AAPG Mem 47

Chapter 21

Pliocene-Holocene Rifting and Associated Volcanism in Southwest Mexico: An Exotic Terrane in the Making

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ABSTRACT

Three late Cenozoic rift systems—the northwest-trending Tepic-Zacoalco rift, the east-trending Chapala rift, and the north-trending Colima rift—intersect 50 km south-southwest of Guadalajara, Mexico to form a rift-rift-rift triple junction. These rifts structurally and topographically dominate the western part of the Mexican Volcanic Belt, a predominantly calc-alkaline continental arc. The Tepic-Zacoalco rift is the site of northwest-trending, late Cenozoic normal and right-lateral strike-slip faulting, whereas the Colima rift and its offshore extension (the Manzanillo Trough) overlies the subducting Rivera fracture zone, the boundary between the Rivera and Cocos plates. Together, the Colima and Tepic-Zacoalco rifts outline the Jalisco block. Associated with the rifts are 4.7 Ma to Holocene alkaline and peralkaline volcanic rocks, which are rarely found in continental volcanic arcs but are typical of continental rift zones. The alkaline volcanic rocks of western Mexico are thought to reflect rifting of the Jalisco block away from the Mexican mainland;

the Jalisco block should eventually accrete to the Pacific plate. This rifting event represents the latest in a series of northward-propagating spreading-ridge jumps along the East Pacific Rise. Ongoing rifting in southwest Mexico may serve as a model for the rifting of Baja California, and for the origin of microplates and exotic terranes.

INTRODUCTION

The east-trending Mexican Volcanic Belt (MVB) is a complex, continental volcanic arc associated with subduction of the Rivera and Cocos plates along the Middle-America Trench (Figure 1; Molnar and Sykes, 1969; Suarez and Singh, 1986). In its western part, the MVB is structurally and topographically dominated by three tectonic lineaments, all clearly visible on ERTS satellite images. These lineaments—the Chapala rift, the Tepic-Zacoalco rift, and the Colima rift— intersect 50 km south-southwest of the city of Guadalajara to form a rift-rift-rift (RRR) triple junction. These rifts are separated by angles of 100°, 115°, and 145°, counterclockwise from the Colima rift; the Colima and the Tepic-Zacoalco rifts outline the Jalisco structural block (Mooser, 1969; the Tepic-Colima block of Allan, 1986).

The Chapala rift trends east-west for 110 km, is 35 to 60 km wide, and contains Lake Chapala. The Tepic-Zacoalco rift, called the Tepic-Zacoalco graben by Demant (1981), is a series of pull-apart basins and grabens extending northwestward from the rift triple junction nearly to the coast bordering the Gulf of California. Significant late Cenozoic right-lateral strike-slip faulting is associated with this structure (Nieto-Obregon et al., 1985). The Colima rift is 20 to 65 km wide and extends southward for 190 km from the rift triple junction to the Pacific Coast. It represents a north-south rift of the east-west MVB, and overlies the subducting boundary between the Rivera and Cocos plates (Luhr et al., 1985).

These rifts appear to strongly control both the placement and style of volcanism in the western MVB. Large, calc-alkaline composite volcanic centers are mainly confined within grabens (Luhr et al., 1985), and alignments of cinder cones parallel to major faults are present, most commonly in the Tepic-Zacoalco rift (Nelson and Carmichael, 1984; Gilbert et al., 1985). Additionally, Pliocene to Holocene alkaline and peralkaline volcanic rocks, not commonly found in the axis of a volcanic arc, are associated with calc-alkaline rocks in the Colima and Tepic-Zacoalco rifts.

The Colima rift marks a major change in the nature of the western MVB volcanoes. To the west, composite volcanoes of the Tepic-Zacoalco rift are 50 km^3 or less in volume (Nelson, 1980; Demant, 1981). At the Colima rift, the MVB front, as represented by Volcán Colima and Nevado de Colima, is offset 90 km toward the trench relative to the volcanic front as expressed by more westerly volcanoes. The Colima volcanoes are an order of magnitude greater in volume (450 km^3; Luhr and Carmichael, 1980) than those to the northwest. Farther east, in the Michoacán-Guanajuato volcanic field (Hasenaka and Carmichael, 1985), cinder and lava cones of relatively small volume (less than several cubic kilometers) dominate the landscape.

It is our contention that these three rifts and their associated alkaline volcanism are interrelated, and that they are manifestations of ongoing rifting of the Jalisco block away from the North American plate. What follows is a review of the structure and geology of these rifts, and the petrology of their volcanic rocks. The reader should bear in mind that the geology of southwestern Mexico is still poorly known, other than descriptions of volcanic centers (Thorpe and Francis, 1975; Luhr and Carmichael, 1980, 1981, 1982; Mahood, 1980, 1981; Nelson, 1980; Nelson and Carmichael, 1984; Nelson and Sanchez-Rubio, 1986). Demant (1978, 1979, 1981) and Demant and Robin (1975) have provided a generalized overview of the western MVB, as have Johnson and Harrison (1989), who mapped the region by Landsat imagery. We have mapped in detail only the Northern Colima graben (Allan, 1984, 1985, 1986), the southeasternmost fault basin of the Tepic-Zacoalco graben (the Zacoalco graben; Allan, 1986), and parts of the Tepic-Zacoalco graben northwest of Guadalajara (M. A. Wopat, unpublished data), as have Nieto-Obregon et al. (1985). Gastil et al. (1978) have provided the most complete treatment to date of the geology of the westernmost MVB, and this work stands as a benchmark for understanding the pre-MVB geology. Structural interpretation of other areas is based primarily on mapping from aerial photographs and LANDSAT imagery, and from limited reconnaissance studies.

COLIMA RIFT

Structure and Nomenclature

The Colima rift (Figure 2) is composed of three structural and morphological entities—the Northern Colima graben, the Central Colima graben, and the Southern Colima rift. Future reference to the general term Colima graben will refer to both the Northern and Central Colima grabens. Previous discussions have referred to the Northern Colima graben as the Sayula depression (Diaz and Mooser, 1972) or the Sayula graben (Herrera, 1967). The Northern Colima graben is defined as extending 65 km south from the rift triple junction to the Colima volcanoes. It is 20 km wide and consists of a well-defined basin bounded by systems of inward-facing normal faults that trend north to north-northeast (Figure 3, cross-section C-C′).

The geology of the Northern Colima graben has been previously described by Allan (1986). High plateaus flank the graben, which is floored by lacustrine sediments and ephemeral lakes. The southern part of the plateau west of the graben appears to roughly define a horst, whereas the eastern plateau extends away from the graben as a broad region of highlands (Figure 3, cross-section C-C′). The geology of both areas flanking the graben is poorly understood. Scarp relief is invariably higher on the western side of the graben, with the disparity becoming greater to the north. The maximum relief on the western graben wall is about 1500 m and averages about 1000 m; it declines to a mini-

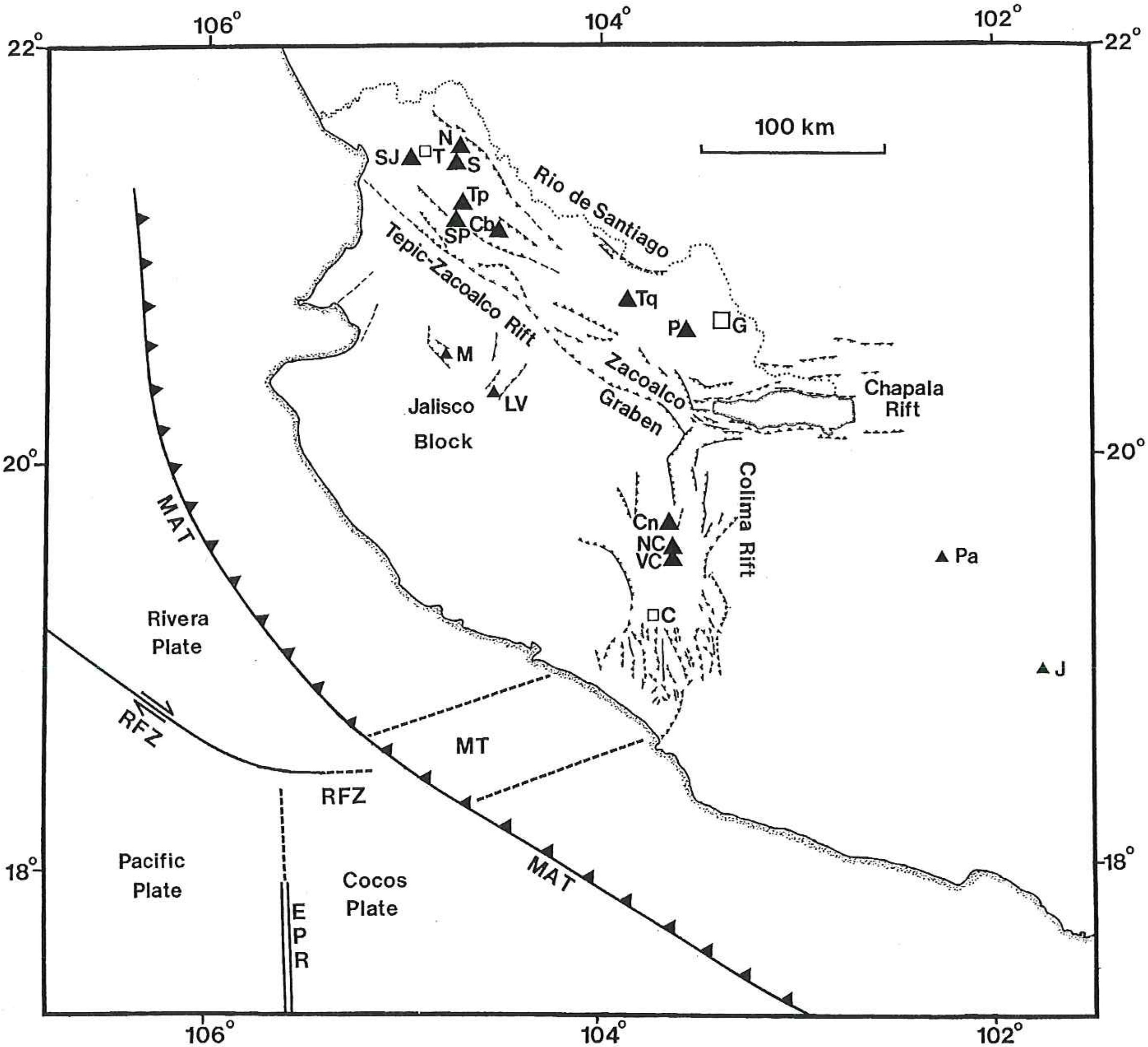

Figure 1—Location map showing the Pliocene to Recent rift structures discussed in the text. Normal faults are generalized and shown by lines with hachures on the down-thrown side when mapped from fieldwork or air photos; lineaments are shown as solid lines. Open squares refer to cities: G = Guadalajara, C = Colima, and T = Tepic. Closed triangles refer to volcanoes or volcanic fields: SJ = San Juan, N = Nevajas, S = Sanganguey, Tp = Tepetiltic, SP = San Pedro, Cb = Ceboruco, Tq = Tequila, P = Primavera, Cn = Cantaro, NC = Nevado de Colima, VC = Volcán Colima, M = Mascota volcanic field, LV = Los Volcanes volcanic field, Pa = Paricutin, and J = Jorullo. Also shown is the approximate location and extent of the Manzanillo Trough (MT), after Bandy et al. (1988), Bourgois et al. (1987), and G. Ness (personal communication, 1985). MAT = Mid-America Trench, RFZ = Rivera Fracture Zone, and EPR = East Pacific Rise. Map is modified by J. Allan and S. Nelson after Allan (1986).

mum of 300 m near the rift triple junction. Maximum relief on the eastern side is 1000 m but is typically less. Exposed normal fault surfaces in the Northern Colima graben dip more than 70° toward the graben axis; the steep scarps on either side of the graben are consistent with an interpretation of high-angle normal faulting. Where relief is low, the flanking plateaus have locally foundered near the edges, producing small grabens (Allan, 1986, his figure 3); nevertheless, the plateaus several kilometers away from the graben show no evidence for rotation (Allan, 1986). Allan (1985) estimated from three-dimensional, two-body modeling of gravity data that the depth of infilling sediments in the northernmost Colima graben is nearly a kilometer, and that the vertical offset is at least 2.5 km. Allan (1986) estimated that the Northern Colima graben represents 1.5 to 3.3 km of brittle extension, corresponding to 6 to 13% extension over the graben structure.

