A Pliocene ignimbrite flare-up along the Tepic-Zacoalco rift: Evidence for the initial stages of rifting between the Jalisco block (Mexico) and North America

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ABSTRACT

The Tepic-Zacoalco rift, a NW-trending corridor ~50 × ~250 km, is one arm of a triple-rift system in western Mexico. Together with the Colima rift and the Middle America Trench, it bounds the Jalisco block, a portion of western Mexico that may be moving independently of North America. The predominant basement rock types in the Tepic-Zacoalco rift are rhyolitic ash-flow tuffs and lavas, which were previously assumed to be Oligocene-Miocene in age, related to the Sierra Madre Occidental volcanic province, or older. New $^{40}Ar/^{39}Ar$ dates on 41 volcanic samples reveal a previously unrecognized, voluminous flare-up of rhyolitic ignimbrites between 5 and 3 Ma throughout the entire corridor of the Tepic-Zacoalco rift; they are often associated with Pliocene high-Ti basalts. The eruption rate during this Pliocene time period was an order of magnitude higher (hundreds of m/m.y.) than that documented in the Tepic-Zacoalco rift over the last 1 m.y. The Pliocene ash-flow tuffs have been faulted along NW-trending lineaments, producing vertical offsets up to at least 500 m. The voluminous ignimbrite flare-up in the Tepic-Zacoalco rift at 5–3 Ma may reflect the initial stages of rifting of the Jalisco block away from North America, analogous to what occurred in the proto-gulf region at 12–6 Ma, prior to the transfer of Baja California from North America to the Pacific plate.

Additionally, new $^{40}Ar/^{39}Ar$ dates show that the Sierra Madre Occidental volcanic province extends across the entire width of the Tepic-Zacoalco rift and terminates abruptly at the northern boundary of the Jalisco block near the Rio Ameca. In contrast, Paleocene-Eocene basement from the Jalisco block extends northward into the Tepic-Zacoalco rift, where it is locally overlain by Sierra Madre Occidental rhyolites.

Keywords: ignimbrite flare-up, lithospheric extension, plate transfer, $^{40}Ar/^{39}Ar$ geochronology, Rivera plate, Sierra Madre Occidental.

INTRODUCTION

The approach of the Pacific-Farallon spreading ridge to the convergent margin of North America at ca. 28 Ma and the subsequent breakup of the Farallon plate into several microplates have significantly influenced the tectonic and volcanic evolution of western North America (Atwater, 1970, 1989; Stock and Lee, 1994; Bohannon and Parsons, 1995). When the spreading centers of the Farallon fragments approached the trench, slab pull diminished and subduction stagnated, leading to the progressive transfer of the various microplates to the Pacific plate (Stock and Lee, 1994; Lonsdale, 1995; Bohannon and Parsons, 1995; DeMets and Traylen, 2000). As part of this process, a sliver of continental lithosphere (Baja California) was transferred to the Pacific plate as well. The smallest of the remaining Farallon microplates, the Rivera plate, currently subducts along the Middle America Trench beneath western Mexico (Figs. 1 and 2). There has been considerable speculation as to its future fate and whether it will eventually suture to the Pacific plate. Luhr et al. (1985) proposed that if the Rivera plate does transfer to the Pacific, it is likely to bring a piece of western Mexico with it, analogous to what occurred with Baja California.

The process outlined above, namely the capture of oceanic microplates near continental subduction zones, has a substantial impact on the deformational and volcanic history of the overriding plate (Stock and Lee, 1994), especially during incipient rifting of continental lithosphere. There is an extensive literature on the extension and diverse volcanism found in western Mexico, onshore from the Rivera plate (e.g., Nieto-Obregon et al., 1985; Luhr et al., 1985; Serpa et al., 1989; Allan et al., 1991; Wallace and Carmichael, 1992; Delgado-Granados, 1993a, 1993b; Ferrari et al., 1994; Michaud et al., 1994; Moore et al., 1994; Righter et al., 1995; Bandy et al., 1995; Kostoglodov and Bandy, 1995; Maillol et al., 1997; Ferrari and Rosas-Elguera, 2000). One region of particular interest, and the focus of this study, is the Tepic-Zacoalco rift, a NW-trending corridor that is ~50 km wide and extends for ~250 km from south of Guadalajara to the Pacific coast, near the city of Tepic (Fig. 2).

The Tepic-Zacoalco rift is part of a triple-rift system, which intersects ~50 km SSW of the city of Guadalajara. The other segments are the west-trending Chapala rift and the north-trending

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GSA Bulletin; January/February 2007; v. 119; no. 1/2; p. 49–64; doi: 10.1130/B25950.1; 8 figures; 8 tables; Data Repository item 2007002.

Colima rift. The Tepic-Zacoalco and Colima rifts define the northern and eastern boundaries, respectively, of the Jalisco block, a portion of western Mexico that Luhr et al. (1985) and Allan et al. (1991) proposed is in the process of being rifted away from North America (Fig. 2). However, if the Jalisco block is presently moving relative to North America, it is moving very slowly, on the order of a few mm/yr or less (Bandy and Pardo, 1994), as global positioning system (GPS) measurements taken over a four-year interval (1995–1999) cannot yet resolve motion of the Jalisco block relative to the stable interior of the North American plate (Hutton et al., 2001). In a review of the tectonics of the Tepic-Zacoalco rift, Ferrari and Rosas-Elguera (2000) concluded that extension within the rift occurred predominantly during two discrete time periods, one in the late Miocene (12–9 Ma) and the other in the early Pliocene (5.5–3.5 Ma), with only minor extensional deformation in the Quaternary.

The question explored in this paper is whether there was an initiation of rifting of the Jalisco block away from North America in the Pliocene. This question is posed on the basis of new $^{40}Ar/^{39}Ar$ dates presented in this study that document a previously unrecognized, voluminous flare-up of rhyolitic ignimbrites (associated with high-Ti basalts) throughout the entire corridor of the Tepic-Zacoalco rift at 5–3 Ma. Analogously, rhyolitic ignimbrites are also found along both margins of the Gulf of California with ages that date back to the earliest stages of rifting that created Baja California (ca. 12.5–6 Ma; Sawlan, 1991; Nagy et al., 1999; Oskin et al., 2001).

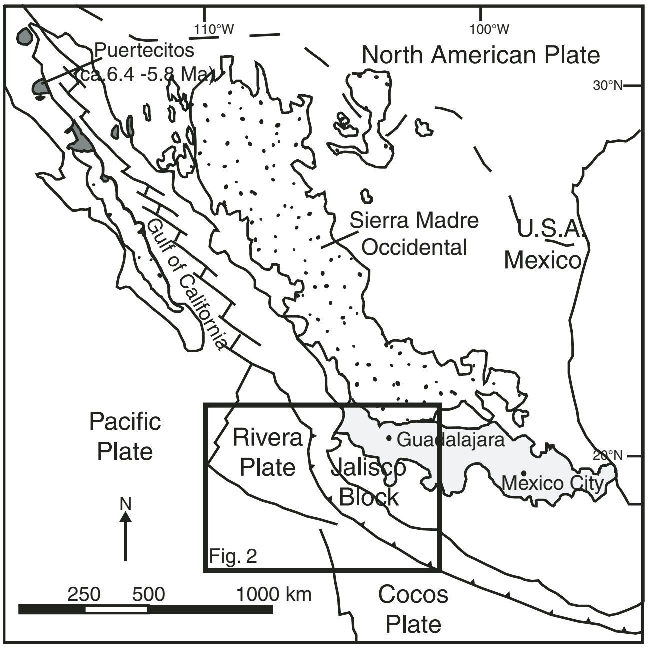

Figure 1. Map of Mexico showing Oligocene to Miocene volcanism and the current configuration of tectonic plates (modified from Ferrari et al. [2002] and Sawlan [1991]). Deposits associated with the Sierra Madre Occidental are shown in dark gray, and deposits associated with the rifting of Baja California are shown in light gray.

In this study, we show that rhyolite eruption rates between 5 and 3 Ma in the Tepic-Zacoalco rift were an order of magnitude higher (hundreds of m/m.y.) than is typical of continental arc volcanism, including that within the Tepic-Zacoalco rift over the last 1 m.y. (Frey et al., 2004b; Lewis-Kenedi et al., 2005). These thick sequences of ash-flow tuffs were subsequently faulted along NW-trending lineaments, producing vertical offsets up to at least 500 m. This extensive rhyolitic volcanism, driven by the emplacement of even larger volumes of asthenosphere-derived

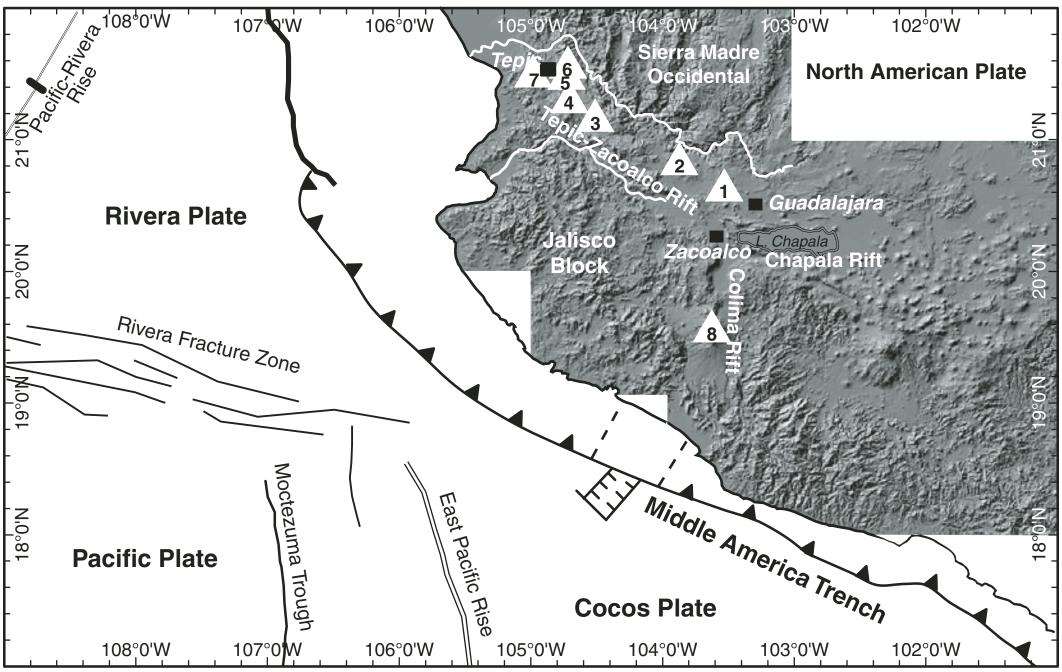

Figure 2. General tectonic map and digital elevation model (DEM) (scale 1:50,000) of western Mexico (modified from Delgado-Granados [1993a] and Bandy et al. [2005]). Numbered triangles in the Tepic-Zacoalco and Colima grabens refer to central volcanoes: 1—Sierra La Primavera, 2—Volcán Tequila, 3—Volcán Ceboruco, 4—Volcán Tepetiltic, 5—Volcán Sanganguey, 6—Volcán Las Navajas, 7—Volcán San Juan, and 8—Volcán Colima-Nevado. The Tepic-Zacoalco and Colima rifts and Middle America Trench define the boundaries of the Jalisco block.

basalt into the crust, followed by normal faulting to produce large offsets, reflects substantial thinning of the lithosphere, which is a prerequisite for any future rifting of the Jalisco block away from North America.

The new data presented in this study are a greatly expanded set of $^{40}Ar/^{39}Ar$ dates on silicic (predominantly rhyolitic) lavas and ash-flow tuffs within the Tepic-Zacoalco rift. Throughout its entire length and width, these rhyolitic units form the dominant basement outcrop. Previously, it was assumed that they were largely of Miocene-Oligocene age (related to the Sierra Madre Occidental volcanic province) or of Paleocene-Eocene to Cretaceous age (related to the Jalisco block: Wallace and Carmichael, 1989; Righter et al., 1995). The boundary between these two tectonic provinces was believed to lie somewhere within the Tepic-Zacoalco rift (Righter et al., 1995; Ferrari and Rosas-Elguera, 2000), but the nature of the boundary and whether the Sierra Madre Occidental ignimbrites were ever on top of, or only laterally (tectonically?) juxtaposed against, the Cretaceous units are not well understood because of limited chronological data. Therefore, an additional goal of this study is to examine the location and nature of the southern terminus of the Sierra Madre Occidental volcanic province and its relationship to the Jalisco block.

