluyó que la tasa de esparcimiento de la cresta del Pacífico Oriental en su sector Pacífico-Rivera, influye fuertemente sobre la tasa de convergencia. De esta manera se puede establecer una correlación positiva entre la evolución de la tasa de esparcimiento de la cresta Pacífico-Rivera y la geología continental. Esta correlación muestra que tasas de esparcimiento relativamente rápidas coinciden con la presencia de volcanismo monogenético calci-alcalíno en la parte occidental de la FVTM cuando menos desde hace 10 Ma y que este tipo de volcanismo continúa hasta nuestros días. Sin embargo, cuando la tasa de esparcimiento se ha hecho más lenta (y por tanto la tasa de convergencia se ha hecho menor) durante el período comprendido entre 6.5 Ma y 3.5 Ma, se ha verficado en la región una tectónica extensional ampliamente distribuída, volcanismo explosivo y sedimentación lacustre en los sistemas rift de Colima, Tepic-Zacoalco y de Chapala; y particularmente entre los 4.6 Ma y 3.9 Ma ha coincidido con volcanismo alcalino en los rift de Colima y Tepic-Zacoalco. Un leve incremento en la tasa de esparcimiento después de los 3.5 Ma coincide con el decremento de actividad volcánica (principalmente alcalína). Durante el período entre 1.7 Ma y 0.7 Ma, la tasa de esparcimiento disminuyó de nuevo coincidiendo con un fallamiento normal contínuo en las tres estructuras rift mencionadas y en parte, con otra etapa de volcanismo alcalino (entre 1.4 Ma y 0.2 Ma) en los rift de Colima y Tepic-Zacoalco. Después de los 0.7 Ma, la tasa de esparcimiento se ha incrementado levemente. Por otra parte, se observa una relación genética entre el contenido de elementos incompatibles en rocas volcánicas de la región con la tasa de convergencia, lo cual implica que tasas de subducción mayores aportan una mayor cantidad de sedimentos acrecionados a la cuña del manto. Esto explica las diferencias geoquímicas entre las rocas volcánicas a lo largo del frente volcánico de la parte occidental de la FVTM.

PALABRAS CLAVE: Cinemática de placas, tectónica, volcanismo, Faja Volcánica Trans-Mexicana, placa de Rivera, tasa de convergencia, tasa de esparcimiento.

ABSTRACT

The calculated convergence rate indicates that tectonics has been tensional in western Mexico for the last 3 m.y. This deformation style is expressed in the formation of rift structures in the western Trans-Mexican Volcanic Belt [TMVB]. The obtained values for the convergence rate predict less tensional tectonics (tending to be neutral) in the southeastern part of the interacting zone Rivera-North America, but more tensional in the northwestern part through time. On the other hand, a qualitative analysis of the spreading rates shows that they were systematically faster before 6.5 Ma than after. Subsequently, after testing different kinematic parameters, it was concluded that spreading rate of the Pacific-Rivera rise strongly influences the convergence rate. Therefore, a positive correlation between the evolution of spreading rate of the Pacific-Rivera rise and geology onland can be made. This correlation shows that relatively fast spreading rate coincides with monogenetic calc-alkaline volcanism in the western TMVB at least since 10 m.y. ago. Nevertheless, this kind of volcanism has continued up to the present. The spreading rate became much slower (and therefore convergence rate became slower) during the period 6.5 Ma~3.5 Ma, coinciding with widespread extensional tectonics, explosive volcanism and lacustrine sedimentation in the Colima, Tepic-Zacoalco and Chapala rifts, and between 4.6 Ma and 3.9 Ma with alkaline volcanism in the Colima and Tepic-Zacoalco rifts. A slight increase in the spreading rate after 3.5 Ma coincides with a decrease in volcanic activity (mainly alkaline). During 1.7 Ma~0.7 Ma, the spreading rate slowed down again coinciding with continuous normal faulting in the Colima, Tepic-Zacoalco and Chapala rifts, and in part with another period of alkaline volcanism (1.4 Ma~0.2 Ma) in the Colima and Tepic-Zacoalco rifts. After 0.7 Ma, the spreading rate became slightly faster. A genetic relationship of the content of incompatible elements in volcanic rocks of the region to convergence rate was found, implying that higher subduction rate supplies more accreted sediments in the mantle wedge. This is used to explain geochemical differences among volcanic rocks along the volcanic front of the western TMVB.

KEY WORDS: Plate kinematics, tectonics, volcanism, Trans-Mexican Volcanic Belt, Rivera plate, convergence rate, spreading rate.

INTRODUCTION

The Colima volcano is located in the western portion of the Trans-Mexican Volcanic Belt [TMVB]. The E~W trending TMVB is a volcanic arc of more than 1000 km in length and 20~150 km in width (Figure 1), related to subduction of Rivera and Cocos plates beneath North America (Molnar and Sykes, 1969; Suárez and Singh, 1986). However, the origin of the volcanism and the structure of the TMVB are not completely understood. Its evolution has been related to a geosuture or ancient zone of crustal weakness (Mooser, 1969, 1972; Cebull and Shurbet, 1987), an extension of the Gulf of California (Mooser *et al.*, 1974), a reactivated paleoshear (Le Pichon and Fox, 1971), a zone of strike slip displacement (Gastil and Jensky, 1973), lateral shear or crustal transtension (Shurbet and Cebull, 1984; Urrutia-Fucugauchi, 1984; Urrutia-Fucugauchi and Böhnel, 1988; Ferrari *et al.*, 1990) or transtension related with sliver tectonics (De Mets and Stein, 1990). Nevertheless, correlation between offshore tectonics and stratigraphy and structure on land is needed in order to elucidate their relationship.

The western portion of the TMVB is characterized by a sudden change of the E~W trend of the belt to the northwest and south-southwest. The Tepic-Zacoalco, Colima and Chapala graben structures (rift structures according to Allan *et al.*, 1991) are the most important features of the region (Figure 2). These tensional structures have been related with a rifting process, and the associated alkaline and peralkaline volcanic rocks, are believed to be consequence of rifting (Luhr *et al.*, 1985, Allan, 1986, Allan *et al.*, 1991). Thus, more structural and stratigraphic studies are critical. This rifting process is assumed to be contemporary with subduction of the western margin of Mexico (Luhr and Carmichael, 1985) and the relationship between both processes is still discussed (Verma and Nelson, 1989; De Mets and Stein, 1990).

The original purpose of this paper was to review the tectonic setting of the Colima volcano. Nevertheless, the current tectonics of the region is a result of a long evolution of the structural elements of western Mexico, and thus a historical evaluation since late Miocene was considered essential. The author chose a wider view of the tectonic setting of Colima volcano for three reasons. First, there is no accurate correlation for the last 10 m.y. between the tectonics offshore western Mexico and the tectonics and volcanism onland. Second, new data from the Pacific-Rivera rise and the Rivera plate motion is available (De Mets and Stein, 1990). Third, the recently developed laws of convergence among plates (Otsuki, 1989) provide a useful way to evaluate the current style of deformation using the new plate-motion data.

In this work, the plate tectonic setting of the region and the evolution of Rivera plate are reviewed. Next, the kinematic parameters of the plate's motion are evaluated and their influence on the deformation style is tested in order to establish a correlation among the variation of the kinematic parameters and the geologic events on land since late Miocene.

PLATE TECTONIC SETTING

The plate tectonic environment offshore western Mexico is represented by the presence of the Rivera plate [R], Cocos plate [C] and Pacific plate [P] interacting with North America [NA] (Figure 2). R was proposed by Atwater (1970) as an independent plate from P, moving relative to NA at a rate of 6 cm/yr not entirely coupled to it yet, but in process of being coupled. Molnar and Sykes (1969) determined that C is moving northeastward relative to NA, at a rate of 3.2 cm/yr (according to seismicity), 1.5~3.5 cm/yr (according to length of the seismic zone) or 4~9 cm/yr (according to rotation about the Euler pole. These authors explain that movement along the Middle America Trench [MAT] is faster in the eastern part of C than in the western part.

The plate boundaries in the vicinity of the western TMVB are not well known. The boundary between R and NA is along the northwestern sector of the Middle America Trench: the Barra de Navidad trench-segment [BNT] (Figure 2), an active subduction zone that represents a seismic hazard (Singh *et al.*, 1985; Kanamori, 1987). Two triple junctions are recognized. The first is in the northern part of R where it joins P and NA through the Tamayo fracture zone, which is also connected with the P-R rise. The second is in the southern part of R, in the junction with P and C. The definition of this triple junction is uncertain, especially near 18.5°N, 105.7°W, where the eastern extension of the Rivera Fracture Zone [RFZ] connects the three plates (Bandy *et al.*, 1988; Eissler and Mc Nally, 1984). The RFZ offsets the southern P-R rise and northern P-C rise. East of 107.5°W there are two parallel transform valleys (Bourgois *et al.*, 1988a). The northern valley is considered inactive by Bourgois *et al.* but several earthquakes larger than M = 5.0 appear to be located there (Eissler and McNally, 1984), thus, some slip motions may occur along those faults. In the southern valley, strike slip motion occurs possibly along multiple fault traces (Bourgois *et al.*, 1988a). In the region where the southern valley is intersected by a north trending rise segment (east of 18.5°N, 106.25°W), P-R strike-slip motion may cease. The trends of the transform valleys and the slip directions of strike-slip earthquakes west of 107.5°W are dominantly N 50°~60° W (De Mets and Stein, 1990). Eissler and McNally (1984) suggest that the R-C boundary may be a left lateral, northeast trending boundary connecting the RFZ to the MAT. On the other hand, Bandy *et al.* (1988) suggest that the northern end of P-C rise may be connected to the MAT through one or more E-W dextral strike slip faults. Bourgois *et al.* (1988b) found two graben structures near the P-R-C triple junction within soon to-be-subducted lithosphere and related them to extension along Colima rift and Manzanillo trough east of the BNT.