In the vicinity of Nevado de Colima, fault basins from the west (the Toliman graben of Herrera, 1967) and the east merge with the Northern Colima graben to form the 60-km-

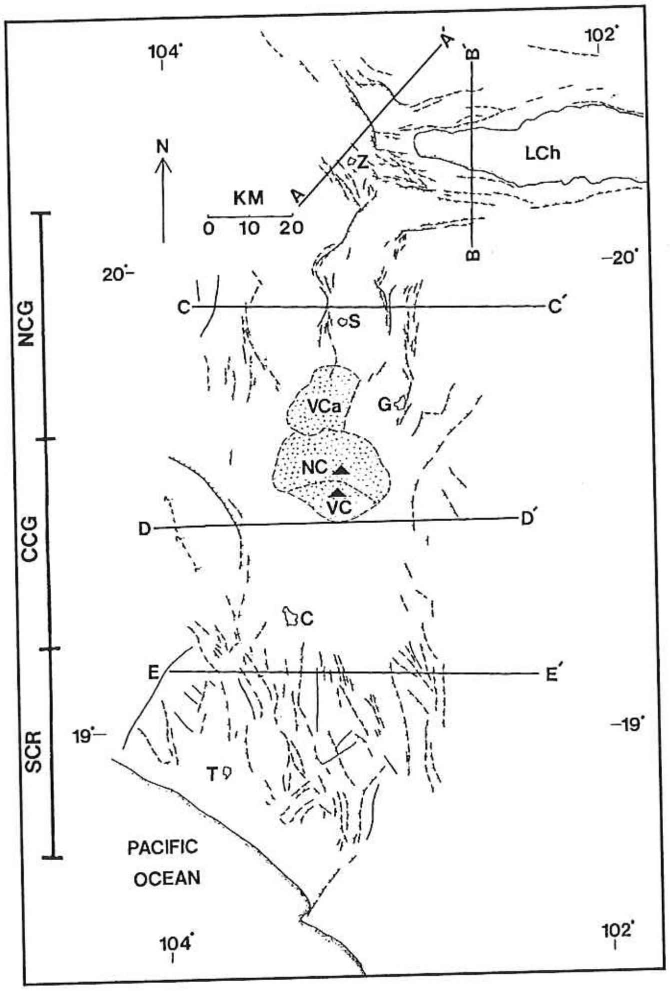

Figure 2—Generalized fault map of the Colima rift, western Chapala rift, and southern Zacoalco graben. Normal faults are shown as lines with hachures on the downthrown side, and are dashed where inferred from aerial photographs; lineaments, as deduced from aerial photographs, are shown as solid lines. NCG, CCG, and SCR refer to the morphological divisions Northern Colima graben, Central Colima graben, and Southern Colima rift, respectively. Large volcanoes (VCa = Volcán Cantaro, NC = Nevado de Colima, and VC = Volcán Colima), cities (Z = Zacoalco, S = Sayula, G = Ciudad Guzman, C = Colima, and T = Tecoman) and the western Lake Chapala (LCh) are also shown. Map compiled by J. Allan.

long, 50- to 60-km-wide Central Colima graben. This section of the Colima rift is a broad, open basin that contains the Quaternary volcanic massifs of Nevado de Colima and Volcán de Colima (Luhr and Carmichael, 1980; Robin et al., 1987), as well as scattered cinder cones (Luhr and Carmichael, 1981). The Central Colima graben is additionally floored by Pleistocene to Holocene volcanic avalanche and mudflow deposits associated with the large volcanoes (Luhr and Prestegaard, 1988), and by Pleistocene to Recent alluvial sediments. The basin is sharply demarcated to the west by steep, normal fault scarps with as much as 1700 m of relief. One of these scarps bounds a large apparent horst (Figure 3, cross-section D-D′). The eastern boundary of the Central Colima graben is diffuse and consists of scattered fault scarps and gently sloping erosional surfaces with eroded uplands beyond to the east (Figure 3, cross-section D-D′). The depth of infilling material and total amount of faulting in the Central Colima graben are unknown.

Approximately 5 km south of the city of Colima (Figure 2), the open, single-basin morphology of the Central Colima graben ends, and the complex structure of the Southern Colima rift begins. For the next 65 km southward, the Colima rift is represented by a 50- to 65-km-wide zone of block faulting that extends to the Pacific Coast. This zone is bounded on its eastern side by steeply dissected highlands (Figure 3, cross-section E-E′). The constituent tilted fault blocks trend predominantly north-south, are highly fractured, and are bounded on one or more sides by steep normal faults. Individual, coherent blocks range from less than 1 km to 25 km in length, and are as much as 12 km in width. Maximum relief may exceed 1000 m. The faulting is more complex in the Southern Colima rift near the Pacific Coast, as the southernmost fault blocks are smaller in size and more random in orientation, implying greater crustal disruption. At the coast is a 50-km-wide, broad alluvial plain bounded on the east and west by block faults, which represents the "mouth" of the Colima rift. The coastline marking the southern extent of this plain is straight with no protruding delta.

Ness et al. (1985), Bourgois et al. (1987), and Bandy et al. (1988) have recently given bathymetric evidence for offshore extension of the Colima rift. This extension, referred to as the Manzanillo Trough, Manzanillo Graben, and Colima Graben by the respective authors, is an elongate, 60-km-wide basin that extends from the onshore Colima rift south-southwestward to the Mid-America Trench (Figure 1). SEABEAM bathymetric data presented by Bourgois et al. (1987) and Bandy et al. (1988) indicate that the Colima rift may actually extend west of the trench, essentially marking the boundary between the Cocos and Rivera plates.

No attempts have been made to estimate the amount of extension represented by the Central Colima graben and the Southern Colima rift. Fault mapping for both areas was done primarily from aerial photographs at a scale of 1:50,000; the lack of ground checks for most faults precludes a thorough understanding of their geometry. Nevertheless, the broader extent of rifting implies that total extension in these areas may be greater than it is in the Northern Colima graben.

The lack of correlative volcanic units across the Colima rift structure makes the estimation of rift age problematic. Faulting rates derived from offset of dated volcanic rocks in the nearby Zacoalco graben (Allan, 1986), and applied to the total offset in the Northern Colima graben, imply that faulting has occurred for approximately 4 to 5 m.y. (million years). Discussion of shallow seismicity possibly associated with extensional activity in the Colima rift is absent from the literature (Singh et al., 1984), although large, subduction-related earthquakes have been described (Reyes et al., 1979; Eissler and McNally, 1984; Singh et al., 1985). Nevertheless, the presence of Y-shaped valleys, steep, triangular-faceted fault scarps truncating spur ridges, and north-south-aligned fault scarplets cutting colluvium, alluvium, and unconsolidated volcanic ash indicate that normal faulting in the northern Colima rift has continued into the late Pleistocene and probably into the Holocene (Allan, 1986).

Geology

Late Miocene-Holocene volcanic rocks (primarily lavas) are dominant in the walls of the Northern Colima graben

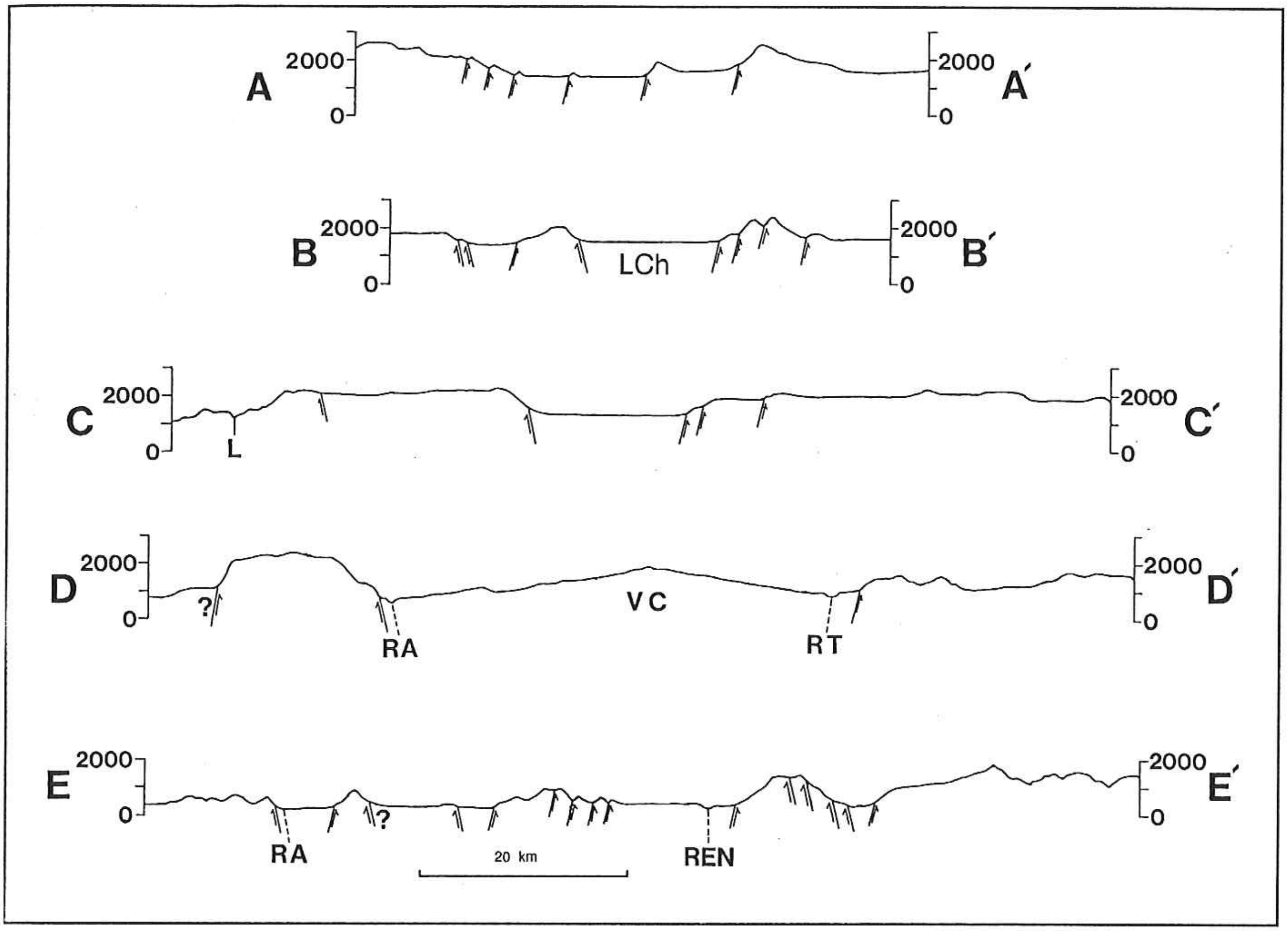

Figure 3—Cross sections through Zacoalco graben (A-A′), Chapala rift (B-B′), and Colima rift (C-C′, D-D′, E-E′). Locations shown on Figure 2. Vertical exaggeration 2.5X. LCh = Lake Chapala, VC = Volcán Colima, RA = Rio Armeria, RT = Rio Tuxpan, REN = Rio El Naranjo, L = lineament shown on Figure 2.

(Allan, 1986). They unconformably overlie shallow-dipping, interbedded volcanic breccias, conglomerates, wackes, argillites, and shales; massively bedded, blue-gray to tan, micritic to biomicritic limestone; and a 69-m.y.-old granodiorite stock (Allan, 1986). Although the ages of the sedimentary rocks in the graben wall have not been directly determined, they likely range from Jurassic to Eocene (Allan, 1986). Thicknesses of the volcanic rocks in the graben walls increase northward, and range from a thin veneer overlying the sedimentary rocks near the Colima volcanoes and Volcán Cantaro to a thickness of nearly 1 km near the end of the northern graben. The sedimentary rocks may also form vertically extensive outcrops; the topographic relief shown by clastic rocks near Sayula (Figure 2) is nearly 700 m (Figure 3, cross-section C-C′), whereas the limestones exhibit a maximum relief of 400 m (Allan, 1986).

Our knowledge of the rocks cropping out in the Central Colima graben and Southern Colima rift is poor, and is based on limited reconnaissance and the sparse available literature. These rocks appear to be Jurassic to Eocene volcaniclastic and clastic sediments interbedded with limestones and scattered lavas, tuffs, and ash flows (Pantoja-Alor, 1983; Pantoja-Alor and Estrada Barreza, 1986; J. Pantoja-Alor, oral and written communication, 1983). They are locally intruded by granitic plutons of Cretaceous to early Tertiary age (Pantoja-Alor et al., 1978; Damon et al., 1981; Pantoja-Alor, 1983). Silicic ash-flow tuffs, similar to those of the mid-Tertiary Sierra Madre Occidental province (McDowell and Keizer, 1977), may also form part of the sequence. Silicic ash-flow tuffs, some dated as Cretaceous, have been observed in reconnaissance traverses west of the Colima rift in various areas of the Jalisco block.

Few age determinations from this region have been reported in the literature. The 1700-m-high fault scarp northwest of the city of Colima (Figure 2; Figure 3, cross-section D-D′) appears to consist entirely of shallow-dipping micritic and biomicritic limestone of Late Cretaceous age (La Madrid Formation, J. Pantoja-Alor, oral and written communication, 1983); this limestone is similar to others that crop out in the Northern Colima graben. Clastic and volcaniclastic rock sequences, described as the late Aptian-early Albian Encino Formation, have been detailed from the Encino mine, approximately 30 km east of the city of Colima (Pantoja-Alor et al., 1978; Figure 2), and from Cerro de Tuxpan, 16 km southeast of Ciudad Guzman (Buitron et al., 1978). The Encino Formation is similar to the undated clastic and volcaniclastic rocks in the Northern Colima graben.