GEOLOGIC AND TECTONIC SETTING AND PREVIOUS WORK

Rivera Plate

The Rivera plate subducts at an initial angle of ~10° along the Middle America Trench (Fig. 2), but increases to a constant dip of ~50° below a depth of 40 km, where earthquakes have been recorded to depths ≤130 km (Pardo and Suarez, 1993). Rivera subduction is currently faster at its southern margin (~38 ± 4 mm/yr) and becomes progressively slower (down to ~15 mm/yr) and more oblique northward (DeMets and Wilson, 1997; Bandy et al., 2000). An earlier model (Kostoglodov and Bandy, 1995) proposed somewhat faster convergence of ~50 mm/yr at the southern end and ~20–30 mm/yr at the northern end. This oblique subduction has led to dextral strike-slip faulting in the forearc region of the Middle America Trench, along the offshore continental slope (Bandy et al., 2005). For the last 10 m.y., the Rivera plate has moved independently of the adjacent Cocos plate.

DeMets and Traylen (2000) used seafloor magnetic lineations to obtain the motion of the Rivera plate since 10 Ma relative to the Pacific and North America plates; their results are briefly summarized here. Between 10 and 5 Ma, there was a gradual decrease in the rate of Rivera subduction from ~50 to ~10 mm/yr, corresponding to a decrease in spreading at the Pacific-Rivera rise. From 4.6 to 3.6 Ma, the convergence rate increased to ~65 mm/yr, but it was highly oblique, imposed significant dextral shear along the trench margin, and probably shut off subduction north of ~20°N. From 3.6 to 2.6 Ma, Rivera subduction slowed again in concert with a substantial decrease in spreading along the Pacific-Rivera rise. Between 2.6 and 1.0 Ma, the Rivera–North America motion diminished to nearly zero and rotated to a direction parallel to the trench, so that only right-lateral strike-slip motion occurred. Thus, subduction ceased over this 1.6 m.y. interval. After ca. 1.0 Ma, subduction of the Rivera plate resumed, once again corresponding to a significant increase in Pacific-Rivera spreading and a clockwise rotation of its ridge. DeMets and Traylen (2000) suggested that slab pull was not an important force driving Rivera plate motion over the last 10 m.y.

Jalisco Block

The Jalisco block is a distinct crustal block, bounded by the Tepic-Zacoalco rift to the north and the Colima rift to the east, two segments of the triple-rift system (Fig. 1). It is composed primarily of Cretaceous to Eocene plutonic and volcanic rocks, with subordinate sedimentary sequences (e.g., Gastil et al., 1978; Köhler et al., 1988; Lange and Carmichael, 1991). In its interior, the volcanic succession is dominated by rhyolitic ash-flow tuffs dated between 65 and 92 Ma (Wallace and Carmichael, 1989; Righter et al., 1995; Rosas-Elguera et al., 1997; Gastil et al., 1978) (Table 1; Fig. 3). The Jalisco block is notable for the occurrence of a series of Pliocene-Quaternary lamprophyric volcanic fields (e.g., Wallace and Carmichael, 1989; Lange and Carmichael, 1991; Carmichael et al., 1996; Righter and Rosas-Elguera, 2001). In nearly all cases, lamprophyric lavas were erupted on top of Cretaceous units; this indicates that Cretaceous rocks were at the surface by ca. 5 Ma.

Sierra Madre Occidental Volcanic Province

The Sierra Madre Occidental is among the largest silicic volcanic provinces in the world, covering an area of ~296,000 km^2 from the southern United States to the Tepic-Zacoalco rift (Fig. 1), and averaging nearly 1 km in thickness (McDowell and Clabaugh, 1979; Swanson and McDowell, 1984). This silicic volcanic province is attributed to the subduction of the Farallon plate beneath western Mexico in the Oligocene–early Miocene (Atwater, 1970) and, more specifically, to a rupture of the Farallon slab at depth (Ferrari et al., 2002). The volcanic products in the Sierra Madre Occidental province range from basalt to rhyolite, but are dominated by rhyolitic ignimbrites (e.g., Wark et al., 1990; Albrecht and Goldstein, 2000). Reported ages range from 45 to 18 Ma, with younger volcanism (34–18 Ma) dominant in the southern portion of the province (Table 1, and references therein). Several Sierra Madre Occidental ignimbrites from the northern portion of the Tepic-Zacoalco rift (along the Rio Santiago, Fig. 3) have been dated, but only four dates (21–18 Ma) are reported for Sierra Madre Occidental units in the interior of the Tepic-Zacoalco rift (Gastil et al., 1978; Ferrari et al., 2002). On the basis of this information, the southern terminus of the Sierra Madre Occidental volcanic province has often been assumed to lie within the middle of the Tepic-Zacoalco rift (e.g., Ferrari and Rosas Elguera, 2000).

Baja California and the Gulf Extensional Province

Baja California is an example of continental lithosphere from North America that was transferred to the Pacific plate (Fig. 1) following cessation of subduction and microplate capture between 15 and 8–7 Ma (e.g., Atwater, 1970; Mammerickx and Klitgord, 1982; Michaud et al., 2004, 2006). A wide variety of geophysical, sedimentary, structural, and geochronologic evidence from the circum-gulf region (or Gulf Extensional Province) illustrates a period of middle Miocene to early Pliocene (16–5 Ma) extension prior to the onset of seafloor spreading (Karig and Jensky, 1972; Angelier et al., 1981; Dokka and Merriam, 1982; Stock and Hodges, 1989, 1990; Lee et al., 1996). Rifting within the Gulf Extensional Province also produced rhyolitic ignimbrites between ca. 12.5 and 6.3 Ma (Stock et al., 1999; Nagy et al., 1999; Oskin et al., 2001).

The proximity of the Tepic-Zacoalco rift to the southern Gulf Extensional Province has led to a shared feature, namely the Pochotitán fault system, which is a series of normal faults that cuts Sierra Madre Occidental ignimbrites (Fig. 3) and determines the northern margin of the Tepic-Zacoalco rift for at least half its length (Allan et al., 1991). In this region, numerous mafic dikes (11.9–11.5 Ma: Damon et al., 1979; Clark et al., 1981) strike parallel to these normal faults (Ferrari and Rosas-Elguera, 2000). Mafic lavas, with ages in this broad range, crop out along the entire northern margin of the Tepic-Zacoalco rift (Fig. 3; Table 2). These include the ca. 10 Ma San Cristobal basalts NW of Guadalajara (Moore et al., 1994), the ca. 9 Ma basalts north of Tepic

(Righter et al., 1995), the ca. 10 Ma basalt near Punta Mita (Gastil et al., 1979), and the 9–11 Ma basalts along the Rio Santiago (Nieto-Obregon et al., 1985; Damon et al., 1979). It is likely that this entire belt of mafic magmatism is related to an extended arm of the Gulf Extensional Province. Moore et al. (1994) showed that a thickness of >600 m of basalts was erupted between 10.2 and 9.6 Ma within this mid-Miocene rift zone. Ferrari (2004) argued that this ca. 11–9 Ma burst of basaltic volcanism along the northern margin of the Tepic-Zacoalco rift may have been a result of Rivera slab detachment at that time, which allowed decompressional melting of upwelling asthenosphere.

Pliocene Bimodal Volcanism in the Tepic-Zacoalco Rift

Despite the widely held perception that the silicic ash-flow units within the Tepic-Zacoalco rift are mostly of Oligocene-Miocene (Sierra Madre Occidental) or Cretaceous-Paleocene (Jalisco block) age, 12 Pliocene ages (2.8–5.5 Ma) are reported in the literature for silicic ignimbrites and lavas in the Tepic-Zacoalco rift (Gastil et al., 1979; Gilbert et al., 1985; Nieto-Obregon et al., 1985; Righter et al., 1995; Rosas-Elguera et al., 1997; Lewis-Kenedi et al., 2005; Table 1; Fig. 4). In addition to the rhyolites, 12 Pliocene ages are reported in the literature for mafic lavas (48–55 wt% SiO_2) in the Tepic-Zacoalco rift (Table 3; Fig. 4). They are characterized by high concentrations of TiO_2 (1.6–2.4 wt%) and range in age from 3.2 to 4.0 Ma (Nieto-Obregon et al., 1985; Gilbert et al., 1985; Moore et al., 1994; Righter et al., 1995; Rosas-Elguera et al., 1997; Lewis-Kenedi et al., 2005).

Quaternary Volcanism in the Tepic-Zacoalco Rift

Bimodal rhyolite and high-Ti basalt volcanism has extended into the Quaternary in the region surrounding Volcán Tequila (Fig. 3; Harris, 1986; Wopat, 1990). Here, ~35 km^3 of rhyolite and ~39 km^3 of basalt erupted contemporaneously between 1.0 and 0.2 Ma, with only minor eruptions of andesite-dacite (<3 km^3) over this same time interval (Lewis-Kenedi et al., 2005). The basalts include fissure-fed eruptions from NW-trending fractures located within the canyon of the Rio Grande de Santiago. At ca. 1 Ma, these basalts filled the canyon and flooded southward to form the Santa Rosa basalt plateau (Lewis-Kenedi et al., 2005). Rhyolite volcanism (~45 km^3) has occurred more recently, between 145 and 30 ka, at Sierra La Primavera (Fig. 3; Mahood and Drake, 1982), a volcanic center ~60 km southeast of Volcán Tequila.

