The Canadian Mineralogist
Vol. 35, pp. 473-500 (1997)

EXTENSIONAL TECTONICS AND THE DIVERSE PRIMITIVE VOLCANIC ROCKS IN THE WESTERN MEXICAN VOLCANIC BELT

JAMES F. LUHR[1]

Department of Mineral Sciences, NHB-119, Smithsonian Institution, Washington, D.C. 20560, U.S.A.

ABSTRACT

In the western portion of the Mexican Volcanic Belt, primitive volcanic rocks are relatively common in comparison with most of the world's subduction-related arcs. These primitive rocks are conveniently grouped in three suites, which have erupted concurrently at least since the Pliocene: (1) *hy*-normative calc-alkaline basalts, (2) *ne*- and *hy*-normative lamprophyres such as minettes, leucitites, spessartites, and kersantites, characterized by phlogopite and hornblende phenocrysts in the absence of plagioclase phenocrysts, and (3) *ne*- to *hy*-normative intraplate-type alkaline basalts. The abundance and diversity of primitive volcanic rocks in the western Mexican Volcanic Belt appear to be primarily related to Plio-Quaternary rifting within and along the margins of the Jalisco Block, which favored passage of primitive magmas to the surface. The lamprophyres are interpreted to form mainly from melting of phlogopite-bearing pyroxenite veins generated in the mantle wedge as melts rising from the subducting slab react with peridotite. Such veins are probably formed by hybridization reactions in most subduction zones, but the low-degree lamprophyre-forming melts rarely erupt to the surface; instead, they stagnate as crustal lamprophyric dikes. Although uncommon, other examples of volcanic lamprophyres are known in active arcs, from Baja California, Japan, and Papua New Guinea. With greater dilution of the vein component by melts from the peridotitic wallrock, calc-alkaline basalts are generated. This process appears to dominate in many arcs. Although abundances of incompatible elements are considerably lower than for the lamprophyres, the two rock types share similar patterns of relative enrichment of elements and Sr, Nd, and Pb isotopic ratios. The "essence" of subduction-zone geochemistry, therefore, is most purely represented by the lamprophyres, with the calc-alkaline basalts being diluted relatives. The intraplate-type alkaline basalts seem to reflect partial melting of convecting upper mantle that was compositionally unaffected by subduction, but advected into the region beneath the rifting continental lithosphere.

Keywords: subduction, rifting, primitive, volcanic, lamprophyre, Mexico.

SOMMAIRE

Dans la portion occidentale de la Ceinture Volcanique Mexicaine, les roches volcaniques primitives sont relativement courantes, en comparaison de la plupart des arcs liés aux zones de subduction. Ces roches primitives sont regroupées en trois suites de laves, qui semblent avoir été en éruption en même temps au moins depuis le Pliocène: (1) basaltes calco-alcalins à orthopyroxène normatif, (2) des variantes lamprophyriques à orthopyroxène et néphéline normatifs, par exemple, minette, leucitite, spessartite et kersantite, que caractérisent la présence de phénocristaux de phlogopite et de hornblende en l'absence de phénocristaux de plagioclase, et (3) des basaltes alcalins de type intra-plaque, à orthopyroxène et néphéline normatifs. L'abondance et la diversité des roches volcaniques primitives dans ce secteur de la ceinture semblent d'abord liées à la présence de rifts plio-quaternaires à l'intérieur du bloc de Jalisco et le long des bordures limitrophes, qui ont favorisé le passage de magmas primitifs vers la surface. Les roches lamprophyriques auraient cristallisé à partir de magmas représentant une fusion partielle de veines de pyroxénite à phlogopite dans le coin de manteau. Ces veines à leur tour représenteraient des produits de réaction de magmas issus de la zone de subduction avec la péridotite sus-jacente. De telles veines résultent probablement de réactions d'hybridation dans la plupart des zones de subduction, mais les magmas aptes à donner des lamprophyres, formés suite à un taux de fusion partielle assez limité, n'atteignent que rarement la surface. Ils formeraient, par contre, des filons à tendance lamprophyrique dans la croûte. Quoiqu'ils sont relativement rares, d'autres exemples de roches volcaniques lamprophyriques ont été signalés dans des arcs présentement actifs, par exemple en Basse Californie, au Japon et en Papouasie – Nouvelle Guinée. Les basaltes calco-alcalins prennent naissance suite à une plus grande dilution de la composante issue de veines de pyroxénite par mélange avec un liquide issu des roches encaissantes péridotitiques. Ce processus est, semble-t-il, prédominant dans plusieurs arcs. Quoique les abondances d'éléments incompatibles sont considérablement plus faibles dans les lamprophyres, les deux variantes de laves primitives partagent plusieurs caractéristiques d'enrichissements géochimiques; de plus, leurs rapports des isotopes de Sr, Nd et Pb se ressemblent. L'essence même des magmas formés dans un contexte de subduction serait représentée par les magmas formateurs de laves lamprophyriques, les basaltes à tendance calco-alcaline représentant des magmas dans lesquels cette composante a été diluée. Les basaltes alcalins à caractère intraplaque semblent résulter d'une fusion partielle du manteau supérieur en convection, non affecté par le phénomène de subduction, mais mis en place dans la région en dessous de la lithosphère continentale en extension.

(Traduit par la Rédaction)

Mots-clés: subduction, extension, lave primitive, volcanique, lamprophyre, Mexique.

[1] E-mail address: luhr@volcano.si.edu

INTRODUCTION

Primitive volcanic rocks, defined as having MgO > 6 wt.% and Mg# > 62, with Mg# = 100 × Mg/(Mg + 0.8 Fe^{total}), are found in remarkable abundance and diversity in the western part of the active, subduction-related Mexican Volcanic Belt. These include calc-alkaline varieties, lamprophyres with phenocrysts of amphibole or phlogopite and an absence of plagioclase phenocrysts, and intraplate-type alkaline basalts. A large body of petrological and geochemical data has accumulated on these primitive rocks and their more abundant differentiates since the early 1970s. Summaries of these studies from regional and plate-tectonic perspectives can be found in Luhr *et al.* (1985, 1989), Allan *et al.* (1991), and Wallace *et al.* (1992).

The purpose of this report is to provide an updated review focused on the diverse primitive volcanic rocks from the western Mexican Volcanic Belt and their complex tectonic setting. Previously unpublished Sr- and Nd-isotopic data are presented for 17 volcanic and basement samples. Along with other Sr, Nd, and Pb isotopic data from the literature and recently published B and Be results for 22 of the primitive rocks, these data are used to support a vein-and-wallrock melting relationship in the sub-arc mantle for the lamprophyres and calc-alkaline basalts, respectively, and a distinct source in the convecting upper mantle for the intraplate-type alkaline basalts.

TECTONIC SETTING

The area of interest (Fig. 1) extends eastward from the Pacific coasts of Nayarit and Jalisco states to the eastern boundary of the Michoacán–Guanajuato Volcanic Field (~100.5°W). Volcanic and tectonic activity in this region is controlled by interactions of the North American, Cocos, Rivera, and Pacific plates.

Subduction of the Cocos and Rivera plates

The Cocos plate subducts northeastward into the Middle America Trench (Fisher 1961) beneath the Pacific coasts of Mexico and Central America (Molnar & Sykes 1969, Nixon 1982). The convergence rate increases from ~5 cm/yr in the west to ~8 cm/yr in the east (Minster & Jordan 1978, McNally & Minster 1981, DeMets *et al.* 1990). Large (M_s > 7) earthquakes, mostly shallow (15–20 km depth) thrust-type events, are common along the Cocos – North American part of the Middle America Trench (McNally & Minster 1981, Singh *et al.* 1981, Chael & Stewart 1982, UNAM Seismology Group 1986). The Wadati–Benioff zone for the Cocos plate beneath Mexico is diffuse and extends to a depth of only about 100 km (Molnar & Sykes 1969, Burbach *et al.* 1984). As such, the Wadati–Benioff zone seismicity is virtually confined to the area south of the active Mexican Volcanic Belt, whose volcanoes presumably overlie the aseismic extension of the subducted Cocos plate.

The existence of the Rivera plate, moving separately from both the Pacific and North American plates, has been debated since the pioneering work of Atwater (1970). A review of ideas concerning the Rivera plate can be found in DeMets & Stein (1990). Today, the Rivera plate appears to be slowly subducting northeastward beneath western Mexico. DeMets & Stein (1990) determined that Rivera – North American convergence varies from 0.6 cm/yr in the north, near the Tres Marias Islands, to 2.0 cm/yr in the south, near Manzanillo (Fig. 1). Although seismicity is sparse along the Rivera – North American trench segment, occasional large thrust-type events have been noted (Eissler & McNally 1984, Singh *et al.* 1981, 1985, DeMets & Stein 1990). Pardo & Suárez (1993) evaluated seismicity related to subduction of the Rivera plate and found that most epicenters cluster southwest of Colima Volcano, with very few events north of 20° latitude. Foci reach 130 km depth and define a Wadati–Benioff zone that dips ~10° down to 20 km, but then steepens to ~50° below 40 km, considerably steeper than the Cocos plate subduction just to the east. Many parallels exist between subduction of the Rivera plate off western Mexico and subduction of the Juan de Fuca plate off Washington and Oregon. In both cases, young and hot lithosphere is subducting steeply in a mainly aseismic fashion, yet recurrent large earthquakes take place.

Seismologists and oceanographers have long puzzled over the nature of the Rivera–Cocos boundary. On the basis of estimated rates of subduction for the Rivera (~2 cm/yr) and Cocos plates (~5 cm/yr) in this area, their boundary was hypothesized to be a zone of left-lateral strike slip at a rate of ~3 cm/yr trending ~N45°E (Nixon 1982, Eissler & McNally 1984). This boundary has been difficult to define because seismicity east of 106.5° longitude is diffuse, and focal mechanisms reveal a variety of styles of faulting (Eissler & McNally 1984, DeMets & Stein 1990). Bandy *et al.* (1995) have associated the differential rates of subduction of the Rivera and Cocos plates with the development of the southern Colima Rift.

