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Notes

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ABSTRACT

The junction of the western Mexican Volcanic Belt and the Gulf of California represents a superposition of subduction and continental rifting tectonic regimes in the late Cenozoic. Subduction of the oceanic Rivera plate has caused late Cenozoic uplift of western Mexico, forming the Jalisco Block. This paper addresses three questions: Where is the northern boundary of the Jalisco Block; how is the continental fracture system related to that offshore; and what is the spatial distribution and composition of subduction-related lavas?

$^{40}Ar/^{39}Ar$ dates on Cretaceous to Paleogene silicic ash flows show that the northern boundary of the Jalisco Block may be defined by the abrupt change in basement age from Cretaceous to Miocene. $^{40}Ar/^{39}Ar$ and K-Ar dates on faulted lavas from the Nayarit region indicate that extension at the edge of the Jalisco Block has occurred since ca. 4.2 Ma. The least principal stress (σ_3) direction associated with these faults has had two different orientations from 4.2 Ma to the present: Several Pliocene to Holocene (4.20, 1.05, and 0.65 Ma) lava flows, and aligned cinder cones have a N45°W associated least principal stress direction, whereas three Pliocene (3.36, 3.38, and 3.11 Ma) lava flows are cut by faults indicating a north to north-northeast least principal stress direction. The two different stress directions may arise either from structural features in the basement of the arc or from changes in offshore plate boundaries (e.g., 2.5 Ma when the Rivera and Mathematicians plates were locked together).

Whole-rock major and trace element analyses of lavas from the coastal Nayarit region reveal three different lava types: an alkali basalt series, basaltic andesite, and andesite. The alkali basalts show FeO and TiO_2 enrichment and have low Ba/Zr and Ba/La ratios, consistent with derivation from an oceanic-island-type mantle. The basaltic andesites and andesites are both alkaline and calc-alkaline, contain hydrous phenocrysts, and have high Sr/Zr and La/Nb ratios, consistent with a subduction-related source. Among these lavas there is a correlation between Sr/Zr, oxygen fugacity, and H_2O contents, suggesting that an oxidized, hydrous fluid is involved in the genesis of the subduction-related lavas. The distribution of subduction-related volcanic centers in the coastal Nayarit region, and areas southeast within the Jalisco Block, defines a volcanic front that parallels the Middle America Trench and is consistent with a 45° dip on the subducted Rivera plate.

INTRODUCTION

The western Mexican Volcanic Belt intersects the Gulf of California on the Mexican coast between San Blas and Puerto Vallarta. Two tectonic regimes, subduction and continental rifting, are superimposed in space and time in this region. The Mexican Volcanic Belt is oriented roughly east-west and formed in response to subduction of the Cocos plate at an angle of 15°–20° beneath the North American plate, along the Middle America Trench (Burbach et al., 1984). The western Mexican Volcanic Belt is formed by the subduction of the oceanic Rivera plate beneath the North American plate, at a higher angle of 45° (Pardo and Suarez, 1993). The Rivera plate, originally part of the Mathematician plate during the Miocene, attained its present boundaries at ca. 2.5 Ma, when a shear zone between these two plates developed into the Rivera Transform (Lonsdale, 1995; see also Fig. 1). The subsequent relative motion of the Rivera and North American plates has been 4° counterclockwise motion around a Euler pole located on the northern edge of the Rivera plate (Lonsdale, 1995).

The opening of the Gulf of California, on the other hand, began as early as 15 Ma, as marine fossils have been discovered in the northern Gulf of California (Durham and Allison, 1960), and the Gulf Extensional Province is well defined in Baja California and northwest Mexico (Stock and Hodges, 1989; Henry, 1989). At the same time the Gulf of California was opening, the East Pacific Rise was jumping eastward as it propagated northward toward western Mexico (Mammerickx and Klitgord, 1982). Luhr et al. (1985) and Allan et al. (1991) have proposed that the latest jump of the East Pacific Rise is along the segment between the Rivera and Tamayo Transforms, thus forming the Colima Rift and the Tepic-Zacoalco rift on the North American plate (Luhr et al., 1985; Barrier et al., 1990; Allan et al., 1991; Fig. 1). These two rifts, along with the Middle America Trench, define the Jalisco Block. The Jalisco Block, then, is at the junction of the Mexican Volcanic Belt and the Gulf Extensional Province, and young volcanism has been focused along its edges (Wallace et al., 1992).

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Data Repository item 9525 contains additional material related to this article.

GSA Bulletin; May 1995; v. 107; no. 6; p. 612–626; 11 figures; 3 tables.

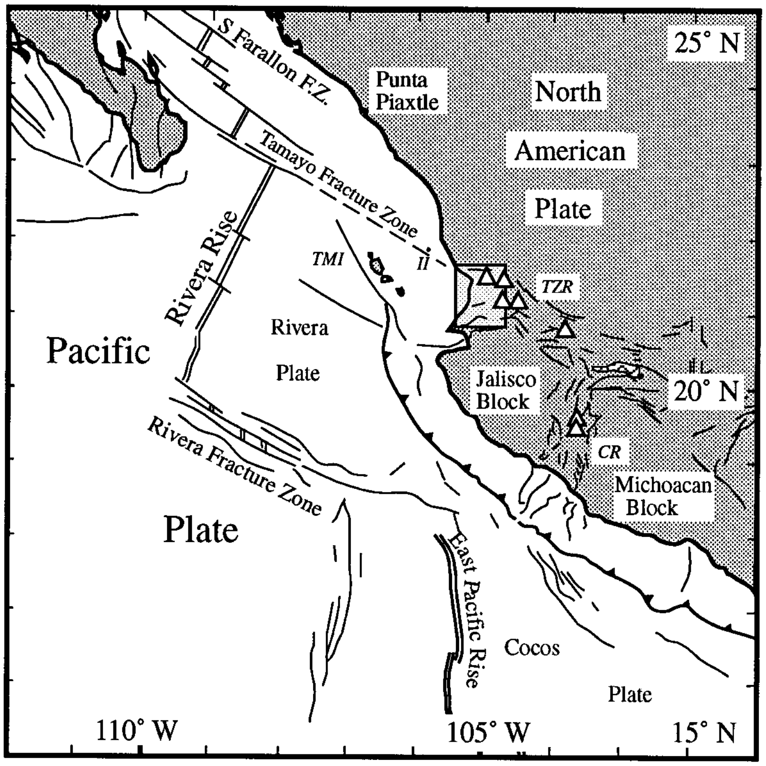

Figure 1. Map of western Mexico, indicating the positions of major tectonic boundaries: the East Pacific and Rivera Rises; the Tamayo and Rivera Fracture Zones; the Cocos, Pacific, Rivera, and North American plates; and the Middle America Trench (fault with teeth). Plate boundaries after Drummond et al. (1981), DeMets and Stein (1990), and Ness et al. (1991); onshore faults from Johnson and Harrison (1989). TMI are the Tres Marías Islands, and II is Isla Isabel. Outlined area is enlarged in Figure 5. TZR and CR indicate the Tepic-Zacoalco and Colima rift systems.

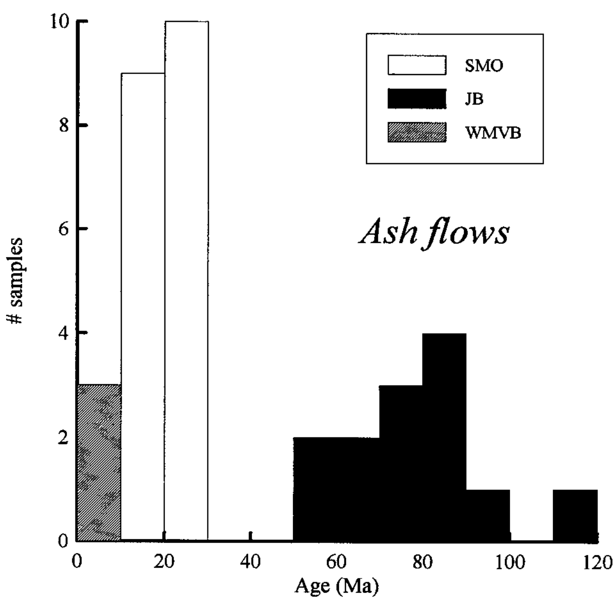

Figure 2. Histogram of radiometric ages determined on silicic ash flows from western Mexico. Sierra Madre Occidental (SMO) ash flow samples were dated by Henry and Fredriksen (1987), Moore et al. (1994), and Gastil et al. (1978); Jalisco Block (JB) ash flows include those reported in Wallace and Carmichael (1989), Gastil et al. (1978, 1979), and this study; western Mexican Volcanic Belt (WMVB) silicic ash flows are from Gastil et al. (1978, 1979) and this study.

Distinguishing faulting and volcanism associated with the Miocene opening of the Gulf of California from that of the younger Jalisco Block and offshore plate reorganizations is a main goal of this study, and the west coast is of interest for several reasons. First, the Tepic-Zacoalco rift widens toward the west coast (Allan et al., 1991), in the same area that the Tamayo Fracture Zone may intersect coastal Nayarit (Fig. 1). The Tepic-Zacoalco rift would thus be the continental expression of the Tamayo Fracture Zone. Second, the relation between the subducted Rivera plate and the location of the volcanic front is poorly understood. Third, the age of faulting in this region is unconstrained. The goals of this study are to determine where the northern boundary of the Jalisco Block is, how the continental fracture system is related to that offshore, and what the spatial distribution and composition of subduction-related lavas are.

GEOLOGIC BACKGROUND AND THE JALISCO BLOCK

The Jalisco Block

The most distinctive lithologic type within the Jalisco Block is Cretaceous to early Cenozoic silicic ash flow (54 to 114 Ma; Gastil et al., 1978; Wallace and Carmichael, 1989). The ages of these ash flows are in contradistinction to the younger Eocene-Oligocene ash flows associated with the Sierra Madre Occidental to the north (see Figs. 2 and 3; Moore et al., 1994; Gastil et al., 1978; McDowell and Keizer, 1977; Aguirre-Díaz and McDowell, 1991). Other lithologic units within the Jalisco Block include low- to medium-grade (staurolite) schists and phyllites in the mountain range east of Puerto Vallarta. These metamorphic rocks are intruded by plutonic rocks (granite-diorite: Böhnel et al., 1992; Köhler et al., 1988; Zimmerman et al., 1988; Gastil et al., 1978; Lange and Carmichael, 1991), which range in age from 40 to 98 Ma. Some of these ages may represent the age of mineral closure, rather than emplacement. Marine sediments are also found near San Sebastian and Puerto Vallarta (Lange and Carmichael, 1990).