TABLE 1. SUMMARY OF ^{40}Ar/^{39}Ar AND K-Ar DATES OF RHYOLITES OLDER THAN 1 Ma

Sample #	Latitude (N)	Longitude (W)	Material dated	Lava type	Age (Ma)	Reference
ETZ-30	20°59.44	104°00.65	gms	Silicic tuff	1.50 ± 0.02	1‡
HOS-7	21°01.00	104°03.10	gms	Silicic tuff	1.84 ± 0.01	1
JRE-2†	20°34.80	103°51.00	plag	Silicic tuff	2.80 ± 0.10	14
ETZ-7	20°46.97	104°05.66	gms	Rhyolite	3.02 ± 0.05	13
ETZ-21C	20°47.07	104°08.70	gms	Rhyolite lava flow	2.91 ± 0.03	1
55-26B†	20°47.00	103°24.48	san	Silicic tuff	3.23 ± 0.04	5
Guad1	20°44.57	103°35.14	gms	Rhyolite lava flow	3.27 ± 0.02	1
ETZ-29	20°49.10	104°13.74	gms	Rhyolite lava flow	3.30 ± 0.01	1
65-4A†	20°44.32	103°21.28	san	Silicic tuff	3.44 ± 0.09	5
ETZ-22	20°57.82	104°05.15	gms	Rhyolite lava flow	3.40 ± 0.04	1
ETZ-13	20°54.07	104°04.76	gms	Rhyolite lava flow	3.54 ± 0.01	1
ETZ-23A	20°56.63	104°08.29	gms	Rhyolite lava flow	3.52 ± 0.01	1
AME-3	20°41.85	104°14.42	gms	Andesite	3.99 ± 0.05	1
IXT-49	21°06.42	104°21.10	gms	Rhyolite lava dome	4.32 ± 0.01	1
Mas-801b	21°05.16	104°25.17	san	Silicic tuff	4.23 ± 0.02	2
COMP-1	21°02.89	104°40.60	gms	Silicic tuff	4.57 ± 0.01	1
284†	21°18.60	104°33.60	plag	Rhyolite	4.60 ± 0.20	3
IXT-50	21°12.80	104°33.50	gms	Rhyolite lava dome	4.72 ± 0.02	1
IXT-67	21°14.54	104°36.57	san	Rhyolite lava flow	4.72 ± 0.04	1
SAN-4	21°18.44	104°36.45	san	Silicic tuff	4.75 ± 0.01	1
995-7B†	20°50.17	103°15.28	gms	Silicic tuff	4.85 ± 0.06	5
JRE-9†	20°15.00	103°33.60	bio	Silicic tuff	4.90 ± 0.30	14
SMO-12	21°19.74	104°39.64	plag	Silicic tuff	4.78 ± 0.04	1
XAL-32	21°19.65	104°48.98	gms	Silicic tuff	4.97 ± 0.02	1
XAL-15	21°22.40	104°42.60	plag	Rhyolite lava flow	4.95 ± 0.02	1
TEQ-9	20°54.60	103°43.20	gms	Silicic tuff	5.12 ± 0.05	13
55-30†	20°56.43	103°25.18	anorth	Rhyolite lava flow	5.19 ± 0.06	5
995-3†	20°48.32	103°20.37	anorth	Rhyolite lava flow	5.47 ± 0.17	5
JAL-7†	20°55.80	103°40.20	plag	Silicic tuff	5.53 ± 0.10	7
KA 3100†	20°46.80	103°19.20	anorth	Silicic tuff	7.15 ± 0.20	5
3†	20°49.80	103°18.60	plag	Silicic tuff	9.10 ± 0.10	15
IL 898	21°01.80	103°25.20	san	Silicic tuff	10.2 ± 0.1	6
1155†	20°55.20	105°31.80	plag	Silicic tuff	11.1 ± 0.2	3
79-20†	21°57.60	104°55.80	plag	Silicic tuff	13.2 ± 0.4	12
Ped Jal 22†	20°55.20	103°43.20	plag	Silicic tuff	16.9 ± 0.5	7
404†	21°15.00	104°55.20	plag	Rhyolite lava flow	18.1 ± 0.8	3
165†	21°12.00	105°04.20	plag	Rhyolite lava flow	18.5 ± 0.7	3
A†	21°50.40	104°48.00	gms	Silicic tuff	18.7 ± 1.1	16
Ped Nay 9†	21°19.80	104°25.20	san	Silicic tuff	19.0 ± 0.4	10
HOS-3	21°01.07	104°11.88	plag	Silicic tuff	19.3 ± 0.3	1
RGS 10†	21°06.00	103°57.60	feld	Feldspar dike	19.5 ± 0.5	7
Gdl 228	21°01.80	104°25.70	gms	Silicic tuff	20.0 ± 0.3	4
ETZ-25	20°44.80	104°04.43	gms	Rhyolite lava flow	20.3 ± 0.1	1
CM 6†	21°03.19	103°56.23	san	Silicic tuff	20.2 ± 0.5	7
HOS-4	21°01.26	104°13.44	bio	Silicic tuff	20.4 ± 0.1	1
HOS-4	21°01.26	104°13.44	plag	Silicic tuff	20.9 ± 0.1	1
246†	21°18.00	104°36.00	plag	Rhyolite lava flow	21.3 ± 0.9	3
AME-4	20°42.21	104°14.64	plag	Rhyolite lava flow	21.3 ± 0.1	1
C†	21°46.80	104°48.00	gms	Silicic tuff	22.4 ± 4.0	16
IL 89 12	21°16.20	103°28.20	san	Silicic tuff	22.9 ± 0.1	6
IL 89 1	21°16.80	103°28.20	san	Silicic tuff	23.0 ± 0.1	6
Ped Jal 1†	23°13.80	103°42.00	plag	Silicic tuff	23.2 ± 0.5	11
Ped Jal 15†	21°00.60	103°46.80	plag	Silicic tuff	23.6 ± 0.5	7
HR460*	21°30.35	103°10.07	–	Silicic tuff	24.9 ± 2.7	9
BQ483*	21°27.38	103°02.32	–	Silicic tuff	25.2 ± 2.2	9
HR467*	21°30.13	103°11.08	–	Silicic tuff	25.3 ± 2.4	9
COMP-25	21°01.80	104°44.79	san	Rhyolite lava flow	25.4 ± 0.2	1
IL 89 5	21°25.20	103°28.80	san	Silicic tuff	27.1 ± 0.1	6
ETZ-15	20°47.35	104°13.40	plag	Silicic tuff	27.6 ± 0.1	1
Ped Zac 3†	21°46.20	103°10.80	plag	Silicic tuff	29.2 ± 0.6	11
ES 2†	21°10.49	103°46.25	bio	Silicic tuff	30.1 ± 0.8	4
AME-2	20°36.37	104°02.70	gms	Silicic tuff	31.9 ± 0.1	1
XAL-30	21°20.93	104°55.17	gms	Rhyolite lava flow	32.4 ± 0.1	1
Ped Nay 4†	21°30.60	104°18.00	san	Silicic tuff	34.1 ± 0.7	10
COMP-33	21°08.56	104°53.64	plag	Rhyolite	46.9 ± 0.1	1
SMO-8	21°25.20	104°33.42	gms	Rhyolite lava flow	47.9 ± 0.1	1
FEL-2	20°58.62	104°41.04	gms	Silicic tuff	48.8 ± 0.1	1
345†	21°08.03	104°49.95	plag	Rhyolite	53.8 ± 1.5	3
COMP-38	21°06.53	104°48.95	san	Rhyolite lava flow	54.6 ± 0.6	1
Mas-433	20°59.50	104°28.00	plag	Silicic tuff	60.9 ± 0.4	2
Mas-427	20°45.21	104°29.50	san	Silicic tuff	65.3 ± 0.2	2
Mas-607	20°11.69	104°22.81	bio	Silicic tuff	70.6 ± 0.2	2
1170†	20°39.00	105°09.00	feld	Silicic tuff	71.2 ± 1.4	3
Mas-808	20°53.86	105°07.81	san	Silicic tuff	74.9 ± 0.2	2
JRE-90	20°18.60	103°54.00	bio	Silicic tuff	78.0 ± 2.0	14
LV-237	20°26.58	104°24.70	bio	Silicic tuff	80.7 ± 0.4	8
LV-250	20°25.85	104°29.00	bio	Silicic tuff	83.3 ± 0.3	8
1168†	20°39.00	105°09.00	feld	Silicic tuff	88.0 ± 1.8	3
1154†	20°37.62	105°13.20	feld	Silicic tuff	91.5 ± 2.3	3

Notes: All errors are reported as 1σ. Material dated: plag—plagioclase; gms—groundmass; san—sanidine; bio—biotite; anorth—anorthoclase; feld—feldspar. Monitor was Fish Canyon Tuff biotite—split 3 (27.99).

*Fission-track dates on zircons.

†K-Ar dates.

‡See GSA Data Repository (see text footnote 1) for complete analytical data and age spectra.

References: 1—this paper; 2—Righter et al. (1995); 3—Gastil et al. (1978); 4—Ferrari et al. (2002); 5—Gilbert et al. (1985); 6—Moore et al. (1994); 7—Nieto-Obregon et al. (1985); 8—Wallace and Carmichael (1989); 9—Webber et al. (1994); 10—Damon et al. (1979); 11—Nieto-Obregon et al. (1981); 12—Clark et al. (1981); 13—Lewis-Kenedi et al. (2005); 14—Rosas-Elguera et al. (1997); 15—Watkins et al. (1971); 16—compiled by Ferrari et al. (2000); 17—Righter and Carmichael (1992).

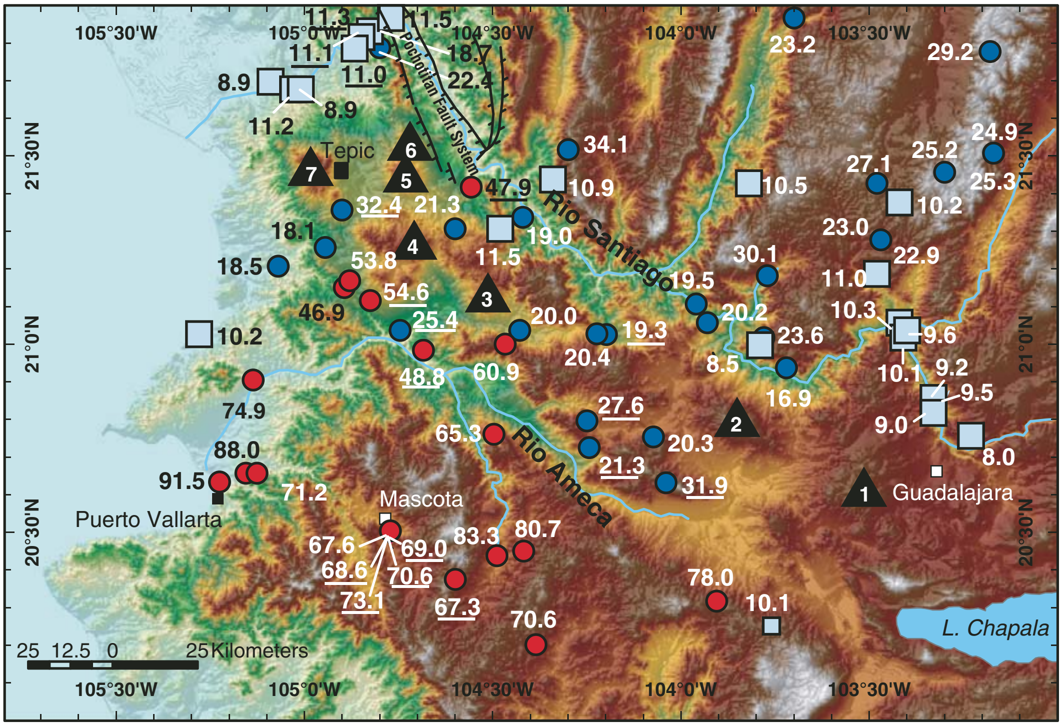

Figure 3. Digital elevation model (DEM, scale 1:250,000) of the Tepic-Zacoalco rift region with sample localities and ages. All ages are in Ma; plain white text indicates data from previous studies (see Tables 1 and 2), and underlined white text are data from this work. Red dots represent Paleocene-Cretaceous silicic ignimbrites associated with the Jalisco block. Blue dots represent Oligocene-Miocene rhyolitic ash-flow tuffs and lavas associated with Sierra Madre Occidental. Light blue squares represent late Miocene basalts associated with proto–Gulf of California extension. Numbered triangles in the Tepic-Zacoalco and Colima grabens refer to central volcanoes: 1—Sierra La Primavera, 2—Volcán Tequila, 3—Volcán Ceboruco, 4—Volcán Tepetiltic, 5—Volcán Sanganguey, 6—Volcán Las Navajas, and 7—Volcán San Juan.

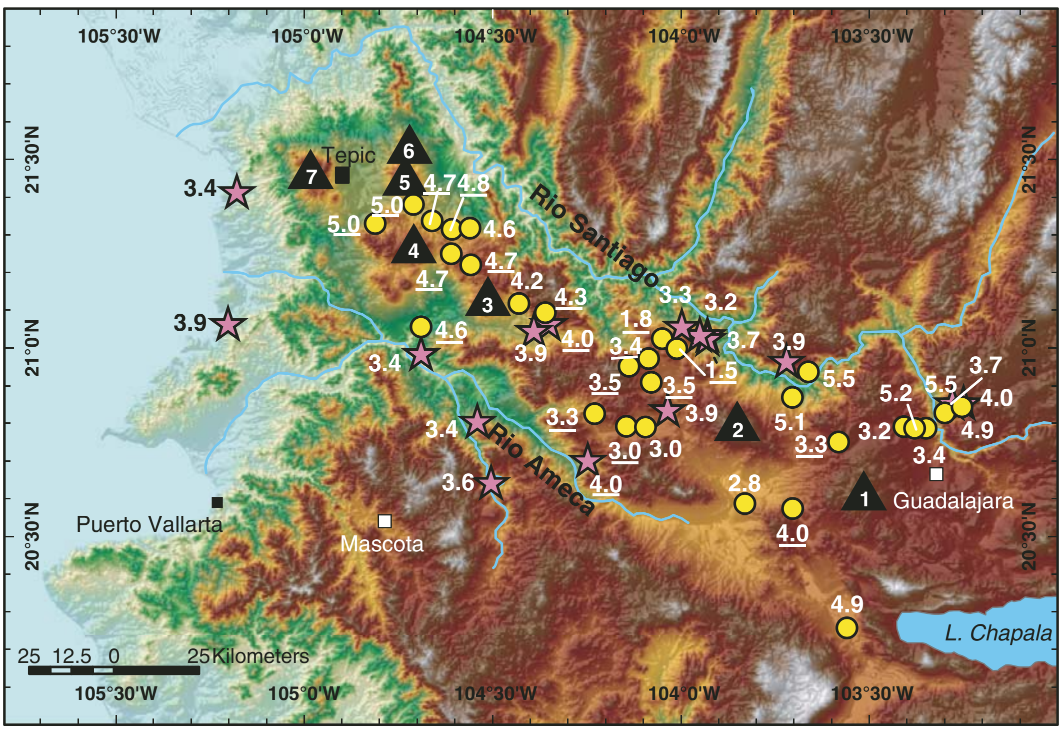

Figure 4. Digital elevation model (DEM, 1:250,000) of the Tepic-Zacoalco rift with sample localities and ages for Pliocene volcanism. All ages are in Ma; plain white text indicates data from previous studies (see Tables 1 and 2), and underlined white text are data from this work. Yellow dots represent rhyolitic lavas and ash-flow tuffs of Pliocene age. Pink stars represent Pliocene high-Ti basalts. Numbered triangles in the Tepic-Zacoalco and Colima grabens refer to central volcanoes: 1—Sierra La Primavera, 2—Volcán Tequila, 3—Volcán Ceboruco, 4—Volcán Tepetiltic, 5—Volcán Sanganguey, 6—Volcán Las Navajas, and 7—Volcán San Juan.