Plate tectonics and rifting of the Jalisco Block

Three large rift zones intersect in western Mexico, about 60 km south–southwest of Guadalajara, to form a structural triple junction (Fig. 1): the Tepic–Zacoalco Rift, the Colima Rift, and the Chapala Rift. Luhr *et al.* (1985) and Allan *et al.* (1991) proposed that this structural triple junction reflects initiation of a major continental rifting event, which will ultimately lead to transfer of the Rivera plate and the Jalisco Block (currently part of the North American plate) to the Pacific plate. The Jalisco Block is the southwestern corner of Mexico, bounded by the Tepic–Zacoalco and

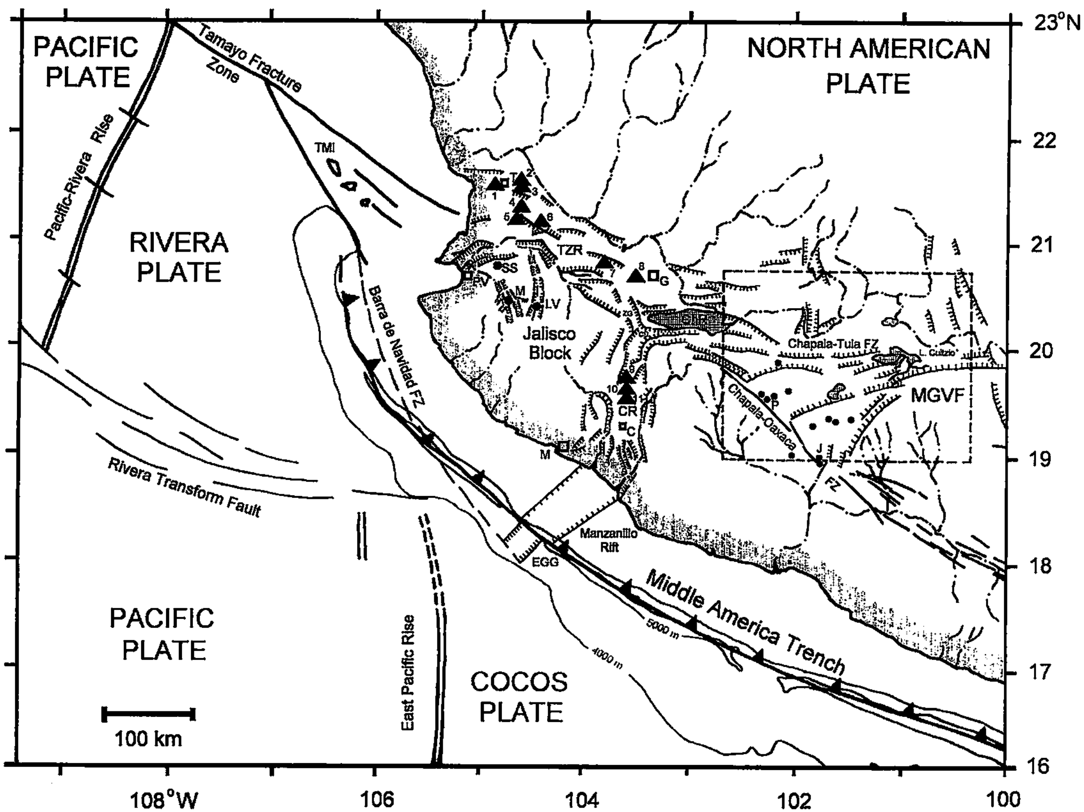

FIG. 1. Simplified map of the western Mexican Volcanic Belt and offshore tectonic features. On-land faults were mostly taken from Johnson & Harrison (1990), with some modifications from Allan *et al.* (1991) and Carmichael *et al.* (1996). The three major rift zones of the westernmost Mexican Volcanic Belt are shown: CR, Colima Rift; ChR, Chapala Rift; TZR, Tepic-Zacoalco Rift. Features of interest at the southeastern end of the TZR are the Zacoalco Graben (ZG) and Citala Depression (CD). Major volcanic centers associated with these rift zones are shown by triangles: 1, Volcán San Juan; 2, Volcán Las Navajas; 3, Volcán Sangangüey; 4, Volcán Tepetiltic; 5, Volcán San Pedro; 6, Volcán Ceboruco; 7, Volcán Tequila; 8, Sierra La Primavera; 9, Volcán Cántaro; 10, Nevado de Colima; 11, Volcán Colima. Within the Jalicso Block are shown three grabens and associated volcanic fields (dots): the Atenquillo Graben, containing the Los Volcanes Volcanic Field (LV), and the Mascota and Talpa Grabens, containing the Mascota Volcanic Field (M). The San Sebastian Volcanic Field (SS) lies northwest of the latter two grabens. Cutting across the Michoacán-Guanajuato Volcanic Field (MGVF) are the Chapala–Tula Fault Zone and the Chapala–Oaxaca Fault Zone (Johnson & Harrison 1990). Dots show the 12 known small volcanoes with primitive rocks in the MGVF: P, Parícutin; J, Jorullo. Open squares show major cities: T, Tepic; G, Guadalajara; PV, Puerto Vallarta; M, Manzanillo; C, Colima. Dash–dot lines show major rivers. Offshore features were mainly taken from Fisher (1961), DeMets & Stein (1990), and Bourgois & Michaud (1991): TMI, Tres Marías Islands; EGG, El Gordo Graben.

Colima Rifts (Fig. 1). This rifting was argued to be related to jumping of the Pacific–Rivera spreading ridge to the site of the Colima Rift. Four similar eastward ridge-jumps have progressed northward in sequence along the East Pacific Rise during the last 12 Ma (Van Andel *et al.* 1975, Klitgord & Mammerickx 1982, Mammerickx & Klitgord 1982), and the proposed on-going ridge-jump would be a continuation of this series and the first event to intersect continental crust.

Several alternatives have been proposed to this model (DeMets & Stein 1990, Michaud *et al.* 1990, Bourgois & Michaud 1991, Ferrari *et al.* 1994, Ferrari & Rosas-Elguera 1997), but no consensus has yet been reached. However, a long-term Global Positioning System survey of western Mexico, conducted by a team of Mexican and U.S. scientists, was begun in March of 1995 (DeMets *et al.* 1995). Fifteen stations were established: eight within the Jalisco Block, one near the on-land triple junction, one within the Colima Rift, one north of the Tepic–Zacoalco Rift, and four east of the Colima Rift. Results of this study should eventually provide unequivocal evidence for the kinematic rates and directions of motion for the Jalisco Block and other crustal terranes in southwestern Mexico.

Various investigators have emphasized that the on-going continental rifting event in western Mexico provides an excellent analog for the initial rifting of Baja California at ~14 Ma (Luhr *et al.* 1985, Allan *et al.* 1991, Lyle & Ness 1991). In the case of Baja's rifting, the slow continental stage lasted ~5–6 Ma and was probably followed by a rapid transition to sea-floor spreading (Lyle & Ness 1991). The Colima Rift, whose floor is now at an average elevation of ~1 km, has apparently been extending for ~5 Ma, and by analogy with Baja rifting, may soon evolve to marine incursion and sea-floor spreading. Modeling of gravity data collected along the axis of the Colima Rift indicates a crustal thickness of 30–46 km, similar to results for the rift flanks (Urrutia-Fucugauchi & Molina-Garza 1992). Likewise, heat flow is not anomalously high within the Colima Rift (Sedlock *et al.* 1993). Thus, the Colima Rift is at an early stage of continental rifting that has not evolved to the point of demonstrable crustal thinning and enhanced heat flow.

The Tepic–Zacoalco Rift

From the structural triple junction, the Tepic–Zacoalco Rift extends northwest for more than 250 km as a zone of normal and strike-slip fault scarps, grabens, half-grabens, and Quaternary volcanic centers (Allan *et al.* 1991). The Tepic–Zacoalco Rift has been interpreted to be part of a larger zone of major strike-slip faulting (Gastil & Jensky 1973, Johnson & Harrison 1990) and has also been shown to correspond to the northern boundary of the Jalisco Block on the basis of abrupt offsets in the ages of ash-flow tuffs across it (Ferrari 1995, Righter *et al.* 1995). Considerable controversy surrounds the timing and nature of faulting in the Tepic–Zacoalco Rift, however. Some investigators argue that the youngest episodes of strike-slip motion are related to opening of the Gulf of California, and that such faulting ceased in the mid-Miocene (Michaud *et al.* 1991, Ferrari *et al.* 1994, Ferrari 1995, Ferrari & Rosas-Elguera 1997). Others have presented evidence that strike-slip motions have continued into the Quaternary (Nieto-Obregón *et al.* 1985, Allan 1986, Nieto-Obregón 1989, Allan *et al.* 1991, Garduño & Tibaldi 1991).

During the Quaternary, two main magma series have erupted in the Tepic–Zacoalco Rift: calc-alkaline and intraplate-type alkaline. Volumetrically dominant among the Quaternary eruptive centers are calc-alkaline andesites, dacites, and rhyodacites of the composite volcanoes Tequila (Wallace & Carmichael 1994), Ceboruco (Nelson 1980), Tepetiltic (Verma & Nelson 1989), Sangangüey (Nelson & Livieres 1986), and San Juan (Luhr 1978), which are strung out along the southeast–northwest trend of the rift zone (Fig. 1). Other calc-alkaline magmas were erupted during Plio-Quaternary time along the Southern Guadalajara Volcanic Chain (Luhr & Lazaar 1985) and from small cones located west of Volcán San Juan in coastal Nayarit (Righter *et al.* 1995). Moore *et al.* (1994) reported calc-alkaline basaltic andesites of Miocene, Pliocene, and Pleistocene age near Guadalajara, and Gilbert *et al.* (1985) described the Pliocene (~4.8 Ma) San Gaspar ignimbrite of andesitic–dacitic composition.

Alkaline basalts and derivative hawaiites, mugearites, and benmoreites also are volumetrically important in the Tepic–Zacoalco Rift. The greatest volumes of these magmas apparently erupted in the Miocene (~10 Ma) at both ends of the rift zone; they are exposed at the eastern end in the deep canyons of the Río Grande de Santiago and its tributaries (Moore *et al.* 1994, Watkins *et al.* 1971, Gilbert *et al.* 1985), and at the western end, north of Tepic (Gastil *et al.* 1979a, b, Righter *et al.* 1995, Ferrari *et al.* 1994). Similar magmas have erupted intermittently since the Miocene, with the youngest (Quaternary) examples known from the canyon of the Río Grande de Santiago north of Volcán Tequila (Moore *et al.* 1994) and from cinder cones on the flanks of Volcán Sangangüey (Nelson & Carmichael 1984, Nelson & Livieres 1986, Verma & Nelson 1989).

A third major group of magmas erupted in the Tepic–Zacoalco Rift is volcanologically and volumetrically important but has little direct relevance for discussions of primitive magmas; these are the peralkaline trachytes and rhyolites of the Sierra La Primavera (Mahood 1980, 1981, Mahood & Drake 1982, Mahood *et al.* 1985, Mahood & Halliday 1988), Volcán Las Navajas (Nelson & Hegre 1990, Verma & Nelson 1989), and the Guadalajara Ignimbrite (Gilbert *et al.* 1985, Mahood *et al.* 1985).

On the basis of the definition of "primitive" stated earlier, 15 primitive samples from the Tepic–Zacoalco Rift are used in this study: one is calc-alkaline, two are transitional, and 12 are alkaline. All primitive samples included in this study are listed in the Appendix.