EVOLUTION OF RIVERA PLATE

R and C are the final products of the evolution of ancestral Farallon plate (McKenzie and Morgan, 1969) and Guadalupe plate [G] (Menard, 1978). Before 12.5 Ma the plate tectonic framework offshore west Mexico was dominated by the presence of G with subduction to the east

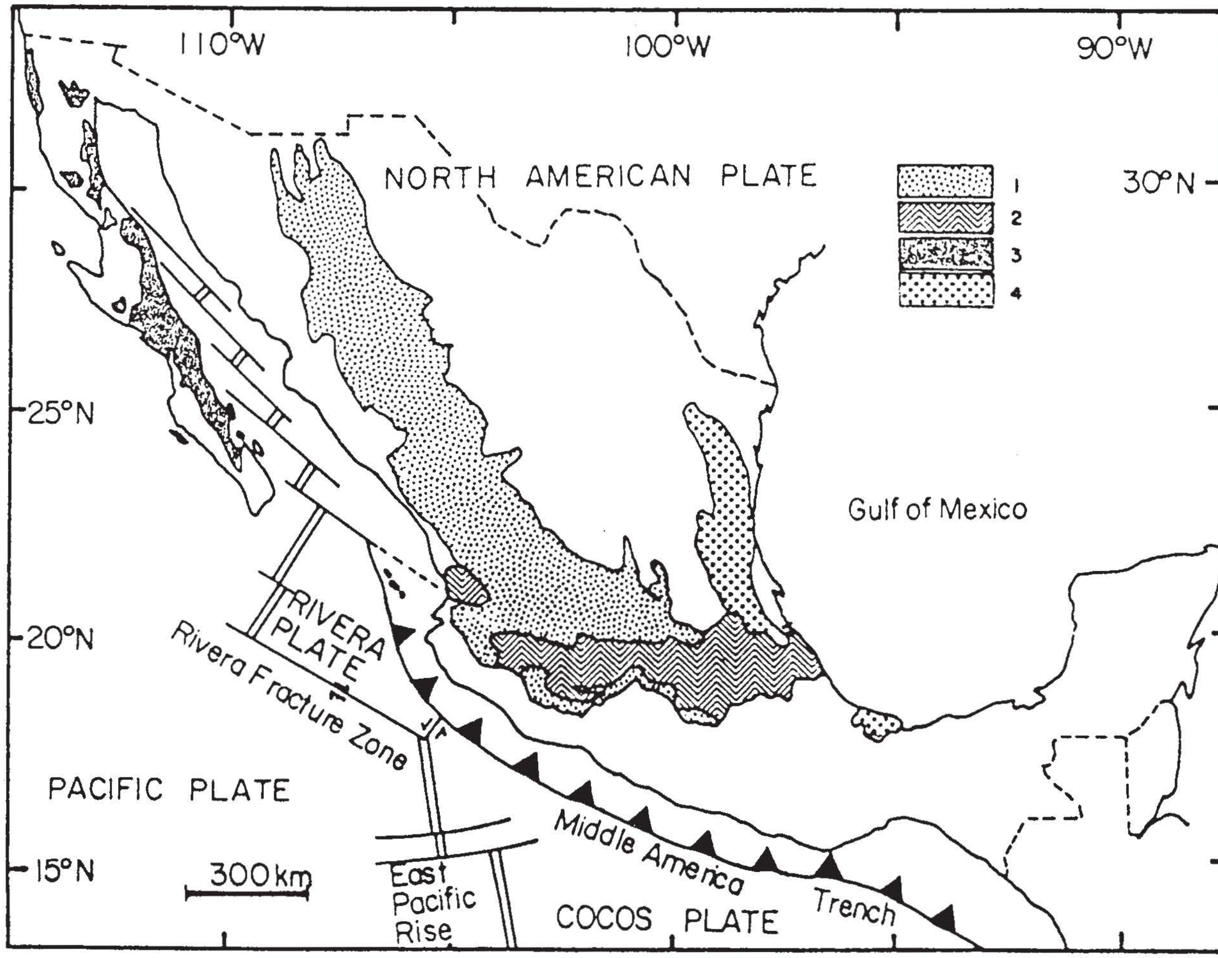

Fig. 1. Main volcanic provinces of Mexico: 1) Sierra Madre Occidental; 2) Trans-Mexican Volcanic Belt; 3) Baja Californian Province; 4) Eastern Alkaline Province. Tectonic outline from Drummond (1981).

(Atwater, 1970). According to Mammerickx and Klitgord (1982), at 12.5 Ma the spreading center G-P died out along the entire segment of Baja California (Figure 3A and 3B). South of Baja California, the spreading centers were still active and after 12.5 Ma rotated clockwise rapidly. Then a new spreading center substituted the G-P ridge (ancestral East Pacific Rise [EPR]) and C and R were originated between 12.5-11 Ma (Figure 3B). The ridge segment south of the Siqueiros fracture zone migrated to the east between 12-10 Ma (Van Andel *et al.*, 1975). The Clipperton ridge was abandoned between 9-8 Ma as spreading began far to the east. Between 11 and 6.5 Ma there were twin spreading centers south of Orozco fracture zone, defining an ephemeral microplate (Figure 3B). At 6.5 Ma the segment of the Mathematicians ridge was abandoned south of the Orozco fracture zone (Figure 3C). After 6.5 Ma, the EPR is the only spreading center between C and P, whereas the P-R boundary is still at the Mathematicians ridge. Then, a new microplate was created between the RFZ and the Orozco fracture zone due to a propagating rift from the Mathematicians ridge to the east (EPR). That microplate died at about 3.5 Ma (Figure 3D) when the Mathematicians ridge was abandoned (Mammerickx, 1984) and the boundary of R was shortened (located between the RFZ in the south and the Tamayo fracture zone in the north). By this time, the Gulf of California was opened (Mammerickx and Klitgord, 1982). Even though Mammerickx (1984) considered that Mathematicians ridge was completely abandoned 3.5 m.y. ago, current volcanic activity at San Benedicto Island (Bárcena volcano) and Socorro Island (Everman volcano) evidences that this last jump has not been completed (Carballido, 1991).

Figure 4 represents the distance from the EPR between R and C to magnetic anomalies mapped by Mammerickx and Klitgord (1982), giving an indirect estimate of the spreading rate of EPR since early the Late Miocene (about 10 m.y. ago). Relatively slow spreading occurred before 8 Ma. Two spreading rate increases are observed between 8 Ma and 6.5 Ma, and after 6.5 Ma the rate again became slower. After 3.5 Ma, the spreading rate became faster and between 1.7 Ma and 0.7 Ma, slowed down slightly again. It is important to note that the spreading rates are systematically faster before 6.5 Ma (Figure 4).

Several authors have suggested a very low subduction rate of R relative to NA along BNT (Ross and Shor, 1965; Moore and Buffington, 1968; Nixon, 1982). Furthermore, others have considered R accreted to NA (i.e. Larson, 1972). Nevertheless, seismic activity in the margins of Co-

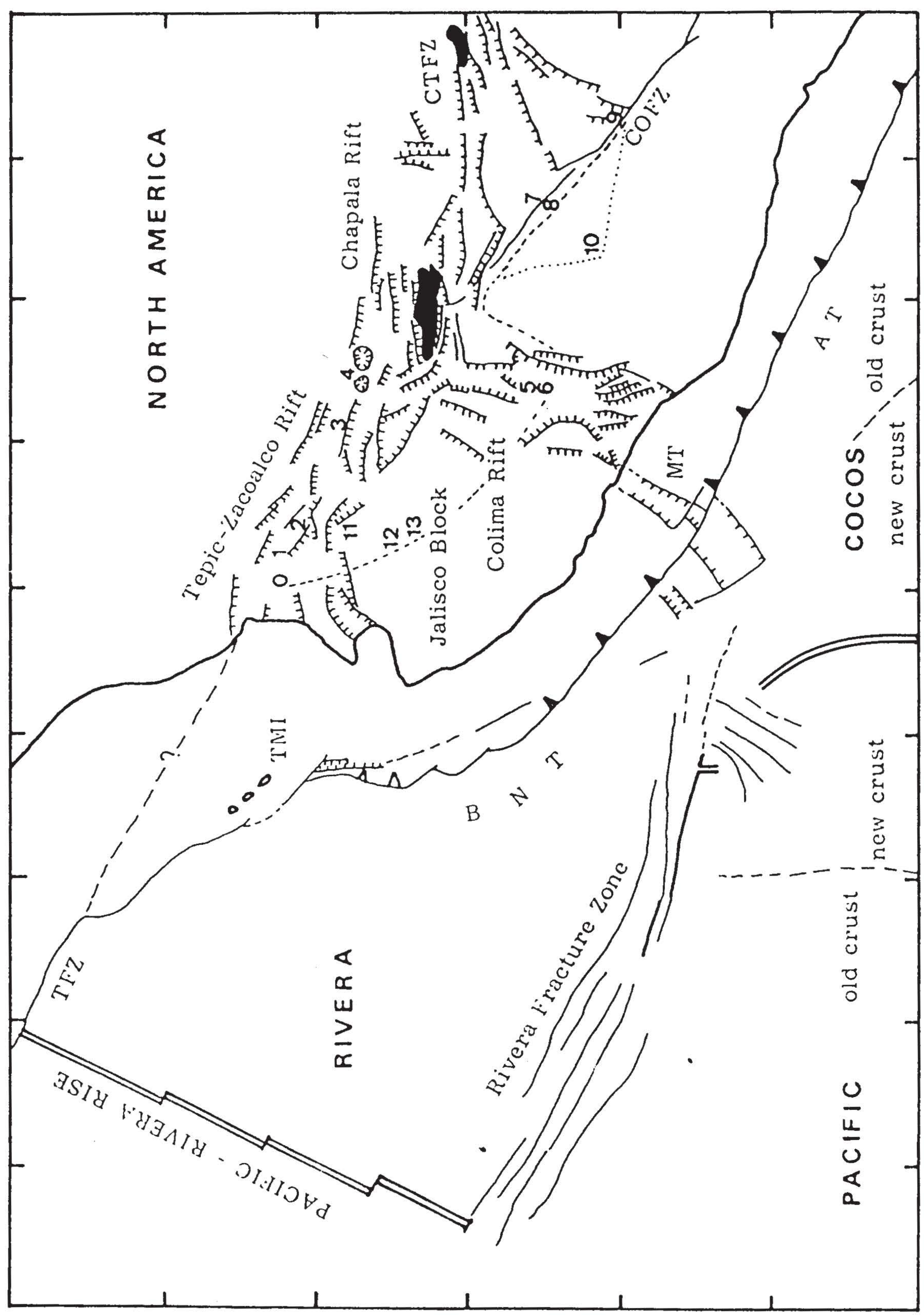

Fig. 2. Tectonic framework in western Mexico. BNT: Barra de Navidad trench-segment; AT: Acapulco trench-segment; TFZ: Tamayo fracture zone; TMI: Tres Marías Islands; MT: Manzanillo trough; COFZ: Chapala-Oaxaca fracture zone; CTFZ: Chapala-Tula fracture zone. Numbers correspond to the following volcanoes and volcanic fields: 0: Sangangüey; 1: San Juan; 2: Ceboruco; 3: Tequila; 4: La Primavera; 5: Cántaro~Nevado de Colima; 6: Colima; 7: Paricutín; 8: Tancítaro; 9: El Jorullo; 10: Buenavista; 11: San Sebastián; 12: Mascota; 13: Los Volcanes. The dashed line depicts the current volcanic front. Tectonic elements are from De Mets and Stein (1990) and Johnson and Harrison (1990).

lima and Jalisco states, confirms an active subducting R (Eissler and Mc Nally, 1984; Singh *et al.*, 1985; Anderson *et al.*, 1989). Moreover, De Mets and Stein (1990) have found that R is not only active, but its activity is increasing. Those authors found that spreading rates averaged over the past 0.7 Ma are systematically faster than 3 Ma average rates, with the difference increasing southward along the ridge. Additionally, the velocity vectors predicted for R are oriented to the northeast.

In Figure 5, it is apparent that spreading rates are systematically faster in the southern segment of the P-R rise than in the north, at least during the last 3.0 m.y. (data from De Mets and Stein, 1990). The spreading rates were faster before and after the period between 1.7 Ma and 0.7 Ma (Figure 6). These plots suggest a decreasing convergence rate between 3.0 Ma and 1.7 Ma but a steady increase after 0.7 Ma (except at 21.15 °N).