Because older ash flows are the distinctive feature of the Jalisco Block in the north, we have dated five additional ash-flow samples from this area, to determine if the change from old to young ash flows is spatially abrupt, and if it corresponds to a younger structural feature along the northern

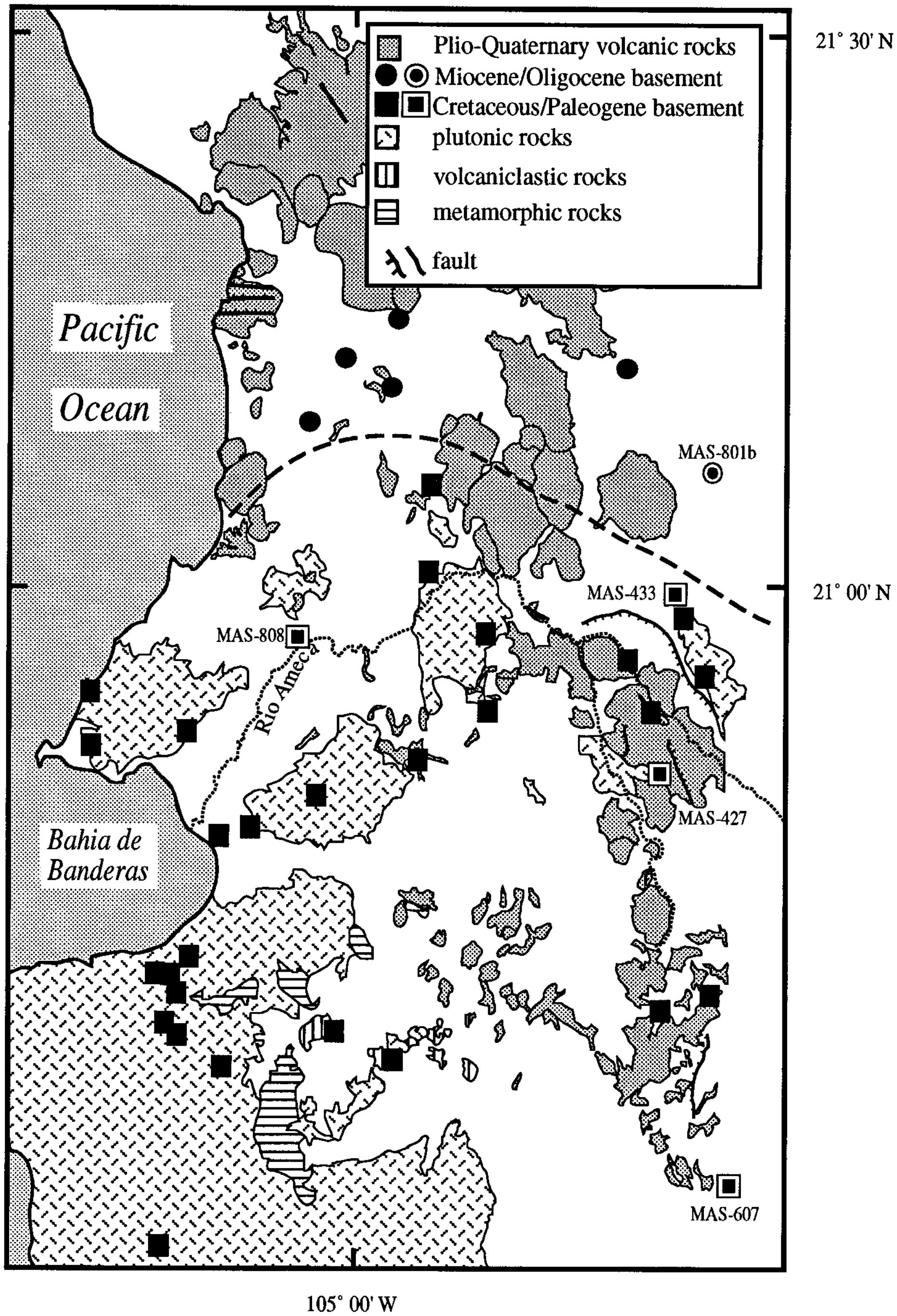

Figure 3. Map of Nayarit and Jalisco, showing the age of basement volcanic and plutonic rocks dated in this study, combined with the dates of Gastil et al. (1978), Zimmerman et al. (1988), Lange and Carmichael (1991), Köhler et al. (1988), and Wallace and Carmichael (1989). Open symbols with solid inside are samples dated in this study. Circles are Miocene to Oligocene ash flows; squares are Cretaceous to Paleogene volcanic and plutonic rocks. The northern boundary of the Jalisco Block may be defined as the transition from Cretaceous volcanic and plutonic rocks to Miocene/Oligocene volcanic rocks north of the Ameca Valley; this is indicated by a dashed line. The shaded areas are Plio-Quaternary volcanic rocks of the Mexican Volcanic Belt. Other patterned areas are explained in the legend.

boundary, such as the Mazatán fault of Allan et al., 1991 (Table 1). If the change is gradual, rather than abrupt, a possible explanation of the data could be migration of the late Cenozoic volcanic front. Four of these ash flows are Cretaceous to early Cenozoic in age (Table 1): MAS-607 is a biotite-bearing rhyolite from the middle of the Jalisco Block, near the town of Ayutla; MAS-433 is an andesitic ash flow from the summit of the Sierra Guamuchil, south of Ahuacatlán; MAS-427 is a silicic ash flow from the region between the Ríos Ameca and Atenguillo; and MAS-808 is a rhyolite from the western part of the Ameca Valley, northeast of Puerto Vallarta (Fig. 3). The fifth ash flow, MAS-801b, is a Pliocene ignimbrite from the middle of the thick volcanic cover just northeast of Volcán Ceboruco (Table 1, Fig. 3). These new dates, together with the published dates of Gastil et al. (1978), Zimmerman et al. (1988), Köhler et al. (1988), Böhnel et al. (1992), and Wallace and Carmichael (1989) (Table 13[1]), show that the transition from younger to older ash-flow units takes place north of the Ameca River Valley (Fig. 3), is abrupt, and is also roughly defined by the presence of Cretaceous plutons (the Ameca and Guamuchil horsts, Fig. 4). The actual boundary between the Jalisco Block and the Sierra Madre Occidental may be concealed in most places by Plio-Quaternary volcanic cover, but it is clear that it is within the Tepic-Zacoalco rift, instead of farther north in the Sierra Madre Occidental ash flows, as suggested by Bourgois and Michaud (1991).

Faulting at the Northern Edge of the Jalisco Block

Pliocene to Holocene. The northern boundary of the Jalisco Block may also be defined by Pliocene to Holocene faulting in the Tepic-Zacoalco rift. Normal faulting of late Pliocene to Quaternary in age has been reported in the Amatlan Tectonic Depression and the Zacoalco graben (Allan, 1986; Righter and Carmichael, 1992). K-Ar and Ar-Ar dates determined in this study place constraints on the age of faulting in two different areas at the northwest edge of the Jalisco Block.

(a) Coastal Nayarit. The thick vegetation in this region makes difficult the determina-

[1]GSA Data Repository item 9525, Tables 4–15, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

TABLE 1. K-Ar AND Ar-Ar DATA FOR LAVAS IN THE NAYARIT AREA

Sample	Rock type	Latitude	Longitude	Material	K (wt%)	Sample weight (g)	^{40}Ar* (10^{-12} mol/g)	% ^{40}Ar*	Age (Ma)	(±2σ)
KR-386	Basalt	21°24.60′N	105°10.71′W	gms	1.2343	1.57012	7.23	30.8	3.36	0.17
KR-389	Andesite	21°24.54′N	105°11.21′W	gms	2.0482	1.34688	11.2	66.7	3.11	0.07
KR-396	Basalt	21°38.84′N	105°02.29′W	gms	0.8486	1.94302	1.57	27.2	1.05	0.11

Sample	Rock type	Latitude	Longitude	Material	Plateau age (Ma)	1σ (Ma)
KR-308	Basalt	21°03.59′N	105°12.11′W	gms	3.88	0.03
KR-313	Basalt	21°10.40′N	105°11.44′W	gms	0.89	0.20
KR-320	Basalt	21°17.10′N	105°09.48′W	gms	1.49	0.03
KR-326	Andesite	21°14.62′N	105°10.17′W	gms	0.074	0.049
KR-381	Basalt	21°41.45′N	105°05.43′W	gms	8.93	0.11
KR-403C	Basalt	20°58.81′N	104°41.41′W	gms	3.38	0.05
KR-452	Basalt	21°40.08′N	105°02.40′W	gms	8.91	0.06

Sample	Rock type	Latitude	Longitude	Material	*N*	Age (Ma)	1σ (Ma)
MAS-801b	Ash flow	21°06.42′N	104°25.17′W	Sanidine	7	4.230	0.016
MAS-808	Ash flow	20°53.86′N	105°07.81′W	Sanidine	6	74.874	0.187
MAS-607	Ash flow	20°11.69′N	104°22.81′W	Biotite	6	70.638	0.203
MAS-433	Ash flow	20°59.50′N	104°28.00′W	Plagioclase	6	60.903	0.356
MAS-427	Ash flow	20°45.21′N	104°29.50′W	Sanidine	6	65.301	0.147

K-Ar notes: Decay constants are $\lambda_\varepsilon + \lambda_{\varepsilon'} = 5.81 \times 10^{-11}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K/K_{Total} = 1.167 \times 10^{-4}$ (Steiger and Jager, 1977); ^{40}Ar* refers to radiogenic component; gms refers to groundmass. Samples were prepared following the methods outlined in Allan (1986). K analyses were performed in duplicate by J. Hampel and K. Righter using flame photometry. Ar extractions were performed by T. Becker using the techniques of Dalrymple and Lanphere (1969).

Ar-Ar notes: The top five groundmass samples were step heated in six steps of 0.5, 0.8, 1.5, 2, 3, and 4 W and the bottom two in ten steps of 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.2, 2.6, 3.0, and 4.0 W, by the Ar-Ar laser probe technique as described by Deino and Potts, 1990. The plateau age is that calculated using three successive steps which together account for >50% radiogenic Ar released. Samples KR-313 and KR-326 have only an integrated age reported, as all of the gas was released in two steps. *N* refers to the number of crystals analyzed, and the age is a weighted mean of the *N* measurements. Complete analytical data are presented in Table 15, available in the GSA Data Repository.