Petrology of Volcanic Rocks

Since the late Miocene, a great diversity of magma types has erupted within the Colima rift (Allan, 1986). This diversity is indicated by representative whole-rock analyses in Table 1 and portrayed by Figures 4 and 5. Alkaline rocks occur throughout the northern 90 km of the Colima rift, and have erupted from small (<1 km^2 in plan view) cinder or lava cones. They comprise less than 5% of the total volume of volcanic rocks in the Colima rift. Calc-alkaline varieties have erupted from large stratovolcanoes (Volcán Colima, Nevado de Colima, and Volcán Cantaro), domes, and lava and cinder cones. Alkaline and calc-alkaline rocks crop out next to one another in the field, and scoriae representing pre-eruptive mixtures of alkaline and calc-alkaline magma were erupted from Volcán Colima in the late Pleistocene (Luhr and Carmichael, 1982). K-Ar dates indicate that there was a geographically widespread "pulse" of alkaline volcanism from 4.6 to 3.9 Ma, with intermittent alkaline volcanism until renewed activity in the late Pleistocene and Holocene (Luhr and Carmichael, 1981; Allan and Luhr, 1982; Allan, 1986). K-Ar dates of calc-alkaline volcanic rocks indicate activity from 10.1 Ma to the present, considering the 1982 eruption of Volcán Colima (Allan and Luhr, 1982; Allan, 1986; Robin et al., 1987). Thus, alkaline and calc-alkaline magmatism have been coeval in the Colima rift since the early Pliocene.

The volcanic rocks from the Colima rift may be organized into evolved and primitive groups (Figure 4). The primitive samples all have relatively high Mg/(Mg+Fe) and high compatible-element contents (such as Cr and Ni), and are thought to represent mantle partial melts that have undergone little evolution since their generation, using the compositional criteria of Sato (1977) and Green (1971). Primitive varieties include ne-normative basanites, leucite basanites, sanidine- and phlogopite-bearing trachybasalts and lamprophyres (minettes), and hy-normative calc-alkaline basalts. The compositional and mineralogical continuity between the differing basic rock types often makes classification difficult (Figure 5). Late Pleistocene examples of both alkaline and calc-alkaline primitive volcanic rocks were described by Luhr and Carmichael (1981).

An alkaline phlogopite-kalsilite-ankaratrite, described by Allan and Carmichael (1984) from the Northern Colima graben, is unlike any of the above rocks. It contains both nepheline and kalsilite ($KAlSiO_4$) and is similar to the potash-ankaratrites and mafurites from the western rift of the East African rift (Holmes and Harwood, 1932; Holmes, 1952a, b; Sahama, 1954, 1962; Brown, 1971). Kalsilite-bearing lavas, to our knowledge, are previously unknown from volcanic arcs associated with subduction.

The evolved volcanic rocks represent magmas that have undergone significant evolution from primitive parental compositions. The most striking of these are the alkaline, phlogopite- and hornblende-bearing lamprophyres, which are notable because of their high incompatible-element contents, and because their feldspars (sanidine or sanidine and plagioclase) are confined to the groundmass (Allan and Carmichael, 1984). A chemical and mineralogical continuum exists within these evolved rocks. This continuum extends to hornblende-bearing high-K andesites (Gill, 1981), which differ from the lamprophyres by containing microphenocrysts of plagioclase and lower amounts of incompatible elements. Other high-K andesites lack hornblende. The entire lamprophyre suite may be derived by crystal fractionation of the primitive phlogopite-lamprophyres, combined in some instances with crustal contamination or magma mixing (Allan and Carmichael, 1984). Derivation of the high-K andesites is problematic, but they may be genetically related to the trachybasalts. Other volcanic rock types in the rift include dacites and medium-K andesites (Gill, 1981), such as those from Volcán de Colima (Luhr and Carmichael, 1980), which are likely derivatives of calc-alkaline basalts (Luhr and Carmichael, 1981). We emphasize the abundance of hydrous phenocrysts in many alkaline (phlogopite- and/or hornblende-bearing) and calc-alkaline (biotite- and/or hornblende-bearing) rocks from the Colima rift, indicating high water contents in all magma types.

K-Ar dating and field mapping within the Colima rift indicate that the most recent alkaline lavas (those less than about 1 m.y. in age) are the most primitive, and that the older alkaline lavas show evidence of much more crystal fractionation and crustal assimilation. The most primitive example of calc-alkaline volcanism within the rift is also of late Pleistocene age (Luhr and Carmichael, 1981). Additionally, before the development of the 1.0- to 1.2-m.y.-old Volcán Cantaro complex (Allan, 1986), volcanism within the Colima rift was confined to relatively small lava and cinder cones. Large, composite volcanoes have only been constructed within the rift since the Pleistocene.

CHAPALA RIFT

The Chapala rift (Figures 1, 2) is composed of an inner graben 10 to 30 km wide and 110 km long (previously referred to by many authors as the Chapala graben), bounded by block faults and containing the shallow Lake Chapala. Associated parallel block faults and fault basins widen the structure to 50 to 60 km (Figure 3, cross-section B-B'). Delgado-Granados and Urrutia-Fucugauchi (1985) have recently begun mapping the Chapala rift structure and suggest that associated faulting may extend at least another 90 km eastward. Other interpretations derived from LANDSAT Thematic Mapper images suggest that faulting associated with the Chapala rift (the Chapala-Tula fault zone, or CTFZ) may extend nearly 400 km eastward from the rift triple junction (Johnson, 1986, 1987; Johnson and Harrison, 1989). Most faults dip toward the center of the rift. Felsic tuffs that crop out north of Lake Chapala in the Chapala rift dip away from the rift center, which is consistent with rotation by block faulting. Numerous unmapped lineaments visible on imagery at 1:250,000 scale with 100-m contours extend 10 km north of any mapped faults. The rift is best defined closest to the rift triple junction; average scarp height decreases and the width of the rift increases eastward. Maximum scarp relief is 900 m.

Little has been published about the geology of the Chapala rift; Delgado-Granados and Urrutia-Fucugauchi (1985, 1986) and Johnson (1986, 1987) recently presented structural and stratigraphic data, and Diaz and Mooser (1972), Mooser (1972), and Johnson and Harrison (1989) provided brief structural overviews. Our limited reconnaissance mapping indicates that most, if not all, rock that crops out in the Chapala rift is volcanic. Basalt and andesite lava flows, volcanogenic sediments, and felsic tuffs have been observed. Numerous basaltic to andesitic lava and cinder cones of obvious late Quaternary age occur within the rift. Unpublished K-Ar dates on an andesite lava (lat. 20°47'N, long. 102°46.5'W) and a felsic ash-flow tuff (lat. 20°20.9'N, long. 103°10.3'W) from the Chapala rift are 3.29 ± 0.26 and 4.20 ± 0.11 Ma, respectively (P. Damon, written communication, 1985). Other dates on nearby volcanic rocks (Watkins et al., 1971; Mahood and Drake, 1982; Gilbert et al., 1985; Allan, 1986; Nixon et al., 1987) support the contention that most volcanic rock in the Chapala rift is Pliocene to Pleistocene in

Table 1. Representative whole-rock analyses.

Number	B116	B60	B43	7E	508	22E	Col9	6	40	121A	107	1	323	4AS	20	19
Rock Type	PKA	PL	HL	PL	B	CAB	A	AB	HAW	TR	PT	A	D	PL	HKA	A
Location	CR	CR	CR	CR	CR	CR	CR	TCR	TCR	TCR	TCR	TCR	TCR	M	M	M
							Analyses in percent									
SiO_2	40.78	50.72	52.26	48.20	48.45	49.42	61.02	47.54	47.05	61.90	71.83	60.90	65.80	49.27	55.10	55.81
TiO_2	3.54	1.70	1.33	1.64	1.01	0.77	0.64	2.46	3.62	0.47	0.12	1.21	0.73	1.75	0.91	0.72
Al_2O_3	9.15	13.41	14.48	11.62	11.85	16.92	17.72	17.54	15.67	15.64	8.20	16.69	16.30	12.70	17.20	17.52
Fe_2O_3	11.22	5.65	5.60	4.22	4.10	4.40	1.77	3.36	4.71			1.41		5.45	2.71	2.10
FeO[T]	3.19	1.90	1.66	3.27	3.78	5.30	3.46	6.60	8.80	[8.77]	[6.67]	4.31	[3.32]	2.48	3.47	4.21
MnO	0.18	0.10	0.12	0.11	0.14	0.15	0.10	0.18	0.23	0.25	0.33	0.12	0.13	0.14	0.12	0.12
MgO	8.28	5.67	6.11	11.81	15.25	9.27	2.76	6.64	4.82	0.04	0.04	2.22	0.50	9.52	5.49	5.98
CaO	6.67	7.91	8.02	8.32	8.86	10.12	5.92	8.59	9.14	0.55	0.11	5.10	2.55	7.66	7.16	7.02
Na_20	2.05	2.30	4.23	3.28	2.12	2.49	4.70	3.36	3.66	4.40	7.11	4.79	5.10	2.89	4.10	4.16
K_20	5.73	4.95	3.46	3.58	3.05	0.65	1.40	1.14	1.00	5.00	4.03	2.19	2.78	5.17	2.28	1.02
P_20_5	0.75	1.46	1.13	1.32	0.71	0.20	0.21	0.41	0.74	0.11	0.02	0.33	0.18	1.28	0.48	0.31
H_20+ [LOI]	4.90	2.76	1.15	1.59	0.31	0.06	0.06	1.27	0.39			0.19	[2.05]			
H_20-	2.93	1.07	0.16	0.37	0.24	0.13	0.10	0.63	0.22			0.07				
Total	99.37	99.60	99.55	99.33	99.87	99.88	99.86	99.72	100.05	97.13	98.46	99.53	99.50	98.31	99.02	98.97
							Analyses in parts per million									
V	307	109	119	265	210	196	150	296	493			107	52			
Cr	145	137	172	265	1280	196	25	203	30			5				
Ni	122	118	136	436	506	221	10	57		10	n.d.	65	3	312	100	145
Rb	45	45	30	73	21	7	19	16	16	51	289	26	45	65.5	24.3	8.4
Sr	3280	2870	2550	3079	1715	444	568	461	465	31	10	500	461	2940	1495	834
Y	15	29	16	29	16	18	17	43	31	254	277	31	35	23	19	19
Zr	307	321	255	554	215	92	152	210	221	445	2054	235	245	561	205	124
Nb	33	23	18	16	6			25	28					17		7
Ba	3120	3340	1350	4230	1590	161	510	122	335	1585	89	921	1265	3331	1138	564
La	84	89	55	82.3	30.9	9.3	12.4	20.3	24.2	254	257	28	47	71	27	13
Ce	180	183	121	188	68	22	27.1	46.1	54.8	128	234	58.9	84	126	65	40
Nd	59	91	64	93	36	12	12	27.1	31.5			28.1		57	6	14
Sm	6.52	12.84	8.9	15.2	6.78	2.96	2.93	5.8	7.2			5.65		11.9	5 1	29
Eu	1.6	3.35	2.42	4.5	2.08	1.13	0.98	2.38	2.88			1.66				
Tb	0.49	1.09	0.69	1.2	0.83	0.61	0.43	1	1.11			0.79				
Yb	0.89	1.36	1.27	1.74	1.3	2.08	1.83	3.15	2.99			2.76				
Lu	0.13	0.18	0.16	0.18	0.14	0.26	0.25	0.44	0.41			0.39				
Hf	8.7	9.4	6.7	17.9	7.1	2.6	3.5	5.14	4.75			5.98				
Ta	1.99	1.03	0.6					1.92	2.35			1.1				
Th	3.51	8.57	3.76	7.13	1.24	0.44	2.01	2.08	2.3			3.28				
U	1.38	0.72	1.15	2.41	1.03	0.33	0.78	0.48	0.69			1.03				
Reference	1	1	1	2	2	2	3	4	4	6	6	7	8	5	5	5

Rock Types are: PKA = Phlogopite-Kalsilite-Ankaratrite; PL = Phlogopite Lamprophyre; HL = Hornblende Lamprophyre; B = Basanite; AB = Alkaline Basalt; CAB = Calc-Alkaline Basalt; HAW = Hawaiite; TR = Trachyte; HKA = High-K Andesite; A = Andesite, D = Dacite; and PT = Pantellerite. Locations are: CR = Colima rift; TCR = Tepic-Chapala rift; and M = Mascota. References are: 1 = Allan and Carmichael (1984); 2 = Luhr and Carmichael (1981); 3 = Luhr and Carmichael (1980); 4 = Nelson and Carmichael (1984); 5 = unpublished data, I.S.E. Carmichael and J. Luhr, analysts; 6 = Hegre (1985); 7 = Nelson (1980); and 8 = Nelson and Livieres (1986). FeO analyses in brackets represent total iron analyzed as FeO. Loss on ignition (LOI) analysis also given in brackets. n.d. = not detected.