TABLE 2. SUMMARY OF $^{40}Ar/^{39}Ar$ AND K-Ar DATES OF MIOCENE BASALTS IN THE TEPIC-ZACOALCO RIFT (8–12 Ma)

Sample #	Latitude (N)	Longitude (W)	Material dated*	Lava type	Age (Ma)	Reference
Ped Jal 11†	20°45.00	103°13.80	gms	Basalt	8.02 ± 0.10	11
Ped Jal 17†	20°59.40	103°47.40	wr	Basalt	8.52 ± 0.10	7
KR-452	21°40.08	105°02.40	gms	Alkali basalt	8.91 ± 0.06	2
KR-381	21°41.45	105°05.43	gms	Alkali basalt	8.93 ± 0.11	2
4†	20°48.60	103°19.80	wr	Basalt	9.00 ± 0.20	15
2†	20°51.00	103°19.80	wr	Basalt	9.20 ± 0.10	15
1†	20°51.00	103°18.60	wr	Basalt	9.50 ± 0.10	15
A-28†	21°01.80	103°23.90	gms	High-Ti basalt flow	9.61 ± 0.28	6
Ped Jal 8†	21°00.60	103°24.60	gms	Basaltic andesite	10.05 ± 0.32	10
JRE-7†	20°15.00	103°40.20	gms	Basalt	10.10 ± 0.50	14
1151	21°01.47	105°16.80	plag	Basalt	10.20 ± 0.80	3
61-180†	21°22.50	103°24.90	gms	Alkali basalt	10.23 ± 0.34	6
A-30†	21°03.00	103°25.60	gms	Alkali basalt	10.25 ± 0.82	6
Ped Zac 2†	21°25.20	103°49.20	wr	Basaltic andesite	10.52 ± 0.22	11
Ped Nay 12†	21°25.80	103°20.40	wr	Basaltic dike	10.92 ± 0.33	10
A-81†	21°10.90	103°29.30	gms	Basaltic andesite	10.99 ± 0.23	6
TEP44D	21°48.54	104°50.93	gms	Basalt	11.10 ± 0.04	1
J†	21°40.20	105°00.60	gms	Basalt	11.20 ± 0.80	16
TEP36D	21°49.43	104°49.59	gms	Basalt	11.30 ± 0.16	1
Ped Nay 3†	21°18.00	104°01.80	wr	Basaltic dike	11.48 ± 0.24	10
I†	21°51.60	104°46.20	gms	Basaltic dike	11.50 ± 0.50	16

Notes: All errors are reported as 1σ. See Table 1 for references.
*Material dated: gms—groundmass; wr—whole rock; plag—plagioclase.
†K-Ar dates.

TABLE 3. SUMMARY OF $^{40}Ar/^{39}Ar$ AND K-Ar DATES OF PLIOCENE BASALT IN THE TEPIC-ZACOALCO RIFT

Sample #	Latitude (N)	Longitude (W)	Material dated*	Lava type	Age (Myr)	Reference
TQ-308†	21°02.40	103°57.40	gms	High-Ti basalt flow	3.19 ± 0.26	6
Mas-530	21°03.10	103°59.90	gms	High-Ti basalt flow	3.26 ± 0.18	6
KR 386†	21°24.60	105°10.71	gms	High-Ti basalt flow	3.36 ± 0.17	2
KR 403C	20°58.81	104°41.41	gms	High-Ti basalt flow	3.38 ± 0.05	2
KR-122†	20°48.00	104°31.80	gms	Hawaiite	3.38 ± 0.10	17
KR-109†	20°37.80	104°30.00	gms	Alkali basalt	3.55 ± 0.21	17
Mas521†	20°51.70	103°17.00	gms	High-Ti basalt flow	3.69 ± 0.13	6
Ped Jal 23†	21°01.20	103°55.80	gms	High-Ti basalt flow	3.72 ± 0.06	7
ETZ-5	20°49.89	104°02.12	gms	High-Ti basalt flow	3.86 ± 0.04	14
IXT-52	21°03.65	105°21.03	gms	High-Ti basalt flow	3.87 ± 0.04	1
KR 308	21°03.59	105°12.11	gms	High-Ti basalt flow	3.88 ± 0.03	2
Ped Jal 24†	21°57.60	103°43.20	gms	High-Ti basalt flow	3.93 ± 0.09	7
SC55†	20°45.87	103°19.30	gms	High-Ti basalt flow	3.97 ± 0.06	5
IXT-46	21°02.51	104°23.40	gms	High-Ti basalt flow	4.01 ± 0.02	1

Notes: All errors are reported as 1σ. See Table 1 for references.
*Material dated: gms—groundmass.
†K-Ar dates.

In addition to this Quaternary basalt-rhyolite volcanism in the SE portion of the Tepic-Zacoalco rift, alkaline volcanism has occurred in the NW portion. Here, Quaternary alkali olivine basalt, hawaiite, mugearite, and benmoreite have erupted as cinder cones and fissure-fed flows along NW-trending lineaments (Nelson and Carmichael, 1984), and central volcanism from nearby Volcán Las Navajas has produced trachyte and peralkaline rhyolite at ca. 0.2 Ma (Fig. 3; Nelson and Hegre, 1990).

The Tepic-Zacoalco rift is also the location of the northwestern arm of the Trans-Mexican volcanic belt, which includes five andesitic stratovolcanoes (Volcán San Juan, Volcán Sanganguey, Volcán Tepetiltic, Volcán Ceboruco, and Volcán Tequila) and numerous peripheral vents (Fig. 2). All five of the andesitic, central volcanoes were constructed <0.6 m.y. ago (Frey et al., 2004a, 2004b; Lewis-Kenedi et al., 2005; Luhr, 2000; Nelson and Carmichael, 1984), and it is plausible that this young andesitic volcanism is related to the resumption of subduction of the Rivera plate at ca. 1 Ma.

GEOCHEMISTRY

Thirty-two samples from within the Tepic-Zacoalco rift were analyzed for major elements and select trace elements by the inductively coupled plasma–mass spectrometry (ICP-MS) method at Activation Laboratories of Ancaster, Ontario (Table 4). Sample compositions were normalized to 100%, and twenty-eight of the samples are classified as rhyolite, based on silica content (71–82 wt% SiO_2). Two samples are classified as basaltic (IXT-52 and IXT-46; 51 wt% SiO_2), and two samples have a more intermediate silica composition (AME-3, 57.2 wt%; XAL-33, 63.4 wt%). The basalts near Volcán Ceboruco have 2.4–1.6 wt% TiO_2 and are similar to the Pliocene high-Ti basalts within the Tepic-Zacoalco rift reported in the literature (e.g., Moore et al., 1994). The composition of the rhyolites is not correlated to the geographic location of the samples, but appears to be correlated with the age of the samples. Ba (13–2057 ppm) and Sr (2–263 ppm) concentrations display a wide range (Table 4), but the Pliocene samples are consistently lower in Sr (Fig. 5).

Nine dike samples, six from the interior of the Jalisco block and three from the NW margin of the Tepic-Zacoalco rift, were analyzed for major elements by X-ray fluorescence of fused glass discs at University of California Berkeley (Table 5). Of the six dikes from the Jalisco block, three are basaltic andesites (53–54 wt% SiO_2) and three are andesites (59–64 wt% SiO_2); these are located close to the town of Mascota (Fig. 4). Of the three dikes from the NW margin of the Tepic-Zacoalco rift, two are basaltic (50 and 53 wt% SiO_2) and one is rhyolitic (79 wt% SiO_2); these samples are from a swarm of >30 dikes that intrude Sierra Madre Occidental ignimbrites along a 15 km segment of the Rio Santiago, north of the city of Tepic (Fig. 4).

$^{40}Ar/^{39}Ar$ CHRONOLOGY

Forty-one samples were dated by the $^{40}Ar/^{39}Ar$ laser ablation method at the University of Michigan, following procedures described in Frey et al. (2004b). Wherever possible, mineral separates (sanidine, plagioclase, or biotite) were handpicked for irradiation, but groundmass separates were used for samples lacking highly potassic minerals (basalts, andesites, and some rhyolites). Neutron-fluence monitor, Fish Canyon Tuff biotite, split-3 (FCT-3) was used as a calibration standard. Irradiation was done at the Phoenix-Ford Memorial Reactor at the University of Michigan (18 samples) and

TABLE 4A. MAJOR AND SELECTED TRACE ELEMENT ANALYSES OF SAMPLES DATED

	Pliocene Rhyolites															
Sample	Guad-1	ETZ-30	COMP-1	HOS-7	IXT-67	IXT-49	ETZ-21C	XAL-15	IXT-50	XAL-32	SMO-12	SAN-4	ETZ-22	ETZ-23A	ETZ-29	ETZ-13
SiO_2	70.8	72.0	72.5	73.3	75.3	75.6	75.9	75.9	76.0	76.3	76.9	77.1	77.2	77.4	77.4	77.8
TiO_2	0.52	0.27	0.43	0.25	0.21	0.18	0.18	0.08	0.19	0.10	0.11	0.08	0.09	0.06	0.10	0.06
Al_2O_3	15.1	15.2	13.8	14.7	12.5	12.9	14.3	14.8	13.3	14.2	13.4	13.1	12.4	12.4	14.1	12.1
$Fe_2O_3^T$	2.92	2.82	3.04	1.79	3.42	3.15	1.27	1.38	0.97	2.15	1.88	1.68	1.20	1.82	1.00	1.57
MnO	0.07	0.11	0.13	0.02	0.05	0.05	0.02	0.03	0.00	0.04	0.02	0.03	0.05	0.06	0.04	0.04
MgO	0.19	0.14	0.28	0.14	0.01	0.05	0.08	0.03	0.01	0.00	0.00	0.00	0.04	0.01	0.05	0.02
CaO	0.93	0.42	0.53	0.56	0.07	0.03	0.51	0.18	0.07	0.05	0.03	0.03	0.29	0.02	0.18	0.01
Na_2O	5.27	4.44	5.05	3.68	3.93	3.51	3.15	3.13	5.05	3.09	3.26	3.70	4.14	3.99	2.29	4.09
K_2O	4.12	4.57	4.12	5.52	4.48	4.55	4.53	4.45	4.44	4.02	4.41	4.25	4.64	4.20	4.81	4.33
P_2O_5	0.08	0.03	0.10	0.03	0.02	0.02	0.05	0.01	0.03	0.04	0.02	0.02	0.02	0.01	0.02	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LOI	1.47	3.98	2.09	1.53	1.86	2.21	1.80	5.00	0.58	3.30	2.07	1.79	0.38	1.13	2.72	0.82
Orig. total	99.03	98.95	100.25	99.23	99.71	100.50	99.17	99.85	100.35	99.44	99.41	100.06	99.97	99.01	98.89	99.50
Ba	1168	638	1155	1030	135	22	962	36	1636	30	29	19	282	13	174	17
Sr	173	93	108	81	2	3	77	4	34	7	2	2	16	2	12	2
Y	58	42	49	11	142	129	11	36	58	79	52	30	41	48	21	47
Zr	368	473	351	246	639	678	175	187	439	382	467	324	131	323	95	287
Elev. (m)	1595	1430	645	1390	1480	1830	1380	1055	1530	1151	1120	1175	1415	1600	1300	1405
Age (Ma)	3.30	1.50	4.57	1.84	4.72	4.32	2.91	4.95	4.72	4.97	4.78	4.75	3.40	3.52	3.30	3.54

Notes: Major and trace elements analyzed by inductively coupled plasma–mass spectrometry at Activation Laboratories of Ancaster, Ontario. Orig. total is the total of the analysis prior to normalization. LOI—loss on ignition.