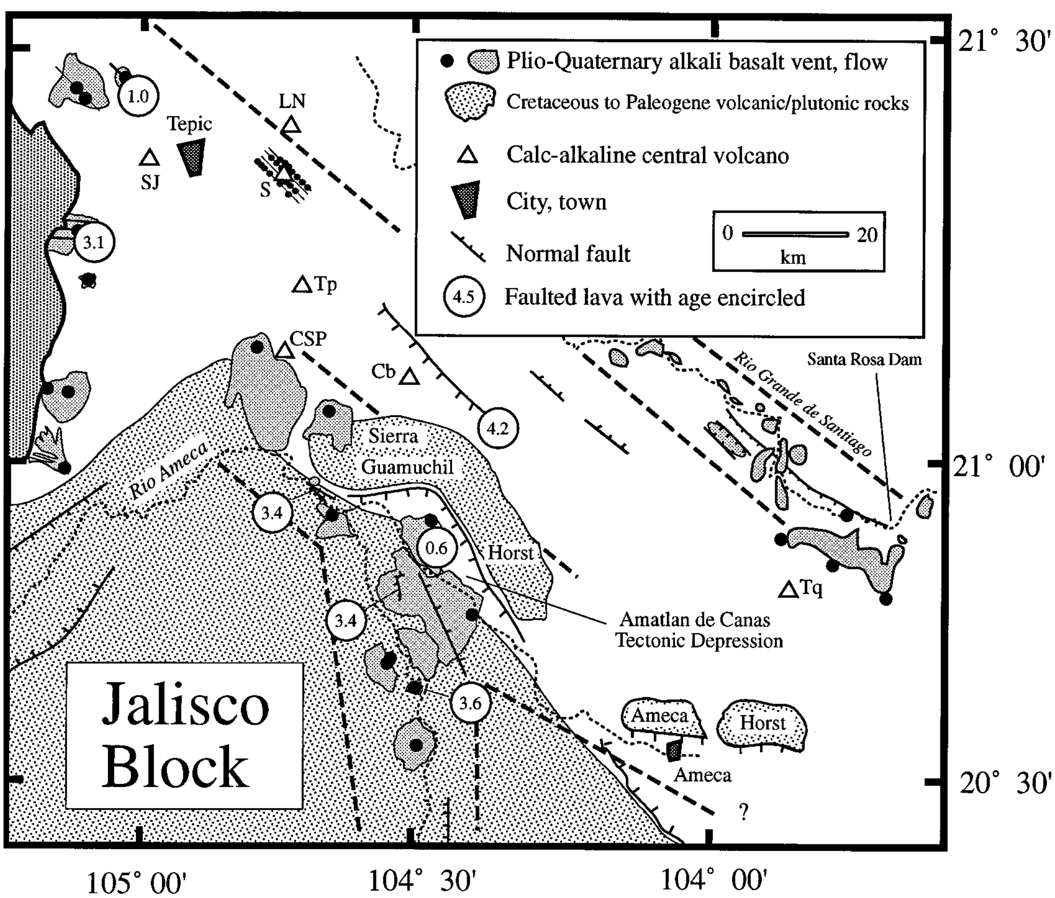

Figure 4. Map of Pliocene to Quaternary faulting in the Tepic-Zacoalco rift, the northern boundary of the Jalisco Block, and associated alkali basaltic volcanism. The volcanoes form shields, plateaus, and cinder cones. Circled numbers represent ages of faulted lava flows—faulting is thus determined to be younger than the age of the flow. Cretaceous to Paleogene units in the Jalisco Block are represented by a stippled pattern. Solid thin lines delineate alkali basalt vents and flows. Dashed lines represent the approximate edges of the Tepic-Zacoalco rift. The Santa Rosa Dam location is indicated at the east edge of the map. Queried region south of Ameca represents a region where alkali basaltic volcanism is expected; this region has not been explored by the authors. Volcanoes are abbreviated as follows: LN = Las Navajas; SJ = San Juan; Tp = Tepetiltec; CSP = Cerro San Pedro; Cb = Ceboruco; S = Sanganguey; Tq = Tequila.

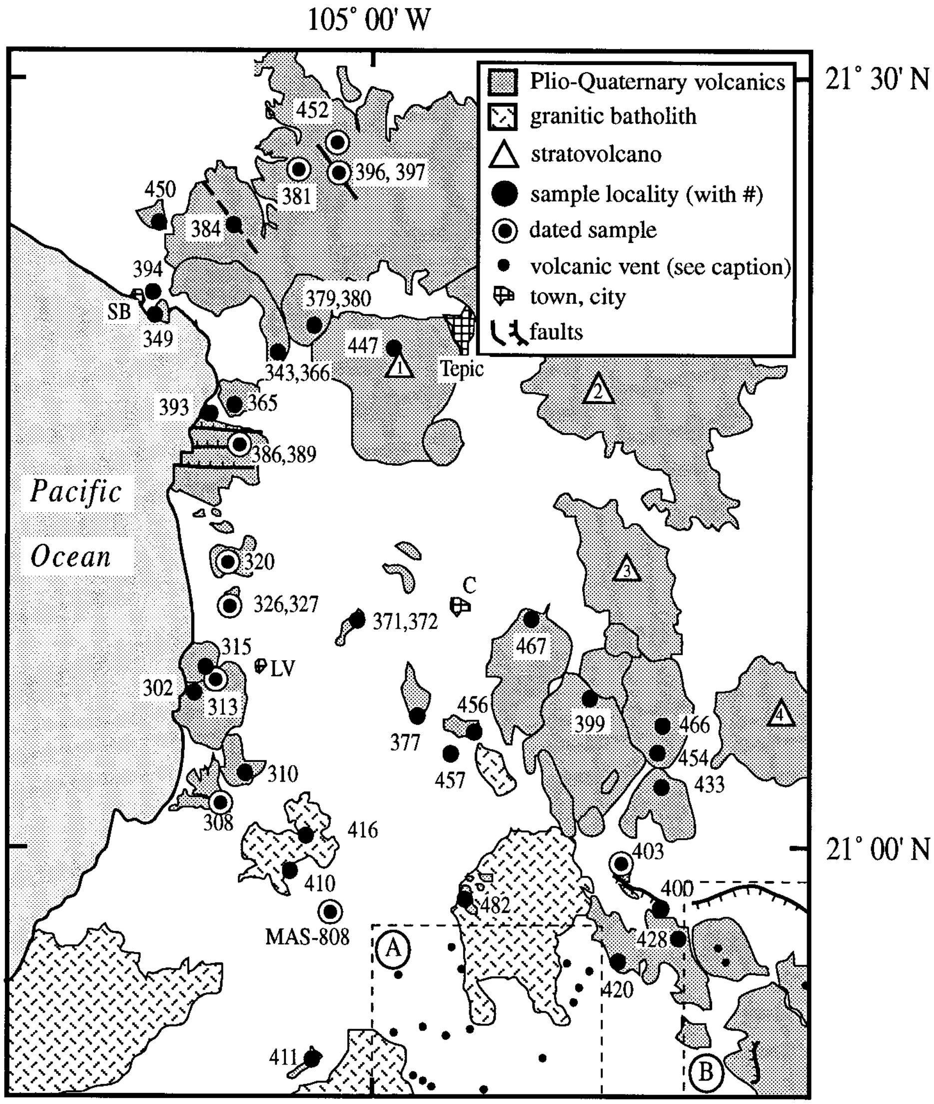

Figure 5. Sample locality map, showing the cities of San Blas (SB), Tepic, Compostela (C), and Las Varas (LV) for reference. Also shown are locations of the stratovolcanoes (triangles): Volcáns San Juan (1), Sanganguey (2), Tepetiltic (3), and Ceboruco (4). Area marked A is that studied by Lange and Carmichael (1990), and B is that of Righter and Carmichael (1992). Solid dots are those samples analyzed in this study. Circled dots are those samples dated by K-Ar and Ar-Ar techniques; see Table 1. Solid lines are normal faults, with tick marks on down side of fault. Dashed line represents an alignment of four Quaternary cinder cones near sample 384.

tion of slip vectors and offsets on the faults. Inspection of the 200 m contour line in the coastal Nayarit region, however, indicates a strong northwest-southeast alignment to ridge and valley orientation. One of these valleys, between the towns of Jumatan and El Limón, has been cut >100 m into the 1.0 Ma Jumatan alkali basalt. Although a fault plane has not been identified, the orientation and depth of the valley and the young age of the flow suggest a structural control (i.e., faulting) to the topography. The 3.1 to 3.4 Ma Jolotemba flows to the south (samples 386 and 389) are both offset by normal faults (Table 1 and Fig. 5). These new dates indicate that the age of faulting in the area is as young as Pliocene to Holocene, in contrast to the Miocene age suggested by Gastil et al. (1978).

(b) Ameca Valley. A basalt from the western part of the Amatlan Tectonic Depression (Cerro la Virgen) yields an Ar-Ar plateau age of 3.38 ± 0.05 Ma (sample 403C); this sample is from the top of a sequence that is offset by 200 m, along an escarpment that is ~1 km in length and oriented N80°W. The offset sequence is a set of olivine basalt lavas overlain by river gravels and sediments. This same sequence is exposed just above river level on the south side of the Ameca River (south of sample 400, Fig. 5), and ~200 m above river level on the north side of the Ameca River (at Cerro la Virgen). This fault may be the western extension of the Guamuchil normal fault that bounds the Amatlan Tectonic Depression. The Llano Grande plateau basalts to the southeast (Righter and Carmichael, 1992) are identical (within error) in age and composition to the Cerro la Virgen sequence, suggesting that the basalt plateau was more extensive than what is currently exposed. If these sections represent what was once a continuous plateau, it has been extensively faulted since then, as the various sections are now at different elevations (Llano Grande, 1400 m; Cerro la Virgen, 700 m).

The northern edge of the Tepic-Zacoalco rift is composed of several en echelon faults, including those near Tepic, just north of Volcán Ceboruco, and between Ceboruco and the Santa Rosa area (Fig. 4). These faults offset young lava flows in a few cases, and the ages of the flows limit the age of faulting, as indicated in Figure 4; ages range from 1.0 to 4.2 Ma. The southern edge of the rift is also defined by a series of discontinuous faults, including the Ameca and Atontonilco Tectonic Depressions, near and southeast of Ameca. These faults offset lava flows as well, the flows ranging from 0.64 to 3.4 Ma in age (Fig. 4). Although Ferrari et al. (1994) suggested that much of the faulting in this region is late Miocene to early Pliocene (e.g., Cinco Minas–Santa Rosa area), it is clear from our radiometric data that the faulting has continued into the Pleistocene or Holocene, since flows as young as 650 ka are affected by normal faults (Fig. 4).

From the age and structural information reported for this region, it seems that there are two distinct stress fields associated with the Pliocene-Holocene extension in the Nayarit and western Jalisco area. Two faulted Pliocene lava flows (3.36 Ma, Jolotemba, and 3.38 Ma, Ameca Valley) are cut by N80°W to N70°W normal faults. Such an orientation is consistent with a north- or north-northeast–oriented σ_3. Other flows (4.2 Ma, Jomulco ash flow; 1.0 Ma, Jumatan; 0.65 Ma, Zacoalco graben; and 0.64 Ma, El Rosario) are cut by N45°W-trending normal faults, consistent with a northeast-oriented