The Colima Rift

The Colima Rift extends southward for ~160 km from the structural triple junction to the Pacific Coast (Fig. 1), and is conveniently divided into three segments: northern, central, and southern (Allan *et al.* 1991). The northern segment is 20 km wide and displays a well-formed graben structure, with steep walls rising up to ~1,500 m above the graben floor and its playa lakes. Modeling of gravity data indicates that: (1) the graben floor is underlain by ~1,000 m of sediments, (2) downdropping of the graben floor has totaled 2.5 km, and (3) east–west extension has reached 1.5–3.3 km (6–13%) (Allan 1986, Allan *et al.* 1991). The central segment (Fig. 1) begins at the latitude of the Colima Volcanic Complex, where the Toliman graben (Herrera 1967) merges from the northwest to broaden the Colima Rift to a width of 50–60 km (Allan *et al.* 1991). The southern segment begins ~5 km south of Colima City, and the extensional style changes dramatically. This segment lacks an obvious graben structure; on the basis of field mapping and geophysical surveys, Serpa *et al.* (1992) have argued that north–south-trending landforms in the area formed by erosion of Cretaceous structures and are not related to modern extension. This interpretation is inconsistent with evidence for extension both to the north and the south. Bandy *et al.* (1993) modeled gravity data in the southern Colima Rift as indicating two major northeast–southwest-trending grabens with a total width of ~100 km and up to 8 km of sedimentary fill. Offshore, the Colima Rift merges with the northeast–southwest-trending Manzanillo Rift (Bourgois *et al.* 1988, Michaud *et al.* 1990, Bourgois & Michaud 1991, Bandy *et al.* 1995). The Manzanillo Rift is a 60-km-wide depression with >1 km of vertical offset, containing a growing quartzofeldspathic sedimentary fan and fault-controlled submarine canyons. The base of the sedimentary fan may mark the beginning of the Colima Rift extension, and may serve as an analog for birth of the Magdalena Fan (14.5–13 Ma) at the mouth of the nascent Gulf of California during the early stages of continental rifting associated with the separation of Baja (Lyle & Ness 1991).

Two main magma series have erupted within the Colima Rift, calc-alkaline and lamprophyre-forming. These two series can be found interbedded within the graben walls in the northern and central segments of the rift, where calc-alkaline rocks extend back to ~10 Ma and the lamprophyres extend to ~4.7 Ma, which may represent the time of initial extension (Allan *et al.* 1991). Both series continued to erupt during the Quaternary, as shown by lamprophyric cinder cones on the flanks of the concurrently active calc-alkaline Colima stratovolcanoes (Luhr & Carmichael 1981). Since the mid-Pleistocene, calc-alkaline eruptions have been mainly confined to the floor of the central segment, where a southward-younging chain of three major calc-alkaline stratovolcanoes has grown: Cántaro, Nevado de Colima, and Colima. Magma compositions have become progressively more primitive as vent position has migrated toward the trench (Luhr 1993). Similar trends are evident among the lamprophyres, for which the most primitive varieties are found in the youngest and most southerly examples, the cinder cones on the flanks of the Colima stratovolcanoes. This study includes 18 primitive samples from the Colima Rift: two are calc-alkaline, and 16 are lamprophyric rocks from the central segment of the Colima Rift (Appendix).

The Chapala Rift

The central axis of the E–W-trending Chapala Rift contains Lake Chapala, Mexico's largest natural lake (Fig. 1). The lake is bounded by a graben 100 km long and 10–30 km wide, whose walls expose middle Miocene- to Pleistocene-age calc-alkaline andesitic volcanic rocks and lacustrine deposits that have been tilted away from the lake by 15–40° (Garduño & Tibaldi 1991, Delgado-Granados 1993). A family of rotated fault-blocks on both the northern and southern sides of the graben serve to widen the Chapala Rift to 50–60 km. Chapala Rift faulting merges to the east with the Chapala–Tula Fault Zone, which continues ~400 km to the east (Johnson & Harrison 1990). In the western rift zone, the east–west-trending Lake Chapala (lake elevation 1520 m) is stranded 160–170 m above the floors of the northwest–southeast-trending Citala Depression and Zacoalco Graben to its west, which are clearly younger (Fig. 1). To date, no detailed description of primitive volcanic rocks from the Chapala Rift has appeared in the literature.

The Jalisco Block

Geologically, the Jalisco Block is the least known part of the western Mexican Volcanic Belt. Granodioritic batholiths with emplacement ages of 85–106 Ma are prominent in the western part of the Jalisco Block (Köhler *et al.* 1988, Zimmermann *et al.* 1988, Righter *et al.* 1995). Roughly coeval rhyolitic ash-flow tuffs (70–114 Ma) cover large parts of it (Gastil *et al.* 1979a, b, Wallace & Carmichael 1989). These are distinctly older than ash-flow tuffs found north of the Tepic–Zacoalco Rift, and this fact has been used to confirm the northern boundary of the Jalisco Block (Ferrari 1995, Righter *et al.* 1995). The Jalisco Block stands high relative to the terrane north of the

Tepic–Zacoalco Rift, apparently the result of Neogene uplift (Ferrari 1995, Righter *et al.* 1995).

Few late-Cenozoic structures have been mapped in the Jalisco Block. Johnson & Harrison (1990) identified several graben structures in the same area, which Wallace & Carmichael (1989, 1992) and Carmichael *et al.* (1996) later named the Talpa, Mascota, and Atenguillo Grabens (Fig. 1). These grabens are 2–5 km wide, with up to 900 m of relief. Topography is subdued, and few young fault scarps have been identified. These structures are well defined, however, by the north to west–northwest courses of tributaries to the Ameca River (Fig. 1).

Four discrete volcanic fields have been defined in the Jalisco Block (Fig. 1). In each one, two distinct magma series erupted from neighboring cones during the same time interval: calc-alkaline and lamprophyre-forming. Eruptions in the Mascota Volcanic Field, including the Talpa Graben, began ~0.5 Ma and continued perhaps into the Holocene. Mascota is dominated by lamprophyres (minette, absarokite, spessartite) and calc-alkaline basalt, basaltic andesite, and andesite (Lange & Carmichael 1990, Carmichael *et al.* 1996). The Mascota minettes are the youngest known lamprophyres, with ages as low as 68,000 ± 80,000 years (Carmichael *et al.* 1996). About 50 km north–northeast of Mascota is the San Sebastian Field, where lamprophyre-forming magmas (represented by minette, absarokite, and kersantite) and calc-alkaline magmas (represented by basaltic andesite and hornblende andesite) also issued from neighboring cinder cones during the interval (0.48–0.26 Ma: Lange & Carmichael 1990, 1991). Los Volcanes Field lies at the southern end of the Atenguillo Graben, and also includes a wide variety of lamprophyres (minette, leucitite, vogesite, absarokite, trachybasalt, trachyandesite) and calc-alkaline rock types (basalt, basaltic andesite, andesite). Dated samples range from 3.4 to 1.7 Ma (Wallace & Carmichael 1989, 1992). At the northern end of the Atenguillo Graben, near the Tepic–Zacoalco Rift, Righter & Carmichael (1992) described several Plio-Pleistocene (3.6–0.6 Ma) shield volcanoes and lava plateaus built either of alkaline basalt, hawaiite, and mugearite, or of calc-alkaline basaltic andesite. A large number (65) of analyzed volcanic rocks from the Jalisco Block satisfy the criteria for primitive character used in this paper: 13 are calc-alkaline, 50 are lamprophyric, and two are alkaline (Appendix).

The Michoacán–Guanajuato Volcanic Field

As defined by Hasenaka & Carmichael (1985a, b, 1987), the Michoacán–Guanajuato Volcanic Field lies between 19.00° and 20.75°N latitude and 101.33° and 102.66°W longitude, covering >40,000 km^2 in the southern part of Guanajuato state and the northern part of Michoacán state. It contains more than 1,000 small volcanic centers, including more than 900 cinder and lava cones, lava flows, maars, tuff rings, and lava domes (Hasenaka & Carmichael 1985b). Among these small centers, two cinder cones associated with lava flows were active historically: Jorullo during 1759–1774 (Luhr & Carmichael 1985) and Parícutin during 1943–1952 (Wilcox 1954, McBirney *et al.* 1987, Luhr & Simkin 1993). The estimated 78 small cones that have erupted in the Michoacán–Guanajuato Volcanic Field during the last 40,000 years, including Jorullo and Parícutin, are exclusively found in the southern part (Hasenaka & Carmichael 1985a). The volcanic field also has about 300 medium-sized volcanoes, mostly shield volcanoes, about 10 km in diameter; these too show a pronounced southward shift during the last 2 Ma (Ban *et al.* 1992). These results conform with many other observations from the main Mexican Volcanic Belt, which clearly show trenchward migration of magmatic activity during the Quaternary (Cantagrel & Robin 1979, Luhr & Carmichael 1980, Nixon *et al.* 1987, Delgado-Granados *et al.* 1995). Little work has been done on the Miocene–Pliocene volcanic rocks of the Michoacán–Guanajuato Volcanic Field, which are mostly covered by the Quaternary units, but like the younger sequences, they appear to be dominantly calc-alkaline (Williams 1950, Ferrari *et al.* 1990).

On the basis of studies in the northeastern quadrant of the Michoacán–Guanajuato Volcanic Field, Pasquarè *et al.* (1986) and Ferrari *et al.* (1990) discussed the evolution of the stress field since the Pliocene, as northeast–southwest compression associated with reverse and strike-slip faulting evolved to Late Quaternary transtension, as reflected in the east–west faults of the Chapala–Tula Fault Zone. Other investigators have mainly focused on Quaternary fault patterns. Johnson & Harrison (1990) recognized two major fault zones extending through the volcanic field from the Chapala Rift (Fig. 1). The Chapala–Tula Fault Zone continues eastward for >420 km, and the Chapala–Oaxaca Fault Zone trends to the southeast. The latter fault is considered to form a structural suture-zone between the Michoacán Block to the southwest and the Guerrero Block to the northeast (Johnson & Harrison 1990). Along the Chapala–Oaxaca Fault Zone lie both historically active cones of the Michoacán–Guanajuato Volcanic Field: Jorullo and Parícutin. Furthermore, Parícutin lies within the densest cluster of Quaternary cinder cones. Thus, the Chapala–Oaxaca Fault Zone seems to have focused much of the magma ascending beneath the Michoacán–Guanajuato Volcanic Field during the Quaternary (Johnson & Harrison 1990).

Hasenaka & Carmichael (1987) showed that the petrology of magmas erupted in the Michoacán–Guanajuato Volcanic Field is related to distance from the Middle America Trench. Most Quaternary volcanic rocks are calc-alkaline, but a group of morphologically old cinder cones in the northern part of the volcanic field is built of evolved alkaline rocks. Primitive magmas exclusively erupted in the southern part of the field, mostly along northeast–southwest-trending alignments (Hasenaka & Carmichael 1987, Connor 1990). This study includes 24 samples of primitive rocks from the southern Michoacán–Guanajuato Volcanic Field: 18 are calc-alkaline, two are lamprophyric, and four are transitional (Appendix). The presence of lamprophyres in the Michoacán–Guanajuato Volcanic Field shows that they are not unique to the extensional tectonic regime of the Jalisco Block.