PLATE KINEMATICS

A number of models have tried to explain the different stress regimes in the backarc region of a volcanic arc system. These models include the diapir model (Karig, 1971), secondary convection model (Sleep and Toksöz, 1971), age of subducted plate (Molnar and Atwater, 1978), the anchored slab model (Uyeda and Kanamori, 1979) and the model of a thickened continental crust (Faure and Charvet, 1991). Alternatively, Otsuki (1989) has proposed laws of convergence rate of plates derived from empirical relationships among the convergence rate of plates, the rollback rate of trench axes, and from island-arc tectonics. Otsuki (op. cit.) applied these laws to island arcs and continental arcs as well. The first law of convergence implies that the deformation style in the overriding plate can be tensional, neutral or compressive depending on the convergence rate of the plates.

The first law of convergence of Otsuki (1989) for a Wadati-Benioff zone of less than 200 km in depth is:

$$V_a = V_{on} + V_{sn} - 3.4 \quad (cm/yr) \tag{1}$$

where V_a denotes the backarc spreading rate (negative) or the contraction rate of arc crust (positive), V_{on} and V_{sn} are the components of absolute motions of overriding and subducting plates respectively (positive when trenchward), perpendicular to the trench direction. The convergence rate $(V_{on} + V_{sn})$ is assumed to be equivalent to the motion of the subducting plate relative to the overriding plate $({}_rV_{sn})$. Hence, eq. 1 can be written as:

$$V_a = {}_rV_{sn} - 3.4 \quad (cm/yr) \tag{2}$$

Equation (2) was applied using the Euler poles and angular velocities for the motion of R relative to NA at 3.0 Ma and 0.7 Ma (De Mets and Stein, 1990), in order to find the kinematic state of the region. The deformation rate of the overriding plate margin (V_a) was calculated, to be negative in all cases (Table 1). This means that the tectonics of the continental margin of western Mexico is dominated by tensional tectonics. In Figure (7), the rate of deformation for several latitudes at 3 Ma and 0.7 Ma is shown. Deformation rate at 0.7 Ma is systematically higher than at 3.0 Ma (except in the northwesternmost part) and therefore, it is becoming less extensional or in other words, tending to be neutral in the southern part of the interaction zone R-NA. The deformation rate is less at 0.7 Ma than at 3 Ma in the northern part implying that it is becoming more extensional.

De Mets and Stein (1990) calculated kinematic parameters of R motion relative to NA at 3.0 Ma and 0.7 Ma. However, we have no precise data on the kinematics of R throughout the period since 10 Ma. Therefore, the correlation between the spreading rate history of EPR and the tectonics and volcanism onland is attempted assuming that tectonics and volcanism have been controlled by the motion of R since the Late Miocene.

RELATIONSHIP AMONG SPREADING RATE AND CONVERGENCE RATE

The deformation style onland is presumed to be mainly influenced by the spreading rate at the P-R rise. If this presumption is valid, then the evolution of the spreading rate through time is responsible for the changes in convergence rate and a positive correlation with the tectonic evolution onland can be made. In order to make a reliable correlation among spreading rate and the geology of western Mexico, it is necessary to evaluate the motion of R relative to NA ($V_{R\text{-}NA}$) through time. $V_{R\text{-}NA}$ can be influenced by the variation of: absolute motion of NA $({}_aV_{NA})$, absolute motion of EPR $({}_aV_{EPR})$ and the eastward spreading rate of EPR $({}_eS_{EPR})$. The relationship between these parameters can be expressed as:

$$V_{R\text{-}NA} = {}_aV_{NA} + {}_aV_{EPR} + {}_eS_{EPR} \tag{3}$$

$V_{R\text{-}NA}$ and ${}_eS_{EPR}$ can be calculated for 0.7 Ma and 3 Ma, whereas ${}_aV_{NA}$ has remained constant since 9 Ma ago (Engebreston *et al.*, 1985); thus eq. (3) can be written as:

$${}_aV_{EPR} = V_{R\text{-}NA} - {}_eS_{EPR} + {}_aV_{NA} \tag{4}$$

In Table 2, the calculated values for ${}_eS_{EPR}$, $V_{R\text{-}NA}$ and $V_{R\text{-}NA}\text{-}{}_eS_{EPR}$ at 3.0 Ma and 0.7 Ma are listed. The difference of ${}_aV_{EPR}$ for both dates is small. This means that the absolute motion of the EPR is negligible and hence, the convergence rate is mainly influenced by the changes in the spreading rate. Therefore, a correlation between spreading rate history and the geological evolution onland can be attempted.

GEOLOGICAL SETTING OF THE WESTERN TMVB

Knowledge of the onland geology is essential for testing the offshore kinematic behavior of plates. In order to test if the evolution of R through time is reflected by the

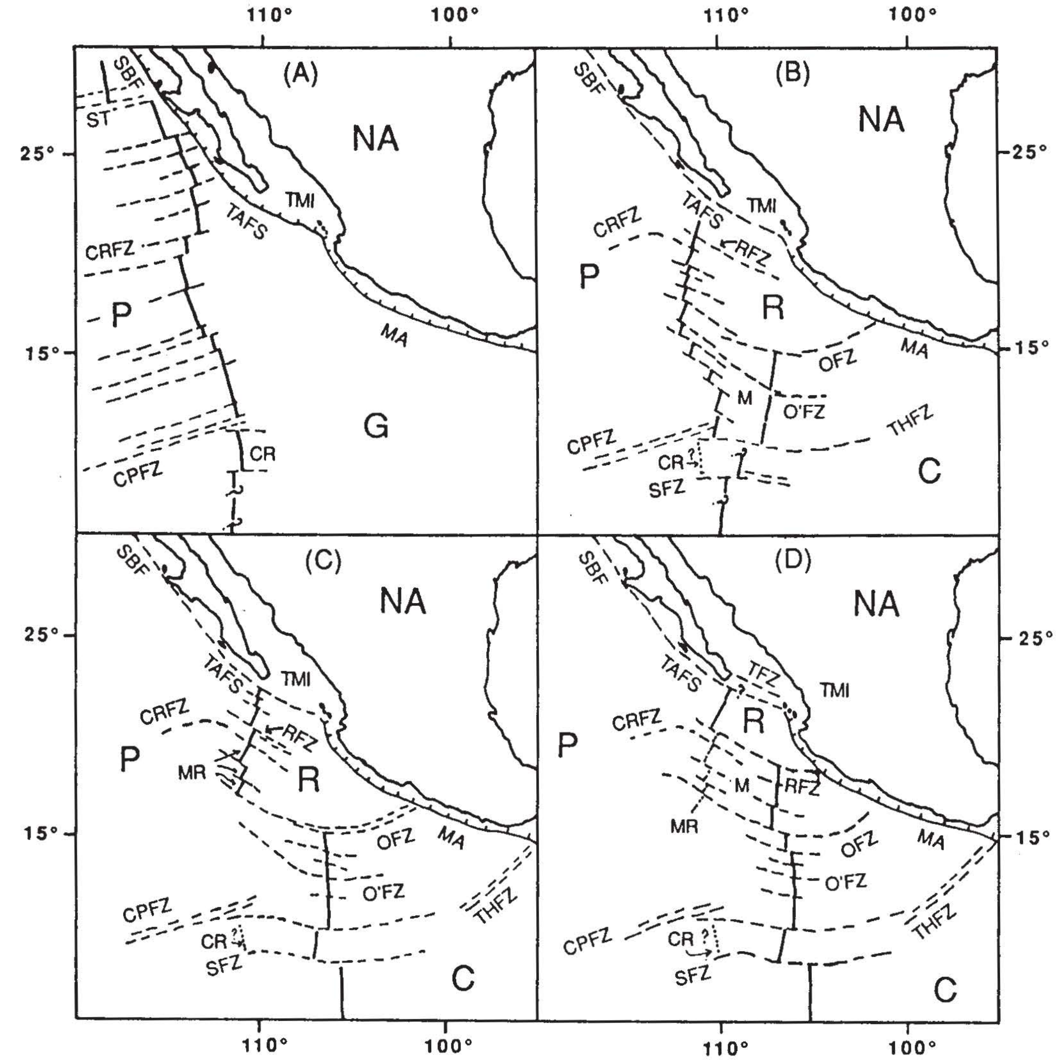

Fig. 3. Tectonic evolution offshore western Mexico since Middle Miocene. (A) Tectonic setting before 12.5 m.y.B.P., subduction was active along Baja California; (B) after the 11 Ma plate reorganization, subduction along Baja California ceased and Rivera [R] and Cocos [C] plates were created during late Miocene, and a microplate [M] south of Orozco fracture zone [OFZ] existed between 11 Ma and 6.5 Ma; (C) configuration during late Miocene (6.5 Ma), the western spreading centers south of OFZ were abandoned and the East Pacific Rise [EPR] north of OFZ was at the Mathematicians ridge [MR]; (D) between 6.5 Ma and 3.5 Ma a microplate [M] existed south of the Rivera fracture zone [RFZ]. At 3.5 Ma the MR was abandoned and the EPR definitely migrated to the east, R was shortened in the process. Keys are as follows: NA: North American plate; G: Guadalupe plate; P: Pacific plate; ST: Shirley trough; SBF: San Benito fault; TAFS: Tosco-Abreojos fault system; MA: Middle America trench; CPFZ: Clipperton fracture zone; CRFZ: Clarion fracture zone; THFZ: Tehuantepec fracture zone; O'FZ: O'gorman fracture zone; SFZ: Siqueiros fracture zone; CR: Clipperton ridge; TMI: Tres Marías Islands. Dashed lines represent fractures. Baja California has not been palinspastically restored. Modified from Klitgord and Mammerickx (1982).

regional geology, a summary of the regional geology is reviewed below.

Tepic-Zacoalco Rift. The structure of this rift has been summarized by Allan *et al.* (1991) as a series of pull apart basins and grabens extending northwesterly from the vicinity of Zacoalco town (Jalisco state) to the Pacific Coast (Figure 2). This rift is bounded by two main fault systems: the Mazatan fault system in the south and the Pochotitan fault system in the north, active since the late or early Miocene to Holocene time. The Pochotitan fault system has dip-slip and strike-slip components. Most of the observed vertical movement occurred between early Pliocene and early Pleistocene. Current right-lateral strike-slip movement along the northern boundary faults of the rift is thought to be at a rate of 0.2 cm/yr (Nieto *et al.*, 1985). Northwest-trending lineaments between the Pochotitan fault system and the Mazatan fault system include cinder cone alignments through Ceboruco, Sangangüey and Las Navajas volcanoes. These alignments imply that the direction of the least compressive horizontal stress is oriented northeast (Allan *et al,* 1991). The Zacoalco half graben (the southernmost structure of the rift) has a different structural style, more akin to the "do-

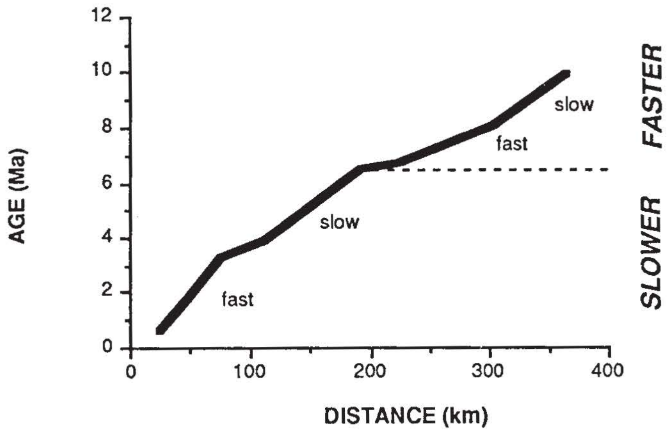

Fig. 4. Distances of magnetic anomalies to the P-R spreading center are plotted against age, since late Miocene. This plot depicts qualitatively the evolution of the spreading rates: the smoother the curve, the spreading rates were relatively faster and the steeper the curve, the rates were relatively slower. Several changes can be seen but in general, the rates before 6.5 Ma were faster than after. The data was taken from Klitgord and Mammerickx (1982).

mino" style of faulting of Chamberlain (1978) in the Rio Grande rift near Socorro, New Mexico (Allan *et al.*, 1991). Delgado (1992) has mentioned that σ_3 is nearly horizontal and σ_1 is very steep. Allan (1986) estimated the brittle extension in the Zacoalco half graben as 7% to 13 % and proposed that its faults have shallower, listric roots.