TABLE 2. MAJOR ELEMENT ANALYSES (XRF) OF NAYARIT LAVAS*

Sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Alkali basalt series												
302	53.8	1.40	16.9	N.D.†	8.02	0.14	4.53	8.00	3.66	1.49	0.43	98.35
308	50.9	1.81	16.7	N.D.	9.26	0.16	5.01	8.59	4.1	1.31	0.54	98.37
313	52.8	1.61	17.3	2.26	6.72	0.16	4.96	7.92	3.79	1.61	0.56	99.61
320	53.6	1.72	18.7	N.D.	6.76	0.13	3.79	6.98	4.66	2.03	0.44	98.76
365	56.9	1.08	17.7	N.D.	6.41	0.10	3.4	6.10	3.9	1.94	0.31	97.81
381	50.8	1.46	16.7	N.D.	8.99	0.15	6.40	8.83	3.7	1.11	0.44	98.59
384	52.0	1.73	17.7	N.D.	7.99	0.14	5.34	8.00	4.7	1.71	0.53	99.83
386	51.7	1.62	16.8	N.D.	8.81	0.14	5.05	8.66	3.57	1.21	0.38	97.92
387	56.2	1.69	17.5	N.D.	8.05	0.12	2.59	6.76	4.2	1.63	0.35	99.12
388	52.1	1.97	17.8	N.D.	8.48	0.13	3.67	7.45	4.2	1.49	0.61	97.89
389	60.3	1.43	16.8	N.D.	6.41	0.12	1.72	4.61	4.58	2.36	0.40	98.70
393	55.8	1.26	16.6	N.D.	6.98	0.17	3.2	6.35	4.1	2.19	0.57	97.21
396	47.8	1.89	17.2	3.75	6.15	0.16	7.19	10.36	3.41	0.78	0.34	98.57
397	46.7	2.31	16.2	N.D.	10.83	0.19	5.92	9.35	4.3	1.10	0.40	97.28
399	53.4	2.07	16.1	N.D.	8.87	0.16	4.2	6.95	4.2	2.10	0.75	98.81
400	50.5	1.41	16.1	N.D.	8.27	0.16	5.8	8.16	3.5	0.99	0.41	95.23
403C	48.8	1.78	16.3	N.D.	9.29	0.15	6.2	8.89	3.8	0.98	0.41	96.55
420	51.6	2.18	16.5	N.D.	10.11	0.17	5.3	8.05	4.0	1.51	0.66	100.06
428	51.4	2.16	16.7	N.D.	10.16	0.18	5.2	8.41	4.2	1.42	0.65	100.41
433	51.0	2.03	16.9	N.D.	9.88	0.18	5.1	8.48	3.9	1.36	0.61	99.39
452	52.9	1.21	17.2	N.D.	8.01	0.14	5.2	8.25	3.6	1.45	0.40	98.42
Basaltic andesites												
310	56.9	0.98	18.4	2.72	3.65	0.11	3.6	6.66	3.9	1.97	0.41	99.37
326	56.1	0.94	17.9	3.87	2.84	0.11	3.9	6.57	4.57	2.16	0.55	99.51
327	55.5	0.98	17.4	N.D.	6.52	0.12	4.0	7.07	4.6	2.25	0.60	99.06
371	55.3	0.95	18.5	3.81	2.98	0.12	3.8	6.84	4.4	2.27	0.49	99.56
372	55.4	0.97	18.8	N.D.	6.56	0.12	3.6	6.66	4.3	2.14	0.48	98.98
377	55.6	0.97	18.9	3.83	2.90	0.11	4.0	7.08	4.4	1.83	0.38	99.87
410	57.6	0.65	19.5	N.D.	5.76	0.11	3.3	6.43	4.6	1.00	0.26	99.14
411	53.2	0.71	16.6	N.D.	6.32	0.12	7.6	9.37	3.7	1.30	0.39	99.24
416	54.0	0.89	18.0	N.D.	6.58	0.12	4.4	7.35	4.9	1.83	0.46	98.49
456	59.2	1.19	17.4	N.D.	5.87	0.11	3.0	5.66	4.2	2.41	0.39	99.41
457	57.9	0.74	18.9	N.D.	5.53	0.10	2.8	6.19	5.0	1.63	0.29	99.09
467	57.2	1.06	18.9	N.D.	6.55	0.12	3.5	6.65	4.3	1.70	0.38	100.31
482	55.4	0.97	17.9	N.D.	6.95	0.12	5.9	7.37	4.6	0.99	0.31	100.44
Andesites												
315	60.7	0.75	17.9	1.87	3.60	0.11	2.5	5.50	4.50	1.73	0.30	99.45
343	61.8	0.65	17.8	N.D.	4.35	0.09	2.3	5.38	4.0	1.85	0.18	98.41
349	62.4	0.66	17.4	1.57	3.11	0.09	2.2	5.04	4.4	1.94	0.20	98.97
366	61.8	0.65	17.9	1.51	3.00	0.08	2.3	5.19	4.32	2.14	0.20	99.02
379	62.9	0.72	18.3	1.70	2.86	0.08	2.4	5.18	4.1	1.95	0.16	100.42
394	61.1	0.77	18.2	N.D.	5.15	0.10	2.5	5.31	4.2	1.92	0.29	99.52
447	60.4	0.72	18.5	N.D.	4.87	0.09	2.6	5.77	4.3	1.62	0.20	99.07
450	59.0	0.81	18.3	N.D.	5.50	0.11	2.8	5.68	4.2	1.89	0.24	98.47
454	62.1	0.62	18.3	N.D.	4.17	0.08	2.7	5.50	3.7	2.14	0.13	99.48
455	62.6	0.64	18.6	N.D.	4.31	0.08	2.7	5.58	3.7	2.19	0.17	100.60
466	63.2	0.60	17.9	N.D.	4.20	0.08	2.4	5.01	4.0	2.26	0.14	99.74

*In weight percent.
†N.D. = no data.

σ_3. Rosas-Elguera et al. (1993) reported young lava flows that are cut by N45°W normal faults in the Ameca and Atontonilco Tectonic Depressions. In addition, at several localities in the western Mexican Volcanic Belt there are alignments of Plio-Quaternary cinder cones in a N45°W direction. The most striking and extensive set of such cones surrounds Volcán Sanganguey (Nelson and Carmichael, 1984; see Fig. 4). There is also a line of cinder cones northwest of Tepic (sample 384; Fig. 5). The two different stress directions may be controlled by structural features in the basement of the arc (e.g., contacts in the Cretaceous basement units such as ash flow, granite, or schist), or by changes in offshore plate boundaries (e.g., 2.5 Ma when the Rivera and Mathematicians plates were locked together; Lonsdale, 1995). The latter hypothesis is difficult to evaluate because the radiometric dates presented in this study do not represent the age of faulting, but rather an upper limit on that age.

Late Miocene. Several of the samples dated are Miocene in age and have been affected by faulting. The sequence exposed at the end of the Highway 15 toll road north of Tepic is composed of nearly 50 thin (2–3 m) basalt flows, striking S25°E and dipping at 15°SW (Fig. 5). This is a continuous sequence, as no break in the stack of flows could be found. The 15th flow up from the base of the exposure on the west side of the southbound roadcut has an $^{40}Ar/^{39}Ar$ plateau age of 8.91 ± 0.06 Ma (sample 452; Table 1). A flow near the town of Cinco de Mayo, dated at 9.9 ± 0.3 by Gastil et al. (1978), was also dated in this study; we obtained a slightly younger $^{40}Ar/^{39}Ar$ plateau age of 8.93 ± 0.11 Ma (sample 381; Table 1 and Fig. 5). The tilted nature of the packet of 50 flows indicates that the tectonic activity associated with this deformation could be as old as late Miocene, in agreement with structural studies to the northeast of Tepic, where basalt rests unconformably against blocks of the Sierra Madre Occidental (L. Ferrari and G. Pasquaré, unpub. data). This tectonic activity predates the activity associated with the Jalisco Block and may instead be related to the opening of the Gulf of California at 12 Ma (Stock and Hodges, 1989). Similar episodes of extensive Miocene alkali basalt were reported by Moore et al. (1994) near Guadalajara.

Late Cenozoic Uplift of the Jalisco Block

The abrupt transition in age of the ash flows south of the Mexican Volcanic Belt indicates a tectonic origin. Although it may represent a terrane boundary (Sedlock et al., 1993), available paleomagnetic data show that both Baja California and southwest Mexico were immobile relative to the North American plate from the mid-Cretaceous until initiation of the opening of the Gulf of California (Böhnel et al., 1992). The boundary may instead have been caused by uplift of the crust in response to subduction of the Rivera plate and its predecessor, the Cocos plate. Geologic evidence for uplift in response to subduction has been documented in many subduction zones (Lajoie, 1982; Muhs et al., 1990). Evidence for uplift in western Mexico includes high Pleistocene-Holocene incision rates on the Atenguillo River (15–20 mm/ka based on the difference in elevation between 650 ka and present river levels; see Righter and Carmichael, 1992), raised Pliocene to Pleistocene marine sediments on the southern coast, between Puerto Vallarta and Manzanillo (Durham et al., 1981), and exposed schists, phyllites, and midcrustal plutons within the Jalisco Block. If all of the late Cenozoic silicic ash flows of the Sierra Madre Occidental were originally present on the Jalisco Block and have been stripped off due to uplift and erosion, nearly 2000 m (McDowell and Keizer, 1977; Clark, 1974; McDowell and Clabaugh, 1979) of Tertiary ash flow may have been eroded. If this uplift and erosion began no earlier than 4.2 Ma, as suggested by the ages of faulted lavas in western Mexico, the missing Sierra Madre Occidental ash flows would require uplift rates on the order of 0.5 m/ka. Such high river incision and average uplift rates are similar to those recorded in subduction zones such as Japan and Oregon (Muhs et al., 1990; Seidl and Dietrich, 1992).

Scenarios that involve uplift of the Jalisco Block by mid-Cenozoic are consistent with

TABLE 3. TRACE ELEMENT ANALYSES (XRF) OF NAYARIT LAVAS*

Sample no.	V	Cr	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	La	Ce	Nd
Alkali basalt series														
302	184	97	54	29	89	23	611	29	214	13	764	30	57	27
308	195	155	57	29	104	22	590	35	198	20	578	21	62	35
313	190	86	34	27	89	19	635	35	272	22	627	37	64	33
320	208	59	40	15	83	26	626	141	200	34	693	39	82	49
365	142	30	35	21	81	26	638	49	220	9	978	88	103	94
381	202	167	77	35	78	22	561	28	162	7	551	19	49	24
384	226	82	67	24	78	21	652	30	205	29	596	32	57	39
386	230	106	59	31	74	16	551	25	162	13	523	21	44	24
387	219	N.D.†	8	27	78	28	521	39	170	13	709	34	56	41
388	238	97	47	21	85	15	550	46	181	19	777	36	63	41
389	155	N.D.	3	8	70	34	451	40	196	13	1170	37	67	41
393	163	83	34	18	92	24	558	32	288	18	1085	38	77	43
396	273	104	64	32	69	18	524	27	153	23	262	17	41	25
397	305	111	22	27	79	14	527	30	188	29	321	23	50	28
399	260	N.D.	21	28	90	27	542	34	278	24	677	35	72	38
400	210	146	79	58	83	8	641	26	169	15	576	24	55	22
403	245	128	70	35	79	6	575	25	156	18	403	21	50	23
420	275	79	45	38	97	23	608	38	220	25	576	29	63	31
428	264	71	45	36	92	20	608	31	210	28	520	25	58	34
433	245	122	85	38	84	21	563	28	196	20	639	22	56	21
452	169	97	37	23	83	24	636	28	198	12				
Basaltic andesites														
310	131	31	21	25	81	16	1051	20	136	7	1178	24	47	37
326	150	N.D.	20	25	85	14	1455	20	186	8	1056	28	57	36
327	142	N.D.	25	29	86	12	1534	20	186	8	1046	32	92	N.D.
371	141	N.D.	14	11	81	18	1542	21	163	5	1199	35	73	48
372	134	N.D.	14	19	89	18	1412	25	153	6	1214	33	74	44
377	122	34	30	22	79	16	1412	24	140	4	1063	34	62	43
410	102	65	19	14	78	7	951	17	100	6	725	15	37	23
411	139	219	117	38	65	10	2100	17	91	6	921	50	90	53
416	135	55	29	29	89	13	1548	16	121	8	998	33	67	38
456	163	59	28	18	77	35	609	25	208	17	1131	40	65	38
457	108	N.D.	12	22	78	14	1270	17	120	8	1005	25	50	29
467	141	N.D.	36	25	81	17	983	26	175	11	845	20	47	29
482	147	173	88	314	81	10	836	19	89	5	640	17	33	25
Andesites														
315	99	N.D.	13	14	80	15	737	21	143	6	888	22	44	32
343	86	N.D.	10	13	55	24	705	17	144	11	681	19	79	N.D.
349	89	N.D.	15	9	64	23	633	17	141	6	896	18	37	31
366	83	N.D.	15	12	56	27	729	19	147	11	800	22	48	33
379	101	N.D.	20	18	51	26	631	21	141	6	1078	24	39	29
394	107	N.D.	10	13	70	19	649	18	143	7	898	20	39	30
447	99	N.D.	17	11	53	20	748	16	109	9	712	12	31	21
450	115	54	17	15	67	16	688	20	140	9	1042	29	42	20
454	88	60	21	19	51	28	736	14	120	6	712	10	30	17
455	94	60	25	20	56	27	734	15	124	4	726	12	34	14
466	84	63	31	18	53	31	647	18	117	6	739	20	27	15

*In parts per million.
†N.D. = no data.

some of the field data (e.g., Pliocene-Quaternary lavas rest directly upon Cretaceous rocks). However, the geomorphological data described above (high bedrock incision rates in the Atenguillo valley) pertain to the Pleistocene-Holocene and indicate that uplift has been more recent than mid-Cenozoic.