Petrology of the Primitive Volcanic Rocks

The definition of primitive rocks

Various criteria have been proposed to identify primitive magmas, those formed by direct partial melting of peridotitic mantle: Mg# [100 × Mg/(Mg + Fe^{2+})] > 63 (Green 1971), FeO^{total}/MgO < 1 (Tatsumi *et al.* 1983), and Ni > 235 ppm (Sato 1977). As emphasized by Myers (1988) and Wallace & Carmichael (1989), however, these criteria derived for application to mid-ocean-ridge and ocean-island basalts may be inappropriate to the source regions of subduction-zone magmas. For the calc-alkaline and lamprophyre-forming magmas of western Mexico, Luhr *et al.* (1989), Wallace & Carmichael (1989, 1992), Allan *et al.* (1991), and Carmichael *et al.* (1996) have suggested a source in the mantle wedge with veins of phlogopite-, amphibole-, and apatite-bearing pyroxenite cutting across the host peridotite (see also Foley 1992b). Magmas formed mainly by melting of these veins, with variable contributions from the wallrock peridotite, need not fulfill the criteria listed above. Furthermore, calculation of Mg# is plagued by uncertainty over the oxidation state of the source region in the mantle, which is probably quite highly oxidized in the case of the lamprophyre-forming magmas, in which much of the iron is in the form of Fe^{3+} (Wallace & Carmichael 1989, Lange & Carmichael 1991, Carmichael *et al.* 1996). Despite these complications, a consistent basis for the definition of primitive calc-alkaline, lamprophyric, and alkaline rocks in the western Mexican Volcanic Belt is desireable. In this paper, for purposes of both CIPW norm calculation and classification, primitive rocks are defined as having Mg# ≥ 62, with Fe^{2+} taken to be 0.8 × Fe^{total}. This Fe^{3+}/Fe^{2+} value is equivalent (Kress & Carmichael 1991) to an oxygen fugacity along the Ni–NiO buffer (Chou 1978). This oxidation state is probably close to that of the calc-alkaline basalts and basaltic andesites, too high for the alkaline magmas, and too low for the lamprophyre-forming magmas, but a good consistent compromise. In addition to the constraint Mg# ≥ 62, rocks with less than 6 wt.% MgO (normalized anhydrous) also were excluded, so as to remove andesites and dacites with quite low MgO values, yet Mg# > 62.

Major elements and classification

On the basis of these two criteria, 122 compositions of primitive volcanic rocks from the western Mexican Volcanic Belt were compiled (Appendix). These are grouped and discussed by both location and rock series: calc-alkaline (34 samples), alkaline (14), lamprophyres (68), and transitional (6). Compositional distinctions among these rock series are illustrated on Figure 2 using the total alkalies *versus* silica classification diagram of Le Bas *et al.* (1986). CIPW normative parameters *ne* + *lc* or *hy* + *q* are plotted against K_2O/Na_2O on Figure 3.

The calc-alkaline rocks

The calc-alkaline rocks have *hy* ± *q* in their CIPW norms and K_2O/Na_2O values (wt.% basis) in the low range 0.19–0.40 (Fig. 3). They have phenocrysts of olivine with spinel inclusions, plagioclase, ± clinopyroxene ± orthopyroxene. On Figure 2, primitive calc-alkaline rocks (circles) are mostly basaltic andesites, with a few basalts and andesites.

The alkaline rocks

The alkaline rocks range from *hy*- to *ne*-normative; two samples have *hy* + *q* (338, 243). Their K_2O/Na_2O values also are low, from 0.09 to 0.46 (Fig. 3). These rocks have phenocrysts of olivine with spinel inclusions, plagioclase, ± clinopyroxene. They erupted only within the Tepic–Zacoalco Rift and in the nearby, northernmost Jalisco Block. On Figure 2, alkaline compositions (squares) fall mostly in the basalt and trachybasalt fields, except for a single example of basaltic andesite. In this study, these alkaline rocks are distinguished from all calc-alkaline rocks by having TiO_2 values (normalized anhydrous) greater than 1 wt.%. For comparison with these alkaline rocks from the western Mexican Volcanic Belt, 16 spinel-lherzolite-bearing *ne*-normative basanitic rocks from the Holocene-age La Breña – El Jagüey Maar Complex (Aranda-Gómez *et al.* 1992, Pier *et al.* 1992) of Durango State, ~450 km NNW of Guadalajara, also are plotted (crosses). These are the youngest and closest of the major intraplate-type lherzolite-bearing magmas that have erupted across the Mexican Basin-and-Range Province during the Quaternary (Luhr *et al.* 1995). The La Breña – El Jagüey basanites straddle the basalt, trachybasalt, and basanite fields on Figure 2, and have K_2O/Na_2O values of 0.53–0.71.

The lamprophyres

The lamprophyres are the most diverse rock suite, both compositionally and mineralogically. True lamprophyres are characterized by phenocrysts (>0.3 mm) of phlogopite or amphibole, with feldspars restricted to the groundmass (<0.03 mm). In the western Mexican Volcanic Belt, a complete transition of rock types is present between lamprophyres and calc-alkaline types, and no precise distinction is possible. Some of the transitional varieties resulted from mixing between the two end-member magmas (Luhr & Carmichael 1982). The lamprophyres form a broad band at high alkali contents across the classification diagram (Fig. 2), falling in all labeled fields except basaltic andesite and andesite. In this paper, the designation lamprophyre is used to include true lamprophyres as well as other rocks that do not meet the strict petrographic criteria, yet show similar geochemical features, such as high K, P, Sr, and Ba contents (Table 1). Most of the field names on Figure 2 are not used for these lamprophyres, in favor of petrographically defined rock-names based on criteria as listed in Table 1. Minette is the dominant lamprophyre type in the western Mexican Volcanic Belt. As seen on Figure 3, most (56 of 68) lampro-

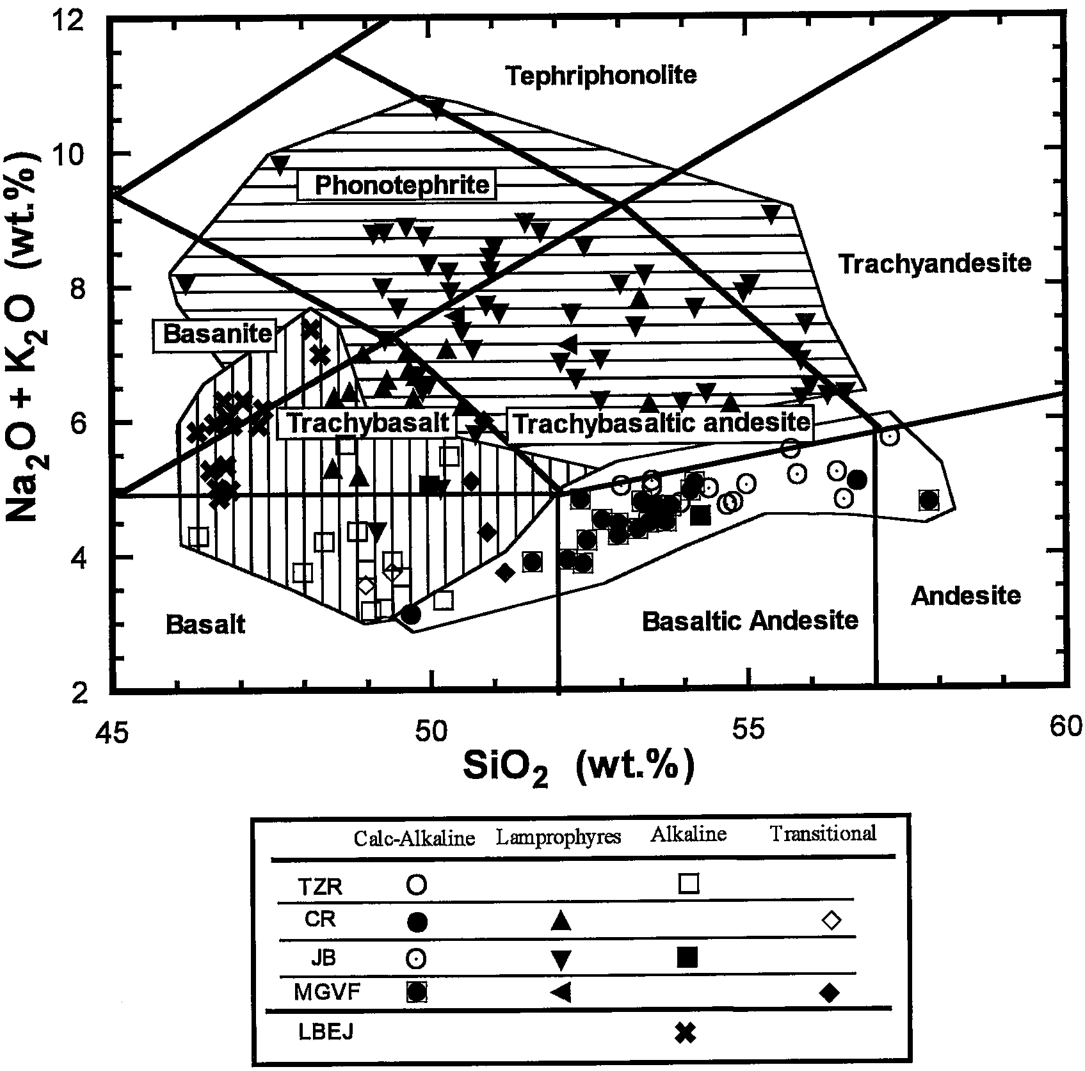

FIG. 2. System of classification based on silica *versus* total alkalies (Le Bas *et al.* 1986), showing 122 primitive volcanic rocks from the western Mexican Volcanic Belt and, for comparison, 16 intraplate-type basanites from the La Breña – El Jagüey Maar Complex (Appendix). All compositions on this and subsequent diagrams are normalized on an anhydrous basis to 100 wt.%, with $Fe^{3+} = 0.2 \times Fe^{total}$. Names of volcanic field in the legend: TZR, Tepic–Zacoalco Rift; CR, Colima Rift; JB, Jalisco Block; MGVF, Michoacán–Guanajuato Volcanic Field; LBEJ, La Breña – El Jagüey Maar Complex.