The pre-Cenozoic rocks include interbedded graywackes, shales, conglomerates and rhyolitic and andesitic volcaniclastic rocks intruded by gabbros, tonalites and granodiorites with ages between 97~20 Ma (Gastil *et al.*, 1978). Basement rocks (sandstones and a granodiorite) have been reported in a borehole near San Marcos (close to the so-called "triple junction") at 1800 m and 2200 m (Venegas *et al.*, 1985). Basement rocks are overlain by extensive early Miocene (22.6~16.9 Ma) acid-intermediate volcanic rocks (Gastil *et al.*, 1978, 1979; Nieto *et al.*, 1985; Pasquaré and Zanchi, 1985). These volcanic rocks are covered by late Miocene (10~7.2 Ma) basalts, andesites and ignimbrites (Gastil *et al.*, 1978, 1979; Watkins *et al.*, 1971; Gilbert *et al.*, 1985). According to Pasquaré and Zanchi (1985), there is a 3 Ma gap in the volcanic activity before the eruption of the next volcanic products. The uppermost part of the sequence (5.7~3.1 Ma) is composed of interbedded pyroclastic rocks, lacustrine sediments and basalts (Wopat and Carmichael, 1984; Gilbert *et al.*, 1985). Part of the volcanism of this period (Pliocene to Holocene) was alkaline and peralkaline in nature, erupted mainly from monogenetic volcanoes (Nelson and Carmichael, 1984). However, Pliocene to Recent calc-alkaline rocks have also erupted from major composite volcanoes (Nelson, 1980).

Colima Rift. Allan *et al.* (1991) describes this rift as composed by three segments: the northern graben [N], central graben [CC] and southern [S] Colima rift. These structures extend south-southwesterly from about 5 km south of the town of Zacoalco for 190 km and are 20~65 km wide: N consists of a system of inward facing, high angle normal faults trending north to north-northeast (Allan, 1986). Infilling sediments of the graben are nearly 1 km thick and the vertical offset is at least 2.5 km. Allan estimated that N represents 1.5~3.3 km (6~13 % over the graben structure) of brittle extension. Allan (1986) proposed that faulting started in N at 4~5 Ma and has continued into the late Pleistocene and probably into the Holocene. The composite volcanoes Nevado de Colima and Volcán de Colima are nested in the CC. The western boundary of CC is delineated by high angle active normal faults whereas the eastern side is a diffuse boundary of scattered fault scarps (Allan *et al.*, 1991). Serpa (1990) quotes that these faults are pre-Cenozoic, and the structure of CC and S should be considered as a half graben. Alternatively, Allan *et al.* (1991) mention that faulting in S is more complex than in the other segments of the Colima rift, consisting of fault blocks, smaller in size and more random in orientation, which implies greater crustal disruption. In addition, Bourgois *et al.* (1988a) and Bandy *et al.* (1988) showed evidence for offshore extension of the Colima rift into the Manzanillo trough (Figure 2).

The basement rocks of N include interbedded volcanic breccias, conglomerates, wackes, argilites, shales and limestones. The age of this sequence ranges from Jurassic to Eocene (Allan, 1986). Basement rocks are intruded locally by Cretaceous~early Tertiary plutonic rocks (Damon *et al.* 1981; Pantoja-Alor, 1983). Allan *et al.* (1991) compare some silicic pyroclastic rocks with rocks described by McDowell and Keizer (1977) in the mid-Tertiary Sierra Madre Occidental province. In N, Allan (1986) reported basalts, andesites and dacites for the period 10 Ma~4.35 Ma and between 2.41 Ma~0.58 Ma andesites and dacites. Allan also reported alkaline rocks for periods between 4.69 Ma~3.29 Ma and 1.26 Ma ~1.15 Ma. The alkaline rocks have been extruded from cinder and lava cones whereas the calc-alkaline rocks were erupted mainly by the large composite volcanoes (Allan, 1986). However, calc-alkaline lavas and alkaline lavas have been erupted by the Volcán de Colima as well (Luhr and Carmichael, 1982).

Chapala Rift. The Chapala and Citala grabens are part of this rift (Delgado, 1992), which extends as far as 420 km to the east (Johnson and Harrison, 1990) of the proposed triple junction of Luhr *et al.* (1985). The Chapala graben is more than 100 km long and 10~30 km wide. The tilted fault blocks of the northern limb of the graben also resemble the "domino" style of faulting (Chamberlain, 1978) with tilted surfaces between 10° and 20° to the north. Crustal extension has been estimated at 1.43 km (11 % across the graben structure) in the western part, 2.27 km (17 %) in the central part, and 1.7 km (9 %) in the eastern part (minimum values). The Cosalá fault system and Ajijic

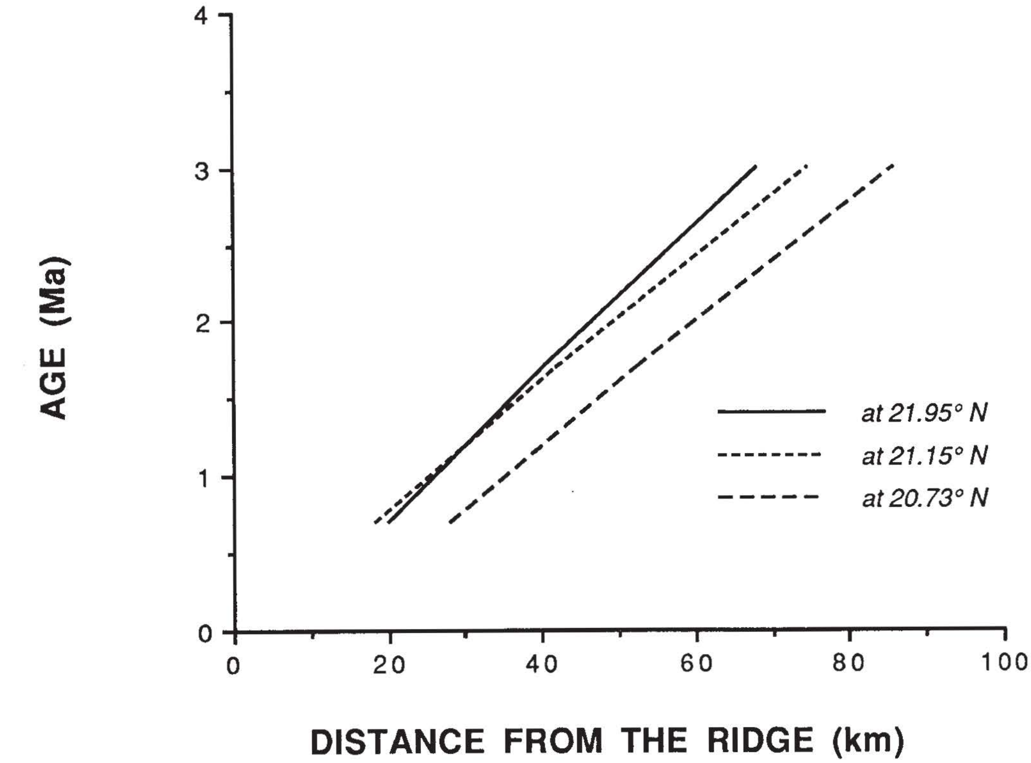

Fig. 5. Distance of magnetic anomalies 1, 2 and 2A to the P-R spreading center plotted against age. The spreading rates of the southernmost part of the rise are systematically faster than those of the north. The data was taken from De Mets and Stein (1990).

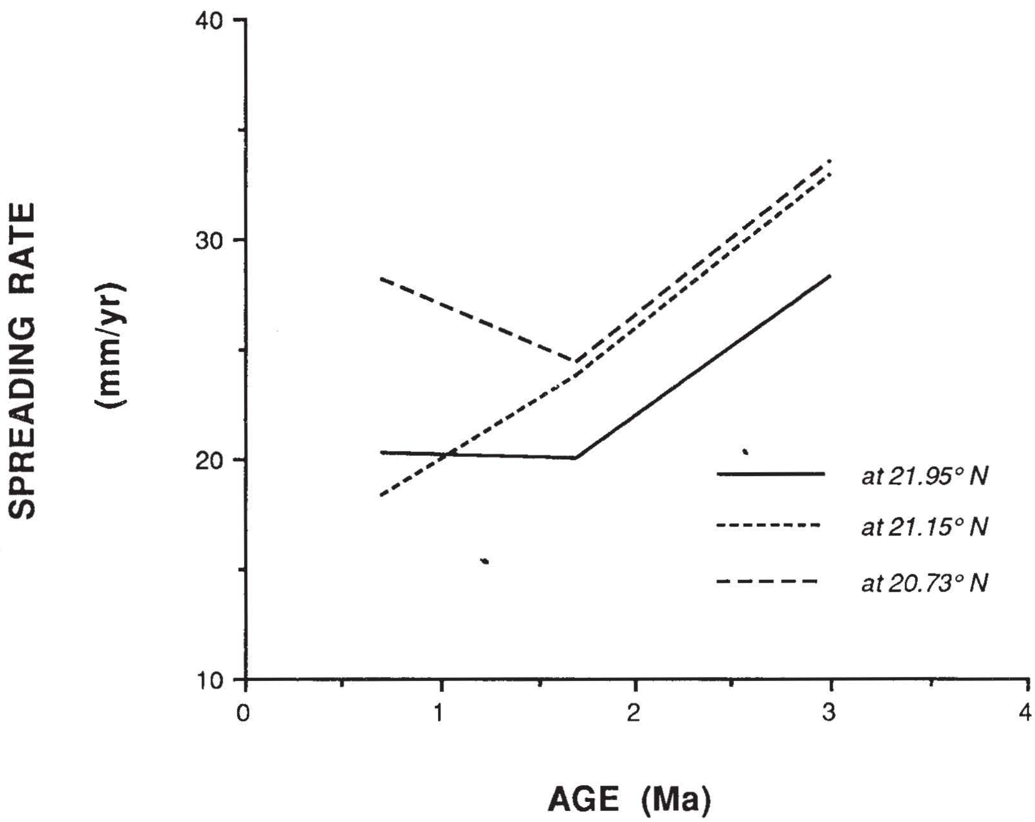

Fig. 6. Half spreading rates are plotted against age in order to show their evolution in time along the ridge. The data was taken from De Mets and Stein (1990).

Table 1.

Convergence rates of Rivera plate. V_{sn} is the component of relative motion of the subducting plate beneath North America perpendicular to the trench axis, V_a is the deformation rate on the backarc region, which in this case represents the backarc spreading rate.