COMPOSITION AND MINERALOGY OF QUATERNARY LAVAS

Pliocene-Quaternary Volcanism

Young volcanism in western Mexico has occurred in three dominant forms.

(1) Large central andesitic volcanoes, such as Volcáns Colima, Tequila, Ceboruco, and San Juan, define the main trend of the Mexican Volcanic Belt (Fig. 5).

(2) Smaller volume lava flows and cones are found in the volcanic front of western Mexico. These lavas are both alkaline and calc-alkaline in composition, and many are lamprophyric, with hydrous phenocrysts (Lange and Carmichael, 1990, 1991; Wallace and Carmichael, 1989, 1992). The range of radiometric ages determined on lavas in the region depicted in Figure 3 is from Pliocene to Holocene, as summarized in Table 14 in the Data Repository. These hydrous lavas, together with those from Jorullo (Luhr and Carmichael, 1985) and the Colima area (Luhr and Carmichael, 1980, 1981; Allan and Carmichael, 1984), define the hydrous volcanic line in western Mexico, as lavas with hornblende and phlogopite phenocrysts are found in the latter two areas as well.

(3) Shield volcanoes, plateaus, and lines of cinder cones are found interspersed among these subduction-related lavas (1 and 2) and are alkali basalts, hawaiites, and mugearites, with compositional characteristics similar to oceanic island basalt rather than typical subduction-related lavas (Righter and Carmichael, 1992; Nelson and Carmichael, 1984).

This pattern of three types of volcanism continues into the coastal Nayarit region, where a large stratovolcano, Volcán San Juan, erupted a thick pumice sequence at 15 ka (Luhr, 1978). Around the periphery of San Juan are many smaller-volume lava flows and cones, as well as the broad shield volcanoes and plateaus (Fig. 5). The area was mapped on a reconnaissance level by Gastil et al. (1978), and later by Nixon et al. (1987). We present petrography, K-Ar and $^{40}Ar/^{39}Ar$ dates, mineral compositional data, and major and trace element analyses of lavas in this area in order to better understand subduction and tectonic processes at the western end of the Mexican Volcanic Belt.

The lavas collected in the Nayarit area have been analyzed by X-ray fluorescence (XRF) techniques. Powders were fused with lithium tetraborate flux for major element analyses and pressed into pellets with a boric acid shell for trace element analyses. Standards utilized include a suite of basaltic to rhyolitic lavas that have been wet chemically analyzed. Major and trace element analyses are presented in Tables 2 and 3. Modal analyses are presented in Table 4 in the Data Repository. Phenocryst and groundmass mineral phases were analyzed by an eight spectrometer electron microprobe. Standards include both natural (albite, diopside, jadeite, magnetite, basaltic glass) and synthetic (MgO, MnO, TiO_2, Al_2O_3) materials. Operating conditions for the microprobe were an accelerating voltage of 15 kV and beam current of 30 nA (on MgO). Modified Bence-Albee correction procedures were used to reduce the data (Armstrong, 1988). Microprobe analyses of olivine, pyroxene, plagioclase, amphibole, and Fe-Ti oxides are presented in Tables 5–10. Because of space limitations, only Tables 1, 2, and 3 are presented here. Tables 4–10, 11 (XRF analyses of groundmass), 12 (summary of water content and temperature calculations), and 13–15 (summary of Jalisco Block radiometric dates) can be obtained from the GSA Data Repository.[2]

Andesites

West and northwest of Volcán San Juan are several lava cones and flows which have

[2]See footnote 1.

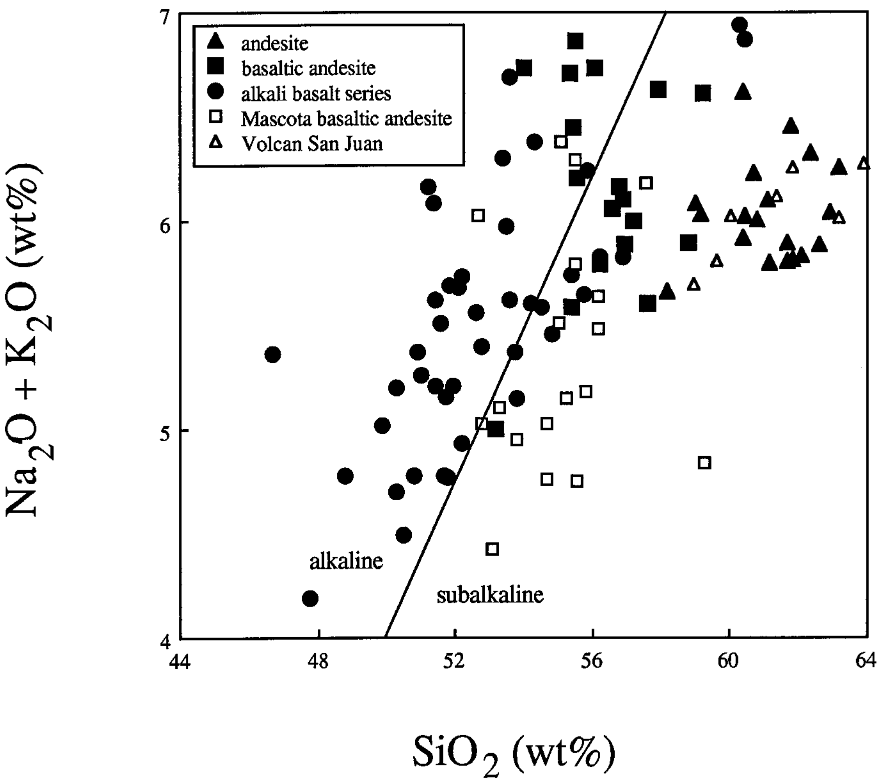

Figure 6. Alkalies vs. silica diagram for the Nayarit lavas, the alkali basalt (circles), andesites (triangles), and basaltic andesites (squares). Shown for reference are the basaltic andesites of Lange and Carmichael (1990) and the andesites from Volcán San Juan (J. F. Luhr, unpub. data). Solid line is the alkaline/subalkaline division of MacDonald and Katsura (1969).

erupted phyric andesites similar to those from San Juan (447), with phenocrysts of plagioclase and orthopyroxene ± augite and hornblende (Table 4). These are (from north to south in Fig. 5) Chacalilla (sample 450), San Blas (394), Las Islitas (349), Cerro Cebadilla (366, 343), Cerro la Yerba (379, 380), Volcán Ceboruco (315), and flows making up Loma Atrevesada (454, 455, 466). Most of these flows have a young morphology (blocky flow top with levees and flow lobes apparent), perhaps as young as the San Juan caldera collapse at 15 ka (Luhr, 1978). Most also have 20% to 40% phenocrysts. These flows compose a total volume of 21 km^3.

The andesitic lavas are mostly phyric, with either plagioclase, augite, and orthopyroxene, or plagioclase, hornblende, and orthopyroxene phenocryst assemblages. There is one volcano (Ceboruco) which has nearly aphyric, glassy lavas. All of these lavas have low alkalies, FeO (4.3 to 5.2), TiO_2 (0.65 to 0.75), P_2O_5 (0.18 to 0.24), and K_2O (1.73 to 2.14), typical of subduction-related calc-alkaline andesites (Figs. 6 and 7). In addition, they have elevated trace element ratios of Sr/Zr > 4, La/Nb > 1.5, and Ba/La > 35 (e.g., Fig. 8). These lavas are similar in composition to the pre- and postcaldera lavas of Volcán San Juan (Luhr, 1978; J. F. Luhr, unpub. data).

Basaltic Andesites

Nine small lava cones and flows have erupted nearly aphyric lava flows with sparse phenocrysts of either olivine and plagioclase (basaltic andesite), or hornblende (lamprophyres; see Table 4). These centers are (from north to south in Fig. 5) Volcán la Tigra (326, 327), Paso de Mesillas (371, 372), Milpillas (467), Volcán Mazatepec (375, 377), Felipe Carrillo (456, 457), Alta Vista (310), Cucaracha (416), Palapa (410), Las Palmas (411), and El Pueblito (482). An $^{40}Ar/^{39}Ar$ date of 74 ± 49 ka was obtained on sample KR-326 (Table 1). The total volume associated with these structures is ~10.5 km^3.

The basaltic andesites are characterized by a paucity of phenocrysts. Some have only amphibole phenocrysts (lamprophyres), whereas others have olivine, plagioclase, and/or augite. Several of these lavas also contain quartz xenocrysts that have pyroxene reaction rims (327, 371, 375, 377). Samples 310 and 371 contain olivine crystals of composition Fo_{68-72}. The composition of olivine that is in equilibrium with a given bulk liquid composition can be predicted using the regular solution model (SILMIN) of Ghiorso et al. (1983); the resulting calculations for samples 310 and 371 yield much more forsteritic olivine compositions (Table 5; Fo_{85-88}). Even if all of the iron oxide in those liquids is assumed to be FeO, the calculated olivine compositions are more forsteritic than those observed. Given these constraints, the olivine crystals in the lavas must be xenocrysts, perhaps derived from an alkali gabbro at depth. Greater concentrations of SiO_2, K_2O, TiO_2, and P_2O_5 in the basaltic andesites distinguish them from the andesitic lavas. Most of the basaltic andesites have low MgO (3.0 to 4.0 wt%) with a few exceptions of 5.5 to 7.0 wt% MgO (Fig. 7). These high-MgO types are common to the southeast, where Lange and Carmichael (1990) documented many such small volcanic centers. All of the basaltic andesites have trace element characteristics similar to the andesites, with Sr/Zr > 4, La/Nb > 1.5, and Ba/La > 35 (e.g., Fig. 8).