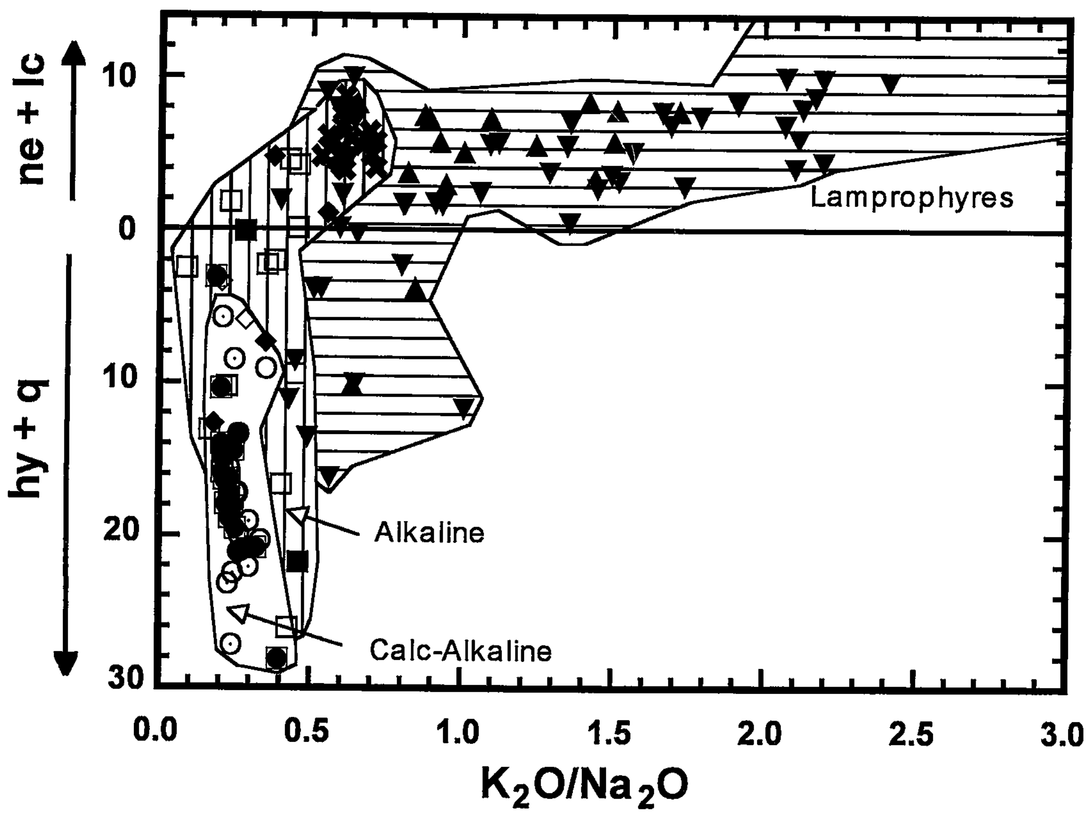

FIG. 3. K_2O/Na_2O *versus* CIPW normative parameters *ne* + *lc* or *hy* + *q*. This plot excludes the only three *lc*-normative samples, all from Wallace & Carmichael (1989), which plot off-scale to the upper right: minette 100, K_2O/Na_2O = 5.2, *ne* + *lc* = 11.2; olivine leucitite 155, K_2O/Na_2O = 3.9, *ne* + *lc* = 15.5, and phlogopite leucitite 166, K_2O/Na_2O = 2.0, *ne* + *lc* = 13.0. Prior to norm calculation, all compositions were normalized on an anhydrous basis to 100 wt.%, with $Fe^{3+} = 0.2 \times Fe^{total}$. Symbols as in Figure 2.

phyres are *ne*-normative, and three of these are also *lc*-normative (plotting off-scale to the upper right). The remaining 12 samples, mostly trachybasalts and trachybasaltic andesites but including two samples of absarokite and one of kersantite, are *hy*-normative; one trachyandesite is also slightly *q*-normative. The high total alkalies of the lamprophyres are a result of elevated K, as seen by the high K_2O/Na_2O values (0.4–5.2) on Figure 3.

Problems of nomenclature plague any literature analysis of volcanic lamprophyres. Most alkaline rocks from subduction zones are now regarded as belonging to the shoshonite association (Morrison 1980). For example, Tatsumi & Koyaguchi (1989) described a Quaternary "absarokite" from Katamata volcano in southwestern Honshu (Japan) with olivine, phlogopite, clinopyroxene, and hornblende phenocrysts. According to the nomenclature used in this paper (Table 1), however, this rock is a kersantite, a variety of lamprophyre. The rock name used by Tatsumi & Koyaguchi (1989) derives from the absarokite – shoshonite – banakite series described by Iddings (1895). For the purposes of this discussion, key features of the shoshonite association (Morrison 1980) are: (1) typically found in subduction zones, (2) high total alkalies (Na_2O+K_2O >5 wt.%), (3) high K_2O/Na_2O (>0.6 at 50% SiO_2), (4) low TiO_2 (<1.3%), and (5) abundant phenocrysts of olivine, clinopyroxene, and plagioclase. Criteria 1–4 are shared by calc-alkaline lamprophyres (nomenclature: Rock 1991). Only by petrography, criterion 5, can shoshonites and lamprophyres be unequivocally distinguished. The unfortunate tendency in many modern petrological studies not to report modal analyses of each sample makes this important distinction difficult to evaluate. Lamprophyres in some cases are mistakenly labeled as shoshonites, but the presence of phenocrystic phlogopite or amphibole (or both) and the absence of plagioclase phenocrysts can clearly

TABLE 1. CHARACTERISTICS OF PRIMITIVE ROCK-TYPES CONSIDERED AS LAMPROPHYRIC IN THIS STUDY

	SiO_2 (wt.%)	CIPW Norm	Phenocryst phases	Microphenocrysts and groundmass phases
			TRUE LAMPROPHYRES	
Minette	48.5 - 55.4	0.6 - 10.1 *ne*	Phlogopite ± Olivine ± Augite	either glassy or rich in Sanidine ± Plagioclase ± Leucite
Phlogopite leucitite	47.7	12.3 *ne*, 13.0 *lc*	Phlogopite ± Augite	Augite, Leucite, Fe–Ti oxides, Apatite
Spessartite	53.3	3.9 *ne*	Hornblende ± Augite	Plagioclase, Sanidine, Augite, Fe–Ti oxides
Kersantite	52.7 - 55.9	13.4 *hy* to 1.8 *ne*	Hornblende + Augite + Olivine ± Phlogopite	Glass, Augite, Fe–Ti oxides, ± Plagioclase
			RELATED TO LAMPROPHYRES	
Basanite	48.5 - 50.5	3.2 - 8.6 *ne*	Olivine + Augite ± Plagioclase	Augite, Plagioclase, Fe–Ti oxides, Glass
Olivine leucitite	46.2	7.5 *ne*, 15.5 *lc*	Olivine + Augite	Phlogopite, Leucite, Fe–Ti oxides, Apatite, Sr-rich Anorthoclase
Absarokite	49.2 - 54.3	3.0 *q*, 18.6 *hy* to 9.1 *ne*	Olivine + Augite	Pyroxene, Plagioclase, Sanidine ± Phlogopite
Trachybasalt	50.4 - 50.5	7.3 - 10.1 *ne*	Hornblende + Olivine + Augite + Plagioclase	Plagioclase, Olivine, Augite, Fe–Ti oxides, Glass ± Orthopyroxene
Trachybasaltic andesite	52.2 - 56.3	3.6 - 11.0 *hy*, 4.9 *ne*	Hornblende + Olivine + Augite + Plagioclase	Plagioclase, Olivine, Augite, Fe–Ti oxides, Glass ± Orthopyroxene

distinguish them. Minettes, kersantites, and other calc-alkaline lamprophyres should be regarded as hydrous equivalents of typical shoshonites.

The transitional rocks

A final group of six samples is designated as transitional. Four of these are transitional between the calc-alkaline and alkaline suites; they are otherwise similar to calc-alkaline rocks, but have 1.1–1.2 wt.% TiO_2. The other two samples are transitional between the calc-alkaline suite and the lamprophyres; they have 1.0–1.1 wt.% TiO_2, just above the defined range for calc-alkaline rocks, elevated Sr (1150–1200 ppm), but no OH-bearing phenocrysts and abundant phenocrysts of plagioclase. These transitional rocks range from *hy*- to *ne*-normative.

In several of the rock suites included in this study, evidence exists for transitions from non-lamprophyres to true lamprophyres with increasing contents of magmatic H_2O and abundances of incompatible elements. For the Quaternary cinder cones of Colima, Luhr & Carmichael (1981) showed that a complete gradation is present from basanite with olivine and minor plagioclase phenocrysts, to minette with phlogopite, olivine, and augite phenocrysts, microphenocrysts of apatite, and an absence of plagioclase phenocrysts. In this sequence, the abundances of P, Sr, Ba, La, Th, and other incompatible elements increase steadily. For the Mascota region, Lange & Carmichael (1990) similarly noted an apparent transition from basaltic andesite with olivine and plagioclase phenocrysts to kersantite with hornblende phenocrysts and no plagioclase phenocrysts. This transition also is accompanied by increases in K and incompatible trace elements. These observations highlight the important role played by H_2O in the petrogenesis of lamprophyres, in stabilizing phlogopite and hornblende and in destabilizing plagioclase. The increases in abundances of incompatible elements that accompany the transition to OH-bearing phenocrysts in these suites are the opposite of trends expected if increased H_2O in the source region lowered the solidus temperature and enhanced the degree of partial melting. Rather, a model involving variable partial melting of phlogopite-bearing pyroxenite veins and surrounding peridotitic mantle is advocated in a later section.

Trace-element characteristics

With the exception of high-Mg# lamprophyres with evidence for accumulation of olivine and inclusions of chromian spinel (Luhr & Carmichael 1981), the three main rock-suites from the western Mexican Volcanic Belt (calc-alkaline, lamprophyres, and alkaline) show a broad overlap in abundances of compatible elements on plots of Mg# *versus* Cr and Ni contents. At a given Mg#, however, magmas erupted in the Jalisco Block, of both the calc-alkaline and lamprophyre-forming series, are depleted in Cr compared to equivalent suites from the Colima Rift and Michoacán–Guanajuato, probably reflecting source-region differences.

The distinctions among the three rock suites are easily apparent on plots showing the concentration of a high-field-strength element, such as Ti, *versus* that of a large-radius lithophile element, such as Ba (Fig. 4). The calc-alkaline rocks (circles) have the lowest values of each parameter. They grade into the broad swarm of lamprophyres (triangles) with increases in both elements. Along a much flatter Ba/Ti trend, the calc-alkaline rocks merge with the alkaline rocks (squares). This trend continues toward the field for basanites from La Breña – El Jagüey (crosses). The intermediate nature of the six samples labeled transitional (open and closed diamonds) is evident on this plot.

Distinctions among the suites in terms of the rare-earth elements (*REE*) are seen on a plot of concentrations of Yb *versus* La in Figure 5. The calc-alkaline rocks (circles) have the lowest abundances of La and of most incompatible elements. The lamprophyres (triangles) attain extremely high values of La and other incompatible elements at relatively low values of Yb. The highest Yb contents are shown by the alkaline rocks (squares) and by the similar basanites from La Breña – El Jagüey (crosses). Representative chondrite-normalized *REE* plots are shown on Figure 6. The calc-alkaline samples have the lowest patterns. Subparallel to them, but shifted to higher concentrations of all *REE*, are the alkaline rocks. The lamprophyres have considerably steeper *REE* patterns that cross the other two types.