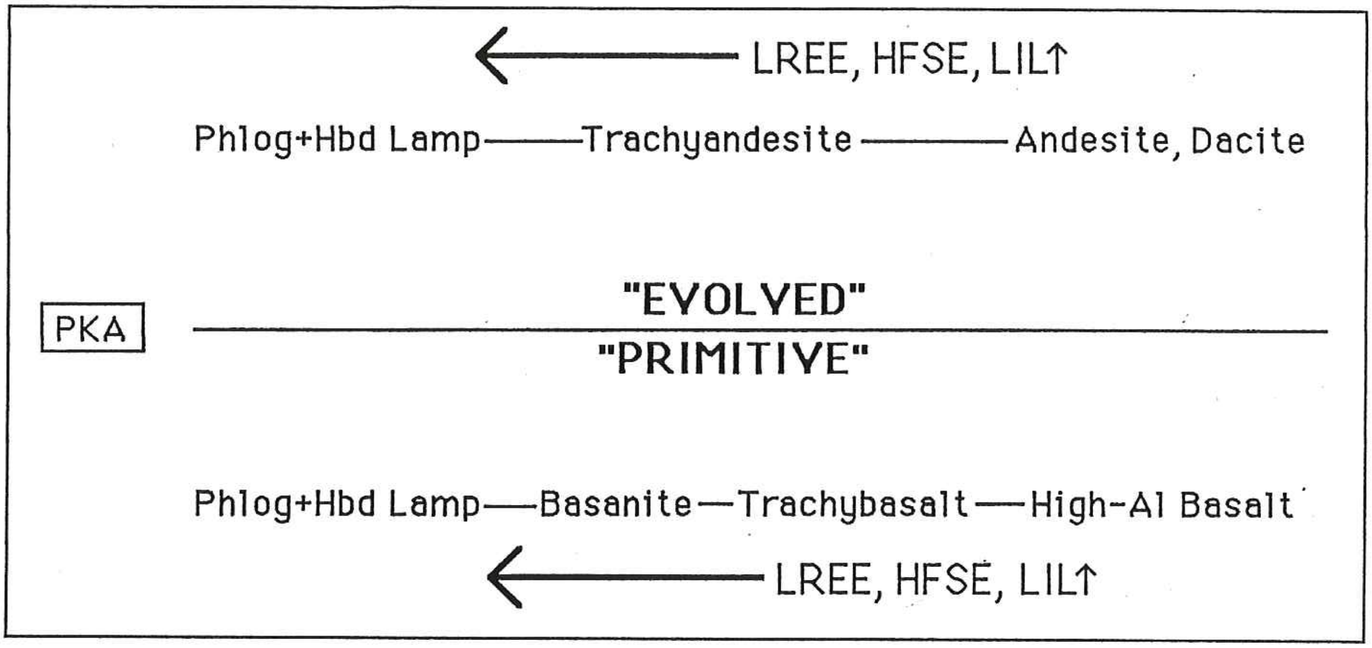

Figure 4—Graphic illustration of compositional diversity of lavas erupted in the Colima rift. Incompatible-element acronyms are: LIL, large-ion lithophile elements; HFSE, high-field-strength elements; and LREE, light rare-earth elements. Arrows indicate general direction of increasing incompatible-element content. PKA refers to phlogopite-kalsilite-ankaratrite; lines between rock types represent compositional continuums.

age. The oldest volcanism is represented by gently dipping basaltic lavas cut by faulting in the northeast, outlying region of the Chapala rift. A sample of these basalts was dated at 10.20 ± 0.30 Ma by Nixon et al. (1987).

The absolute ages and total offsets of the faults comprising the rift are unknown. Diaz and Mooser (1972) have suggested that the earliest faulting occurred in the Pliocene. Nevertheless, the steepness, linearity, and lack of dissection of fault scarps, together with abundant evidence for faulting of lava and cinder cones of unquestionable Pleistocene age (strikingly seen north of Lake Chapala), indicate that faulting in the Chapala rift has likely extended into the late Quaternary.

TEPIC-ZACOALCO RIFT

Structure

The Tepic-Zacoalco rift is 250 km long and 45 to 65 km wide (Figure 6) and consists of a series of pull-apart basins and grabens having as much as 1000 m of relief and extending from the rift triple-junction northwestward to the Pacific Coast. Broad lakes, alluviated plains, and Pliocene to Holocene volcanic rocks floor the basins. North of Volcán Tequila, the rift is filled by Pleistocene alkali basalts, forming a plateau. Most of the faults trend northwest. For the westernmost 150 km of the rift, they are largely confined between two general bounding fault systems, the Mazatan fault system to the south and the Pochotitan fault system to the north (Figure 6). About 55 km east of Volcán Ceboruco, the northern bounding fault for the rift is offset slightly northward, where it continues southeastward for 50 km before disappearing under tephra of the Guadalajara plain. As the Rio Santiago leaves the eastern end of Lake Chapala, it follows a course northeast of the Pochotitan fault system. Near the latitude of Volcán Ceboruco, however, the Rio Santiago jogs westward and follows the Pochotitan system. The Pochotitan fault system truncates older, north-northeast-trending normal faults that dip to the west and extend northward. The southeasternmost part of the rift is represented by the Zacoalco graben, described separately below. Cross-sections showing the rift structure are given in Figure 7.

The north-bounding faults of the rift contain both dip-slip and strike-slip components. The directions and amounts of offset are difficult to constrain because of the Pliocene to Holocene volcanic cover, which fills the valleys south of the fault system. Rocks of probable Pliocene age have been downfaulted to the southwest along the fault north of Volcán Ceboruco (Figure 7, cross-section C-C′), and pre-Pliocene rocks northeast of the Pochotitan fault system have been tilted by faulting so that they dip to the northeast.

The bounding faults near the Rio Santiago north of Volcán Tequila (Figure 6) have been mapped in detail. East of Volcán Ceboruco, where the major bounding fault of the Tepic-Zacoalco rift shifts outward to the northeast, the rift is bounded by the 4-km-wide, northwest-trending Cinco Minas graben. The 400-m-high, northeast-bounding fault scarp of the graben contains vertical striations and separates 20-m.y.-old ignimbrites on the upthrown block from 3.8-m.y.-old alkaline basalts in the graben (K-Ar dates from Nieto-Obregon et al., 1985). On the southwest side of the graben, alkaline basalts estimated from stratigraphy to be about 4 m.y. old cap both the upthrown and downthrown blocks and have been offset 100 m or more. The northeast-bounding fault can be traced for 15 km northwestward from the Rio Santiago canyon, and forms the northern boundary of the canyon for another 25 km to the southeast. Consequently, the north wall of the canyon northeast of Volcán Tequila is 600 to 800 m higher than the young basalt plateau south of the river, and total vertical offset may be as much as 900 m. In the same area west of the Santa Rosa dam (SRD,

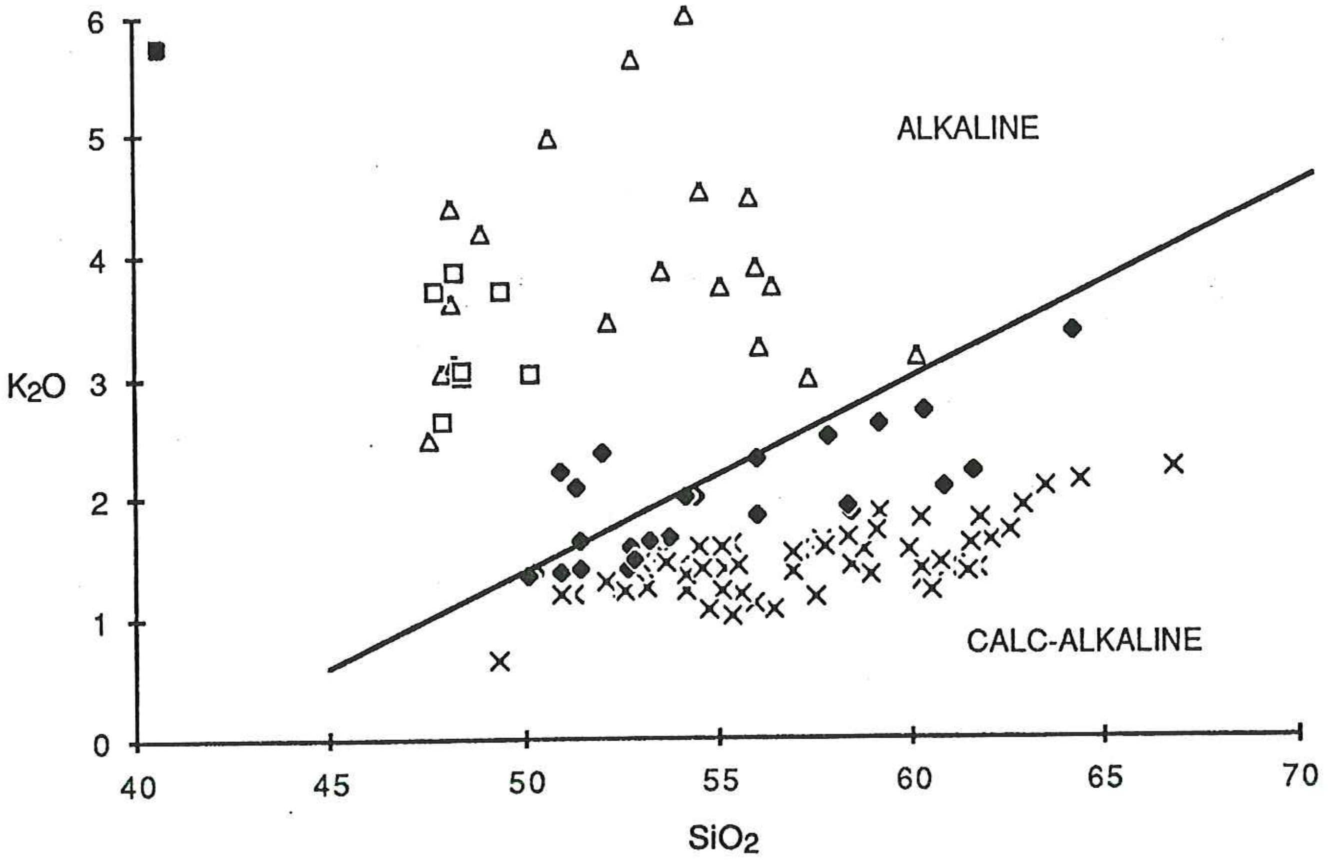

Figure 5—Compositional definition of alkaline and calc-alkaline lavas used in this paper. Open triangles represent lamprophyres; open squares represent basanites and leucite basanites; crosses represent calc-alkaline basalts, andesites, and dacites; solid diamonds represent trachybasalts and high-K andesites or trachyandesites; and the solid squares represent the phlogopite-kalsilite-ankaratrite. Compositions plotted represent whole-rock data from Luhr and Carmichael (1980, 1981), Allan (1984), Allan and Carmichael (1984), and unpublished data. Data plotted as weight %.

Figure 6), a 400-m-thick early Pliocene sequence of pumiceous tuffs, lacustrine sediments, and intercalated basalts is exposed in the southern canyon wall. This sequence is 1000 m higher in the northern canyon wall, where it is only 100 m thick and caps the stratigraphic sequence. These relationships indicate that there may have been significant vertical relief by early Pliocene time and that there has been significant vertical faulting since then (Nieto-Obregon et al., 1985). Moreover, the underlying bimodal ash-flow tuff sequence of late Miocene age is exposed only in the northern canyon wall. Three kilometers east of the Santa Rosa dam, well-bedded tuffs and lavas of early Pliocene age on the north side of the canyon are vertically offset 400 m. At the southeast end of the Cinco Minas graben (CM, Figure 6), where the trace of the fault cuts Pleistocene lavas near the Rio Santiago, 0.90-m.y.-old lavas show only about 10 m of vertical offset. We therefore conclude that most of the observed vertical movement in this area surrounding the Rio Santiago occurred between early Pliocene and early Pleistocene times, with only small amounts of vertical faulting since.