Alkali Basalts, Hawaiites, and Mugearites

The most voluminous type of volcanism (~70 km^3) is that of ten shield volcanoes and plateau lavas, and associated cinder cones. These are olivine, augite, and plagioclase basalts (Table 4) and are (from north to south in Fig. 5) at the termination of the Highway 15 toll road (452), Jumatan falls (396, 397), Cinco de Mayo (381), Cerro la Dos (384), Cerro Tecuitata (365), Santa Cruz (393), Jolotemba (386–389), Cerro el Palmoso (320), Laguna Encantada (302), Amado Nervo (399), Cerro Colorado (433), El Divisadero (313), El Tonino (308), Cerro la Virgen (400, 403), Los Charcos (420), and Mesa Jocuixtle (428). Although many of the alkali basalt flows and plateaus are associated with faulting in this region, there are several Pliocene-Pleistocene flows that have not been affected by faulting. An upper flow from the shield along the coast (sample 313) yields an $^{40}Ar/^{39}Ar$ whole-rock date of 0.89 ± 0.20 Ma. Two other flows along the coast have been dated at 3.88 ± 0.03 Ma

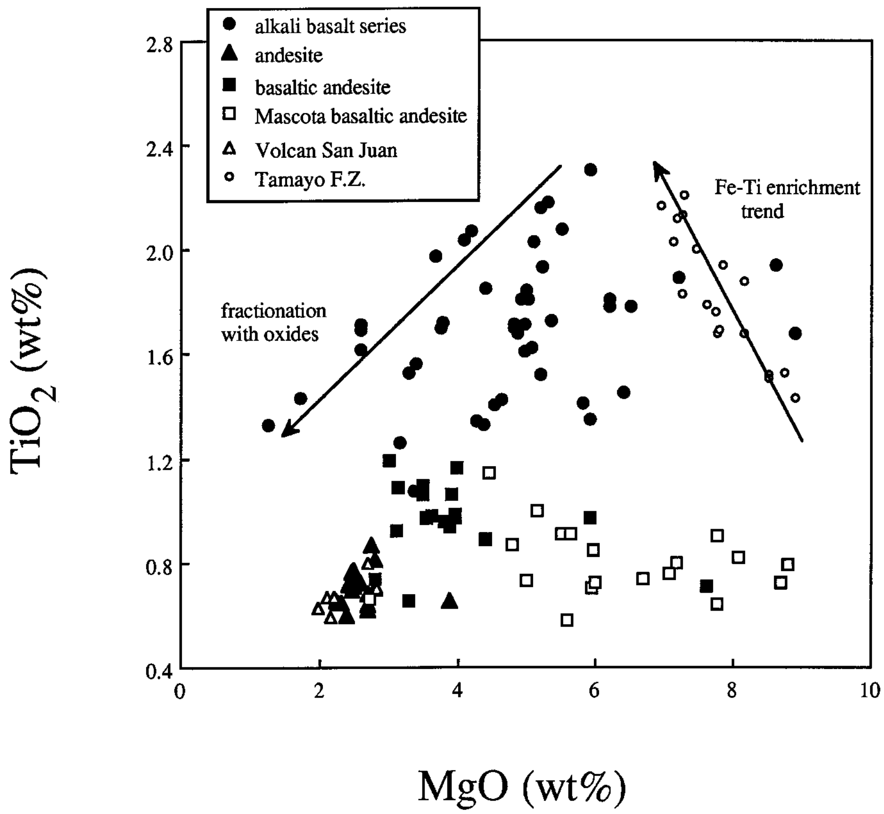

Figure 7. MgO vs. TiO_2 for the Nayarit lavas, the alkali basalt (circles) (including analyses from Punta Piaxtle, Righter and Carmichael, 1993), andesites (triangles), and basaltic andesites (squares). Shown for reference are the basaltic andesites of Lange and Carmichael (1990), the andesites from Volcán San Juan (J. F. Luhr, unpub. data), and MORB (mid-oceanic-ridge basalt) glasses from the Tamayo Fracture Zone (Bender et al., 1984). The fractionation lines are indicated for oxide-free (Fe-Ti enrichment) fractionation, and later oxide-present fractionation (see text for a discussion).

(sample 308) and 1.49 ± 0.03 Ma (sample 320), respectively (both plateau ages; Table 1).

The lavas in this group are nearly aphyric with mostly olivine and minor plagioclase phenocrysts (Table 4). Silica contents range from 46.7 to 60.3 wt% and total FeO is high, from 6.41 to 10.83 wt%. Many of these flows are either alkali basalt, hawaiite, or mugearite, based on their alkali content ($Na_2O - 2 > K_2O$; Table 2), groundmass plagioclase compositions (andesine to oligoclase), and their differentiation index (45 to 60) (Muir and Tilley, 1961; Thompson, 1972; LeBas et al., 1986; Nelson and Carmichael, 1984). A few of these lavas have lower alkalies than the dividing line of LeBas et al. (1986), but they are included in this group because they have unique minor and trace element compositions. All of these lavas are distinguished by their low Sr/Zr, Ba/La, and La/Nb ratios, similar to oceanic-island basalts (Fig. 8).

The compositional diversity within this group of lavas can be explained by fractionation of olivine, plagioclase, augite, and oxides from an alkali basalt parent (see also Righter and Carmichael, 1992). Alkali basalts from vents along the coast in southern Sinaloa (Punta Piaxtle; see Henry, 1989, and Righter and Carmichael, 1993), perhaps the southern extension of the South Farallon Fracture Zone (Ness and Lyle, 1991), are typically MgO rich (7.0 to 10.0 wt%) and show an Fe-Ti enrichment trend with decreasing MgO contents (Fig. 7). This trend is produced by fractionation of olivine, augite, and plagioclase from a parent magma. Such trends are also observed in lavas from the Galápagos Islands, Hawaii, and Iceland (Carmichael, 1964; McBirney and Williams, 1969; Wood et al., 1979), except the enrichment stops at MgO contents of ~6%, and liquids farther along the fractionation trend have less FeO and TiO_2. This reverse trend is due to the appearance of one or two Fe-Ti oxides among the fractionating assemblage. These trends have been demonstrated experimentally (Snyder et al., 1993) and are consistent with gabbroic xenoliths erupted at such localities; MgO-rich basalts from Punta Piaxtle and Jumatan, Mexico, have olivine-clinopyroxene-plagioclase gabbro xenoliths (Righter and Carmichael, 1993), whereas the MgO-poor hawaiites from Mauna Kea, Hawaii (Fodor and Vandermeyden, 1988), and Valle de Santiago, Mexico, have olivine-clinopyroxene-plagioclase-titanomagnetite-ilmenite gabbros (Righter and Carmichael, 1993). The Nayarit alkali basalts together with the Punta Piaxtle basalts define such an Fe-Ti enrichment trend (Fig. 7), suggesting that the melting associated with the fracture zones may extend beneath continental Mexico.

INTENSIVE VARIABLES IN QUATERNARY LAVAS

Oxygen Fugacity

The oxygen fugacities of these lavas have been estimated using two different techniques. The oxygen fugacity of lavas has been calibrated as a function of temperature, pressure, composition, and ferric/ferrous ratio (Kress and Carmichael, 1991). The redox state of a natural lava (above the liquidus) does not change relative to an oxygen buffer such as NNO (nickel-nickel oxide) when cooled along a buffer, thus allowing one to calculate the redox state of a lava relative to such a buffer at a nominal temperature (Kress and Carmichael, 1991); this relative value is referred to as ΔNNO. We have utilized the bulk composition of these lavas, as well as the FeO/Fe_2O_3 ratios to calculate the oxygen fugacity at 1200 °C. The second technique is the calculation of oxygen fugacity based on the compositions of coexisting Fe-Ti oxides, using the calibration of Ghiorso and Sack (1991).

FeO contents of eight lavas were measured by titration (Table 2), thus allowing calculation of Fe_2O_3 by difference. Utilizing the expression of Kress and Carmichael (1991), values of NNO have been calculated for these lavas (Fig. 9A). Several trends are apparent from these calculations. The alkali basalts have values straddling the NNO buffer (−0.5 to +0.5), similar to such lavas from the nearby Atenguillo graben (Righter and Carmichael, 1992). The andesites are between ΔNNO = +1.0 and +2.0, similar to andesites from Volcán San Juan (Luhr, unpub. data). Three basaltic andesites plot

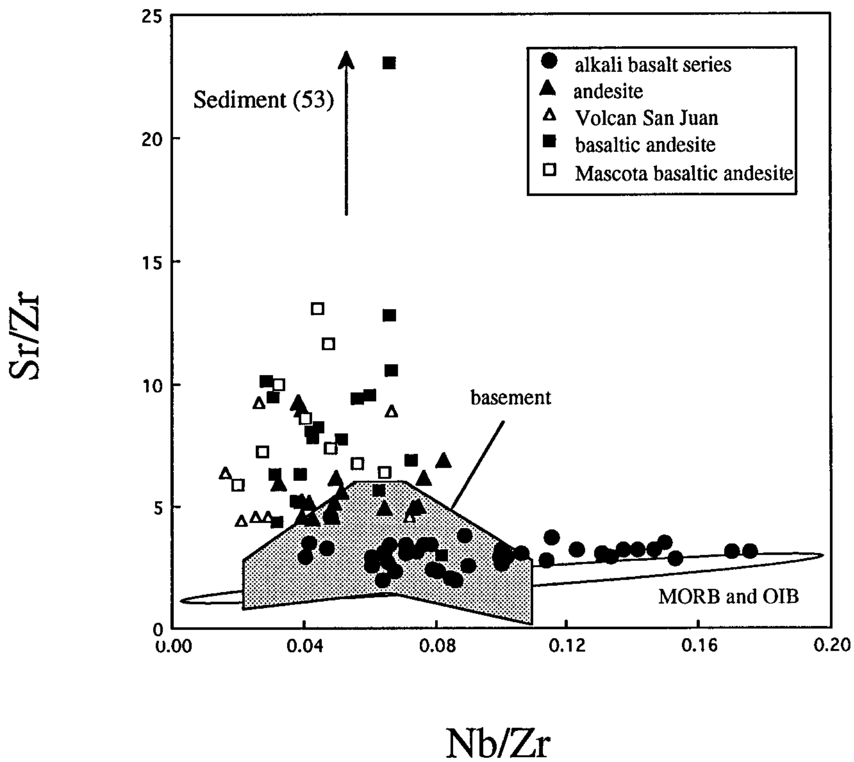

Figure 8. Sr/Zr vs. Nb/Zr for the Nayarit lavas, the alkali basalt (circles), andesites (triangles), and basaltic andesites (squares). Shown for reference are the basaltic andesites of Lange and Carmichael (1990), the andesites from Volcán San Juan (J. F. Luhr, unpub. data), and MORB and OIB (oceanic-island basalt) samples from the Tamayo Fracture Zone and Hawaii (Bender et al., 1984; BVSP, 1981). Also shown are fields for north Pacific pelagic sediment (Hole et al., 1984) and granitic basement in western Mexico (Köhler et al., 1988).

near ΔNNO = +3.0, whereas one is lower (+2.1). These values are all within the range defined by basaltic andesites from near the Mascota area (Lange and Carmichael, 1990). The most oxidized of these basaltic andesite lavas also have higher K_2O, TiO_2, and P_2O_5 than the other basaltic andesites from western Mexico. All of the subduction-related lavas are more oxidized than those derived from a suboceanic mantle, such as basalts from the Tamayo Fracture Zone (Fig. 9A), just 100 km off the Mexican coast.

Calculations of oxygen fugacities from coexisting Fe-Ti oxides are in agreement with the above calculations (Table 10). Coexisting oxides from alkali basalt sample 320 equilibrated below the NNO buffer (−1.3; Table 10), whereas those from basaltic andesites 310, 326, 375, and 457 and andesites 447 and 454 equilibrated higher (ΔNNO > 1.0; Table 10).