Representative samples from the three suites are displayed on a multi-element plot in Figure 7. Three calc-alkaline samples (circles), which have the lowest values of most elements, show the typical patterns associated with subduction-zone magmas: relative enrichments in the large-radius lithophile elements Ba, K, and Sr, and relative depletions the high-field-strength elements Ta, Nb, Hf, and Ti. Four lamprophyres (triangles) mimic the calc-alkaline patterns and their characteristic enrichments (Ba, K, Sr) and depletions (Ta, Nb, Hf, Ti), but are shifted toward much higher concentrations for nearly all elements. The alkaline samples, two from the western Mexican Volcanic Belt (squares) and one from La Breña – El Jagüey (crosses), have entirely different patterns. They extend through the middle of the plot, with maxima at Ta and Nb, and do not show the characteristic peaks and troughs of subduction-zone magmas.

B and Be systematics

Hochstaedter *et al.* (1996) presented B and Be concentrations for a large set of volcanic rocks from the western Mexican Volcanic Belt, including 22 of the primitive rocks discussed in this paper: seven are calc-alkaline, 11 are lamprophyric, one is alkaline, and three are of transitional character. Concentrations of Be are well correlated with those of K_2O (R = 0.94), P_2O_5 (R = 0.94), Ba (R = 0.92), and Sr (R = 0.90). Calc-alkaline

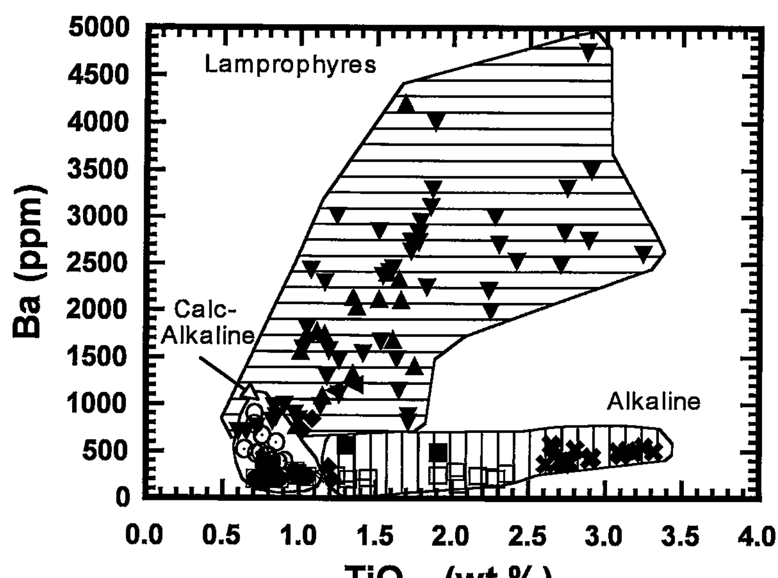

FIG. 4. TiO_2 *versus* Ba contents. Symbols as in Figure 2.

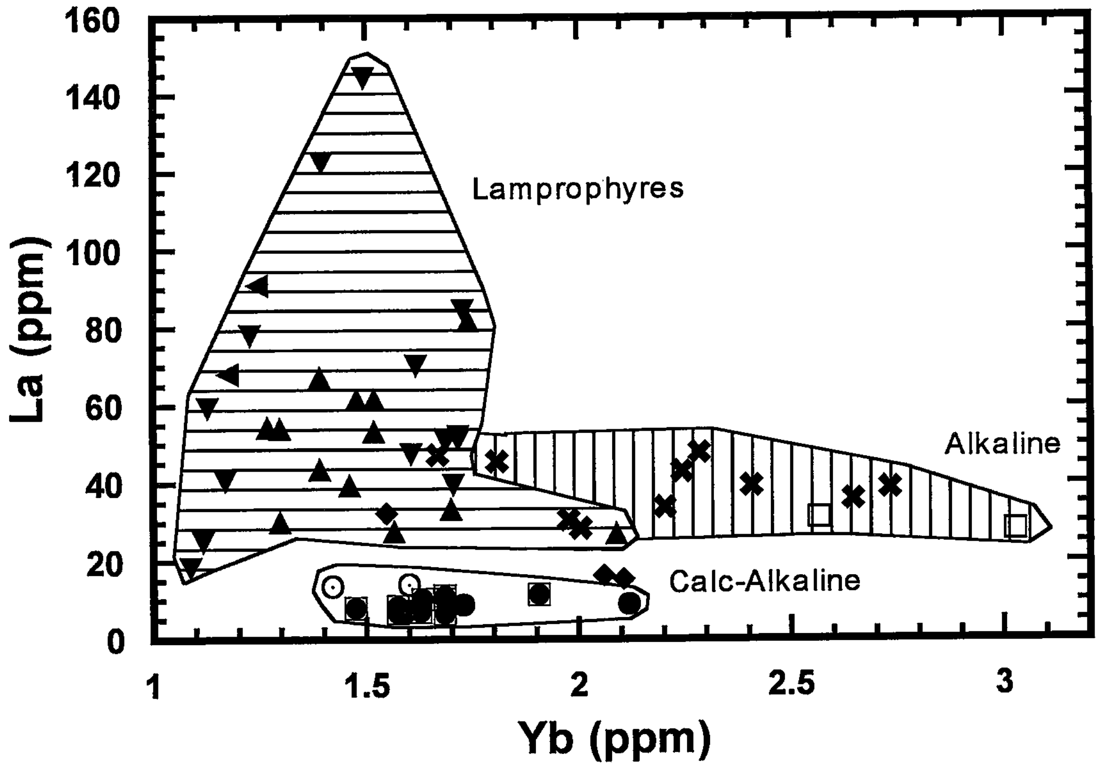

FIG. 5. Yb *versus* La contents. Symbols as in Figure 2.

rocks have 0.6–1.1 ppm Be, lamprophyres have 2.8–6.7 ppm Be, and the alkaline rock is intermediate, with 1.6 ppm Be. Concentrations of B show no such systematics, and are roughly similar for all suites: 2.3–6.5 ppm in calc-alkaline rocks, 0.7–10.6 ppm in the lamprophyres, and 1.4 ppm in the alkaline rock. B/Be values, controlled by the Be concentrations, are 2.1–8.8 in calc-alkaline rocks and distinctly lower in lamprophyres (0.2–1.9) and alkaline rock (0.9). Figure 8 is a plot of Ba concentrations *versus* B/Be values, on which the three suites are clearly distinct and a transitional sample bridges the gap. As emphasized by Hochstaedter *et al.* (1996), the primitive rocks from the western Mexican Volcanic Belt have low concentrations of B and low B/Be values, comparable to other "hot" subduction zones, such as the Cascades (Leeman *et al.* 1990), where young oceanic lithosphere is subducting. These low ratios contrast strongly with B/Be values up to 100 for rocks from "cold" subduction zones, such as the Central American or Aleutian arcs (Morris *et al.* 1990, Ryan & Langmuir 1993, Leeman *et al.* 1994). In "hot" subduction zones, much of the B may be released from the slab at relatively shallow depths and may not be carried into the zone of sub-arc melting (Bebout *et al.* 1993).

Magmatic oxygen fugacity

If a volcanic rock has not undergone post-eruptive oxidation, its Fe^{3+}/Fe^{2+} value and whole-rock composition can be used to calculate the oxygen fugacity of the magma (Sack *et al.* 1980, Kress & Carmichael 1991). The influence of temperature in this calculation is only to shift the oxygen fugacity parallel to synthetic oxygen buffers, and thus it has become common practice to express these oxygen fugacities relative to the Ni–NiO (NNO) solid oxygen buffer using the notation ΔNNO = $\log f(O_2)$ (sample) – $\log f(O_2)$ (NNO) buffer (Huebner & Sato 1970) at the same temperature (Carmichael & Ghiorso 1986, Christie *et al.* 1986).

Of the 122 rocks considered in this study, 82 were analyzed for both loss on ignition (LOI) and FeO by titration. From this subset, 16 samples (20%) with LOI greater than 1.5 wt.% were excluded from oxygen fugacity evaluation, as these are the most likely to have been oxidized during post-eruptive alteration. The set of 82 samples, however, shows no good correlation between LOI and ΔNNO, and all excluded samples have $\Delta NNO > 2$; these are 15 samples of lamprophyre and one alkaline rock.

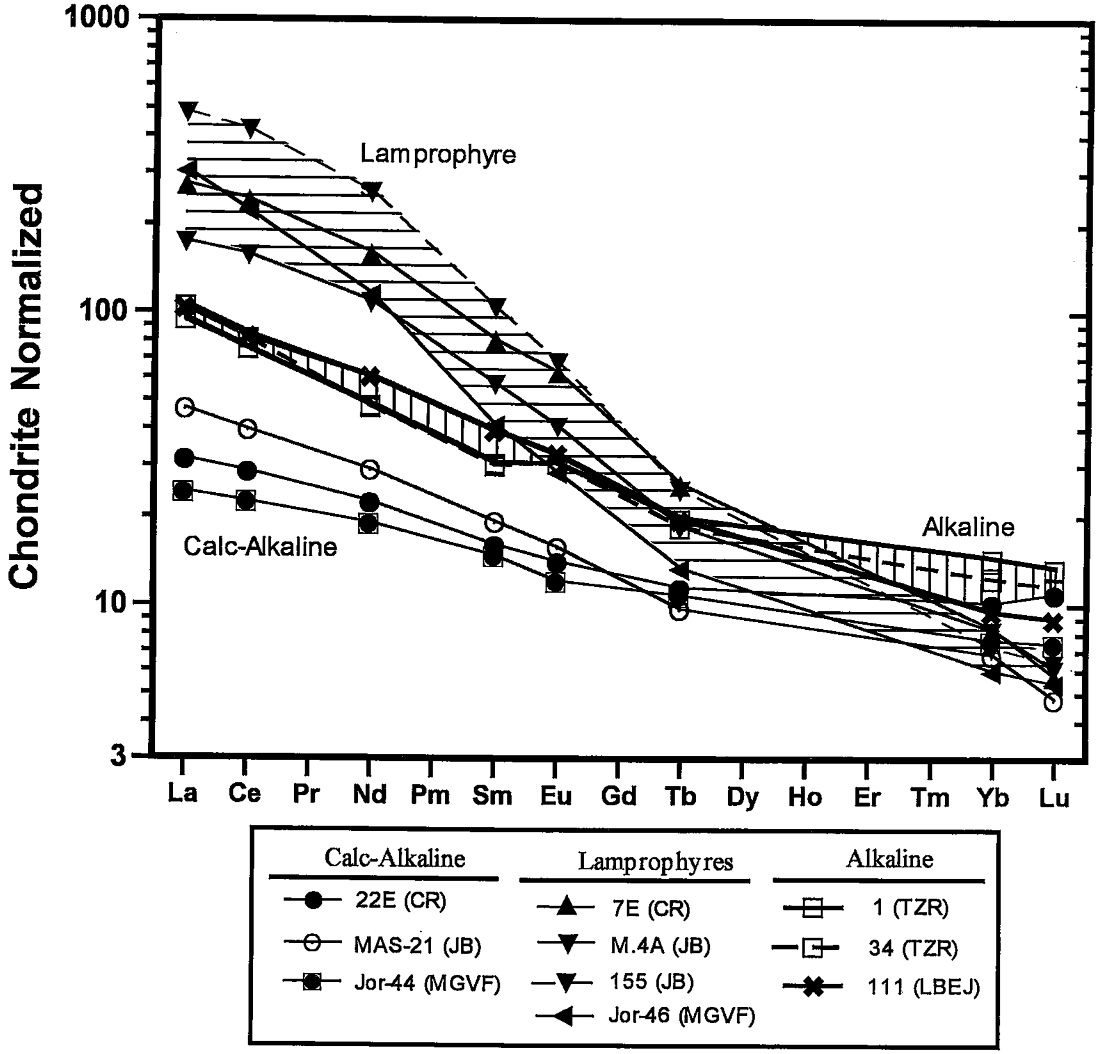

FIG. 6. Chondrite-normalized *REE* diagram, with values normalized to 1.274 times the concentrations listed for the mean C1 chondrite of Anders & Grevesse (1989), which corrects the latter to a volatile-free equivalent. Legend identifies sample names (Appendix) followed by volcanic field in parentheses (see Figure 2, caption).