A growing body of evidence indicates significant late Cenozoic, right-lateral strike-slip movement along the northern boundary faults of the Tepic-Zacoalco rift. Very large outcrops (some at least 100 m long) that exhibit horizontal slickensides have been preserved in the Santiago canyon north of Volcán Tequila. They are particularly well developed in silicified rhyolite just west of the Santa Rosa dam, 20 km northeast of Volcán Tequila. Nieto-Obregon et al. (1985) mapped numerous fractures and small faults oblique to the major northwest-trending faults along and adjacent to the Rio Santiago canyon, and interpreted them as riedel shears associated with major right-lateral faulting. A 150-m-high lava cone found in the canyon about 3.5 km northwest of the Santa Rosa dam is additional evidence of strike-slip movement. This 0.36-m.y.-old lava cone (K-Ar; unpublished data of M. Wopat) has been cut in half by faulting. Rocks almost identical in appearance and composition to those in this cone occur 0.7 km to the northwest on the opposite side of a pair of northwest-trending faults, implying approximately 0.2 cm/yr of right-lateral displacement since eruption. Recent faulting has been measured by triangulation at the Santa Rosa dam. Field evidence shows that the dam is built on a 400-m-wide shear zone of mylonitized rhyolite. Nieto-Obregon et al. (1985) reported that triangulation data collected adjacent to the dam between 1964 and 1981 show that the dam and adjacent canyon walls move southwestward 0.2 cm/yr. They interpreted the movement as caused by right-lateral displacement along an active strike-slip fault. Gastil and Jensky (1973) and Gastil et al. (1978) proposed significant right-lateral movement along the Tepic-Zacoalco rift to account for the offset in plutonic,

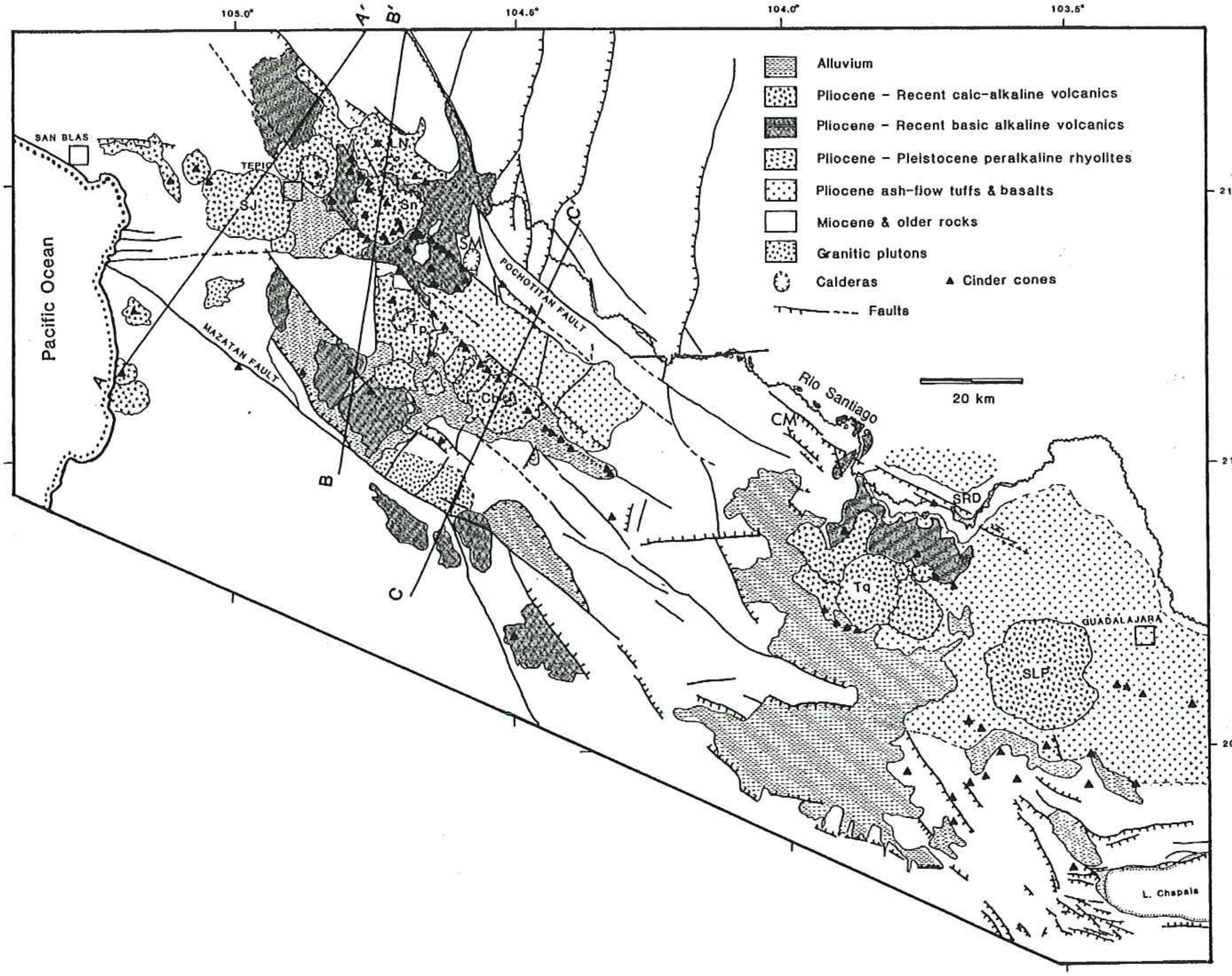

Figure 6—Structural and lithological map of Tepic-Zacoalco rift. Hachures represent downthrown side of inferred or mapped normal faults, which are dashed where uncertain. Volcanic centers shown are: SJ = San Juan, Sn = Sanganguey, LN = Las Navajas, Tp = Tepetiltic, Cb = Ceboruco, Tq = Tequila, and SLP = Sierra La Primavera. Santa Rosa dam (SRD), Cinco Minas graben (CM), and Santa Maria del Oro caldera (SM) are also shown. Map compiled by S. Nelson.

metallogenic, and other geologic trends in southwest Mexico. Preliminary paleomagnetic data from the Rio Grande de Santiago near Guadalajara indicates clockwise rotation of the paleomagnetic vectors with respect to the current magnetic field, supporting the evidence for right-lateral strike-slip movement farther west (J. Urrutia-Fucugauchi, written communication, 1987). In contrast, right-lateral displacement along the MVB east of the Tepic-Zacoalco rift is not supported by paleomagnetic data (Urrutia-Fucugauchi, 1981, 1983a, b). Here, interpretation of LANDSAT imagery by Johnson (1986, 1987) and Johnson and Harrison (1989) suggests left-lateral transtension in the easternmost extension of the Chapala rift, along the Chapala-Tula fault zone west of Morelia. This interpretation is consistent with kinematic plate modeling (DeMets and Stein, in press).

The Mazatan fault system, which marks the southern boundary of the Tepic-Zacoalco rift, has juxtaposed pre-Cenozoic rocks against Miocene and younger rocks at its western end (Figure 7, cross-sections B-B' and C-C'). In the area south of the Sierra Guamuchil, the fault system has cut flat-lying basaltic rocks of probable Pliocene age, and appears to have triggered landslides. In the same area, the Mazatan fault truncates two older, north-northwest-trending faults, and truncates granites and metamorphic rocks that crop out only north of the fault. Much more detailed mapping of the Mazatan fault system is necessary before the relative amounts of dip-slip and strike-slip motion along its length can be estimated.

Between the Pochotitan and Mazatan fault systems are other northwest-trending faults and lineaments. One such fault north of Volcán Ceboruco has apparently dropped the block containing the volcano down to the southwest, cutting ash-flow tuffs of apparent Pliocene age. Northwest-trending lineaments include cinder cone alignments through the Ceboruco, Sanganguey, and Las Navajas volcanoes. Such alignments of eruptive vents indicate tectonic stress conditions (Nakamura, 1977, Nakamura et al., 1977) and imply that the direction of least compressive stress is oriented northeast, which is consistent with the development of pull-apart basins by northwest-trending right-lateral faulting.

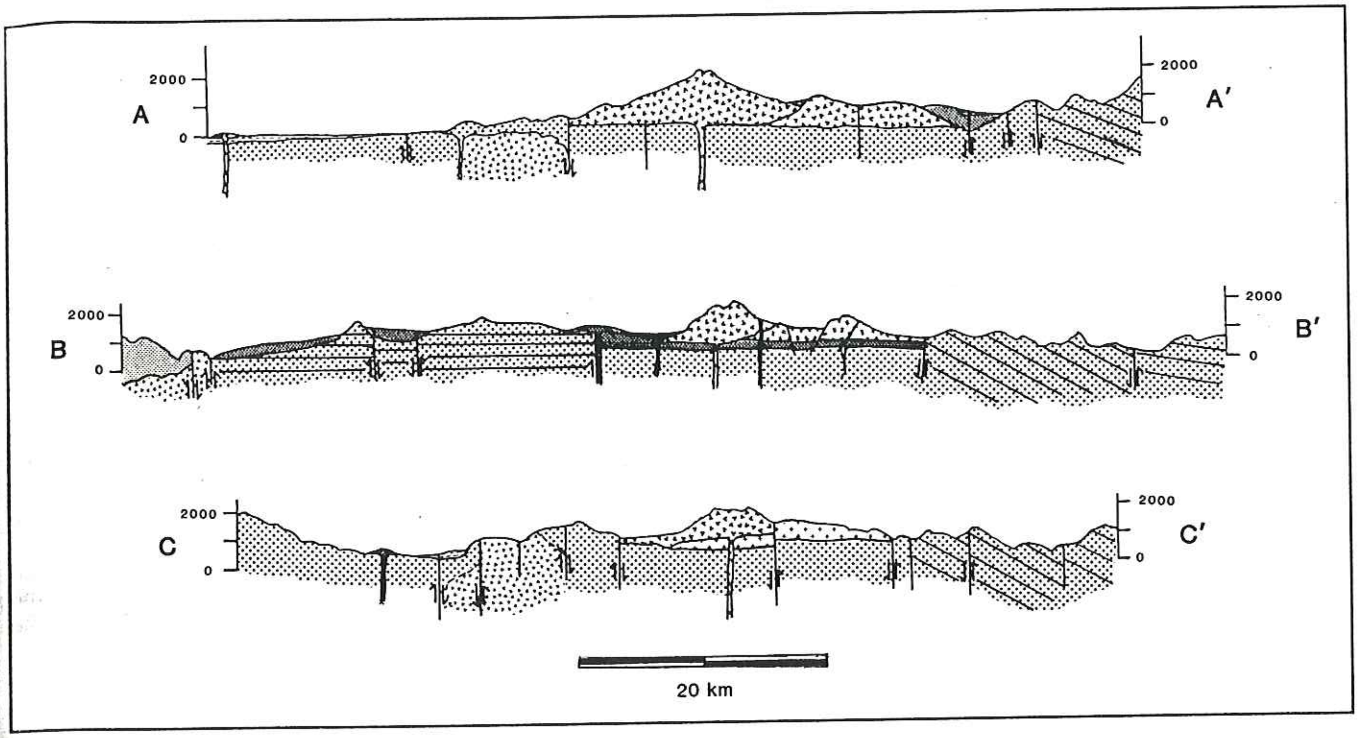

Figure 7—Cross-sections shown in Figure 6; vertical exaggeration 2.5 X. Symbols and patterns are the same as in Figure 6, except that Miocene and older rocks are shown as a rectilinear dot pattern. Relative motion indicators on faults are estimated from topographic expression only, and all faults have probably experienced some strike-slip motion, as discussed in the text. Compiled and interpreted by S. Nelson.

Other short fault segments within the rift are not aligned in the predominant northwest direction. These include north-trending faults that cut Miocene ash-flow tuffs west of Volcán Tepetiltic and north of Volcán Ceboruco, and a N15°W-trending fault 20 km north-northwest of Volcán Tequila, which vertically offsets 1.2-m.y.-old lavas by 30 m. Some of these faults may be remnants of, or reactivation along, the pre-Pliocene faults that cut Miocene strata north of the area, or alternatively, may be conjugate faults to the predominant northwest-trending faults. West of Tepic several short east-trending fault segments appear to have right-laterally offset the coastline, with an apparent dip-slip component dipping to the north.

In summary, abundant evidence exists for vertical and right-lateral movement along a series of northwest-trending fault traces in the Tepic-Zacoalco rift during Pliocene to Holocene time. Northwest-trending faults appear to have become active near the end of the Miocene or the beginning of the Pliocene. The fault patterns and cinder cone alignments indicate that maximum extensional stress is northeast-southwest. Older faults north of the Tepic-Zacoalco rift are oriented north-south and may be related to initiation of rifting of Baja California away from the Mexican mainland. Because of extensive Pliocene to Holocene volcanic cover and the lack of ground-based mapping, the extent of faulting is not well understood.

Zacoalco Graben

The Zacoalco graben (Allan, 1986), which is the southeasternmost fault basin of the Tepic-Zacoalco rift (Figures 1, 2), at its southeast end intersects the Northern Colima graben and the inner graben of the Chapala rift. Because of its strong structural contrast with the adjacent Northern Colima graben (Allan, 1986), the Zacoalco graben will be discussed in more detail.

The 10- to 20-km-wide, 30-km-long graben and the fault basin between the graben and the Chapala rift are delineated by tilted fault blocks (Figure 3, cross-section A-A') composed of Pliocene to Pleistocene lavas and a few interbedded volcanic sediments. The Zacoalco graben is bounded on both sides by southwest-dipping, northwest-trending normal faults and is floored by playa-lake sediments of unknown thickness. Relief may exceed 900 m, and the youthful appearance of the fault scarps indicates that normal faulting has extended into the late Pleistocene or Holocene (Allan, 1986). Faulting of dated volcanics shows that some normal faults have been vertically offset 600 m in the last 1.3 m.y. The youngest dated volcanic rock offset by normal faulting is a 650,000-yr-old (K-Ar; Allan, 1986) andesitic breccia that underlies the extensive (covering 150 km^2 in plan view) late Pleistocene Acatlan ignimbrite (Wright and Walker, 1977, 1981). The breccias and the ignimbrite are vertically offset at least 40 m (Allan, 1986). Downfaulting in the Zacoalco graben has created a serrate topographic profile on the southwest side of the graben (Figure 3, cross-section A-A'), similar in profile to the "domino" style of faulting described by Chamberlin (1978) in the Rio Grande rift near Socorro, New Mexico.