LATITUDE	LONGITUD	AGE (Ma)	Vsn (cm/yr)	Va (cm/yr)
22.5° N	107.5° W	3	0.60	-2.80
21.5° N	106.8° W	3	0.70	-2.70
20.0° N	106.3° W	3	1.20	-2.20
18.9° N	105.2° W	3	2.00	-1.40
22.5° N	107.5° W	0.7	0.30	-3.10
21.5° N	106.8° W	0.7	0.90	-2.50
20.0° N	106.3° W	0.7	1.90	-1.50
18.9° N	105.2° W	0.7	2.80	-0.60

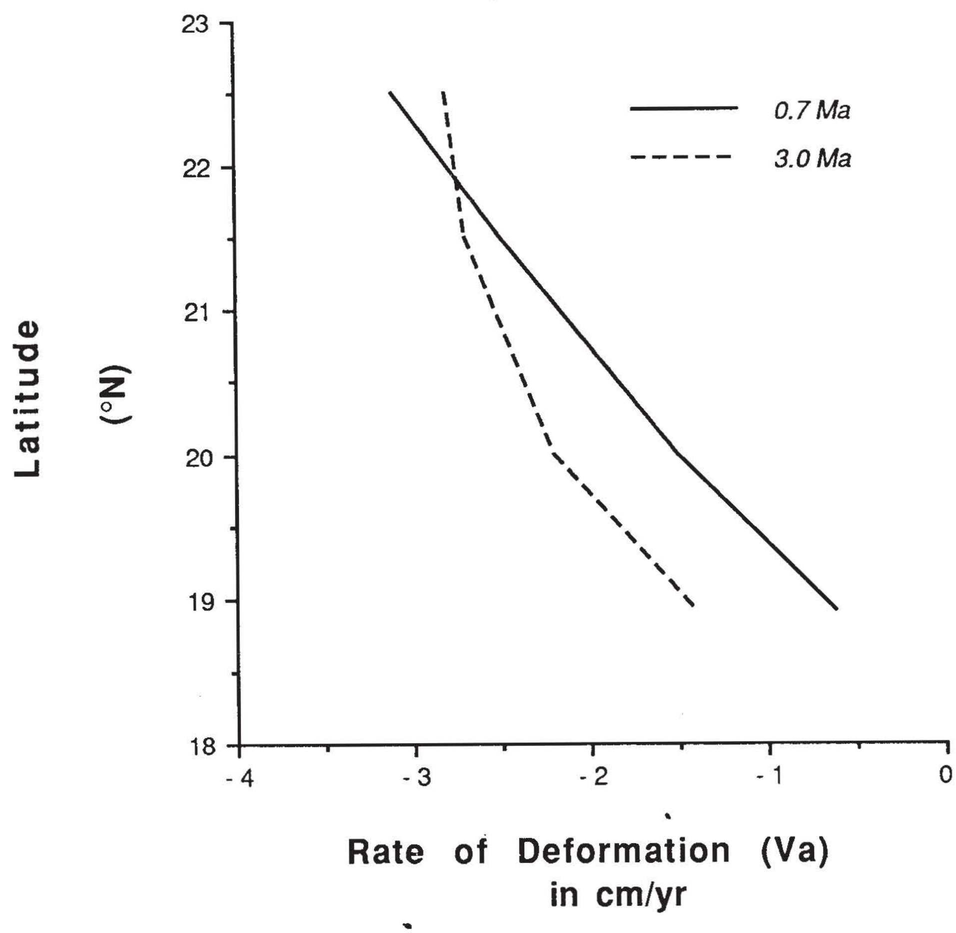

Fig. 7. Deformation rates in the backarc region of western Mexico due to the interaction between Rivera and North American plates. The rates are all tensional but tending through the time to be neutral except in the north where it is becoming more tensional.

fault system (N 70° E dipping 44°–74°) are part of the bounding normal faults of the Chapala graben, which have a small left handed horizontal component (Delgado, 1992). Interestingly, these fault systems have a right-step-like arrangement in accordance with a left lateral transcurrent faulting. However, the stress tensors are nearly horizontal (σ_3) and very steep (σ_1), indicating only extensional events. On the other hand, the available striation data suggest that there is no important lateral component (Delgado, unpublished data). The age of this faulting has been determinated by Delgado (1992) between 6.7 Ma and 1.7 Ma. This means that Chapala graben was failed as part of a rifting process during the Late Pliocene-Early Pleistocene. Nevertheless, the eastern extension of the N 86° E trending La Angostura Fault System (Pajacuarán fault) shows evidence of neotectonic activity. The Citala graben

Table 2

Influence of the absolute motion of EPR ($_aV_{EPR}$) on the convergence rate. The values of the eastern spreading rate of EPR ($_eS_{EPR}$) and the motion of R relative to NA ($V_{R\text{-}NA}$) for three latitudes at 3.0 Ma and 0.7 Ma are sustracted to obtain $_aV_{EPR}$. The difference of $_aV_{EPR}$ at 3.0 Ma and 0.7 Ma is small. The absolute motion of NA ($_aV_{NA}$) has remained constant since 9 Ma (Engebreston *et al.*, 1985) and during sustraction is eliminated.

	AT 3.0 Ma			AT 0.7 Ma			
LATITUDE (°N)	$_eS_{EPR}$ (mm/yr)	$V_{R\text{-}NA}$ (mm/yr)	$V_{R\text{-}NA} - {}_eS_{EPR}$ (mm/yr)	$_eS_{EPR}$ (mm/yr)	$V_{R\text{-}NA}$ (mm/yr)	$V_{R\text{-}NA} - {}_eS_{EPR}$ (mm/yr)	$_aV_{EPR\ (0.7\ Ma)} - {}_aV_{EPR\ (3\ Ma)}$ (mm/yr)
22.5	24.0	6.4	-17.5	24.6	2.9	-21.6	-4.0
21.5	26.0	9.9	-16.0	28.3	9.9	-18.3	-2.3
20.0	29.2	14.6	-14.6	33.3	19.5	-13.7	0.8

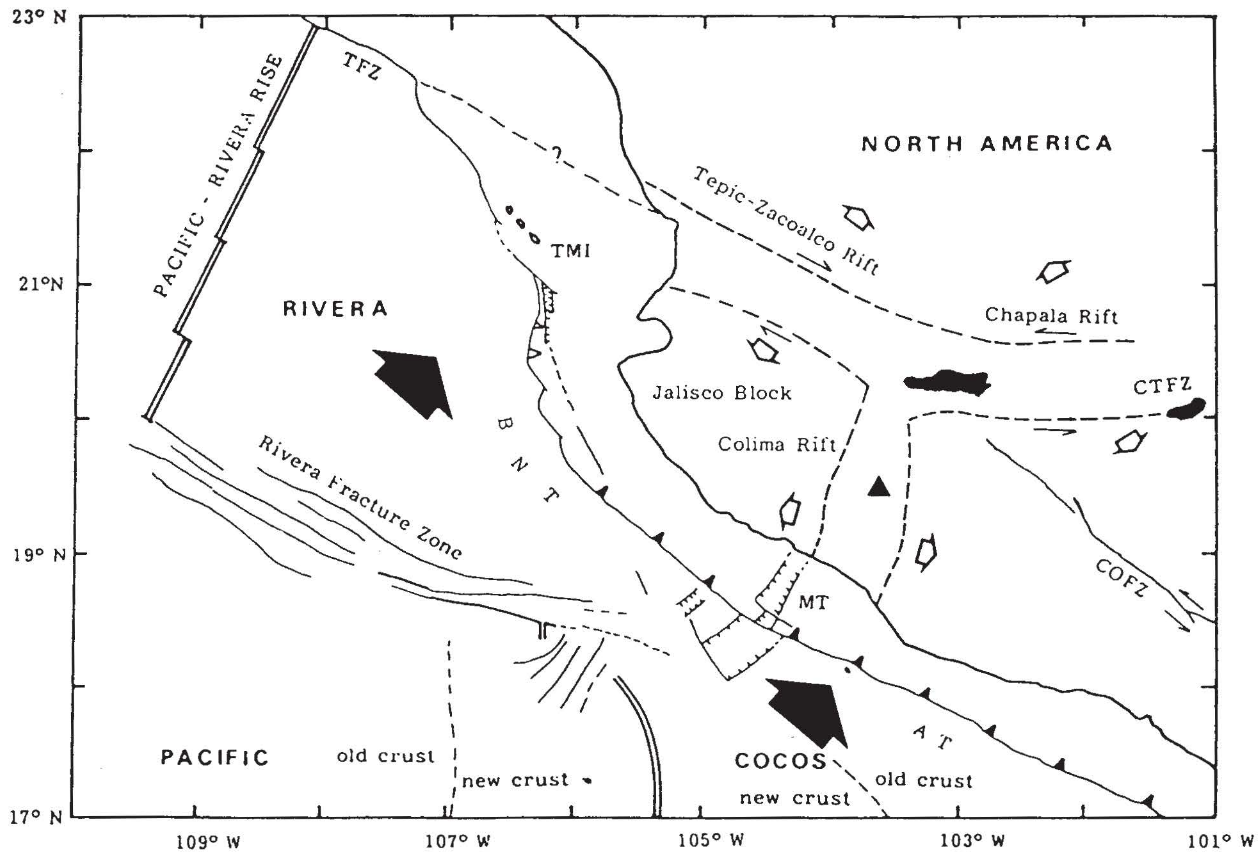

Fig. 8. Tectonic patterns in western Mexico. NE-SW extensional tectonics is parallel to the direction of the general movement of Rivera plate; NW-SE transcurrent faulting in the Tepic-Zacoalco rift is induced by a horizontal component resulting from oblique subduction of Rivera plate. This horizontal component also contributes to the E-W extension in the Colima rift which at the same time is induced by a horizontal component resulted from the oblique subduction of Cocos plate beneath North America and produces transcurrent faulting along the Chapala-Oaxaca fracture zone. The transtensional faulting along the Chapala rift is part of a large scale left lateral shear along the Trans-Mexican Volcanic Belt. Keys are the same as in Figure 2. The triangle represents the Colima volcano. Black arrows represent the direction of relative movement of Rivera and Cocos plates according to De Mets and Stein (1990), small arrows represent the different tectonic patterns along the main regional structures.

is a smaller subparallel structure (30 km long, 7-18 km wide) with an estimated crustal extension of 1.26~2.92 km (21~15 % over the structure). This graben is bounded in the north by the Citala fault system (normal faults trending N 80° W, dipping 59° S) whereas the southern boundary is not well defined. Faulting in this graben started in the Late Miocene and continued probably shortly after 1.7 Ma. Subsidence rate of the Chapala graben is considered 0.039~0.04 cm/yr and Citala graben 0.006 cm/yr (Delgado, 1992). Delgado and Urrutia-Fucugauchi (1986) have suggested an event of regional uplifting with the axis in the region of Zacoalco. This uplift is estimated to be 150~300 m (west of the axis) and 400 m (northeast of the axis) based on the observation of sudden geomorphic rejuvenation of Ayutla, Alejo, Ameca and Santiago rivers about 50~70 km away from the uplift axis. Elevation of late Miocene~early Pliocene volcano-sedimentary deposits (400~600 m, 10~15 km from the axis) also indicates regional uplifting and suggests an early~late Pliocene age for the event. Similarly, pillow lavas of the Travesaño Group (4 Ma~4.3 Ma) are also elevated more than 200 m above the current lake level.