The ΔNNO values of the remaining 66 samples are plotted in histogram form in Figure 9. The calc-alkaline rocks (n = 27) have a mean ΔNNO value of 0.9 ± 0.8 (1σ). Only two samples each of the alkaline and transitional groups are included, and these plot in the range of the calc-alkaline samples. The basanites from La Breña – El Jagüey show a broad range of ΔNNO values, extending down to –1.5. The lamprophyres (n = 33) are much more oxidized than these other groups, with a mean ΔNNO value of 3.3 ± 1.4.

Sr, Nd, and Pb isotopes

Previously unpublished results of Sr and Nd isotopic analyses by D.J. DePaolo for various rocks from the western Mexican Volcanic Belt are listed in Table 2, along with results of Pb isotopic analyses for many of the same samples from Heatherington (1988).

Sr and Nd isotopic data for all available primitive rocks of the western Mexican Volcanic Belt are shown in Figure 10; again the compositions of the La Breña –

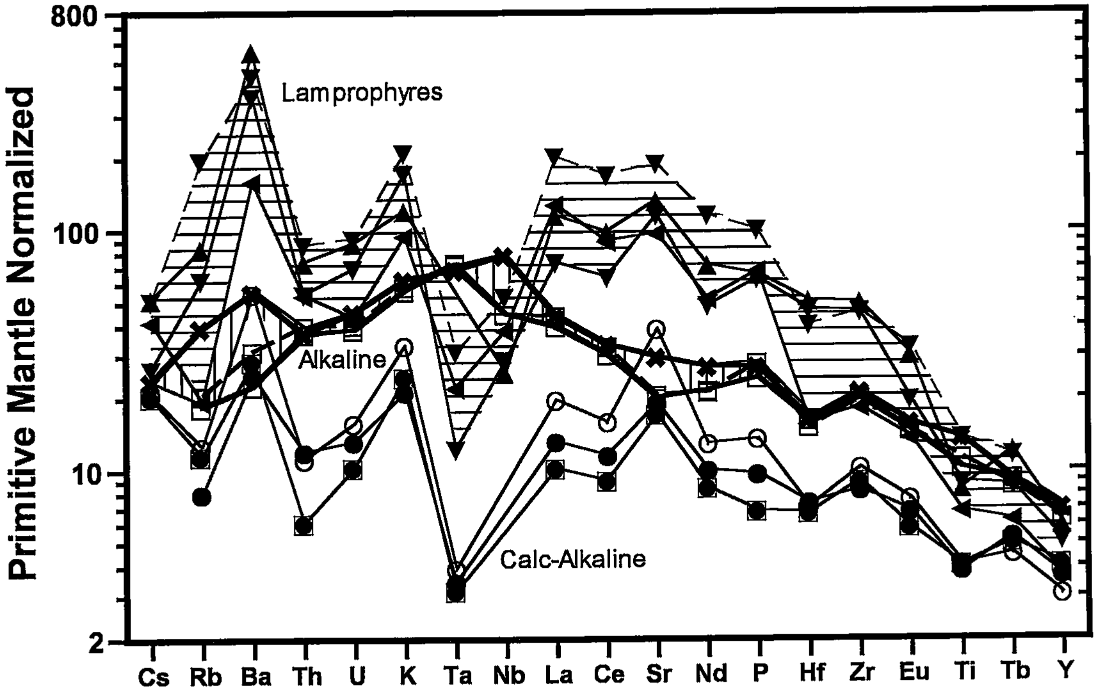

FIG. 7. Multi-element plot, normalized to primordial-mantle values of Wood *et al.* (1981). Symbols as in Figure 6.

El Jagüey basanites are grouped with the alkaline rocks from the Tepic–Zacoalco Rift. The calc-alkaline samples and lamprophyres show considerable overlap, with calc-alkaline sample 22E defining the depleted end, and lamprophyre Jor-46 marking the enriched end. Curiously, the six lamprophyres from the Colima Rift form a vertical trend on this plot, along which the abundances of P, K, La, and other incompatible elements increase with decreasing ϵ_{Nd}. The two alkaline samples from the Tepic–Zacoalco Rift and the La Breña – El Jagüey basanites form a trend that is crudely subparallel to the overlapping calc-alkaline and lamprophyre fields, but shifted to lower $^{87}Sr/^{86}Sr$ values at a given ϵ_{Nd} value. This distinction may reflect involvement of seawater during subduction-related metasomatism of the sub-arc mantle source for both the calc-alkaline suite and the lamprophyres, which is considered to raise $^{87}Sr/^{86}Sr$ values with little effect on ϵ_{Nd} (DePaolo & Johnson 1979). Also shown on Figure 10 are results of analyses of mid-ocean ridge basalts from the East Pacific Rise (Macdougall & Lugmair 1986, White *et al.* 1987, Prinzhofer *et al.* 1989), and of basalts from nearby seamounts (Zindler *et al.* 1984, Graham *et al.* 1988). Most of these oceanic basalts are more depleted than any of the western Mexican Volcanic Belt samples, with most seamount samples having similar to slightly enriched Sr–Nd isotopic compositions compared to East Pacific Rise basalts. Shimada Seamount, which lies about 1100 km west of the East Pacific Rise at ~17°N, however, is more enriched than any of the primitive Mexican rocks (Graham *et al.* 1988). Shimada Seamount is important in the interpretation of isotope ratios for the Mexican primitive rocks because it demonstrates that the adjacent sub-oceanic mantle contains enriched domains of high Sr and low Nd isotopic ratios. These enriched domains, perhaps former basalts, are envisioned to be intimately mixed into the dominant depleted peridotite (Zindler *et al.* 1984, Graham *et al.* 1988, Prinzhofer *et al.* 1989). Low degrees of partial melting can generate liquids that mainly tap the enriched domains, which begin melting at relatively lower temperatures compared to the surrounding depleted peridotite.

Only nine samples of primitive calc-alkaline and lamprophyric character from the western Mexican Volcanic Belt have been analyzed for Pb isotopes (Heatherington 1988). In Figure 11, these data are shown on a plot of $^{206}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$, along with data for seven basanites from La Breña – El Jagüey, which might indicate the Pb isotopic compositions for alkaline rocks from the western Mexican Volcanic Belt, none of which have been analyzed. The total isotopic variation is relatively small, and broad overlap is apparent among the different suites. Also shown are data for basalts from the East Pacific Rise and nearby seamounts. The primitive Mexican rocks

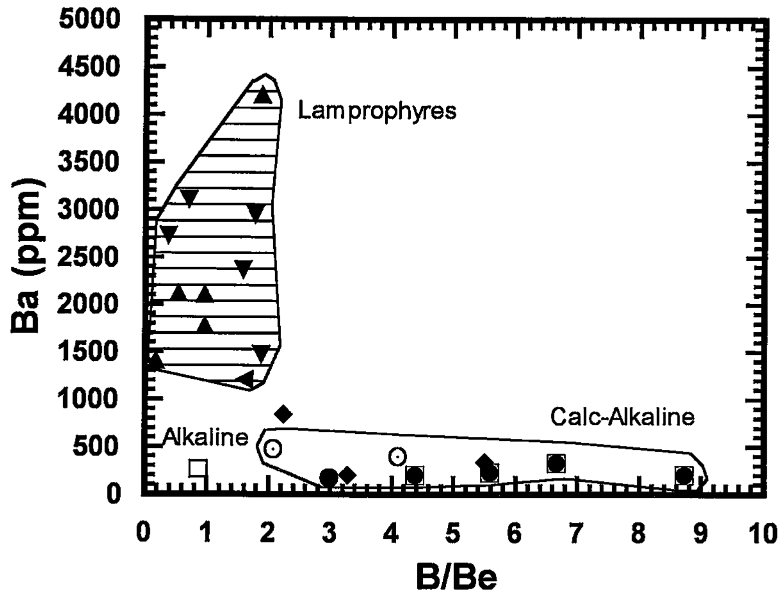

FIG. 8. B/Be values *versus* Ba concentrations for primitive volcanic rocks from the western Mexican Volcanic Belt. B and Be data are from Hochstaedter *et al.* (1996). Samples plotted are: 66, 22E, 500, 507, 511, 6E, 7E, MAS–19, MAS–21, MAS–196, MAS–198, M.3A, M.4A, M.9, Jor–44, 109089, 426B, 517A, 408A, 417A, 542, and Jor–46 (Appendix). Symbols as in Figure 2.

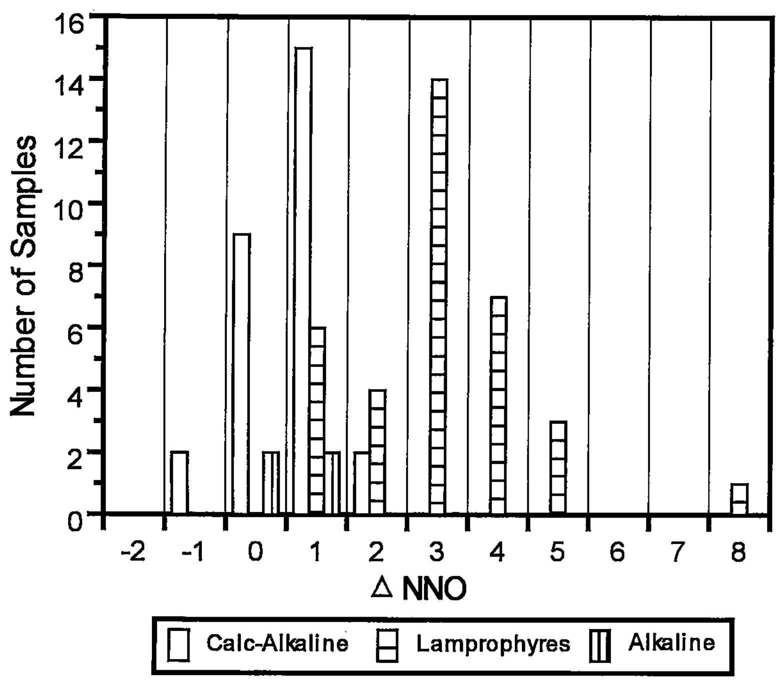

FIG. 9. Histogram of ΔNNO values for 66 rocks from the western Mexican Volcanic Belt with values of LOI <1.5 wt.% and 16 La Breña – El Jagüey basanites.