TABLE 4B. MAJOR AND SELECTED TRACE ELEMENT ANALYSES OF SAMPLES DATED

	Sierra Madre rhyolites								Eocene rhyolites			
Sample	HOS-3	AME-2	HOS-4	AME-4	ETZ-15	ETZ-25	XAL-30	COMP-25	SMO-8	COMP-38	FEL-2	COMP-33
SiO_2	71.3	71.6	73.9	75.8	76.2	78.8	80.1	81.5	76.1	76.6	77.2	78.6
TiO_2	0.47	0.35	0.47	0.19	0.17	0.17	0.17	0.26	0.33	0.11	0.08	0.11
Al_2O_3	14.6	15.2	14.3	12.9	13.4	13.1	13.2	9.6	15.4	13.8	12.6	12.9
$Fe_2O_3^T$	3.32	2.45	2.48	1.72	2.01	0.23	1.81	1.53	1.05	1.47	1.39	0.76
MnO	0.07	0.06	0.07	0.10	0.05	0.01	0.01	0.03	0.01	0.01	0.04	0.01
MgO	0.95	0.75	0.69	0.18	0.64	0.62	0.52	0.17	0.89	0.35	0.94	0.27
CaO	0.60	2.58	0.80	0.28	0.74	0.07	0.10	0.82	0.04	0.27	0.57	0.10
Na_2O	4.04	4.46	3.47	4.23	2.05	2.02	0.30	2.66	0.13	3.77	1.50	2.23
K_2O	4.55	2.40	3.74	4.59	4.69	4.97	3.72	3.27	6.07	3.67	5.64	4.96
P_2O_5	0.09	0.15	0.10	0.02	0.03	0.02	0.01	0.12	0.02	0.02	0.03	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LOI	2.51	3.46	3.20	0.87	3.73	3.62	4.21	1.78	3.21	2.27	4.26	1.62
Orig. total	99.97	99.39	99.30	99.76	99.16	99.00	99.73	99.62	99.05	99.50	99.22	99.02
Ba	1269	383	1492	461	727	2057	600	1483	1466	898	818	898
Sr	263	228	184	55	80	79	43	202	106	110	73	106
Y	18	8	30	44	50	28	19	52	19	29	24	26
Zr	191	161	335	253	174	149	124	180	150	155	92	147
Elev. (m)	1040	1400	1275	1530	1370	1510	1100	730	550	985	600	870
Age (Ma)	19.3	31.9	20.4	21.3	27.6	20.3	32.4	25.4	47.9	54.6	48.8	46.9

Notes: LOI—loss on ignition. Orig. total is the total of the analysis prior to normalization.

at the McMaster Nuclear Reactor at McMaster University in Hamilton, Ontario (16 samples). For both irradiations, FCT-3 biotite yielded a K-Ar age of 27.99 ± 0.04 Ma (2 sigma error), as calibrated against MMhb-1 (Hall and Farrell, 1995; Samson and Alexander, 1987), and within error of 28.02 ± 0.16 Ma reported for sanidine from the Fish Canyon Tuff by Renne et al. (1998). The neutron-flux measure J was monitored as a function of position in the irradiation package using FCT-3 and interpolated for application to age calculations for individual sample positions.

For groundmass and biotite separates, five grains (total mass ~20 mg) of each sample were step-heated at increasing levels of laser power until complete fusion was achieved, using a defocused beam from a Coherent Innova 5 W continuous argon-ion laser. For plagioclase and sanidine separates, a focused beam at 4000 mW of power was used on individual grains. Several grains were dated to obtain a mean age for the sample. Fusion-system blanks were run after every five steps of analysis and subtracted from all gas fractions. The data were corrected for interference reactions due to Ca, K, and Cl, and for ^{37}Ar and ^{39}Ar decay.

RESULTS

A summary of the ages of the samples from the Tepic-Zacoalco rift is included in Tables 6A, 6B, and 6C. Samples included in Table 6A

TABLE 4C. MAJOR AND SELECTED TRACE ELEMENT ANALYSES OF SAMPLES DATED

	Basalts		Intermediate	
Sample	IXT-52	IXT-46	AME-3	XAL-33
SiO_2	51.0	51.3	57.2	63.4
TiO_2	2.35	1.61	0.93	0.88
Al_2O_3	16.5	17.5	18.4	16.6
$Fe_2O_3^T$	11.39	10.15	7.09	5.46
MnO	0.17	0.15	0.11	0.10
MgO	4.96	5.80	3.50	1.87
CaO	8.41	9.11	6.86	4.61
Na_2O	3.64	3.43	4.11	4.54
K_2O	1.05	0.66	1.53	2.30
P_2O_5	0.56	0.26	0.26	0.24
Total	100.00	100.00	100.00	100.00
LOI	0.39	0.15	0.81	0.45
Orig. total	99.24	100.33	99.11	99.50
Ba	605	317	766	1156
Sr	537	575	952	526
Y	76	21	19	50
Zr	156	115	113	167
Elev. (m)	1340	1060	1100	1076
Age (Ma)	3.87	4.01	3.99	2.25

Notes: LOI—loss on ignition. Orig. total is the total of the analysis prior to normalization.

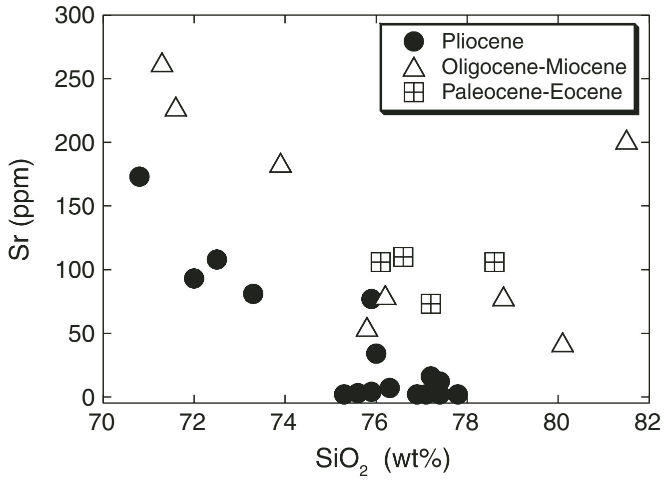

Figure 5. Plot of Sr versus silica content shows the range and diversity of rhyolites erupted in the Tepic-Zacoalco rift since the Cretaceous. The Pliocene rhyolites are typically lower in Sr than the Sierra Madre Occidental rhyolites at a given Si composition.

TABLE 5. MAJOR ELEMENT ANALYSES OF DIKES NEAR TEPIC AND MASCOTA

Sample	TEP-36D	TEP-44D	TEP-51D	MAS-16D	MAS-7D	MAS-8D	MAS-5D	MAS-3D	MAS-6D	MAS-4D
SiO_2	50.2	52.6	78.7	53.4	53.9	54.1	54.1	61.0	65.6	65.7
TiO_2	1.44	1.05	0.24	1.03	1.01	1.04	1.06	0.77	0.86	0.83
Al_2O_3	16.8	18.5	12.3	18.1	18.0	18.3	18.4	19.5	16.1	16.1
$Fe_2O_3^T$	10.59	8.45	2.57	9.19	8.38	8.59	8.67	5.11	4.86	4.59
MnO	0.17	0.14	0.03	0.17	0.16	0.17	0.13	0.10	0.12	0.09
MgO	5.25	5.39	0.13	5.46	4.60	4.33	4.60	1.72	1.35	1.28
CaO	12.10	7.35	0.18	7.77	6.27	6.33	5.97	3.20	3.23	2.42
Na_2O	2.77	3.78	0.29	3.68	2.80	3.55	4.61	5.44	4.23	4.20
K_2O	0.48	2.42	5.51	1.00	4.72	3.40	2.23	2.98	3.33	4.50
P_2O_5	0.28	0.32	0.04	0.20	0.20	0.21	0.21	0.26	0.29	0.27
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LOI	8.91	–	2.62	–	6.62	5.85	–	–	–	–
Orig. total	100.68	96.09	100.10	97.07	100.59	99.89	96.51	96.64	96.22	97.23

Notes: Major elements and loss on ignition (LOI) analyzed by X-ray fluorescence at the University of California–Berkeley. Original total is total prior to normalization, and including LOI, if measured.

yielded isochron and/or plateau ages and did not show evidence of systematic ^{40}Ar loss. Samples included in Table 6B showed evidence of alteration petrographically (feldspar breakdown to clay) and yielded spectra with low apparent ages in the first several fractions of gas release. Because of the alteration to clay and possible Ar isotope recoil effects, the "reduced plateau age" method of Turner et al. (1978) was adopted. This method eliminates the low-temperature gas fractions that show obvious signs of radiogenic ^{40}Ar loss and calculates an integrated age from the remaining fractions, referred to as a reduced integrated age. The effects of recoil artifacts are thus minimized. Samples included in Table 6C did not yield plateau, isochron, or reduced integrated ages and are reported as total gas ages. All samples from Tables 6A, 6B, and 6C are shown in Figure 6. The summary of the total gas ages for the dikes near Tepic and Mascota is included in Table 7. Gas spectra and isochron diagrams for each sample are given in the GSA Data Repository.[1] The error analysis incorporates uncertainties in peak signals, system blanks, spectrometer mass discrimination, reactor corrections, and J values. The errors reported for plateau ages were derived from standard weighting of errors by variance (Taylor, 1982).

[1]GSA Data Repository item 2007002, Ar gas release spectra and isochron diagrams, is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

Cretaceous and Paleocene-Eocene

The six dikes from the interior of the Jalisco block, near the town of Mascota, yielded total gas ages that range from 67 to 73 Ma (Table 7). The saddle-shaped argon release spectra from these samples suggest that they have been partially altered to clay, and they do not display a plateau. However, the total gas age is considered equivalent to a K-Ar age and indicates that the samples are Cretaceous in age, and clearly not Oligocene-Miocene (i.e., related to the Sierra Madre Occidental province).

Within the Tepic-Zacoalco rift, four rhyolite samples (COMP-38, COMP-33, FEL-2, SMO-8) gave Paleocene-Eocene ages of 55, 47, 49, and 48 Ma, respectively (Tables 6A and 6C). None of these samples displays a plateau, although a correlation age was obtained for COMP-38. For the remaining three, the total gas age is used and indicates that the samples are Eocene in age, and clearly neither Cretaceous nor Miocene.

Oligocene-Miocene

Six of the rhyolite samples within the Tepic-Zacoalco rift (HOS-3, HOS-4, ETZ-25, AME-4, COMP-25, and ETZ-15) gave correlation ages of 19, 20, 20, 21, 25, and 28 Ma, respectively, which indicate that they are part of the Sierra Madre Occidental province (Table 6A, 6B, 6C; Fig. 3). Two additional rhyolites (AME-2 and XAL-30) were sufficiently altered that only total gas ages (32 Ma for both; Table 6C; Fig. 3) could be obtained; nonetheless, these Oligocene dates clearly place them as part of the Sierra

TABLE 6A. SUMMARY OF TOTAL FUSION, CORRELATION, AND PLATEAU $^{40}Ar/^{39}Ar$ AGES†

Sample #	Latitude (N)	Longitude (W)	Composition	Material dated*	Total gas age (Ma)	Correlation age (Ma)	Correlation MSWD	$(^{40}Ar/^{36}Ar)_i$	Points fitted	Plateau age	Plateau MSWD	Plateau % ^{39}Ar
ETZ-30	20°59.44	104°00.65	Rhyolite	gms	1.42 ± 0.01	1.50 ± 0.01	4.54	289.9 ± 3.1	10 of 13	1.50 ± 0.02	1.63	51
Guad1	20°44.57	103°35.14	Rhyolite	gms	3.28 ± 0.02	3.30 ± 0.02	5.03	296.2 ± 1.3	9 of 10	3.27 ± 0.02	1.56	100
ETZ-22	20°57.82	104°05.15	Rhyolite	gms	3.44 ± 0.02	3.40 ± 0.04	0.52	293.6 ± 4.3	7 of 9	3.40 ± 0.03	0.30	75
ETZ-23A	20°56.63	104°08.29	Rhyolite	gms	3.56 ± 0.01	3.51 ± 0.01	0.85	298.6 ± 3.7	4 of 13	3.52 ± 0.01	1.18	55
ETZ-13	20°54.07	104°04.76	Rhyolite	gms	3.54 ± 0.01	N/A				3.58 ± 0.01	1.21	89
IXT-52	21°03.65	105°21.03	Basalt	gms	3.83 ± 0.08	3.87 ± 0.20	1.45	293.2 ± 1.4	12 of 13	3.87 ± 0.07	1.95	100
AME-3	20°41.85	104°14.42	Andesite	gms	3.79 ± 0.03	3.99 ± 0.05	2.51	289.3 ± 1.2	13 of 13	3.92 ± 0.06	1.72	65
IXT-46	21°02.51	104°23.40	Basalt	gms	3.76 ± 0.11	4.01 ± 0.02	0.98	290.6 ± 2.0	13 of 13	3.83 ± 0.11	1.34	100
IXT-67	21°14.54	104°36.57	Rhyolite	san	4.71 ± 0.02	4.72 ± 0.04	2.19	294.1 ± 15	5 of 5	N/A		
IXT-50	21°12.80	104°33.50	Rhyolite	gms	4.79 ± 0.03	3.27 ± 0.02	1.78	295.8 ± 1.7	13 of 13	4.72 ± 0.02	1.62	75
SAN-4	21°18.44	104°36.45	Rhyolite	san	4.76 ± 0.02	4.75 ± 0.01	0.69	296.3 ± 1.2	6 of 6	N/A		
XAL-15	21°22.40	104°42.60	Rhyolite	plag	4.94 ± 0.01	4.95 ± 0.02	0.49	285.6 ± 26	7 of 7	N/A		
HOS-3	21°01.07	104°11.88	Rhyolite	plag	19.3 ± 0.3	19.0 ± 0.3	2.23	295.3 ± 0.7	5 of 6	19.3 ± 0.3	2.77	100
HOS-4	21°01.26	104°13.44	Rhyolite	bio	20.4 ± 0.1	20.4 ± 0.1	1.23	301.1 ± 10	8 of 8	20.5 ± 0.1	0.58	100
COMP-25	21°01.80	104°44.79	Rhyolite	san	25.2 ± 0.3	25.4 ± 0.2	1.23	293.4 ± 1.3	4 of 5	N/A		
ETZ-15	20°47.35	104°13.40	Rhyolite	plag	27.7 ± 0.1	27.6 ± 0.1	2.84	298.9 ± 27	4 of 5	N/A		
COMP-38	21°06.53	104°48.95	Rhyolite	san	58.3 ± 0.3	54.6 ± 0.6	2.1	298.6 ± 1.6	13 of 13	N/A		

Notes: All ages are in Ma, and errors are reported as 1σ. Monitor was Fish Canyon Tuff biotite—split 3 (27.99 Ma). MSWD—mean square of weighted deviates.
*Material dated: plag—plagioclase; gms—groundmass; san—sanidine; bio—biotite.
†See GSA Data Repository (Figure and Table DR1 [see text footnote 1]) for age spectra and isochron diagrams and complete analytical data set of step-heating and volumes of Ar isotopes released.