The stratigraphy of this rift has been studied recently by Delgado (1992) who established seven stratigraphic groups comprising mainly volcanic rocks. The Mio~Pliocene Undifferentiated Volcanics [MPUV] and the Tizapán Group [TG] are the oldest outcropping rocks of this rift (10.2 Ma~4.58 Ma; Nieto *et al.*, 1981; Nixon *et al.*, 1987; Delgado, unpublished data) consisting mainly of andesites and basalts. The Chapala Group (6.5 Ma~4.2 Ma) comprising volcano-sedimentary rocks and acidic volcanic rocks, was partially contemporaneous with the MPUV and TG. The Travesaño Group (4.28 Ma~4.19 Ma, mainly andesites and basalts) and Grande Group (2.73 Ma~1.31 Ma, basalts and andesites) are separated by a hiatus in the volcanic activity of more than one million years. These two groups are made up of andesites and basalts. The Santa Cruz Group (<0.65 Ma~1.39 Ma) consisting mainly of andesites and basalts, and the Acatlán Group (<0.65 Ma ~ 1.07 Ma) comprising dacites and rhyolites, represent coeval intermediate~acidic volcanism. In contrast with the alkaline volcanism of Tepic-Zacoalco and Colima rifts during the Pliocene~Holocene, the character of the volcanism in the Chapala rift is mostly calc-alkaline, though transitional rocks are also present and very few not so well defined alkali basalts (Delgado, unpublished data).

DISCUSSION

The evolution and activity of R has strongly influenced the tectonics and volcanism in western Mexico since the Late Miocene. The spreading rate of the EPR increased at 8 Ma (Figure 4) during the eastward jump of EPR, when the Clipperton ridge was abandoned (Figure 9). By this time, the volcanism of western Mexico was calc-alkaline. In the Tepic-Zacoalco rift area, basalts and andesites were the common products (10 Ma~7.2 Ma) while in the Chapala rift area the volcanism was monogenetic (represented by shield volcanoes, lava cones, etc.), mainly basaltic~andesitic (10 Ma~6.5 Ma). About 6.5 Ma ago another segment of the EPR was abandoned in the Mathematicians ridge and a new ridge appeared to the east (Figure 3C). During this new jump, the spreading rate became slower (Figure 9). This could make the convergence rate smaller than before and therefore, the deformation became tensional onland, producing normal faulting with creation of sedimentary basins. The calc-alkaline volcanism continued, but at this time explosive volcanism also erupted in the region of the Tepic-Zacoalco rift and in the Chapala rift area. Some of those acidic volcanic products were intercalated with lacustrine sediments (Late Miocene-Early Pliocene) and filled the sedimentary basins. Since 4.6 Ma more primitive magmas from mantle sources reached the surface through a very fractured crust due to widespread normal faulting. The alkaline volcanism had a widespread "pulse" (Allan *et al.*, 1991) in the Colima and Tepic-Zacoalco rifts between 4.6 and 3.9 Ma. Although in the Chapala rift the volcanism was mostly calc-alkaline, slightly alkaline basalts and trachyandesites were erupted between 6.7 Ma and 4.5 Ma. During the interval 3.07 and 2.73 Ma there is a short regional hiatus in the volcanic activity. Among the published dates of several authors there is no date in this interval (alkaline or calc-alkaline). This may result from a lack of data. Pasquaré *et al.* (1988) reports a NE-SW compressional phase during the Late Pliocene in central Mexico, characterized by strike slip and reverse faults. The relationship between uplift and the compressional phase is still unknown. By this time, the last jump of the EPR to the east occurred (at 3.5 Ma, south of the RFZ), and spreading rate at EPR became slightly faster (Figure 4, 6 and 9). The calculated convergence rates since 3 Ma are consistent with tensional tectonics for the region (Figure 7). This coincides with normal faulting in the Tepic-Zacoalco, Colima and Chapala rifts. Notwithstanding, contemporaneous right lateral displacement also occurred at Tepic-Zacoalco rift. Alternatively, volcanism was resumed in the region since 2.7 Ma. In the Tepic-Zacoalco and Colima rifts it was calc-alkaline and alkaline (since 1.4 Ma) but in Chapala rift it was entirely calc-alkaline.

The structures of the entire region suggest the presence of four superposed tectonic patterns in the last 3 Ma (Figure 8): a) NE-SW extensional tectonics, b) NW-SE transcurrent faulting, c) N-S trending extensional faulting, and d) transtensional faulting (NE-SW trending normal faulting during Late Pliocene~Early Pleistocene and ENE-WSW during Late Pleistocene~Holocene). The NE-SW extensional tectonics has been induced by a low convergence rate under a subduction regime of R relative to NA. The northwest trending volcanic chain southeast of Guadalajara (Luhr and Lazaar, 1985), the volcanic field in the vicinity of Acatlán and the alignments of cinder cones through the Ceboruco, Sangangüey and Las Navajas volcanoes are evidences of this NE-SW extension. Also there are several normal faults with the same trends (i.e. Pochotitan, Mazatan and San Marcos faults). These alignments and faults are in the same direction as the expected trends parallel to the BNT. Right lateral displacement associated with normal faults in the Tepic Zacoalco rift can be correlated with oblique subduction of R. The predicted

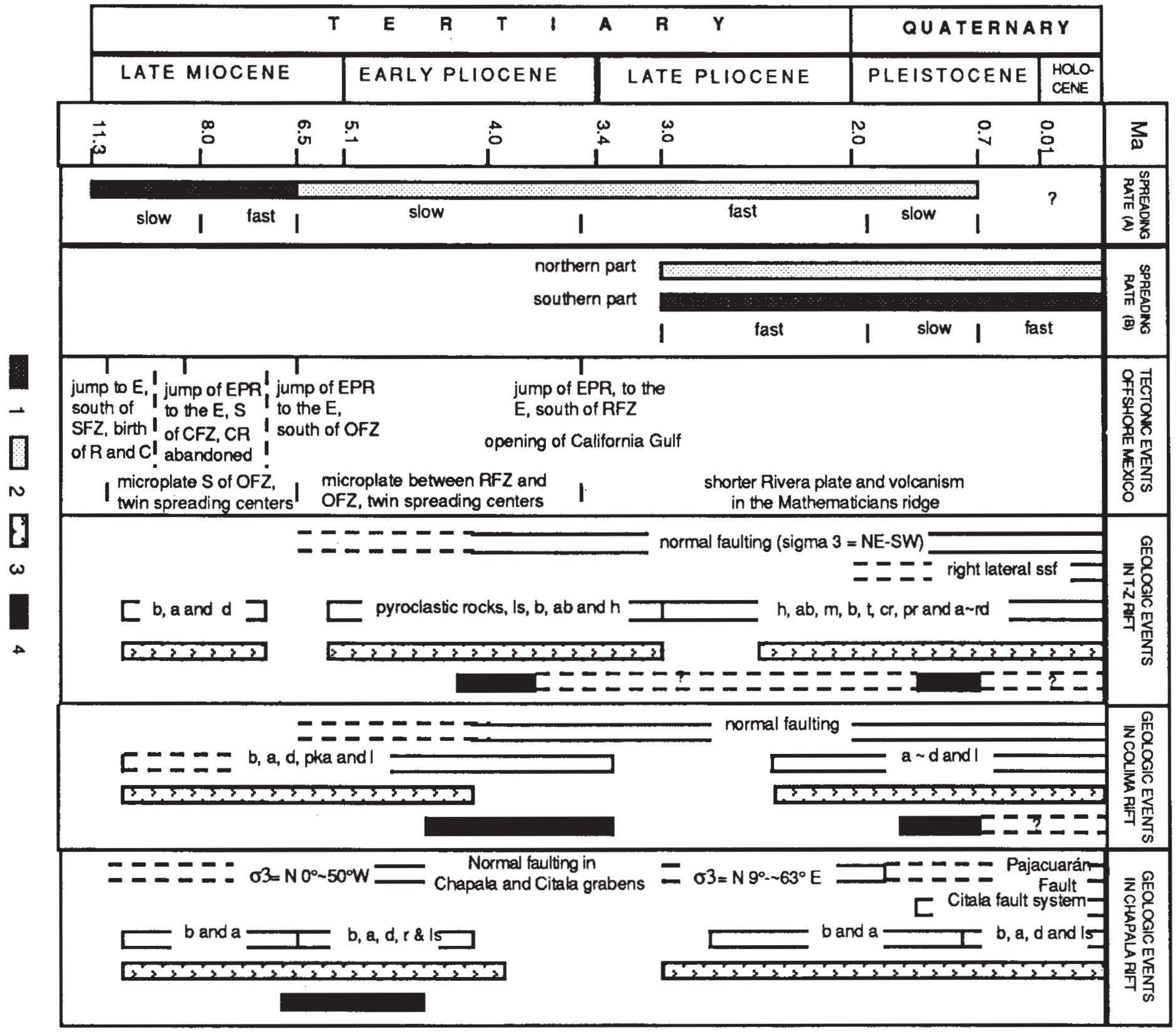

Fig. 9. Correlation table between the spreading rate, the tectonic events offshore western Mexico and the geologic events onland. A: data from Mammerickx and Klitgord (1982; see Figure 4); B: data from De Mets and Stein (1990); 1: faster spreading rate; 2: slower spreading rate; 3: calc-alkaline volcanism; 4: alkaline volcanism; T-Z: Tepic-Zacoalco; R: Rivera plate; C: Cocos plate; EPR: east Pacific rise; SFZ: Siqueiros fracture zone; CFZ: Clipperton fracture zone; CR Clipperton ridge; OFZ: Orozco fracture zone; RFZ: Rivera fracture zone; b: basalt; a: andesite; d: dacite; rd: rhyodacite; r: rhyolite; ab: alkali basalt; h: hawaiite; m: mugearite; t: trachybasalt; cr: comenditic rhyolite; pr: pantelleritic rhyolite; pka: phlogopite-kalsilite ankaratrite; l: lamprophyre; ls: lacustrine sedimentation; nf: normal faulting; ssf: strike-slip faulting; llc: left-lateral component. Geological events of Tepic-Zacoalco rift were taken from Allan *et al.* (1991); geologic events of Colima rift were taken from Allan (1986) and geologic events of Chapala rift are from Delgado-Granados (1992).

velocity vectors for R (De Mets and Stein, 1990) are systematically pointing to the NE. This subduction trend can induce NW displacement of the Jalisco block through NW-SE trending right lateral displacement faults. Alternatively, the N-S trending extensional faulting of the Colima rift also has been explained in terms of oblique subduction by De Mets and Stein (1990). In this case, the Michoacan block is moving southeast along the Chapala-Oaxaca Fracture Zone of Johnson and Harrison (1990) due to oblique subduction of C under NA, leaving the Colima rift as a "pull apart basin". In agreement with this explanation, several volcanoes are aligned N-S in the Colima rift (Cántaro-Colima volcanic chain) and in the Jalisco block lava cones and flows are in a north-trending basin at Los Volcanes (Allan *et al*, 1991). The volcanic front (Figure 2) can be delineated by the Sangangüey volcano (about 175 km from the trench), the volcanoes of the Mascota and Los Volcanes volcanic fields (about 170 km from the trench) and the Cántaro-Colima volcanic complex (about 170 km from the trench). Ceboruco, San Juan volcanoes and San Sebastian volcanic field are closely associated with this volcanic front whilst La Primavera volcanic complex is about 120 km behind the volcanic front (280 km from the BNT). All these volcanoes are related to subduction of R along the BNT under western Mexico. Volcanoes of the Michoacán-Guanajuato Volcanic Field are separated from the previously mentioned volcanoes by a volcanic discontinuity (Figure 2). Buenavista, Tancítaro, Paricutín and Jorullo volcanoes, for example, are related to subduction of C and the latter is part of the current volcanic front in this region. In the Tepic-Zacoalco rift there are systematic differences in relative and absolute incompatible-element abundances and Sr and Nd isotopic ratios (Verma and Nelson, 1989) in comparison with the lavas in the southeast. The volcanic rocks in the Chapala and Colima rift, Mascota and Los Volcanes regions are enriched in incompatible elements (i.e. K) though Sr, Nd and Pb isotopic compositions of lavas from Colima rift and Jalisco block are similar (De Paolo and Carmichael, 1980; Heatherington *et al.*, 1987). The aforementioned differences in incompatible elements in magma indicate an increase in contents southeastwardly (from the northwesternmost part of Tepic-Zacoalco rift). Alternatively, the shortening of R due to the eastward jumping of the EPR implies a younger and hotter subducting slab through time. The southern portion of this obliquely subducting plate is underthrusting NA more rapidly than the northern portion. Thus, the convergence rate of R-NA becomes larger southeastward too. These two facts, southeastern increase of content of incompatible elements in volcanic rocks and convergence rate, suggest a genetical relation of the former to the latter. Namely, higher subduction rate supplies more accreted sediments to the mantle wedge.