The structural style of the Zacoalco graben, reminiscent of the Basin and Range province of the United States (Stewart, 1978), is much different from that of the Northern Colima graben, where the plateaus flanking the graben have horizontal topographic surfaces. Allan (1986) deduced that the Zacoalco graben likely represents greater brittle extension (7 to 13%) over its width than the Northern Colima graben and proposed that its faults have shallower, perhaps listric, roots (Jackson and McKenzie, 1983). Alkaline volcanic rocks have not been found in the Zacoalco graben, even though the northernmost occurrence of alkaline rocks in the Colima graben is only several kilometers to the south. This observation is consistent with the idea that deeper rooted faults of the Colima graben have allowed an easier pathway to the surface for these small-volume, alkaline magma bodies (Allan, 1986).

Pre-Pliocene Lithologies

Any discussion of the rock types in the Tepic-Zacoalco rift is constrained by the fact that detailed field mapping is sparse. Broadly, Pliocene-Holocene volcanic rocks dominate and overlie Cretaceous to Tertiary intrusive, sedimentary, and metamorphic rocks, and Miocene volcanic rocks.

Most of the known pre-Cenozoic geology of the area comes from the work of Gastil et al. (1978). To summarize their work, extensive exposures of pre-Cenozoic, interbedded graywackes, argillites, conglomerates, and rhyolitic and andesitic flows and tuffs occur to the south of the Mazatan fault, due south of Tepic (Figure 6). Another block of pre-Cenozoic rocks occurs south of Volcán Ceboruco, north of the Mazatan fault. This block contains andesitic volcaniclastic rocks that have been intruded and metamorphosed by gabbros, tonalites, and granodiorites. Gastil et al. (1978) also describe several other intrusions within the rift, which range in age from 20 to 97 Ma and include diorite, tonalite, and gabbro.

Nieto-Obregon et al. (1985) describe late Oligocene biotite granodiorite and diorite exposed in the Rio Santiago canyon north of Volcán Tequila. The plutons are overlain by extensive early Miocene (22.6 to 16.9 Ma) ash-flow tuffs and acid-intermediate volcanic rocks, which in turn are overlain by upper Miocene (10 to 7.2 Ma) intercalated basalts and ignimbrites (Watkins et al., 1971; Gilbert et al., 1985; Nieto-Obregon et al., 1985). Capping the sequence are 5.7 to 3.1 Ma interbedded tuffs, welded ash-flow tuffs, lacustrine sediments, and basalts (Wopat and Carmichael, 1984; Gilbert et al., 1985).

Other Miocene volcanic rocks, found on the northeast side of the Pochotitan fault system, consist of interbedded rhyolitic ash flow tuffs and andesites. Gastil et al. (1978, 1979) dated a rhyolite from this area at 7.8 ± 0.6 Ma, and suggest that rocks north of the Rio Santiago could be older and similar in age to the 23 to 35 Ma rocks dated by McDowell and Keizer (1977) in southern Sinaloa and Durango. Outcrops of other Miocene andesites and rhyolites east of Volcán Las Navajas, west and northeast of Volcán Tepetiltic, surround the caldera of Santa Maria del Oro (Gastil et al., 1978, 1979). Miocene andesites cover areas north and southeast of Tepic; these were mapped as basalts by Gastil et al. (1978), who dated flows at 9.9 ± 0.3 and 13.8 ± 3.1 Ma (Gastil et al., 1978, 1979). In the early Pliocene, calc-alkaline volcanic rocks associated with the development of the Mexican Volcanic Belt began to cover this older Miocene calc-alkaline sequence (Gastil et al., 1978, 1979).

Petrology of Pliocene-Holocene Volcanic Rocks

As in the Colima rift, coeval alkaline, peralkaline, and calc-alkaline magmas also erupted in the Tepic-Zacoalco rift. Analyzed lavas and scoriae from the Tepic-Zacoalco rift are plotted in Figure 8 and representative analyses are given in Table 1. Occurrences of alkaline and peralkaline rocks are described first.

Mostly alkaline basaltic lavas and scoriae fill low-lying areas in a broad tectonic basin of likely Pliocene age east and northeast of Tepic. Their thicknesses may exceed 200 m. Other alkaline basalts are exposed in valleys tributary to the Rio Grande de Santiago north and northwest of Volcán Las Navajas and north of Santa Maria del Oro caldera (SM, Figure 6). One of these gently dipping lavas, a hawaiite, dated by Gastil et al. (1978, 1979) at 4.3 ± 0.1 Ma, represents the oldest dated alkaline volcanic rock in the rift. Nelson and Carmichael (1984) have shown that many of these alkaline basalts have erupted from cinder cones aligned along northwest trends that extend through the Pleistocene calc-alkaline volcano, Sanganguey. As these lavas underlie and have erupted through the Sanganguey volcanic edifice, alkaline basaltic volcanism has likely extended from the Pliocene into the Holocene. Nelson and Carmichael (1984) report that the cinder cones have erupted a range of mildly alkaline lavas, including alkaline basalts (both silica-saturated and undersaturated), hawaiites, mugearites, and benmoreiites. Geomorphic evidence indicates that the oldest lavas are the most differentiated, whereas those that erupted through the Sanganguey edifice are restricted to alkaline basalt and appear to be late Quaternary in age.

The Pleistocene volcanic complex of Las Navajas, north of Sanganguey, has erupted a variety of alkaline and peralkaline lavas (Nelson and Hegre, 1990). The oldest eruptives are alkaline basalts, some of which erupted from northwest-oriented lines of cinder cones, and also include trachytes and comenditic and pantelleritic (peralkaline) rhyolites, similar to rocks that underlie Sanganguey. Late-stage eruptives from Las Navajas are pantelleritic rhyolite obsidian flows, and a welded ash-flow tuff dated by Nelson and Carmichael (1984) at 0.2 ± 0.1 Ma by K-Ar. Peralkaline rhyolite flows of similar Pleistocene age have also been found adjacent to Volcán Tequila; their mean K-Ar ages are 0.66 ± 0.03 Ma (Harris, 1986).

Alkaline basalts have erupted elsewhere in the rift. South of Volcán Tepetiltic is a broad shield volcano capped by a small Pleistocene cinder cone that erupted mugearites (Rogg, 1983). Two cinder cones on the flanks of Tepetiltic have also erupted mugearites. Large outpourings of Pleistocene trachybasalts and basaltic trachyandesites have episodically erupted from vents in the vicinity of Volcán Tequila and have formed an extensive, rift-flooring sequence now exposed as a plateau. These lavas range from ≤0.24 to 1.4 Ma in age (Gilbert et al., 1985; Nieto-Obregon et al., 1985; Nixon et al, 1987; M. Wopat, unpublished K-Ar data); most of these trachylavas erupted 0.6-0.9 m.y. ago. Older K-Ar dates have been reported for alkaline basalt from the Cinco Minas graben (3.8 ± 0.1 Ma; Nieto-Obregon et al., 1985).

Pliocene to Recent calc-alkaline volcanic rocks have erupted from six major composite volcanoes, all located within fault basins. At least eight eruptions have taken place at Volcán Ceboruco over the last 1000 years, the last in 1870 (Iglesias et al., 1877; Thorpe and Francis, 1975; Nelson, 1980). The lavas of Volcán Ceboruco range from andesite to rhyodacite. Volcán Sanganguey and Volcán Tepetiltic have erupted lavas that range from andesite to rhyodacite (Livieres and Nelson, 1983; Deremer and Nelson, 1985; Nelson and Livieres, 1986). Volcán San Juan is primarily constructed of hornblende-andesite lavas but also produced a large quantity of rhyodacite pumice and ash during a caldera-forming Plinian eruption about 15,000 years ago (Luhr, 1978). Interestingly, Volcán Ceboruco and Volcán Tepetiltic also erupted large amounts of compositionally similar rhyodacite during Plinian eruptions related to

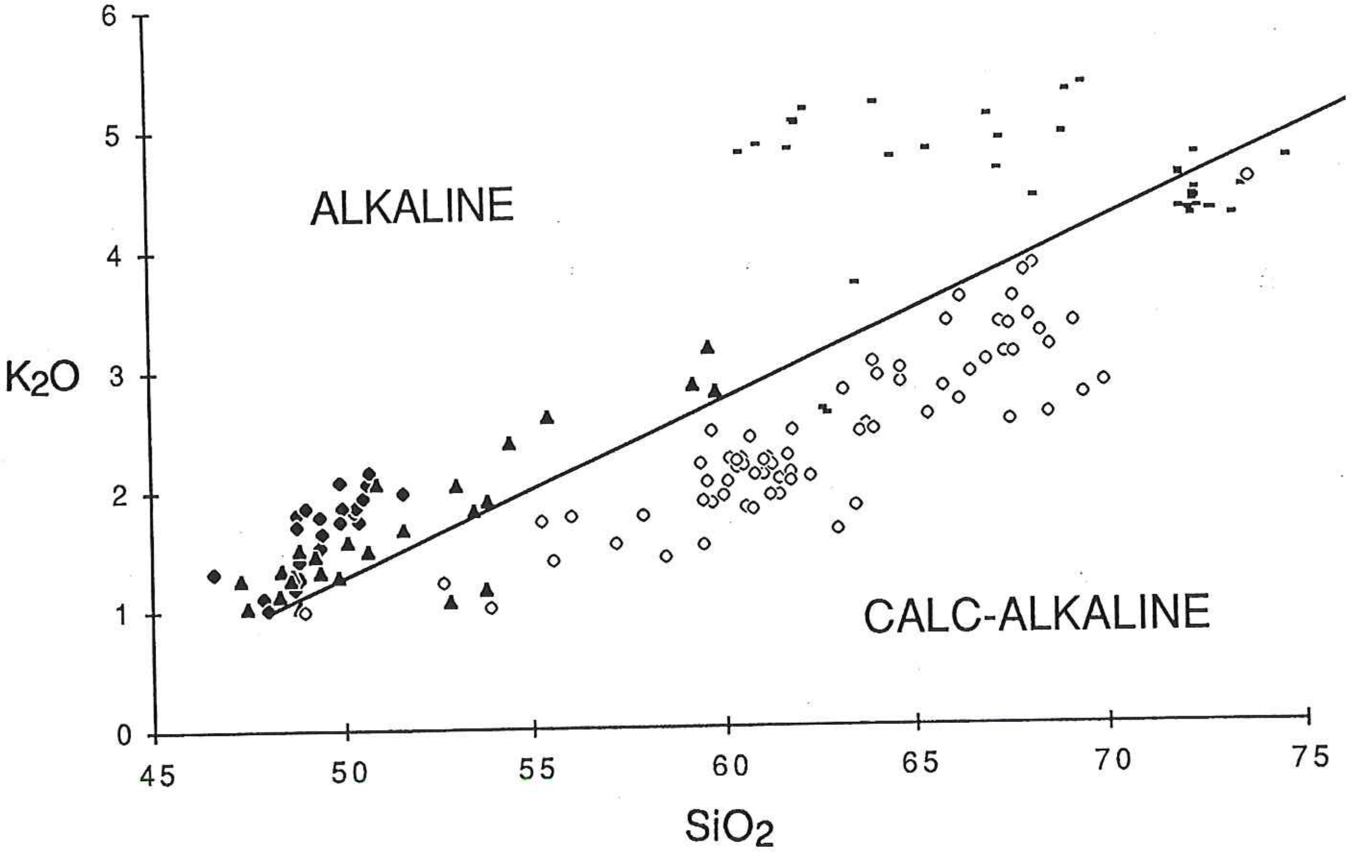

Figure 8—K_2O vs SiO_2 plot for lavas from the Tepic-Zacoalco rift. The field dividing the alkaline and calc-alkaline fields is the same as in Figure 5. Alkali basalts are shown as solid diamonds, hawaiites and basanites are shown as solid triangles, trachytes and peralkaline rhyolites are shown as bars, and calc-alkaline lavas (basalts, andesites, dacites, and rhyolites) are shown as open diamonds. Data from Nelson (1980), Nelson and Carmichael (1984), Hegre (1985), and Nelson and Livieres (1986). Data plotted as weight %.

caldera formation. The Pleistocene volcano Tequila, its last activity represented by the 0.21 ± 0.01 Ma central spine, has produced only andesitic lavas (Harris, 1986), as has the large Pliocene Tepic caldera northeast of the city of Tepic. Numerous other smaller centers have produced rhyolite, rhyodacite, dacite, andesite, and basalt.

In summary, there has been coeval alkaline, peralkaline, and calc-alkaline volcanism in the Tepic-Zacoalco rift since the early Pliocene, a pattern similar to that of the Colima rift. In contrast, however, the compositional diversity of the alkaline lavas is not nearly as great as in the Colima rift, where rocks of more extreme alkalinity (particularly in potassium) are found.