TABLE 6B. SUMMARY OF TOTAL FUSION AND REDUCED INTEGRATED $^{40}Ar/^{39}Ar$ AGES†

Sample #	Latitude (N)	Longitude (W)	Composition	Material dated*	Total gas age (Ma)	Integrated age (Ma)	Steps used
HOS-7	21°01.00	104°03.10	Rhyolite	gms	1.70 ± 0.01	1.84 ± 0.01	6–13
XAL-33	21°20.54	104°49.01	Andesite	gms	2.16 ± 0.02	2.25 ± 0.02	5–13
ETZ-21C	20°47.07	104°08.70	Rhyolite	gms	2.79 ± 0.03	2.91 ± 0.03	2–5
ETZ-29	20°49.10	104°13.74	Rhyolite	gms	3.12 ± 0.01	3.30 ± 0.01	5–13
IXT-49	21°05.15	104°21.10	Rhyolite	gms	4.26 ± 0.02	4.32 ± 0.01	3–13
COMP-1	21°02.89	104°40.60	Rhyolite	gms	4.44 ± 0.03	4.57 ± 0.01	7–13
XAL-32	21°19.65	104°48.98	Rhyolite	gms	4.88 ± 0.02	4.97 ± 0.02	4–13
ETZ-25	20°44.80	104°04.43	Rhyolite	gms	20.4 ± 0.1	20.27 ± 0.06	4–13

Notes: All ages are in Ma, and errors are reported as 1σ. Monitor was Fish Canyon Tuff biotite—split 3 (27.99 Ma).
*Material dated: gms—groundmass.
†See GSA Data Repository (Figure and Table DR1 [see text footnote 1]) for age spectra and isochron diagrams and complete analytical data set of step-heating and volumes of Ar isotopes released.

TABLE 6C. SUMMARY OF TOTAL FUSION $^{40}Ar/^{39}Ar$ AGES†

Sample #	Latitude (N)	Longitude (W)	Lava type	Material dated*	Age (Ma)
HOS-4	21°01.26	104°13.44	Rhyolite	plag	20.9 ± 0.4
AME-4	20°42.21	104°14.64	Rhyolite	plag	21.3 ± 0.1
AME-2	20°36.37	104°02.70	Rhyolite	gms	31.9 ± 0.1
XAL-30	21°20.93	104°55.17	Rhyolite	gms	32.4 ± 0.1
COMP-33	21°08.56	104°53.64	Rhyolite	plag	46.9 ± 0.1
SMO-8	21°25.20	104°33.42	Rhyolite	plag	47.9 ± 0.1
FEL-2	20°58.62	104°41.04	Rhyolite	gms	48.8 ± 0.1

Notes: All ages are in Ma, and errors are reported as 1σ. Monitor was Fish Canyon Tuff biotite—split 3 (27.99 Ma).
*Material dated: plag—plagioclase; gms—groundmass.
†See GSA Data Repository (Figure and Table DR1 [see text footnote 1]) for age spectra and isochron diagrams and complete analytical data set of step-heating and volumes of Ar isotopes released.

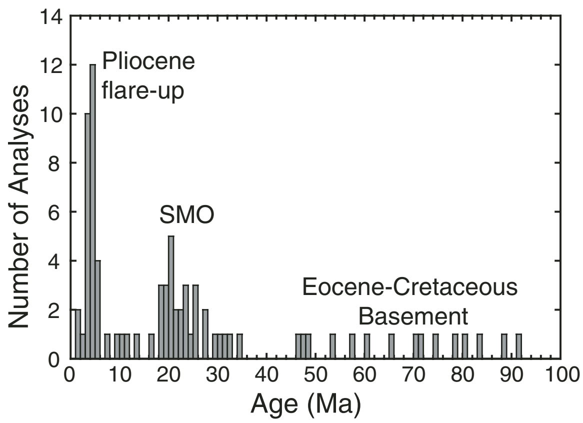

Figure 6. Histogram of the reported ages of silicic samples in the Tepic-Zacoalco rift.

Madre Occidental volcanic province and neither Cretaceous nor Pliocene in age.

The three dike samples (TEP44D, TEP51D, and TEP36D) along the NW margin of the Tepic-Zacoalco rift (near Tepic) all yielded total gas ages of 11 Ma, as shown in Figure 3 and Table 7. The argon release spectra for these samples do not yield a plateau. Ca/K and Cl/K ratios suggest that the dikes have been partly altered to clays.

Pliocene

Fifteen of the samples yielded Pliocene ages (Table 6A; Fig. 4); correlation ages or reduced integrated ages are the preferred dates for these samples. The two youngest (1.5 and 1.8 Ma) are silicic ash-flow tuffs in the central Tepic-Zacoalco rift (ETZ-30 and HOS-7). Six rhyolite domes (Table 4) located west and east of Volcán Tequila gave ages of 2.9, 3.3, 3.3, 3.4, 3.5, and 3.5 Ma (ETZ-21C, Guad 1, ETZ-29, ETZ-22, ETZ-23A, and ETZ-13). Rhyolite ash-flow tuffs and domes further NW in the Tepic-Zacoalco rift are older: 4.3, 4.6, 4.7, 4.7, 4.8, 5.0, and 5.0 Ma (IXT-49, COMP-1, IXT-50, IXT-67, SAN-4, XAL-32, and XAL-15). In addition to the rhyolites, two samples of high-Ti basalt near Volcán Ceboruco are dated at 3.9 and 4.0 Ma (IXT-52 and IXT-46), thus postdating the rhyolitic volcanism in the area. One intermediate composition lava (basaltic andesite) yields a similar age of 4.0 Ma (AME-3).

Oligocene-Pliocene

Nineteen sanidine separates were dated from pumiceous rhyolitic blocks in an unconsolidated pyroclastic flow NE of Volcán Tepetiltic (SMO-12). Seventeen of the separates yielded ages between 4.7 and 4.9 Ma, and one separate yielded an age of 26 Ma (Table 8). Thus in a single sample, there are crystals of both Pliocene and Oligocene age.

OUTCROP PATTERN FOR PLIOCENE UNITS

Within the Tepic-Zacoalco rift, more than 45% of the surface exposure has been mapped as silicic ash-flow tuffs, lavas and domes, by INEGI, the National Institute of Statistics, Geography and Data Processing (Mexico). From Tepic to Guadalajara, the Tepic-Zacoalco rift is ~185 km long and averages ~50 km wide, so the areal extent is ~9250 km^2, and the area of silicic volcanic products is ~4200 km^2 (Fig. 7). The silicic ash-flow tuffs and domes dominate the landscape, forming relatively high plateaus (up to ~2000 m above sea level). With ^{40}Ar/^{39}Ar dates in hand, we undertook an evaluation of the outcrop pattern of the Pliocene silicic ash-flow tuffs and lavas relative to the older Sierra Madre Occidental ignimbrites. To first order, the Sierra Madre Occidental units are more deeply dissected on the high-resolution digital elevation models than the younger Pliocene units. This is most evident in the sequence of ash-flow tuffs northeast of Volcán Ceboruco (Fig. 7). The more deeply dissected terrain yielded Sierra Madre Occidental ages.

On the basis of the distribution of dated ash-flows tuffs and erosional morphology patterns, as well as the geologic map by Ferrari et al. (2000), the areal extent of the Pliocene ignimbrites was estimated and is outlined in white and filled with a white stippled pattern in Figure 7. The largest area of Pliocene ignimbrites, northeast of Volcán Ceboruco, encompasses ~450 km^2 and features the greatest density of geochronological data. Other areas of documented or inferred Pliocene sequences are to the west and north of Volcán Tepetiltic, the central Tepic-Zacoalco rift, northwest of Volcán Tequila, and north of Guadalajara. The total estimated area of exposed Pliocene rhyolitic volcanism is ~2030 km^2. Thus, of the ~4200 km^2 mapped as silicic ash-flow tuffs and lavas, ~48% is estimated to be Pliocene in age. Well logs from drill holes located near Volcán Ceboruco and Sierra La Primavera (Ferrari and Rosas-Elguera, 2000; Fig. 7) identify Pliocene rhyolitic ignimbrite sections that are covered by Quaternary deposits. When these Pliocene rhyolites are included (dashed regions in Fig. 7), their areal extent increases to ~4230 km^2.

The thickest sequences of the Pliocene silicic ash-flow tuffs are at least 500 m and are exposed as faulted ash-flow tuffs north-northeast of Volcán Ceboruco. Silicic ash-flow tuffs west of Volcán Tequila are 200–300 m thick. In the well logs, the Pliocene rhyolitic ignimbrite sections are ~40 m thick near Volcán Ceboruco and ≥140 m thick beneath Sierra La Primavera (Ferrari and Rosas-Elguera, 2000).

DISCUSSION

Southern Termination of the Sierra Madre Occidental Volcanic Province

The boundary between the Miocene ignimbrites of the Sierra Madre Occidental and the Cretaceous ignimbrites of the Jalisco block has been inferred to lie somewhere within the Tepic-Zacoalco rift, concealed by more-recent volcanism of the Trans-Mexican volcanic belt (Righter et al., 1995; Rosas-Elguera et al., 1996). The extensive outcrops of rhyolitic ash-flow tuffs and domes in the Tepic-Zacoalco rift indicate that the boundary is not concealed, but simply poorly mapped owing to a lack of radiometric ages. It is not possible to distinguish the age of the silicic ignimbrites or lavas in the Tepic-Zacoalco rift by hand sample or whole-rock major or trace element analyses (although Pliocene rhyolites tend to have lower Sr concentrations; Fig. 5). New ^{40}Ar/^{39}Ar dates from this

TABLE 7. ^{40}Ar/^{39}Ar AGES OF DIKES NEAR TEPIC AND MASCOTA†

Sample #	Latitude (N)	Longitude (W)	Material dated	Lava type	Age (Ma)
TEP51D	21°48.51	104°52.00	groundmass	Rhyolite	11.00 ± 0.04
TEP44D	21°48.54	104°50.93	groundmass	Basalt	11.10 ± 0.04
TEP36D	21°49.43	104°49.59	groundmass	Basalt	11.30 ± 0.16
MAS16D	20°22.10	104°35.62	groundmass	Basaltic andesite	67.30 ± 0.30
MAS4D	20°29.98	104°46.12	groundmass	Andesite	67.60 ± 0.20
MAS7D	20°29.83	104°45.98	groundmass	Basaltic andesite	68.60 + 0.20
MAS8D	20°29.82	104°45.97	groundmass	Basaltic andesite	69.00 ± 0.20
MAS6D	20°29.88	104°46.02	groundmass	Andesite	70.60 ± 0.20
MAS3D	20°29.98	104°46.13	groundmass	Andesite	73.10 ± 0.30

Notes: All errors are reported as 1σ.
†See GSA Data Repository (text footnote 1) for complete analytical data and age spectra.