Temperatures

Pre-eruptive equilibration temperatures have been calculated using four methods, the plagioclase-hornblende thermometer of Blundy and Holland (1989), the two-pyroxene thermometer of Wells (1977) and Frost and Lindsley (1992), the olivine-spinel geothermometer of Sack and Ghiorso (1991), and the olivine-liquid thermometer of Roeder and Emslie (1970). Andesite samples 343, 352, 379, 380, and 447 have two pyroxenes (Tables 8 and 9) that yield temperatures between 930 and 1075 °C, respectively, using either thermometer. Andesite samples 349, 447, and 454 and basaltic andesite sample 327 have coexisting amphibole and plagioclase phenocrysts (Tables 10 and 12), which yield temperatures of 975 and 970 °C at 2.5 kbar. These calculations suggest that the hornblende-bearing andesites equilibrated at slightly (50 °C) lower temperatures than those lavas without hornblende. The agreement between these two thermometers is evident in sample 447, which gives a two-pyroxene temperature of 930 °C and a plagioclase-hornblende temperature of 915 °C. Olivine phenocrysts in samples 411, 381, and 399 have spinel inclusions, which, together with the olivine, yield temperatures of 1065, 1085, and 1055 °C, respectively. Those lavas with olivine phenocrysts yield temperatures ranging from 1000 °C to 1160 °C (Table 12). The basaltic andesite samples (375) give lower temperatures than the alkali basalts (313, 109, 260).

Temperatures calculated from groundmass Fe-Ti oxides (Ghiorso and Sack, 1991) in basaltic andesite sample 375 are slightly lower than those calculated above (900–930 °C; Table 10), reflecting equilibration of the groundmass at lower temperatures than the phenocrysts (perhaps during cooling).

Water Content

In order to estimate pre-eruptive water contents of these lavas, we have utilized the plagioclase-liquid hygrometer calibrated by Housh and Luhr (1991). Plagioclase phenocryst cores and rims were analyzed by electron microprobe (Table 7), and groundmass was separated magnetically and then powdered and analyzed by XRF spectrometry (Table 11). Temperatures determined in the previous section were also used in these calculations. Results of the H_2O calculations (for both the anorthite and albite exchange reactions) are summarized in Table 12 and Figure 9B.

The two-pyroxene andesites (343, 352, 379, 380) have calculated water contents of 3.0–3.4 wt%, whereas those with hornblende (349, 447, 454) have higher water contents of 3.7–5.7 wt% (Fig. 9B). This pattern has also been observed in andesites from the stratovolcanoes, Colima and Ceboruco (Luhr, 1992): hornblende-free Ceboruco flows have low water contents (0.5–2.2 wt%), whereas the hornblende-bearing Colima andesites have higher water contents (2.5–4.5 wt%). The basaltic andesite samples 310 and 375 both have only olivine and plagioclase phenocrysts, yet yield high water contents of 3.2–5.8 wt%. The high-MgO basaltic andesites from Mascota (Lange and Carmichael, 1990) are also deduced to have higher water contents, thus stabilizing olivine in the groundmass. The alkali basalt samples (313, 109, and 260) all yield much lower water contents (1.5%–1.8%;

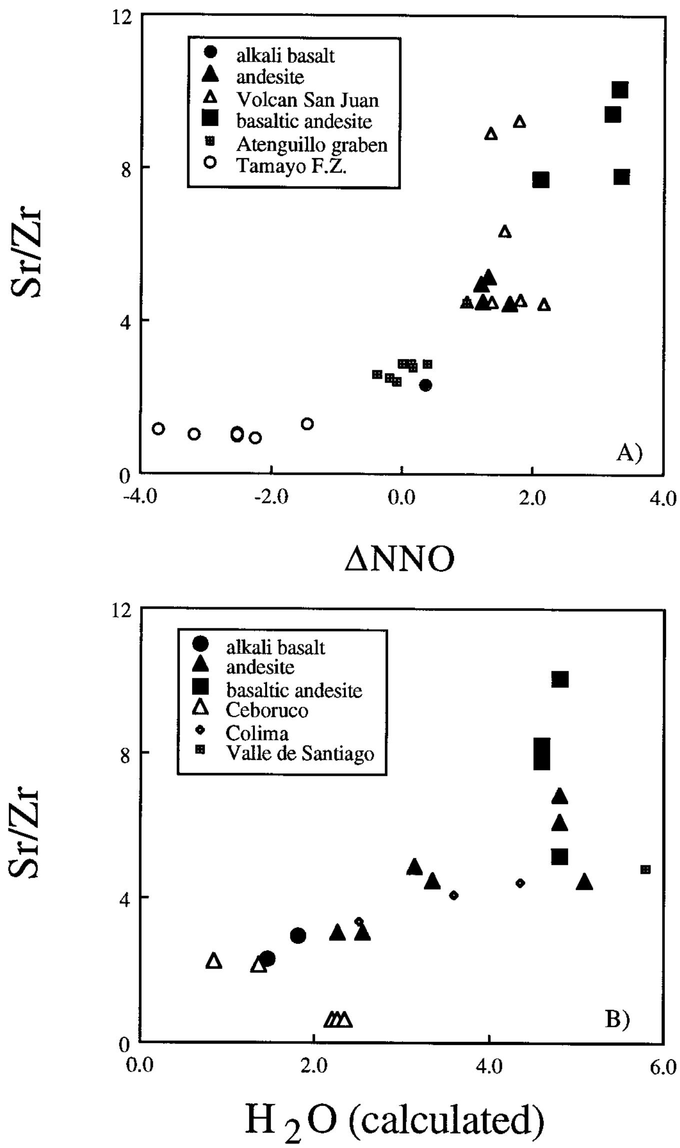

Figure 9. (A) Sr/Zr vs. ΔNNO for the Nayarit lavas, with comparative values for Tamayo Fracture Zone basalt (Bender et al., 1984; Christie et al., 1986), Volcán San Juan (J. F. Luhr, unpub. data), and basic lavas from the Atenguillo graben (Righter and Carmichael, 1992). ΔNNO calculated from whole-rock analyses, a temperature of 1200 °C, and using the expression of Kress and Carmichael (1991). (B) Sr/Zr vs. H_2O (calculated) for all Nayarit lavas for which these values can be calculated. Shown with the Nayarit lavas are andesite lavas from Volcán Colima (Luhr and Carmichael, 1980), Volcán Ceboruco (Nelson, 1980), and scoria from the Valle de Santiago Maar Field (Righter and Carmichael, 1993).

Table 12), consistent with derivation from an asthenospheric source in the mantle.

Wet, Oxidized, Incompatible-Element-Enriched Lavas

There are some general correlations that are apparent with the addition of data from neighboring areas of western Mexico (Righter and Carmichael, 1992, 1993; Bender et al., 1984; Luhr and Carmichael, 1980; Nelson, 1980; Luhr, 1992). There is a positive correlation between water content and trace element ratios such as AE/HFSE (alkaline earth—Ba, Sr)/(high-field-strength elements—Zr, Y, Nb) or LREE/HFSE (light rare-earth elements—La, Ce, Nd), oxidation state and trace element ratios, and oxidation state and water content (e.g., see Fig. 9). Also, many of the most-oxidized samples (>NNO) have amphibole phenocrysts. These correlations suggest that the subduction-related lavas, which universally have higher trace element ratios such as Ba/La, La/Nb, and Sr/Zr (Gill, 1981; Hickey and Frey, 1982; Hildreth and Moorbath, 1988; Perfit et al., 1980), are also hydrous and more oxidized. The trace element signature may be associated with the fluids involved in their genesis. A positive correlation between oxidation state and LREE enrichments was observed in mantle peridotites by Mattioli et al. (1989), hinting that the redox state of the lavas is inherited from the source region. Recent experimental work on basic lavas (Moore et al., 1994) and observations from natural systems (Carmichael, 1991) indicate that water has no effect on the redox state of natural silicate liquids—further evidence that the oxidized nature of the lavas is inherited from the source region.

SUBDUCTION IN THE WESTERN MEXICAN VOLCANIC BELT

Relation of Rivera Plate Dynamics to Onshore Tectonics and Volcanism

The Rivera plate attained its present boundaries at ca. 2.5 Ma (Lonsdale, 1995). It was previously north of the Mathematicians plate, the two plates being separated by a broad shear zone, evidence for which is recorded in structures on the Rivera plate today (Lonsdale, 1995). The Rivera Transform developed between the Rivera and Pacific plates (2.5 Ma), and a new Rivera–North America Euler pole was established near the northern boundary of the Rivera plate. The 4° counterclockwise movement around this pole is consistent with extension in the northern and southern rift zones west of the Euler pole (Lonsdale, 1995), and subduction-related lavas on the coast of Mexico, east of the Euler pole (this study). The different stress fields associated with extension in the Jalisco Block also may be in response to the formation of the new Rivera microplate. The more-prevalent northeast direction of least principal stress may be associated with the presence of the offshore Rivera plate, whereas the less-common north-south direction of least principal stress may be associated with the locked Rivera and Mathematicians plates. Alternatively, these two orientations may be controlled by structural features in the arc basement, such as contacts between the granite,