GUADALAJARA REGION

The city of Guadalajara is built on a relatively flat plain at an elevation of 1600 m. This plain is underlain by a thick section of late Miocene to Pleistocene volcanic rocks dominated by rhyolitic ignimbrites interbedded with basalt and basaltic-andesite lava flows. The area is noteworthy because it is near the rift triple junction. The volcanic sequence underlying the city is well exposed in the walls of the 500-m-deep canyon of the Rio Santiago, which forms the eastern margin of the Guadalajara plain. Watkins et al. (1971) gave K-Ar dates for units exposed in this sequence which ranged from about 9 Ma at river level to 4.7 Ma near the top of the canyon. Gilbert et al. (1985) and Mahood et al. (1985) focused on two widespread ignimbrites near the top of the section: the 4.8 Ma San Gaspar ignimbrite (Watkins et al., 1971, report the date as 4.7 Ma), and the 3.3 Ma Guadalajara ignimbrite. Significantly, the glass of the Guadalajara ignimbrite is peralkaline. The oldest alkaline lava found in the Guadalajara area is a coarsely porphyrytic alkali basalt on both sides of the Rio Santiago north of Guadalajara, which has been dated at 3.97 ± 0.12 Ma (Gilbert et al., 1985). These dates demonstrate the presence of apparent extension-related Pliocene magmas in the Guadalajara region.

Gilbert et al. (1985) argued against significant deformation of the Guadalajara city area during the last 5 m.y. (other than Quaternary regional uplift that formed the canyon) because of the undissected Guadalajara plain; the uniform, subhorizontal San Gaspar ignimbrite; and the thin, widespread ignimbrite on both sides of the present Santiago canyon. Most outcrops of the ignimbrite and most of Guadalajara lie east of the Tepic-Zacoalco rift. Nevertheless, the westernmost outcrops of the San Gaspar ignimbrite were displaced tens of meters by northeast-trending normal faults (Gilbert et al., 1985).

Directly south of Guadalajara is the Southern Guadalajara Volcanic Chain, consisting of eight small basaltic andesite lava cones which form a 35-km-long alignment along an azimuth of 112° (Luhr and Lazaar, 1985). Mahood et al. (1985) give a K-Ar date of 1.4 Ma for a sample from Cerro el Papantón de Juanacatlán, the southeasternmost volcano of this chain, an age that likely approximates the age of the entire chain. The orientation of the cones indicates that the local maximum horizontal extensional stress direction at this time (following Nakamura, 1977) trended about 22°, subperpendicular to the orientations of the Chapala and Tepic-Zacoalco rifts.

The youngest volcanic rocks in the Guadalajara region are mildly peralkaline rhyolitic lavas and pyroclastic rocks from the Sierra la Primavera, a Pleistocene rhyolitic dome complex covering about 500 km^2 on the western side of the city (Mahood, 1980, 1981, 1983; Clough, 1981; Clough et al., 1981, 1982; Walker et al., 1981; Wright, 1981, 1983; ; Mahood and Drake, 1982; Mahood et al., 1983). Detailed K-Ar dating (Mahood, 1980; Mahood and Drake, 1982) indicates eruptive activity of the complex from 120,000 to 30,000 years ago. The pyroclastic deposits associated with this center underlie most of the Guadalajara region and, together with the domes, represent a total of 60 km^3 of erupted rhyolitic magma (Walker et al., 1981). In summary, the Guadalajara region has been the site of intense silicic volcanism for much of the last 9 m.y., with alkaline/peralkaline volcanic activity beginning around 4 m.y. ago.

JALISCO BLOCK

The structural geology of the Jalisco block is very poorly known. Inspection of LANDSAT images, topographic maps, and aerial photographs suggests that numerous basins of likely fault origin exist subparallel to the larger rifts. Only a few faults from the Jalisco block are mapped in Figure 1, because of our fragmentary knowledge of the area.

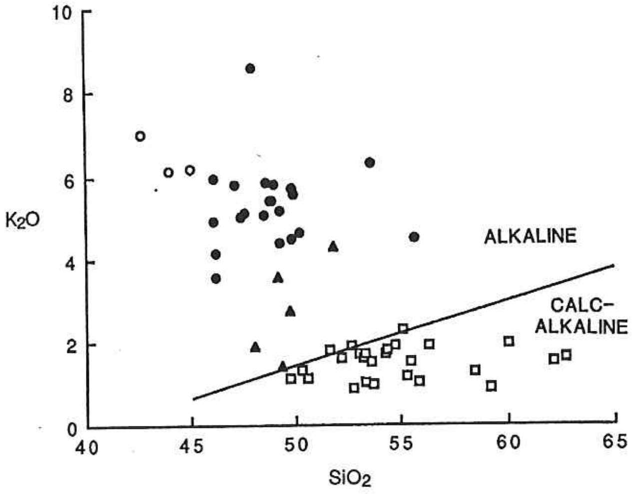

Figure 9—K$_2$O vs SiO$_2$ plot for lavas from the Mascota and Las Volcanes regions. The field dividing the alkaline and calc-alkaline fields is the same as in Figure 5. Phlogopite lamprophyres (minettes) are shown as solid circles, leucitites as open circles, and absarokites as solid triangles. Calc-alkaline lavas (basalts, basaltic andesites, and andesites) are shown as open squares. Note that the range in composition is similar to that in the Colima rift suite. Analyses taken from unpublished data of Wallace and Carmichael. Data plotted as weight %.

Two basins in particular, one near the city of Mascota and the other near Los Volcanes, Jalisco, have been the loci of eruption for a variety of calc-alkaline and unusual alkaline magma types since the late Pliocene (Luhr and Carmichael, 1985; Wallace et al., 1988; Wallace and Carmichael, 1989). Representative analyses of these rocks are plotted in Figure 9 and given in Table 1. Late Pliocene volcanic rocks found in a north-trending basin surrounding the town of Los Volcanes represent eroded and dissected lava cones and flows. This basin is largely fault bounded and has a maximum relief of 1000 m, but the age of the onset of faulting is unknown. The city of Mascota, 40 km to the northwest, lies in another basin that contains numerous well-preserved cinder and lava cones and Quaternary lava flows. Many of these volcanic centers are aligned north-south. This basin is also partially fault bounded, especially the northwest side, which is demarcated by steep, northwest-trending normal fault scarps having 300 m of relief. K-Ar and ^{40}Ar-^{39}Ar dates indicate that volcanism in the Los Volcanes region occurred from 3.3 to 1.8 m.y. ago. Volcanism in the Mascota field and in several smaller fault basins to the north is much younger, beginning about 0.5 m.y. ago (Wallace and Carmichael, 1989). An unvegetated block lava flow just west of Moscota demonstrates that volcanism has essentially continued until the present.

A wide spectrum of volcanic rock types is present in these areas, ranging in SiO$_2$ content from 42 to 62 wt. %. The most common basic (more primitive) varieties are phlogopite lamprophyres (minettes), high-K basaltic andesites, and absarokites. The absarokites contain olivine and augite phenocrysts in a groundmass composed predominantly of sanidine. Also present in the Los Volcanes region are hornblende lamprophyres (vogesites) and strongly silica undersaturated olivine- and phlogopite-bearing leucitites. Leucitites are not common in volcanic arcs associated with subduction but occur elsewhere in parts of the Sunda-Banda arc in Indonesia (Hutchison, 1982). Hornblende andesites have also erupted in the Mascota and Los Volcanes regions, forming lava cones and flows of comparable volume to those of the basic lavas. Many of the rock types from this region of southwest Mexico are similar in bulk composition and mineralogy to varieties within the Colima rift, sharing with the latter an abundance of phlogopite and hornblende, which indicate high water contents for both the alkaline and the calc-alkaline magmas.

In contrast with these small-volume cones and lava flows are several shield volcanoes and lava plateaus north of the basin surrounding Los Volcanes (Wallace et al., 1988). These are composed of high-K basalts and basaltic andesites which are geochemically distinct from the lavas described above. K-Ar dates of 0.7 and 0.8 Ma for two of these basalts suggest that much of this lava may have been erupted after volcanism near Los Volcanes had ceased, just before the onset of volcanism in the Mascota volcanic field.

Much of the region surrounding Mascota and Los Volcanes and extending west to the coast is underlain by regionally extensive ash-flow tuffs of Late Cretaceous age. Two samples of this tuff have been dated using the ^{40}Ar-^{39}Ar method on biotites, yielding ages of 81 and 83 Ma (Wallace and Carmichael, 1989). These ages agree with those obtained by Gastil et al. (1978) for ash-flow tuffs that crop out to the northwest, near Puerto Vallarta. These data indicate that the ash-flow tuffs in this region could be much older than the rhyolitic volcanic rocks dated in the Sierra Madre Occidental, which is continuous with this region to the north (McDowell and Keizer, 1977).

DISCUSSION

Relationship Between Magma Diversity and Rifting

The western Mexican Volcanic Belt is notable for its diversity of volcanic rocks, a variety much greater than typically reported in volcanic arcs. Of special interest are the alkaline and peralkaline rocks that are more common in areas of continental rifting or on oceanic islands. A striking feature of these volcanic rocks, especially those from the Colima rift and from the Mascota and Los Volcanes regions in the Jalisco block, is the enrichment in incompatible elements such as K (Table 1; Figures 5, 9). Nevertheless, the Sr, Nd, and Pb isotopic compositions of the late Pleistocene alkaline and calc-alkaline lavas from the Colima rift and Jalisco block are quite similar (Carmichael and DePaolo, 1980; Heatherington et al., 1987; Verma and Luhr, in press). Luhr et al. (1989) concluded that both the alkaline and calc-alkaline lavas from these two areas were derived from a common source, represented by mantle overlying the subducting Rivera and Cocos plates. This source is heterogeneously and variably enriched in the incompatible elements, which are concentrated in phlogopite-, amphibole-, and apatite-bearing lherzolite dikes and metasomatic veins. Enrichment of this subarc mantle was likely accomplished by hybridization and metasomatic alteration (Lloyd and Bailey, 1975) from silicate liquids or fluids derived from the subducting slab and associated sediments (Wyllie and Sekine, 1982). Luhr et al. (1989) proposed that the alkaline lavas resulted from relatively small amounts of partial melting of this heterogeneous source, so that a relatively large part of the alkaline melt was derived from these incompatible-element-rich dikes and veins. Calc-alkaline lavas were proposed to result from larger amounts of partial melting of this source, diluting the dike and vein component.

In contrast, the relationships between the calc-alkaline lavas and the alkaline and peralkaline lavas of the Tepic-Zacoalco rift are more complex. These suites of lavas must have been derived from different mantle sources because of systematic differences in relative and absolute incompatible-element abundances and Sr and Nd isotopic ratios (Verma and Nelson, 1989). The alkaline and peralkaline lavas of the Tepic-Zacoalco rift contain much higher amounts of the high-field-strength elements (such as Nb, Zr, and Ti) relative to large-ion lithophile elements (such as K and Sr) than other calc-alkaline and alkaline lavas of southwestern Mexico. For this reason, Verma and Nelson (1989) proposed that they were derived from an oceanic island-type source rather than from a mixed mantle/slab-derived source.

Alkaline rocks are common in the Colima and Tepic-Zacoalco rifts because crustal faulting and crustal thinning associated with rifting allowed relatively easy pathways for magmas to reach the surface. As a result, small magma bodies such as those represented by the southwest Mexico alkaline rocks were able to erupt. This inference is corroborated by the compositions of volcanic rocks in the adjacent Northern Colima and Zacoalco grabens. Alkaline rocks have not been found in the Zacoalco graben; only the deeper rooted faults of the Northern Colima graben have apparently allowed such magmas to reach the surface near the rift triple-junction (Allan, 1986). The diversity of volcanic rocks seen in the rifts reflects the variety of mantle compositions and melting processes in the western MVB , and thus presents a "window" into the subarc mantle. Highly alkaline lavas in other arcs are typically found in areas of unusual or complex tectonic activity, commonly characterized by deep crustal faulting or rifting (see Luhr and Carmichael, 1981, for a summary of alkaline lavas in volcanic arcs). Apparently, both oceanic and continental arcs may produce alkaline lavas without the addition of "enriched" mantle from outside the arc system. It is clearly dangerous, as outlined by Luhr and Carmichael (1985), to blindly use K_2O content of lavas for determining paleoarc polarity or trench distance.

K-Ar ages of western MVB lavas indicate that alkaline volcanism started around 4 to 4.5 Ma. The Colima rift shows a geographically widespread concentration of alkaline lava ages in the 4 to 4.6 Ma range, leading Allan (1986) to conclude that the onset of rifting in southwest Mexico occurred by this time. This estimate correlates well with the Colima rift age calculated using the Zacoalco graben faulting rate and is consistent with the character of volcanic development within the rift. The decreasing amount of magma-crust interaction and the decreasing crustal residence time, as shown by the alkaline lavas in the rift, reflects the "opening up" of the rift, as does the development of the large central volcanoes Colima, Nevado de Colima, and Cantaro during the Pleistocene.