Luhr *et al.* (1989) state that lavas (alkaline and calc-alkaline) from the Colima and Tepic-Zacoalco rifts were derived from a common source (mantle overlying R). Fluids and melts derived from the subducting slab and sediments produce heterogeneous and variable enrichment of the subarc mantle in the incompatible elements (concentrated in phlogopite, amphibolite and apatite-bearing lherzolite dikes and metasomatic veins) accomplished by hybridization and metasomatic alteration (Allan *et al.*, 1991). The alkaline lavas result from some partial melting of that heterogeneous source, derived from the incompatible-element-rich dikes and veins (Luhr *et al.*, 1989). According to Allan *et al.* (1991), these alkaline lavas reach the surface through deep-rooted faults produced by tensional tectonics. Calc-alkaline lavas, however, result from larger amounts of partial melting of this source, diluting the dike and vein component. Verma and Nelson (1989) mention that the lavas in the northwestern part of Tepic-Zacoalco rift seem to be derived from different mantle sources as compared to the lavas of the southeastern part. These lavas are enriched in high-field-strength elements (i.e. Nb, Zr and Ti) and relatively depleted in lithophile elements (i.e. K and Sr) in comparison with the alkaline and calc-alkaline lavas described for the Mascota and Los Volcanes regions and Colima rift. According to Verma and Nelson (1989), the lavas in this sector are derived from an oceanic island type source rather than from a mixed mantle slab-derived source. Nevertheless, smaller amounts of accreted sediments with the subducting slab must have influenced the character of the magmatism in this part. The lack of sediments accompanying the subducting slab due to a lower convergence rate, could explain the difference in geochemistry (i.e. depletion in lithophile elements) among lavas from the northwestern part of the Tepic-Zacoalco rift relative to the rest of the western TMVB, even though lavas from Sangangüey and Ceboruco volcanoes have trace element characteristics akin to the Colima rift calc-alkaline lavas.

CONCLUSIONS

The Colima volcano is located in the volcanic front of the western TMVB arc (delineated by Sangangüey volcano, Mascota and Los Volcanes volcanic fields and the Cántaro-Colima volcanic complex). The tectonism and volcanism of this region is highly influenced by the tectonic elements offshore western Mexico, which is dominated by the presence of the Rivera, Cocos, Pacific and North American plates (Figure 2). The volcanism of the western part of TMVB can be related to subduction of R beneath NA along the Barra de Navidad trench-segment, R being an active plate whose activity is consistently increasing since 3 m.y. ago (De Mets and Stein, 1990). The evolution of R is intimately related to the eastward migration of the East Pacific Rise, and becomes shorter through time since its birth between 12.5 and 11 m.y. ago (Mammerickx and Klitgord, 1982). Ridge jumps at 12~10 Ma, 9~8 Ma, 6.5 Ma and 3.5 Ma (Van Andel *et al.*, 1975) have shortened R considerably and have influenced tectonism and volcanism onland. Those jumps are related with an increase or decrease of the spreading rate at the ridge, changing the kinematic parameters of the convergence rate and modifying it. The qualitative analysis of the spreading rates at EPR north of Rivera Fracture Zone shows that they were relatively slow before 8 Ma (calc-alkaline volcanism was present in the entire region since 10 Ma), faster between 8~6.5 Ma, slower between 6.5~3.5 Ma (with associated widespread normal faulting which allowed the rise of alkaline magmas by 4.6~3.9 Ma), faster between 3.5 Ma and 1.7 Ma (a regional volcanic hiatus is recorded between 3.07 Ma and 2.73 Ma), slower between 1.7 Ma and 0.7 Ma (widespread normal faulting) and faster again after 0.7 Ma. In general, the spreading rates are faster in the southern part of the EPR than in the north. An analysis of the convergence rate since 3 Ma shows that the expected tectonic regime onland is tensional, becoming less tensional in the south of the BNT (tending to be neutral) and more extensional in the north. This tensional tectonic style coincides with normal faulting in the Tepic-Zacoalco, Chapala and Colima rifts. The structures of the region in the last 3 Ma evidence the presence of four tectonic patterns (Figure 8): a) NE-SW extensional tectonics, b) NW-SE transcurrent faulting, and c) N-S extensional faulting. NE-SW extensional tectonics is induced by a low convergence rate under a subduction regime between R and NA, NW-SE transcurrent faulting is mainly represented by a right lateral displacement faulting probably induced by oblique subduction of R, and N-S extensional faulting is thought to be originated by oblique subduction of Cocos plate beneath NA. The calc-alkaline nature of most of the volcanism is in accordance with a subduction process present off-shore since at least 10 m.y. ago and monogenetic volcanism is related to a highly fractured crust under an extensional regime since at least 6.7 Ma. The alkaline volcanism of the western arc can be explained by the interaction of a hot, short and young subducting slab and a highly fractured crust. Nevertheless, the alkaline volcanism of the southern part is geochemically different from the volcanism of the northwestern part, influenced by differences in convergence rate, which induce a difference in the amount of accreted sediments by the subducting slab. This produces a higher enrichment in the southeastern part of incompatible-elements (Allan *et al.*, 1991). The alkaline volcanism of the northwestern part is related to an oceanic island type source (Verma and Nelson, 1989) with a lower content of incompatible elements related with a low convergence rate and probably with a smaller amount of accreted sediments.

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BIBIOGRAPHY

ALLAN, J. F., 1986. Geology of the northern Colima and Zacoalco grabens, southwest Mexico: Late Cenozoic rifting in the Mexican Volcanic Belt. *G.S.A. Bulletin, 97,* 473-485.

ALLAN, J.F., S. A. NELSON, J. F. LUHR, I.S.E. CARMICHAEL, M. WOPAT and P. J. WALLACE, 1991. Pliocene-Holocene rifting and associated volcanism in southwest Mexico: an exotic terrane in the making. Mem. A.A.P.G., 47, 421-445.

ANDERSON, J. G., S. K. SINGH, J. M. ESPINDOLA and J. YAMAMOTO, 1989. Seismic strain release in the Mexican subduction thrust. *Phys. Earth Planet. Inter., 58,* 307-322.

ATWATER, T., 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *G.S.A. Bulletin, 81,* 3513-3536.

BANDY, W. T, W. C. HILDE, and J. BOURGOIS, 1988. Redefinition of the plate boundaries between the Pacific, Rivera, Cocos, and North American plates at the north end of the Middle America trench, abstract, *EOS Trans. AGU, 70,* 1342.

BOURGOIS, J., V. RENARD, J. AUBOUIN, W. BANDY, E. BARRIER, T. CALMUS, J. CARFANTAN, J. GUERRERO, J. MAMMERICKX, B. MERCIER DE LEPINAY, F. MICHAUD and M. SOSSON, 1988a. La jonction orientale de la dorsale Est-Pacifique avec la zone de fracture de Rivera au large du Mexique. C. R. Acad. Sci. París, 307, Ser. II, 617-626.

BOURGOIS, J., V. RENARD, J. AUBOUIN, W. BANDY, E. BARRIER, T. CALMUS, J. CARFANTAN, J. GUERRERO, J. MAMMERICKX, B. MERCIER DE LEPINAY, F. MICHAUD and M. SOSSON, 1988b. Fragmentation en cours du bord Ouest du continent Nord-Américain: Les frontières sous-marines du Bloc Jalisco (Mexique). C. R. Acad. Sci. París, 307, Ser. II, p. 1121-1130.

CARBALLIDO, E., 1991, Geología de la Isla Socorro, Islas Revillagigedo, México. Convención Nacional sobre la Evolución Tectónica de México, abstract, p. 20-22.

CEBULL, S. E. and D. H. SHURBET, 1987. Mexican volcanic belt: an intraplate transform? *Geofís. Int., 26,* 1-13.

CHAMBERLAIN, R. M., 1978. Structural development of the Lemitar Mountains, an intrarift tilted fault-block uplift, central New Mexico abstract. Program and Abstracts, 1978 International Symposium on the Rio Grande Rift, New Mexico Bureau of Mines and Mineral Resources, p. 22-24.

DAMON, P. E. , M. SHAFIQULLAH and K. F. CLARK, 1981. Age trends of igneous activity in relation to metallogenesis in the southern cordillera, *In:* W. R. Dickinson and W. D. Payne, eds., Relations of tectonics to ore deposits in the Southern Cordillera, Arizona Geological Society Digest, 14, p. 137-154.

DELGADO-GRANADOS, H., 1992. Geology of the Chapala rift. Tohoku University, Fac. of Science, Doctor of Science dissertation, 283 p.

DELGADO-GRANADOS, H. and J. URRUTIA-FUCUGAUCHI, 1986. Estructura del Graben de Chapala. Inst. de Geof. , UNAM., Com. Téc., Ser. Inv., 32, 12 p.

DE METS, C. and S. STEIN, 1990. Present-day kinematics of the Rivera plate and implications for tectonics in southwestern Mexico. *J. Geophys. Res., 95,* B13, 21931-21948.

DE PAOLO, D. J. and I. S. E. CARMICHAEL, 1980. Nd and Sr isotopes in the lavas of Colima, Mexico, abstract. GSA Abstracts with Programs, 12, 398.

DRUMMOND, K. J., chairman, 1981. Plate tectonic map of the Circum-Pacific region northeast quadrant, scale 1:10'000,000. Am. Assoc. Petrol. Geol., Tulsa, Okla., U.S.A.

EISSLER, H. K. and K. C. MC NALLY, 1984. Seismicity and tectonics of the Rivera plate and implications for the 1932 Jalisco, Mexico, earthquake. *J. Gephys. Res.*, *89*, 4520-4530.

ENGEBRESTON, D.C., A. COX and R. G. GORDON. Relative motions between oceanic and continental lates in the Pacific basin. Geol. Soc. Am., sp. paper 206, 6.