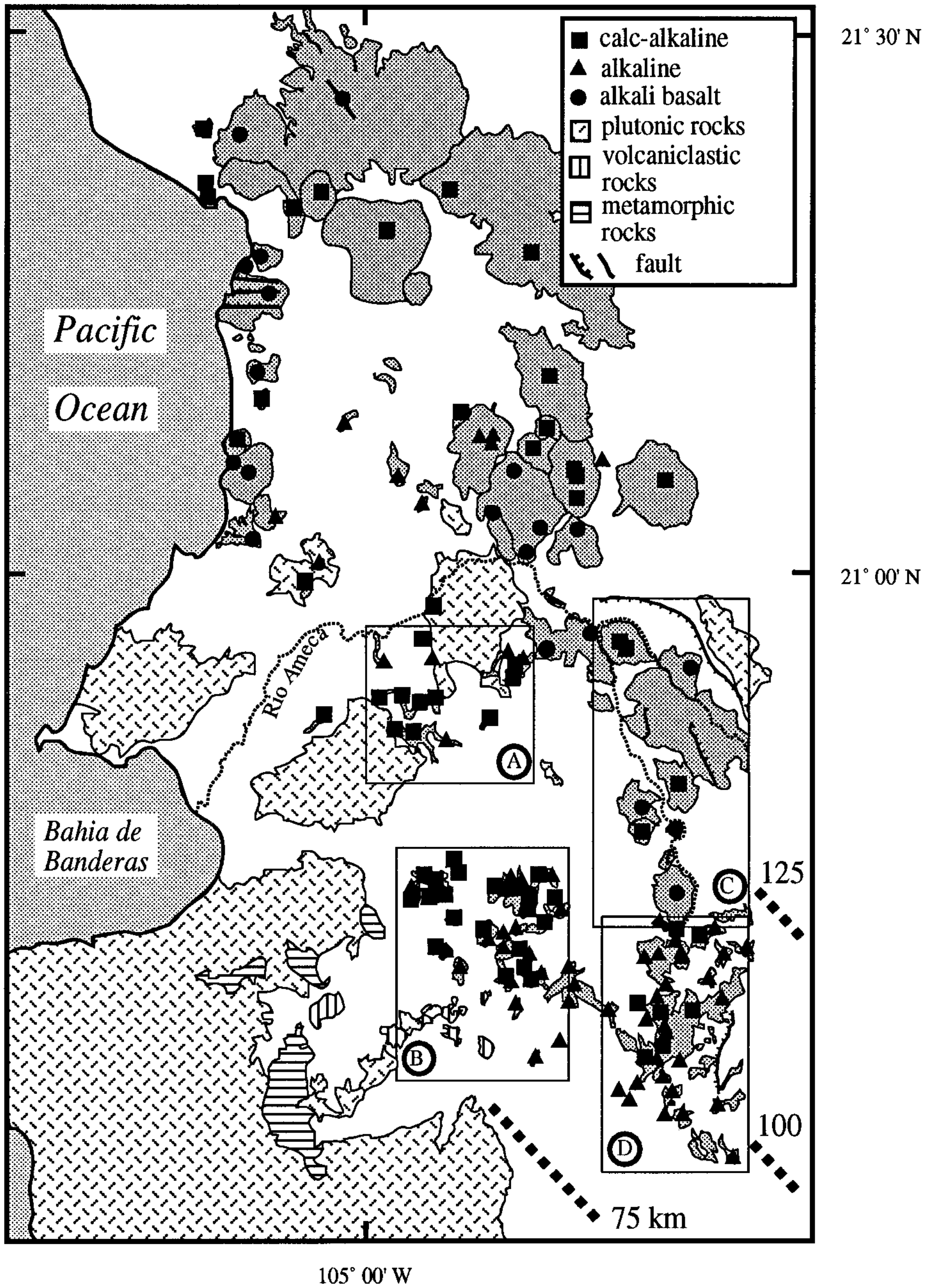

Figure 10. Map of western Mexico. A, B. Study areas of Lange and Carmichael (1990, 1991). C. Study area of Righter and Carmichael (1992). D. Study area of Wallace and Carmichael (1989, 1992). Nayarit lavas are mapped as follows: Solid dots are alkali basalt; solid triangles are alkaline subduction-related lavas; and solid squares are calc-alkaline subduction-related lavas. Diagonal hachuring is the Puerto Vallarta batholith. Dashed lines are approximate Rivera slab depth contours based on results of Pardo and Suarez (1993). Shaded areas are Plio-Quaternary lava flows of the Mexican Volcanic Belt.

schist, and Cretaceous ash flows (see Figs. 4 and 10).

Many aspects of the subduction of the Rivera plate are uncertain, as there are not many teleseismic earthquakes (Burbach et al., 1984; Pardo and Suarez, 1993). Geologically, the western boundary of the plate must be just north of San Blas (Fig. 5), where a Quaternary andesite lava cone and flow have erupted. The pattern of occurrence of the volcanoes in the front of the arc help define the angle of subduction of the Rivera plate, especially when coupled with seismic data (Pardo and Suarez, 1993). Preliminary results suggest that the top of the Rivera plate is ~80–100 km below the volcanic front in Nayarit and Jalisco (Fig. 10). Based on the teleseismic events recorded in western Jalisco and near Volcán Colima, the Rivera plate appears to be striking at N45°W, and dipping at ~45° (Pardo and Suarez, 1993). This represents a significant steepening of subduction angle, as compared to central Mexico, where the Cocos plate is being subducted at an angle of 15°–20° (Burbach et al., 1984).

Location and Landward Extension of the Tamayo Fracture Zone

Alkali basalt has erupted from 4 Ma to present in this area of western Mexico. Many of these flows and plateaus are cut by faults with a northwest-southeast orientation and an east-west orientation (Fig. 4). This association suggests that the alkali basaltic volcanism is associated with extension, which has already been documented in the Santiago River area (Nieto-Obregon et al., 1985; Wopat, 1990; Moore et al., 1994) and the Atenguillo graben (Righter and Carmichael, 1992). Although one might be tempted to argue that these volcanoes could be related to back-arc extension, several of these volcanoes are in the volcanic front (Righter and Carmichael, 1992; this study).

Bathymetry data (Dauphin and Ness, 1991) suggest that the Tamayo Fracture Zone is covered from the Rivera Rise eastward. The question remains as to whether it is north or south of the Tres Marías Islands. If it is south of the Tres Marías Islands, it may continue south and connect with the Middle America Trench, near the Bahía de Banderas (Bourgois and Michaud, 1991); yet, there is subduction-related volcanism north of there, near Tepic (see Fig. 5). More likely the Tamayo Fracture Zone is just north of the Tres Marías Islands, connecting to the Tepic-Zacoalco rift through the well-documented San Blas Basin and San Blas Gravity Low (Couch et al., 1991). This location of the Tamayo Fracture Zone is also consistent with the onshore volcanism, and with the Pliocene to Holocene faulting along the Nayarit coast near San Blas. In addition, the lava flows of the small basaltic island off the coast of Nayarit, Isla Isabel (Fig. 1), may have erupted along the Tamayo Fracture Zone (Ortega-Gutiérrez and Gonzalez-Gonzalez, 1980; Aranda-Gomez and Ortega-Gutiérrez, 1987). It seems that the

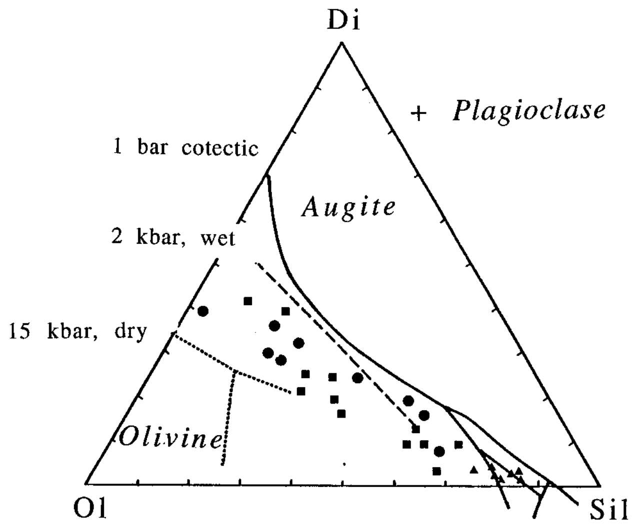

Figure 11. Diopside-olivine-silica projection of Sack et al. (1987) showing 1 bar cotectic defined by the experiments of Walker et al. (1979) and Grove et al. (1982), a schematic 2 kbar cotectic defined by Spulber and Rutherford (1983), and a 15 kbar cotectic taken from Stolper (1980). Alkali basalt series lavas are shown as solid circles, basaltic andesite lavas as squares, and andesitic lavas as triangles.

Pliocene to Holocene alkali-basaltic activity in western Mexico could be related to the propagation of the Tamayo Fracture Zone onto the Mexican mainland. Such propagation would introduce a fracture system along which oceanic-island-type mantle melts could rise.

Petrogenesis of Subduction-Related Lavas

The three lava types recognized in this study illustrate the diversity of magmas generated in the Mexican Volcanic Belt. Similar diversity has been documented in the Cascades arc, where tholeiites, shoshonites, high-alumina basalts, and alkali basalts have erupted together with the andesitic central volcanoes (Bacon, 1990; Leeman et al., 1990). The pseudoternary phase diagram of clinopyroxene-olivine-silica indicates that many of the Nayarit lavas equilibrated in the midcrust at pressures of 5–8 kbar (Fig. 11). Attempts to derive one group of lavas from another by crystal fractionation of observed phenocryst phases fail, suggesting that these lava types have different sources. Similar arguments were outlined by Righter and Carmichael (1992) for calc-alkaline and alkaline lavas from the Atenguillo graben. Many of the Atenguillo lavas also equilibrated in midcrustal magma chambers.

There are hydrous and anhydrous equivalents within the two subduction-related groups. Among the andesites are hornblende-orthopyroxene-plagioclase (wet) varieties and also clinopyroxene-orthopyroxene-plagioclase (dry) varieties, suggesting that a reaction such as clinopyroxene + liquid + water = hornblende is operating in the andesites. Within the basaltic andesite group, there are olivine and plagioclase varieties along with hornblende only, again suggesting a reaction such as olivine + plagioclase + water = hornblende. The occurrence of these two varieties shows that there is variable water activity in the subarc magma chambers. The source of the water may be from fluid released from the subducted Rivera slab, which then migrates into the overlying mantle wedge by percolation (Navon and Stolper, 1987; Hawkesworth et al., 1993). The hydrous lavas thus would inherit their water and trace-element-enriched (high AE/HFSE and LREE/HFSE) character from the source region.

The cause of the elevated trace element ratios (AE/HFSE and LREE/HFSE) of the subduction-related lavas remains enigmatic. Hildreth and Moorbath (1988) have shown that Andean lavas change in composition along the strike of the arc, sympathetic with a change in crustal thickness. Several studies of Mexican lava suites have concluded that granitic or granodioritic material has been assimilated to produce the compositional trends within the suite (e.g., Allan and Carmichael, 1984; McBirney et al., 1987). Of all of the crustal units exposed in western Mexico, the granites, granodiorites, and ash flows are most common; metamorphic rocks such as the schists and phyllites in Figure 3 are volumetrically insignificant, and they are found westward of the volcanic front. However, most of the subduction-related lavas in Nayarit have high Sr and Ba concentrations, which could not be the result of assimilation of the relatively low Sr and Ba granites and ash flows within the Jalisco Block (Fig. 8).

Another potential source of high AE/HFSE and LREE/HFSE material in western Mexico is subducted sediment. There is no accretionary wedge in the front of the arc (Couch et al., 1991), despite a sedimentary cover on the Rivera plate (Timofeev et al., 1983). This suggests that the Rivera plate sediments are being subducted along with the oceanic plate. Pelagic sediment often contains large amounts of Ba and Sr and could be responsible for these enrichments in the lavas of western Mexico. Sediments from a drill core from the eastern Pacific Ocean have been analyzed for trace elements (Hole et al., 1984), and these data are represented in Figure 8. Isotopic and trace element data from other arcs provide further insight into the sources of material involved in arc magma genesis. Arc basalts (those <53% SiO_2) can be divided into two groups based on their Ce/Yb ratios (Hawkesworth et al., 1993). Sites with high-Ce/Yb lavas include the Aeolian Islands, Philippines, Andes (CVZ, SVZ), Grenada, and Indonesia, whereas those with low Ce/Yb include Tonga-Kermadec, South Sandwich Islands, Mariana Islands, Aleutian Islands, and New Britain. The high Ce/Yb lavas are also those that appear to have sediment input in their source region, as evidenced by Sr, Nd, Pb, and Th isotopes (Hawkesworth et al., 1993). It is interesting to note that many of the Mexican basic lavas also have high Ce/Yb, suggesting again that sediment may have played a role in their genesis.

An alternative explanation for the different groups of lavas defined by trace element and isotopic data is that there are variable amounts of important minor phases in the mantle source that is being melted. For instance, the elevated Ce/Yb could thus be correlated with the amount of apatite, phlogopite, and amphibole present in the region of melting. Such variable mineralogy may arise from differing degrees of metasomatism in the subarc mantle. The mantle beneath western Mexico may be substantially modified by subduction processes, as subduction has been active in that region since the generation of the extensive ash-flow province of the Sierra Madre Occidental around 20 to 25 Ma.

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