TABLE 8.
^{40}Ar/^{39}Ar AGES OF SMO-12

Run	Age (Ma)
a34a	25.94 ± 0.24
a34b	4.13 ± 0.40
a34c	4.73 ± 0.03
a34d	4.76 ± 0.01
a34e	4.76 ± 0.03
a34f	4.79 ± 0.03
a34g	4.86 ± 0.03
a34h	4.83 ± 0.06
a34i	4.82 ± 0.02
a34j	4.84 ± 0.03
a34k	4.85 ± 0.08
a34l	4.78 ± 0.03
a34m	4.79 ± 0.09
a34n	4.92 ± 0.07
a34o	4.85 ± 0.04
a34p	4.83 ± 0.03
a34q	4.81 ± 0.02
a34r	4.91 ± 0.22
a34s	4.79 ± 0.02

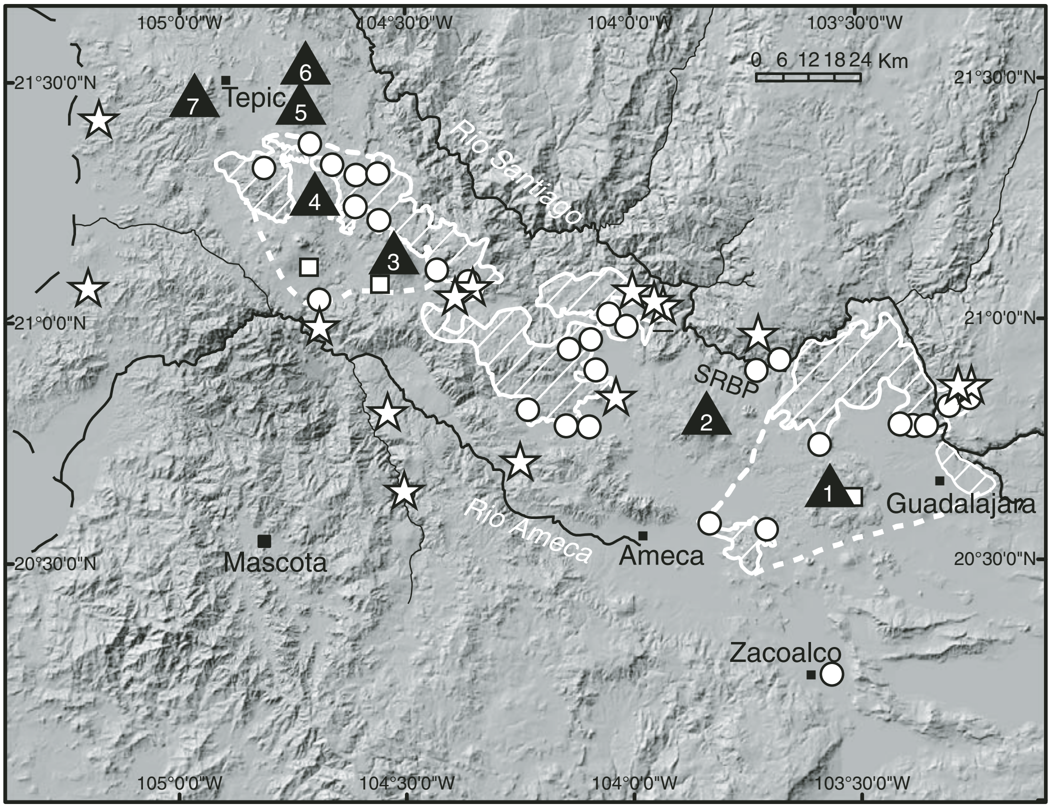

Figure 7. Digital elevation model (scale 1:50,000) of the Tepic-Zacoalco rift. Pliocene rhyolites between the Rio Santiago and Rio Ameca are outlined in white and have a striped pattern. Sample localities of the Pliocene rhyolites are denoted by white circles. Additional Pliocene rhyolites are inferred from well-log data (Ferrari and Rosas-Elguera, 2000) and are delineated by dashed white lines. The three well locations are denoted by white squares. Pliocene basalts are denoted by white stars. Numbered triangles in the Tepic-Zacoalco and Colima grabens refer to central volcanoes: 1—Sierra La Primavera, 2—Volcán Tequila, 3—Volcán Ceboruco, 4—Volcán Tepetiltic, 5—Volcán Sanganguey, 6—Volcán Las Navajas, and 7—Volcán San Juan. SRBP—Santa Rosa basalt plateau.

study demonstrate that Sierra Madre Occidental pyroclastic flows and lavas extend further south than previously realized. In the central Tepic-Zacoalco rift, twelve samples, including eight dated in this study, yielded Sierra Madre Occidental ages. Three new dated samples (AME-4, AME-2, COMP-25) of Sierra Madre Occidental age (21, 32, and 25 Ma; Table 6) are located close to the Rio Ameca and indicate that the Sierra Madre Occidental province extends across the entire width of the Tepic-Zacoalco rift to the Rio Ameca (Fig. 3).

Given the occurrence of Sierra Madre Occidental ignimbrites throughout the Tepic-Zacoalco rift, there has been some speculation as to whether they extended further into the interior of the Jalisco block, either by flowing across the northern boundary from calderas within the Tepic-Zacoalco rift, or alternatively from vents located within the Jalisco block. One possibility considered by Righter et al. (1995) is that Sierra Madre Occidental ash-flow tuffs may once have partially covered the Jalisco block, but were subsequently stripped off due to uplift and erosion. The average thickness of Sierra Madre Occidental ignimbrites estimated to have been removed is ~1200 m, based on stratigraphic sections measured north of the Tepic-Zacoalco rift (Nieto-Samaniego et al., 1999); however, thinner sections are possible if the Sierra-Madre Occidental ignimbrites only flowed (and thinned) across the northern boundary of the Jalisco block. The rate of uplift required to accommodate the removal of ~1200 m of material depends on the time scale considered. The occurrence of Pliocene potassic lavas directly on top of Cretaceous ignimbrites in the Jalisco block interior (e.g., Wallace and Carmichael, 1992; Righter and Rosas-Elguera, 2001) indicates that nearly complete erosion of the Sierra Madre Occidental sequence (if it was ever there) must have occurred prior to ca. 5 Ma.

There is ample evidence for recent uplift of the Jalisco block. Marine terraces are exposed at levels up to 100 m along the coastal margin of the Jalisco block (Ramirez-Herrera and Urrutia-Fucugauchi, 1999). Paleontologic data from molluscs on the coastal plains of the Jalisco block suggest slow uplift during the Quaternary, on the order of 0.06 mm/yr (Durham et al., 1981). Higher uplift rates are suggested by bedrock incision rates of 0.23–0.25 mm/yr over the last 2.7 m.y. in the Atenguillo valley in the interior of the Jalisco block (Righter, 1997). However, there is little information on the uplift history of the Jalisco block over the time period in question, namely ca. 20–5 Ma.

To date, there have been no reports of any silicic ash-flow tuffs of Sierra Madre Occidental age in the Jalisco block. The $^{40}Ar/^{39}Ar$ results on several dikes that crosscut silicic ignimbrites in the interior of the Jalisco block all yield Cretaceous ages (67–73 Ma; Table 7). Therefore, there is no clear evidence that Sierra Madre Occidental magmas ever erupted through or flowed across the Jalisco block, and thus the southern terminus of the Sierra Madre Occidental province is put at the northern Jalisco block boundary, close to the Rio Ameca.

Paleocene-Eocene Basement

In the SW corner of the Tepic-Zacoalco rift, silicic ash-flow tuffs and lavas of Paleocene-Eocene age are in close proximity to those of Miocene age (i.e., Sierra Madre Occidental) (Fig. 3). In addition to the four Paleocene-Eocene samples dated in this study, Gastil et al. (1979) reported a date of 54 Ma for a rhyolite, and Righter et al. (1995) reported a date of 61 Ma for a silicic ash-flow tuff near the crest of the Sierra Guamuchil block, at 1500 m. This latter sample is just a few kilometers SE of a Miocene ignimbrite (20 Ma; Ferrari et al., 2002) that crops out at 1100 m. However, the Paleocene-Eocene samples dated in this study crop out at 550–870 m, several hundred meters lower than most of the Sierra Madre Occidental samples (1040–1510 m). Therefore, it appears likely that most of the Sierra Madre Occidental units are stratigraphically on top of Paleocene-Eocene rhyolites within the Tepic-Zacoalco rift, although some Paleocene units have been brought to high elevations through uplift.

It appears that Cretaceous-Eocene basement (Fig. 6) extends from the Jalisco block into the Tepic-Zacoalco rift. Granitoid plutons are exposed in the Tepic-Zacoalco rift near the Rio Ameca, and a sample was dated at 62 Ma by Gastil et al. (1978). Because this is a K-Ar date on a plutonic rock, it is a cooling age only. Paleocene-Eocene volcanic rocks have been reported at depths several hundred meters below sea level in geothermal wells drilled in the central Tepic-Zacoalco rift (Ferrari and Rosas-Elguera, 2000). Eocene cooling ages have been obtained on plutonic rocks in the Jalisco block (e.g., Lange and Carmichael, 1991); this suggests that Eocene-Paleocene volcanic rocks may once have covered the Jalisco block.

Pliocene Ignimbrite Flare-Up in the Tepic-Zacoalco Rift

The map of the areal extent of the Pliocene rhyolites (Fig. 7) is based on the geographic distribution of dated units and their topographic contrast to the older, more deeply dissected Sierra Madre Occidental units. The total inferred area of exposed Pliocene rhyolites is ~2030 km^2. Substantial offsets due to normal faulting indicate the sequences range from ~200 to >500 m thick. If these thicknesses are applied to the entire areal exposure of Pliocene rhyolites in the Tepic-Zacoalco rift, the estimated minimum and maximum volumes are ~400 and 1000 km^3. If the inferred area (based on well-log data) near Volcán Ceboruco is included, with an inferred thickness of 40 m, then the additional volume is ~34 km^3. Similarly, if the inferred area near Sierra La Primavera is included, with a thickness of ~140 m (minimum based on well-log data), then the additional volume is ~190 km^3. These estimates do not include additional Pliocene rhyolites that may be covered by Pliocene basalts and/or Trans-Mexican volcanic belt deposits, not delineated in Figure 7. Thus, the best estimate of the minimum volume of Pliocene rhyolitic volcanism in the Tepic-Zacoalco rift is close to ~600 km^3.

Although not as geographically extensive as the Sierra Madre Occidental volcanic province (Fig. 1), the Pliocene rhyolitic volcanism in the Tepic-Zacoalco rift was likely of equivalent intensity, at least locally, based on the thickness of ash-flow tuffs accumulated within 1 m.y. (Figs. 4 and 7). The average thickness of the Sierra Madre Occidental ignimbrites in the southern part of the province is ~1200 m (Nieto-Samaniego et al., 1999), but volcanism spans 18–34 Ma. By comparison, the Pliocene rhyolitic ash-flow tuffs accrued to thicknesses of at least 500 m in less than 1 m.y. in the Tepic-Zacoalco rift near Volcán Ceboruco. This indicates a local accumulation rate of >50 cm/k.y., which is an order of magnitude higher than that documented for arc volcanism in the Tepic-Zacoalco rift over the last 1 m.y. in the Tequila and Ceboruco–San Pedro volcanic fields (5–8 cm/k.y.; Frey et al., 2004b; Lewis-Kenedi et al., 2005).

The Pliocene High-TiO$_2$ Basalts: Evidence of Lithosphere Thinning

Outcrops of Pliocene basalts are found throughout the Tepic-Zacoalco rift (Fig. 4). Near Volcán Ceboruco, Pliocene (3.9 and 4.0 Ma) basalt flows appear to have erupted along the fault escarpment, abutting the steep (500 m) ash-flow cliffs created by normal faulting. Other basalts occur stratigraphically on top of rhyolite domes and tuffs. High-Ti basalts and basaltic andesites (48–56 wt% SiO$_2$), ranging in age from 3.2 to 4.0 Ma, occur in the north-central and eastern Tepic-Zacoalco rift (Nieto-Obregon et al., 1985; Gilbert et al., 1985; Moore et al., 1994; Righter et al., 1995; Rosas-Elguera et al., 1997; Lewis-Kenedi et al., 2005), as shown in Figure 4 and Table 2.

The compositions of Pliocene basaltic lavas in the Tepic-Zacoalco rift are variable, but they are all characterized by relatively high-Ti concentrations (>1.5 wt%). Such high-Ti basalts are not typical of subduction zone settings and are often referred to as OIB-like (ocean-island basalt) and ascribed to extension and decompressional melting of asthenospheric mantle. Further evidence that the Pliocene high-Ti basalts in the Tepic-Zacoalco rift are not solely the result of subduction is suggested by major and trace element geochemistry. Arc basalts are typically enriched in large ion lithophile elements (e.g., Rb, Sr, Ba, K) relative to high field strength elements (e.g., Nb, Ta, Hf, Zr, Ti). A diagram of K$_2$O/TiO$_2$ versus Zr/Ba (Fig. 8) shows that the Pliocene basalts from the Tepic-Zacoalco rift plot between arc basalts from the Michoacan-Guanajuato volcanic field (Hasenaka and Carmichael, 1987) and Hawaiian basalts (BVSP, 1981). Thus, it appears that the Pliocene basalts are transitional between asthenosphere-derived basalts unrelated to subduction and those typical of arcs. These basalts were probably formed by decompressional melting of an asthenospheric mantle that had a history of subduction, as suggested by Ferrari (2004) for the 11–9 Ma basalts exposed along the Rio Santiago. This observation, along with the paucity of lavas of intermediate composition and the occurrence of extensive normal faulting, suggests that the Pliocene volcanic flare-up was a consequence of lithospheric thinning and extension, and not necessarily active subduction.