Rifting in Southwest Mexico

We have previously proposed (Luhr and Carmichael, 1981; Luhr et al., 1985; Allan, 1986) that the three rift structures discussed in this paper are manifestations of an ongoing rifting of the Jalisco block away from southwest Mexico, much as Baja California rifted away from the Mexican mainland in the late Cenozoic (Larson et al., 1968; Karig and Jensky, 1972; Hausback, 1984). Alkalic basalts virtually identical in composition to phlogopite lamprophyres in the Colima rift began to erupt on the east coast of Baja California Sur north of La Paz about 12.5 m.y. ago, and eruptions continued to the late Pleistocene (Hausback, 1984, 1986); other alkaline basalts described by Sawlan and Smith (1984) occur between lat. 25° and 28° N in Baja California and range in age from 10 Ma to late Pleistocene. The initiation of alkaline volcanism correlates with the beginning of block faulting associated with the initial rifting of the Baja peninsula from the Mexican mainland.

Luhr et al. (1985) and Allan (1986) further proposed that the current rifting event is only the latest in a series of northward-propagating, eastward ridge jumps involving the EPR (East Pacific Rise) over the last 11 to 12 m.y. (Van Andel et al., 1975; Lynn and Lewis, 1976; Mammerickx and Klitgord, 1982; and Figure 10, this paper). If the proposed ridge jump goes to completion, the East Pacific Rise between the Rivera and Tamayo fracture zones will jump to the current site of the Colima rift, the Jalisco block will be transferred to the Pacific plate, and the Chapala rift will be left as an aulacogen.

Mammerickx and Klitgord (1982) emphasized that during ridge jumping, twin spreading ridges will be active as spreading propagates up the axis of the new rift, leading to the creation of short-lived microplates between them. Perhaps an analogous situation is developing between the Colima rift and the above-mentioned part of the EPR. Our model is consistent with the geometry of the rift structures in southwest Mexico and with the presence and direction of strike-slip faulting along the Tepic-Zacoalco rift. We point out that the age of initial alkaline volcanism in the Colima rift is approximately the same as the age when spreading had propagated northward to the vicinity of the Rivera fracture zone along the current axis of the EPR (Lynn and Lewis, 1976; Mammerickx and Klitgord, 1982). This age is also contemporaneous with the northerly transfer of the Cocos-Rivera plate boundary from the Orozco fracture zone to the

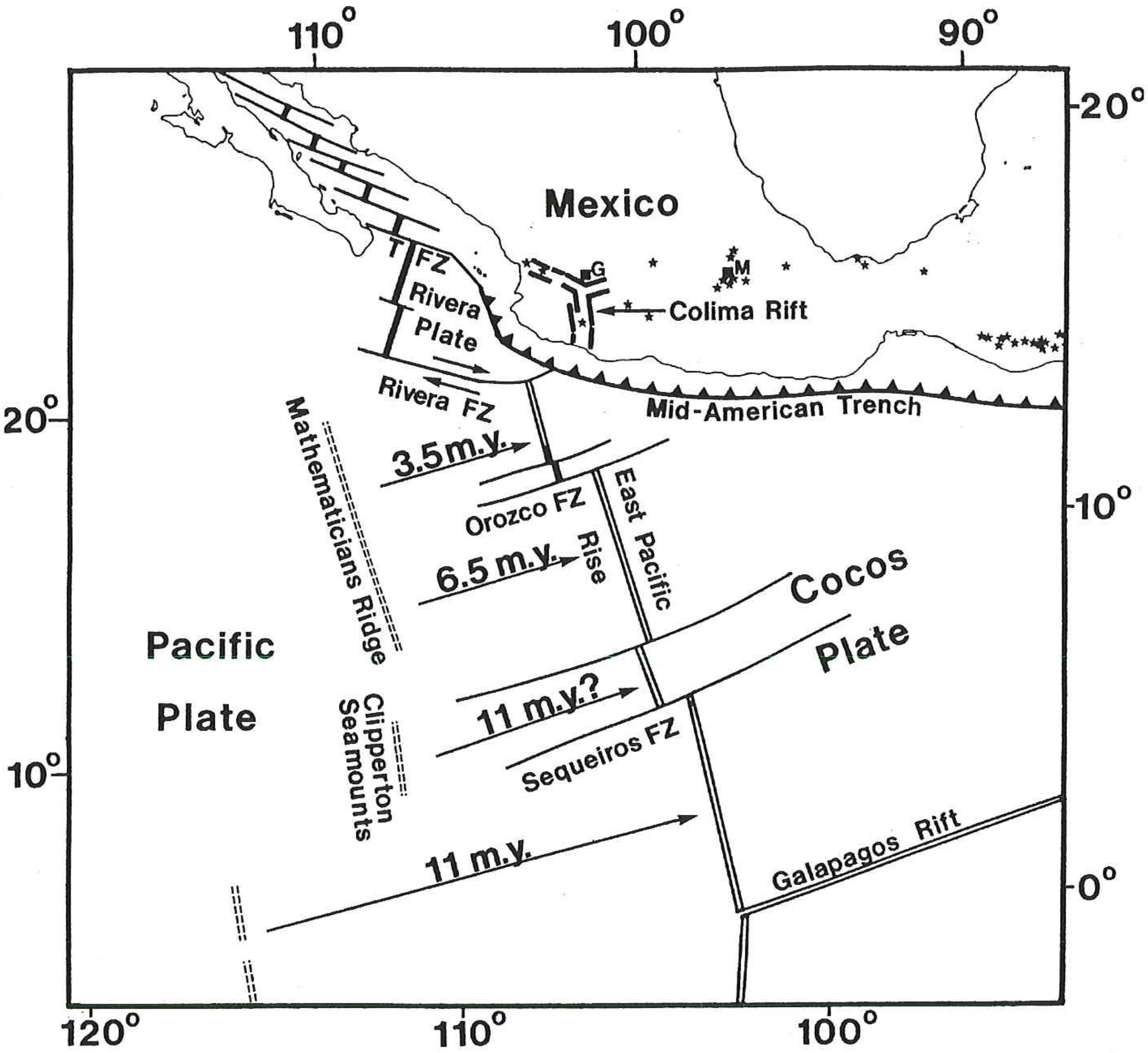

Figure 10—Map showing regional plate boundaries and northward-propagating spreading-ridge jumps of the East Pacific Rise (ridge jump dates from Mammerickx and Klitgord, 1982). Volcanoes of known Holocene activity are shown as stars (Simkin et al., 1981); locations of Guadalajara and Mexico City are shown as squares. Locations of plate margins are generalized and adapted from the Plate Tectonic Map of the Circum-Pacific Region, northeast quadrant (Circum-Pacific Map Project, 1981) and from Mammerickx (1984). TFZ represents the Tamayo Fracture Zone.

Rivera fracture zone (Mammerickx and Klitgord, 1982), the subducting portion of which the Colima rift now overlies. Similarly, the initial age of alkaline volcanism in southwest Mexico is approximately contemporaneous with the initiation of continuous spreading in the Gulf of California (Larson, 1972). Therefore, rifting in southwest Mexico may have begun at least partially in response to the detachment of Baja California from the North American plate. We also note that this age represents the time of significant change in the absolute and relative motions of the Pacific and North American plates (Pollitz, 1986, 1988), which may have provided the driving force for the initiation of rifting in southwest Mexico. We believe that southwest Mexico may serve as a model for studying incipient continental arc rifting, and may represent a type example of the initial development of an exotic terrane that may be transported northward and accreted to other parts of western North America at a later time. Northward propagation of spreading preferentially into the adjacent, tensionally weaker continent (southwest Mexico) rather than continuing in oceanic crust is consistent with other, earlier examples of spreading ridge jumps and ridge propagation (Vink et al., 1984), including that of the rifting of Baja California from the North American plate.

Knowledge of the the current motion of the Rivera plate s critical to our model. There has been considerable debate over whether the Rivera plate is in fact subducting (Molnar, 1973; Sharman et al., 1976; Singh et al., 1985) or whether it has accreted to the North American plate (Larson, 1972). Greatly complicating the problem is the presence of only shallow recorded earthquakes along the relevant part of the Middle America Trench (Nixon, 1982).

Minster and Jordan (1979) published a rotation vector for the Rivera plate with the pole of rotation located within the plate. This location of the pole leads to a wider range of subduction velocity and azimuth estimates over the length of the subduction zone—from 2.5 to 1.6 cm/yr and N40°E to nearly N-S, respectively. Nixon (1982) treated the entire Rivera plate as a single geographic point and from vector diagrams deduced a subduction rate and azimuth of about 2 cm/yr and N45°E, respectively, by using data from Larson 1972), Molnar (1973), and Minster et al. (1974). Nixon (1982) noted that the Cocos plate is subducting at a greater velocity about 5.3 cm/yr at the Cocos-Rivera-southwest Mexico transform-trench-trench triple junction, which we calculated using the RM2 model of Minster and Jordan, 1978) than the Rivera plate, and proposed that the Colima rift is the surface expression of a hinge fault between the two subducting plates. More recently, Eissler and McNally (1984) discussed focal plane solutions of earthquakes along the diffuse boundary between the Rivera and Cocos plates and concluded that they were consistent with left-lateral motion between the plates.

A recent analysis by DeMets and Stein (in press) of magnetic lineations along the Rivera-Pacific spreading center predicts 6 to 10 mm/yr of convergent motion along the Tamayo fracture zone between the North American and Rivera plates. This and other kinematic data require an independent Rivera plate (DeMets and Stein, in press). Their interpretation is consistent with a thrust-fault first-motion solution for the February 9, 1976 earthquake at the Trés Marias escarpment, near the Trés Marias Islands in the Gulf of California (Goff et al., 1987), and with strong evidence that the great Jalisco earthquakes of 1932 were associated with Rivera plate subduction (Singh et al., 1985).

Another analysis of Rivera plate motion comes from Ness et al. (1985), who derived rotation vectors for Rivera-North American plate motion, partially from their analysis of magnetic lineations in the Gulf of California. Their Rivera-North America pole predicts that the Rivera plate is moving away from the North America plate, at azimuths of N45° to 47°W, and at velocities of 1.4 to 1.5 cm/yr. The key to their model is their interpretation that the EPR is spreading 1.2 cm/yr faster north of the Tamayo fracture zone than south of it. Using other data as well, they predicted that a separate southern Mexican plate is moving 1.4 cm/yr to the northwest along the current trace of the MVB, relative to North America. Therefore, if the Rivera plate is subducting at all, the Jalisco block must be moving northwestward along the Tepic-Zacoalco rift at least 1.5 cm/yr relative to North America. Geodetic measurements using the Global Positioning System may help to resolve these proposed tectonic movements (Ness et al., in press). Shurbet and Cebull (1984) also proposed that southern Mexico is a separate microplate, moving in a right-lateral manner relative to the North American plate. Bandy et al. (1988) proposed that the Rivera plate and the Jalisco block are actually acting together as a coherent microplate, currently rifting away from the North American plate. At present, our data set cannot predict faulting rates, but late Pleistocene to Holocene right-lateral motion along the Tepic-Zacoalco rift has indeed occurred. Clearly, before our model may be evaluated further, there is a critical need for greater knowledge of the geology offshore southwest Mexico, as well as a need for more basic geological knowledge of the three rifts and the Jalisco block.

ACKNOWLEDGMENTS

We are grateful to the United States Defense Mapping Agency for an extensive set of aerial photographs of southwest Mexico made available to J. Allan while he was a research fellow at the Smithsonian Institution, Washington, D.C. We are also indebted to Sr. F. X. Lopez and others at the Office of International Geology, Cartographic Division, United States Geological Survey for making available to us LANDSAT-based regional maps of Mexico, and to B. Hausback and J. Urrutia-Fucugauchi for constructive reviews and information concerning this work.

We would like to thank A. Aydin, R. Batiza, P. Damon, P. Dauphin, C. DeMets, G. Gastil, J. Harris, C. Johnson, A. Jones, M. Lyle, B. Marsh, P. Morgan, G. Ness, M. Perfit, M. Sawlan, L. Serpa, S. Stein, J. Varekamp, and D. Wiens for stimulating and informative conversations concerning this work. We would also like to thank P. Dauphin and B. R. T. Simoneit for editorial handling of the manuscript. J. Allan would like to acknowledge financial support from the Office of Fellowships and Grants, Smithsonian Institution, from a grant to R. Batiza, Washington University (now at the University of Hawaii) from the National Science Foundation (NSF OCE-8508042), and from a NSERC Strategic Operating Grant to S. D. Scott and R. L. Chase, University of British Columbia, during three postdoctoral appointments when this manuscript was written. S. Nelson acknowledges the financial support of the Roger Thayer Stone Center for Latin American Studies and the Mesoamerican Ecology Institute, both of Tulane University. P. Wallace acknowledges the financial support of a National Science Foundation Graduate Fellowship. We also acknowledge the generous support from the following National Science Foundation Grants to I. S. E. Carmichael that made much of our field work possible: EAR 74-12782; EAR 78-03642; EAR 80-06043; EAR 81-03344, EAR 82-19945, and EAR85-00813.

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