FAURE, M. and J. CHARVET, 1991. L'ouverture des mers marginales péri-asiatiques est-elle initiée par amincissement d'une croûte préalablement épaissie? C. R. Acad. Sci. Paris, t. 312, série II, 1367-1372.

FERRARI, L., G. PASQUARÉ and A. TIBALDI, 1990. Plio-Quaternary tectonics of the central Mexican Volcanic Belt and some constraints on its rifting mode. *Geofís. Int.*, *29*, 1, 5-18.

GASTIL, G. and W. A. JENSKY. 1973, Evidence for strike-slip displacement beneath the Trans-Mexican Volcanic Belt. Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System, R.L. Kovach and A. Nun, eds., Stanford Univ. Pub. Geol.. Sci., XIII, 171- 181.

GASTIL, G., D. KRUMMENACHER and W. A. JENSKY, 1978. Reconaissance geology of west-central Nayarit, Mexico. GSA Map and Chart Series MC24, 1:200 000.

GASTIL, G., D. KRUMMENACHER and J. MINCH, 1979. The record of Cenozoic volcanism around the Gulf of California. *G.S.A. Bull.*, *90*, 1, 839-857.

GILBERT, C. M., G. A. MAHOOD and I. S. E. CARMICHAEL, 1985. Volcanic stratigraphy of the Guadalajara area, Mexico. *Geofís. Int.*, *24*, 1, 169-192.

HEATHERINGTON, A. S. A. BOWRING and J. F. LUHR, 1987. Petrogenesis of alkaline and calc-alkaline volcanic rocks from the western Mexican Volcanic Belt-Pb Isotopes, abstract. G.S.A. Abstracts with Programs, 19, 698.

JOHNSON, C. A. and C. G. A. HARRISON, 1990. Neotectonics in central Mexico. *Phys. of the Earth and Plan. Int.*, *64*, 187-210.

KANAMORI, H. K., 1987. Importance of historical seismograms for geophysical research. *In:* Historical Seismograms and Earthquakes of the World, edited by W. H. Lee, H. Meyers, and K. Shimazaki. Academic Press San Diego, Calif., 16-33.

KARIG, D. E., 1971. Origin and development of marginal basins in the Western Pacific. *J. Geophys. Res.*, *76*, 2542-2561.

KLITGORD, K. D. and J. MAMMERICKX, 1982. Northern East Pacific Rise: Anomaly and Bathymetric framework. *J. Geophys. Res.*, *87*, B8, 6725-6750.

LARSON, R. L., 1972. Bathymetry, magnetic anomalies, and plate tectonic history of the mouth of the Gulf of California. *G.S.A. Bull.*, *83*, 3345-3360.

LE PICHON, X. and P. J. FOX, 1971. Marginal offsets, fracture zones, and early opening of the South Atlantic. *J. Geophys. Res.*, *87*, 6294-6308.

LUHR, J. F. and I. S. E. CARMICHAEL, 1982. The Colima volcanic complex, Mexico: Part III, ash and scoria fall deposits from the upper slopes of volcan Colima. *Contrib. Mineral. Petrol.*, *80*, 262-275.

LUHR J. F. and I. S. E. CARMICHAEL, 1985. Contemporaneus eruptions of calc-alkaline and alkline magmas along the volcanic front of the Mexican Volcanic Belt. *Geofís. Int.*, *24*, 1, 203-216.

LUHR, J. F. and P. LAZAAR, 1985. The southern Guadalajara volcanic chain, Jalisco, Mexico. *Geofís. Int.*, *24*, 691-700.

LUHR, J.F., S. A. NELSON, J. F. ALLAN and I. S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: manifestations of an incipient eastward sreading-ridge jump. *Geology*, *13*, 54-57.

LUHR, J. F., J. F. ALLAN, I. S. E. CARMICHAEL, S. A. NELSON and T. HASENAKA, 1989. Primitive calc-alkaline and alkaline rock types from the western Mexican Volcanic Belt. *J. Geophys. Res.*, *94*, 4515-4530.

MAMMERICKX, J., 1984. The morphology of propagating spreading centers; new and old. *J. of Geophys. Res.*, *89*, 1817-1828.

MAMMERICKX, J. and K. D. KLITGORD, 1982. Northern East Pacific Rise: evolution from 25 m.y. BP to the present. *J. of Geophys. Res.*, *87*, 6751-6759.

MC DOWELL, F. W. and R. P. KEIZER, 1977. Timing of mid Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlán, Mexico. *G.S.A. Bulletin*, *88*, 1479-1487.

MC KENZIE, D. P. and W. J. MORGAN, 1969. The evolution of triple junctions. *Nature*, *224*, 125-133.

MENARD, H. W., 1978. Fragmentation of the Farallon plate by pivoting subduction. *J. Geol.*, *86*, 99-110.

MOLNAR, P. and L. R. SYKES, 1969. Tectonics of the Caribean and Middle America regions from focal mechanisms and seismicity. *G.S.A. Bulletin, 80,* 1639-1684.

MOLNAR, P. and T. ATWATER, 1978. Interarc spreading and cordilleran tectonics as alternates related to the age of subducted ocean lithosphere. *Earth Planet. Sci. Lett., 41,* 330-340.

MOORE, D. G. and E. C. BUFFINGTON, 1968. Transform faulting and growth of the Gulf of California since the late Pliocene. *Science, 161,* 1238-1241.

MOOSER, F., 1969. The Mexican Volcanic Belt, structure and development, formation of fractures by differential crustal heating. Simposio Latinoamericano del Manto Superior, part 2, 15-22.

MOOSER, F., 1972. El Eje Volcanico Mexicano, debilidad cortical pre-Paleozoica reactivada, Soc. Geol. Mex. Resúmenes II Conv. Geol. Nal., 186-188.

MOOSER, F., A. E. M. NAIRN and J. F. W. NEGENDANK, 1974. Paleomagnetic investigations on the Tertiary and Quaternary igneous rocks, VIII. A paleomagnetic and petrologic study of volcanics of the Valley of Mexico. *Geol. Rundsch., 63,* 451-483.

NELSON, S.A., 1980. Geology and Petrology of volcán Ceboruco, Nayarit, Mexico. *Geol. Soc. Am. Bull.,* part II, 91, 2290-2331.

NELSON, S.A. and I. S. E. CARMICHAEL, 1984, Pleistocene to recent alkalic volcanism in the region of Sangangüey volcano, Nayarit, Mexico, *Contrib. Mineral. Petrol., 85,* 321-335.

NIETO, O. J., L. A. DELGADO and P. E. DAMON, 1981. Relaciones petrológicas y geocronológicas del magmatismo de la Sierra Madre Occidental y el Eje Neovolcánico, en Nayarit, Jalisco y Zacatecas. Asoc. Ing. Min. Met. y Geol. Mex., Mem. Téc. XIV, 327-361.

NIETO, O. J., L. A. DELGADO and P. E. DAMON, 1985. Geochronologic, petrologic, and structural data related to large morphologic features between the Sierra Madre Occidental and the Mexican Volcanic Belt. *Geofís. Int., 24,* 4, 535-550.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted ocean lithosphere. *G.S.A. Bull., 93,* 514-523.

NIXON, G. T., A. DEMANT, R. L. ARMSTRONG, and J. E. HARAKAL, 1987. K-Ar and geologic data bearing on the age and evolution of the Trans-Mexican Volcanic Belt. *Geofís. Int., 26,* 1, 109-158.

OTSUKI, K., 1989. Empirical relationships among the convergence rate of plates, rollback rate of trench axis and island-arc tectonics:"laws of convergence rate of plates". *Tectonophysics, 159,* 73-94.

PANTOJA-ALOR, J., 1983. Geocronometría del magmatismo Cretácico-Terciario de la Sierra Madre del Sur. *Bol. Soc. Geol. Mex., 44,* 1-20.

PASQUARÉ, G. and A. ZANCHI, 1985. Cenozoic volcanism and tectonics in west-central Mexico. *Rend. Accad. Naz. Lincci, 95,* 293-301.

PASQUARÉ, G., F. FORCELLA, A. TIBALDI, L. VEZZOLI and A. ZANCHI, 1986. Structural behaviour of a continental volcanic arc: the Mexican Volcanic Belt, in: F. C. Wezel (ed.), The Origin of Arcs. Elsevier, Amsterdam, 509-527.

PASQUARÉ, G., V. H. GARDUÑO, A. TIBALDI and M. FERRARI, 1988. Stress pattern evolution in the central sector of the Mexican Volcanic Belt. *Tectonophysics, 146,* 353-364.

ROSS, D. A. and G. G. SHOR, 1965. Reflection profiles accross the Middle America trench. *J. Geophys. Res., 70,* 5551-5572.

SERPA, L, C. KATZ and C. SKIDMORE, 1990. Potential field studies south of Volcán de Colima abstract, "Colima Volcano", Second National Reunion. Univ. de Colima, p. 36.

SHURBET, D.H. and S. E. CEBULL, 1984. Tectonic interpretation of the Trans-Mexican Volcanic Belt. *Tectonophysics, 101,* 159-165.

SINGH, S. K., L. PONCE and S. P. NISHENKO, 1985. The great Jalisco, Mexico earthquake of 1932 and the Rivera subduction zone. *Bull. Seism. Soc. Am., 75,* 1301-1314.

SLEEP, N. H. and M. N. TOKSÖZ, 1971. Evolution of marginal basins. *Nature, 233,* 548-550.

SUÁREZ, G. and S. K. SINGH, 1986. Tectonic interpretation of the Trans-Mexican Volcanic Belt-Discussion. *Tectonophysics, 127,* 155-160.

URRUTIA-FUCUGAUCHI, J., 1984. On the tectonic evolution of Mexico: paleomagnetic constraints, A.G.U. *Geodyn. Ser., 12,* 29-47.

URRUTIA-FUCUGAUCHI, J. and H. BÖHNEL, 1988. Tectonics along the Trans-Mexican volcanic belt according to palaeomagnetic data. *Phys. Earth and Planet. Int.*, *52*, 320-329.

UYEDA, S. and H. KANAMORI, 1979. Back arc opening and the modes of subduction. *J. Geophys. Res.*, *84*, 1049-1061.

VAN ANDEL, T. H., G. R. HEATH and T. C. MOORE, 1975. Cenozoic history and paleoceanography of the central equatorial Pacific Ocean: a regional synthesis of Deep Sea Drilling Project data. G.S.A. Memoir, 143, 134.

VENEGAS, S. S., J. F. HERRERA and F. R. MACIEL, 1985. Algunas características de la Faja Volcanica Mexicana y de sus recursos geotérmicos. *Geofís. Int.*, *24*, 1, 47-82.

VERMA, S. P. and S. A. NELSON, 1989. Isotopic and trace element constraints on the origin and evolution of alkaline and calc-alkaline magmas in the northwestern Mexican Volcanic Belt. *J. Geophys. Res.* *94*, 4531-4544.

WATKINS, N. D., B. M. GUNN, A. K. BASKI, D. YORK and J. ADE-HALL, 1971. Paleomagnetism, geochemistry, and potassium-argon ages of the Rio Grande de Santiago volcanics, Central Mexico. *Geol. Soc. Am. Bull.*, *82*, 1955-1968.

WOPAT, M. A. and I. S. E. CARMICHAEL, 1984. Geology of the Santiago Canyon near Tequila, Mexico. *EOS, Transactions A.G.U.*, *65*, 45, 1145.

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