Melting of the Upper Crust Driven by Basaltic Emplacement

During the Pliocene, volcanism in the Tepic-Zacoalco rift was bimodal, with few intermediate composition lavas, which is atypical of a volcanic arc setting. The Pliocene rhyolites could have been produced by remelting or partially melting Sierra Madre Occidental–age silicic lavas and ignimbrites (or their plutonic

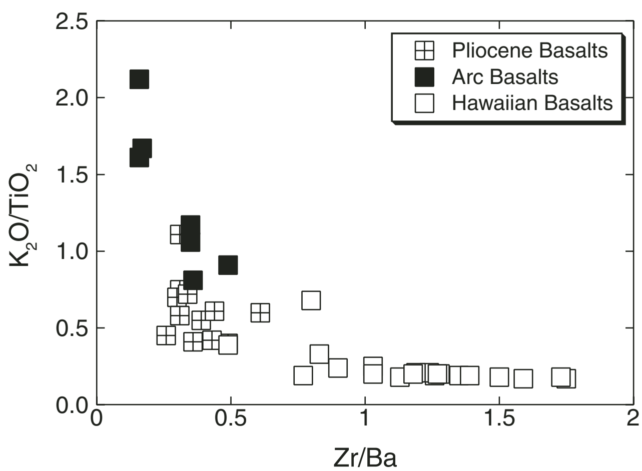

Figure 8. Plot of K$_2$O/TiO$_2$ versus Zr/Ba for Pliocene basalts (Table 3 and references therein), high-Mg basalts from western Mexico (Hasenaka and Carmichael, 1987), and Hawaiian tholeiites (Basaltic Volcanism Study Project, 1981). The Pliocene basalts are transitional between the tholeiites and the typical arc basalts of western Mexico.

equivalents), driven by the emplacement of hot, basaltic magma into the upper crust. Evidence for this is found in the pyroclastic flow NE of Volcán Tepetiltic (SMO-12), where sanidine crystals yield ages of either Pliocene (4.7–4.9 Ma) or Oligocene (26 Ma) age (Table 8). The older sanidine crystals are probably derived from a Sierra Madre Occidental rhyolitic protolith and were preserved during partial melting to produce the Pliocene rhyolite. A similar scenario has been invoked for the formation of the Lava Creek Tuff rhyolite at Yellowstone by remelting of previously emplaced rhyolitic tuffs (down-dropped blocks), as inferred from $\delta^{18}O$ and age analysis of zircons (Bindeman et al., 2001). Derivation of the Pliocene rhyolites by crustal partial melting and not crystal fractionation of intermediate lavas is supported by the paucity of intermediate composition lavas in the Tepic-Zacoalco rift during the Pliocene.

This hypothesis is also consistent with the Sr trace element data (Table 4). For all the rhyolite samples dated in this study, the Pliocene samples consistently have the lowest Sr concentration at a given silica concentration, whereas the Paleocene-Eocene rhyolites have the highest, with the Oligocene-Miocene (Sierra Madre Occidental) rhyolites intermediate between the two (Fig. 5). This pattern is consistent with the hypothesis that the rhyolites are being partially remelted and recycled over time, because of the preferential partitioning of Sr into sanidine and plagioclase relative to rhyolite liquid, with D_{Sr} values of 5–10 for sanidine-liquid pairs and 20–26 for plagioclase-liquid pairs (Davies et al., 1994). The low Sr concentrations (ranging down to 2 ppm; Table 4) in the high-Si Pliocene rhyolites likely reflect the effects of repeated partial melting of either Sierra Madre Occidental–age or Eocene-age protoliths.

Boundaries of the Tepic-Zacoalco Rift: Rio Ameca and Rio Santiago

The southern margin of the Tepic-Zacoalco rift is defined here as the Rio Ameca, the course of which is controlled by the Ameca tectonic depression (Nieto-Obregon et al., 1992), which has been further subdivided by Ferrari and Rosas-Elguera (2000) into three depressions. The Rio Ameca is significant because no Sierra Madre Occidental–age ash-flow tuffs or lavas have yet been found south of the river, which suggests that the Sierra Madre Occidental volcanic province extends across the Tepic-Zacoalco rift, but has a southern terminus at the present-day Rio Ameca. The present-day course of the Rio Ameca follows this pre-existing southern boundary of the Sierra Madre Occidental province, which was subsequently used to accommodate extension in the Pliocene to create the southern margin of the Tepic-Zacoalco rift.

The northern margin of the Tepic-Zacoalco rift is defined here as the Rio Santiago, where 11–9 Ma basalts extend across the entire length (Fig. 3) (Gastil et al., 1979; Damon et al., 1979; Clark et al., 1981; Nieto-Obregon et al., 1985; Moore et al., 1994; Righter et al., 1995; this study). Similar to the case for the Rio Ameca, it appears that the course of the present-day Rio Santiago follows a preexisting tectonic boundary. In this case, it was an extended arm of the Gulf Extensional Province into which a thickness of >600 m of basalt was erupted between 10 and 9 Ma (Moore et al., 1994); this burst of volcanism may additionally have been related to the tearing of the Rivera slab at depth (Ferrari, 2004). This preexisting extensional rift, near the present-day course of the Rio Santiago, was reused in the Pliocene to create the northern margin of the Tepic-Zacoalco rift.

Evidence for Extension in the Tepic-Zacoalco Rift into the Quaternary

Although the voluminous, corridor-wide, ignimbrite flare-up in the Tepic-Zacoalco rift during the Pliocene does not appear to have extended into the Quaternary (except near Volcán Tequila and Sierra La Primavera), NW-oriented extension and normal faulting have. For example, the 1 Ma Santa Rosa basalt plateau (north of Volcán Tequila; Fig. 7) dips at an angle of ~1° toward the Rio Santiago canyon, where the northern rim is ~700 m higher than the southern rim. This basaltic plateau formed by fissure-fed eruptions within the canyon; the basalt filled and ponded within the canyon and spilled southward (owing to the barrier of the higher northern rim), thus creating a horizontal surface across the plateau at ca. 1 Ma (Lewis-Kenedi et al., 2005). The 1° dip across the 10 km distance of the plateau (between the canyon and Volcán Tequila) indicates that there may have been ~175 m of vertical displacement over the last 1 m.y. along the normal fault that separates the northern and southern rims of the Santiago canyon. If this rate of displacement (~0.175 mm/yr) is extended back in time, the 700 m offset between the northern and southern rims could have developed entirely within the last 4 m.y.

In addition, recent seismicity in the Tepic-Zacoalco rift indicates that extensional faulting continues to the present time. For example, a sequence of small earthquakes in April–May 1997 near the town of Zacoalco (Pacheco et al., 1999), as well as a cluster of 48 seismic events in the Ameca river valley between 1996 and 1998 (Núnez-Cornú et al., 2002) showed normal motion along NW-oriented faults at crustal depths (0–35 km). These recent events are consistent with the evidence for a large-magnitude earthquake (>7.0 M_W) near the towns of Ameca and Zacoalco in 1568. The distribution of intense shaking, derived from historical reports of damage, indicates that rupture most likely occurred either along one of several faults along the Ameca river valley or one of the faults near Zacoalco (Suarez et al., 1994). In summary, these recent seismic events underscore that any model for the development of the Tepic-Zacoalco rift in the Pliocene must account for continued normal faulting into the Quaternary.

Previous Models for the Development of the Tepic-Zacoalco Rift

Three different hypotheses have been put forward to explain the development of the Tepic-Zacoalco rift. The Pliocene ignimbrite flare-up along the entire corridor of the Tepic-Zacoalco rift, documented in this study, but previously unknown, warrants a reexamination of these models. In the first model, Luhr et al. (1985) suggested that the Tepic-Zacoalco rift is part of a triple-rift system, which is the result of the propagation of eastward, spreading-ridge jumps and the continuation of the East Pacific Rise. According to this model, the Jalisco block and Rivera plate are being transferred northwestward to the Pacific plate via extension and strike-slip faulting in the Tepic-Zacoalco rift and normal faulting in the Colima graben, similar to what occurred with Baja California. The initial rifting of the Baja Peninsula from the Mexican mainland was coincident with alkaline volcanism ~12.5 m.y. ago (Hausback, 1984). A similar pulse of alkaline volcanism was documented in the Colima rift from 4.6 to 3.9 Ma (Allan, 1986) and was cited as evidence for the initiation of rifting.

In the second model, Serpa et al. (1989) proposed that oblique subduction of the Rivera plate is causing dextral strike-slip slivering within the forearc region, including the Jalisco block and the Tepic-Zacoalco rift. Evidence of dextral strike-slip faulting within the offshore forearc region, south of the Colima rift, was presented in Bandy et al. (2005). In addition, Bandy (1992) and Maillol et al. (1997) have suggested that the progressive increase in the obliquity of subduction led to NW-SE–oriented extension within the Jalisco block.

In the third model, Rosas-Elguera et al. (1996) argued that the Tepic-Zacoalco rift is an extensional feature that developed in response to slab rollback, owing to the retreating subduction of the Rivera plate. A deformational response to slab rollback is common in many volcanic arcs

(Otsuki, 1989), and Delgado-Granados (1993a) used this relationship to hypothesize extensional deformation in western Mexico. Proponents of the third model contend that there is no evidence for strike-slip faulting within the Tepic-Zacoalco rift in the late Miocene to Quaternary (Ferrari et al., 1994; Ferrari, 1995; Ferrari and Rosas-Elguera, 2000), contrary to the assertions of Nieto-Obregon et al. (1985), Allan et al. (1991), and Moore et al. (1994). In this study, we suggest that a modification of the first model (Luhr et al., 1985) may best describe the underlying cause of the substantial lithospheric extension within the Tepic-Zacoalco rift during the Pliocene.

Evidence for the Initiation of Rifting of the Jalisco Block from North America?

The model of Luhr et al. (1985) calls for significant strike-slip faulting in the Tepic-Zacoalco rift. However, because extension (and not strike-slip faulting) appears to have been the dominant mode of deformation in the Tepic-Zacoalco rift over the last 5 m.y., an analogy may be drawn with the initial stages of rifting in the Gulf of California to create Baja California. Since 4.7 Ma, significant dextral motion has occurred between the Pacific and North American plates in the Gulf of California (Stock and Hodges, 1989; Stock et al., 1999). However, this was not the case during the earliest stages of rifting in the "proto-gulf" region between ca. 12.5 and 6 Ma. Recent work by Stock and co-workers (Lewis and Stock, 1998; Nagy et al., 1999; Oskin et al., 2001) has shown that strike-slip faulting in the gulf region was delayed 6–7 m.y. after the initiation of rifting at ca. 12.5 Ma. Instead, extension, silicic ash-flow volcanism, and only minor dextral motion occurred in the area at the time. Then, after a long and protracted period of extension and rhyolitic volcanism, there was a relatively abrupt (within 1.6 m.y.) onset of substantial strike slip between Baja California and North America. By 4.7 Ma, the Gulf of California finally became the principal site of plate boundary slip (Oskin et al., 2001). Therefore, it is plausible that the Pliocene ignimbrite flare-up in the Tepic-Zacoalco rift may be analogous to the late Miocene rhyolitic volcanism observed along both margins of the Gulf of California and may have been driven by similar tectonic events. Although it is unknown if the Jalisco block will eventually rift away from North America, the Tepic-Zacoalco rift is clearly a zone of lithospheric weakness and extension, and transfer of the Jalisco block to the Pacific, as initially proposed by Luhr et al. (1985), may yet occur. Therefore, an analogy between the Tepic-Zacoalco rift and the development of the Gulf of California may well be appropriate.

ACKNOWLEDGMENTS

This study was supported by National Science Foundation (NSF) grants EAR-0409052 and EAR-0228919, as well as an NSF graduate research fellowship to Frey. We thank Marcus Johnson for his assistance in the geochronology laboratory. Reviews by William Bandy, Gordon Moore, and Scott Baldridge improved the clarity of the manuscript.

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Manuscript Received 12 December 2005
Revised Manuscript Received 1 June 2006
Manuscript Accepted 19 July 2006

Printed in the USA