TABLE 2. Sr, Nd, AND Pb ISOTOPIC RATIOS FOR VOLCANIC ROCKS FROM THE WESTERN MEXICAN VOLCANIC BELT

Sample	Type	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	ε_{Nd}	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
			LAMPROPHYRIC ROCKS				
Colima Rift							
500	Bas	0.70390	0.512076	+4.7	18.696	15.604	38.492
507	Bas	0.70386	0.512094	+5.0			
511	Min	0.70393	0.512091	+5.0	18.664	15.595	38.446
8H	Min	0.70391	0.512048	+4.1			
7E	Min	0.70388	0.511990	+3.0	18.636	15.559	38.365
S33	TBA				18.683	15.600	38.472
B43	Sp	0.70385	0.512112	+5.4			
Cerro La Pilita							
Jor-46	TB	0.70443	0.511948	+2.2	18.702	15.600	38.518
Mascota Field							
M.4A	Min				18.677	15.586	38.430
M.18	Min				18.649	15.580	38.372
			CALC-ALKALINE AND ALKALINE ROCKS				
Colima Volcano and Adjacent Cinder Cones							
22E	B	0.70363	0.512134	+5.8	18.575	15.558	38.226
Col-11	BA	0.70374	0.512153	+6.2	18.589	15.584	38.312
Col-2	A	0.70355	0.512125	+5.6	18.578	15.550	38.290
17B	BA	0.70351	0.512098	+5.1			
Michoacán-Guanajuato Volcanic Field							
Jor-44	B	0.70405	0.512031	+3.8	18.619	15.571	38.344
Jor-11	BA	0.70404	0.512051	+4.2	18.645	15.616	38.380
1050-400A	BA	0.70385	0.512039	+4.0			
1050-558A	AB	0.70375	0.512005	+3.3			
Mascota							
MAS-21	B				18.690	15.615	38.452
			BASEMENT GRANITIC ROCKS				
LHG	Gr	0.70641	0.511984	+2.9	18.862	15.599	38.699
1050-540G	Gd	0.70550	0.512001	+3.2			
MAS-4B	GX				18.804	15.618	38.662

The Sr and Nd isotopic analyses were made by Don DePaolo at UCLA using techniques described in DePaolo (1981). Analytical uncertainties (2σ) are: in $^{87}Sr/^{86}Sr$, 0.00004, in $^{143}Nd/^{144}Nd$, 0.000022, equivalent to 0.5 in ε_{Nd}. Results of Pb isotopic analyses are reprinted from Heatherington (1988). Type: rock types abbreviated as Bas, basanite; Min, minette; TB, trachybasalt; TBA, trachybasaltic andesite; Sp, spessartite; B, basalt; BA, basaltic andesite; Gr, granite; Gd, granodiorite; GX, granitic xenolith. Several of these samples are not primitive, and are not discussed in this paper or listed in the Appendix: M.18 (Carmichael *et al.* 1996), Col-11 and Col-2 (Luhr & Carmichael 1980); 17B (Luhr & Carmichael 1981); Jor-11 and LHG (Luhr & Carmichael 1985); 400A and 558A (Hasenaka & Carmichael 1987); 1050-540G and MAS-4B (unpubl. data). Locations of basement granitic rocks: LHG in Luhr & Carmichael (1985), 1050-540G in Hasenaka (1986), and MAS-4B from the same minette cone as M.4, described in Carmichael *et al.* (1996).

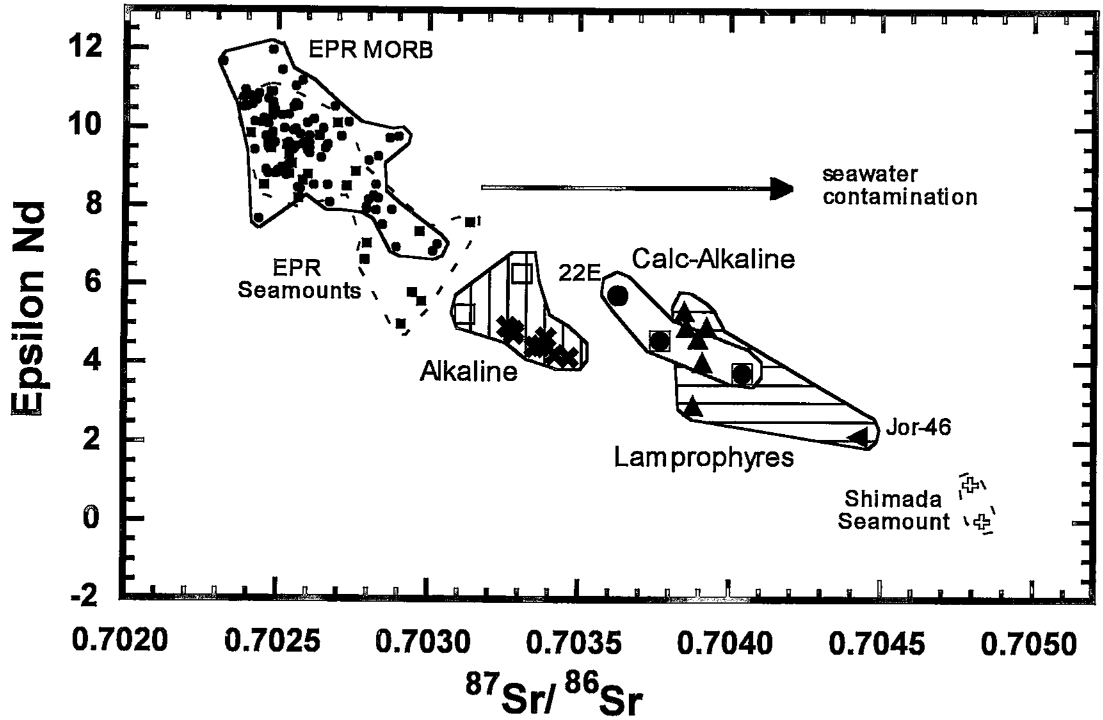

FIG. 10. Sr–Nd isotopic plot for primitive volcanic rocks of the western Mexican Volcanic Belt. Samples plotted are from Table 2, and are shown with symbols from Figure 2: (22E, 500, 507, 511, 8H, 7E, B43, Jor–44, Jor–46), Verma & Nelson (1989: 46, 66), and T.B. Housh (unpublished: 109089). Also shown are data for La Breña – El Jagüey basanites (Pier *et al.* 1992), mid-ocean ridge basalts from the East Pacific Rise (EPR MORB) [small dots: Macdougall & Lugmair (1986), White *et al.* (1987), Prinzhofer *et al.* (1989)], and basalts from East Pacific seamounts [small squares, open plus signs show Shimada Seamount basalts: Zindler *et al.* (1984), Graham *et al.* (1988)].

define a steeper trend than that formed by most oceanic basalts, but a trend nearly identical to that of the Shimada Seamount basalts. As in the case of Sr–Nd variations (Fig. 10), the Pb isotopic data for the Mexican volcanic rocks can be interpreted as a source-mixing trend between East Pacific Rise basalts and a component represented by the extreme sample from Shimada Seamount. Similar trends toward high $^{207}Pb/^{204}Pb$ values are characteristic of volcanic rocks from many subduction-related arcs, and are generally interpreted as evidence for subduction of marine sediments, either continent-derived or pelagic, with high $^{207}Pb/^{204}Pb$ values (Church 1973, 1976, Church & Tilton 1973, Kay *et al.* 1978, Davidson 1987). Importantly though, the intraplate-type alkaline basalts from La Breña – El Jagüey, proxies for unanalyzed relatives from the study area, range to the highest $^{207}Pb/^{204}Pb$ values among the primitive volcanic rocks of western Mexico (Fig. 11). These rocks, completely lacking in the geochemical signature of subduction zones (Figs. 4, 7), cannot have gained their elevated $^{207}Pb/^{204}Pb$ values from sediment subduction. Instead, these elevated values, and by extension those of the primitive calc-alkaline rocks and lamprophyres from western Mexico, may reflect dominance of the Pb budget by the same small-scale, enriched mantle component as advocated by Graham *et al.* (1988) to explain basalts from Shimada Seamount (Fig. 11).

DISCUSSION

A schematic cross-section depicting subduction of the Rivera Plate beneath the Jalisco Block is given in Figure 12, which serves as a focus for the following discussion. The mantle is shown to contain small-scale geochemical heterogeneities, which account for the enriched isotopic components found in seamount basalts (Figs. 10, 11). Five key steps are numbered on Figure 12:

(1) Fluids begin to migrate from the young and hot subducted Rivera slab at shallow depths, carrying B into the overlying mantle peridotite.

(2) Amphibole breaks down in the subducted crust by ~80 km depth, producing hydrous melts that rise into the mantle wedge and react with peridotite to form phlogopite–pyroxenite veins. These veins and the

enclosing peridotite are dragged downward by induced convection in the mantle wedge.

(3) At a depth of ~100 km beneath the volcanic front the phlogopite pyroxenite veins begin to melt, generating primitive lamprophyre-forming magmas that rise into the crust. Some stagnate to form dikes in the crust, but others erupt at the surface because lithospheric extension favors their ascent.

(4) The phlogopite pyroxenite vein component is diluted by partial melts from the surrounding peridotite to generate the calc-alkaline basalts. These larger-volume magmas also rise into the crust. A few erupt directly at the surface, but most feed into calc-alkaline composite volcanoes.

(5) Slab-driven corner flow in the mantle wedge brings in convecting upper mantle that is unmodified by subduction and is thus lacking in the subduction-zone geochemical signature shared by the lamprophyres and calc-alkaline basalts. This mantle ascends beneath the rifting lithosphere and undergoes decompression-induced melting in the spinel lherzolite field to form intraplate-type alkaline basalts enriched in the heavy *REE* compared to the lamprophyres and calc-alkaline basalts.

Primitive lamprophyre-forming and calc-alkaline magmas: partial melting in a veined mantle

In the western Mexican Volcanic Belt, lamprophyre-forming and calc-alkaline magmas have erupted side by side since the Pliocene. Primitive members of these two groups have quite distinct major-element compositions (Fig. 2), proportions of normative minerals (Fig. 3), mineral assemblages, oxygen fugacities (Fig. 9), trace-element abundances (Figs. 4–7), and B/Be values (Fig. 8). Nonetheless, they are similar in their relative trace-element abundances (Fig. 7) and have overlapping Sr, Nd, and Pb isotopic ratios (Figs. 10, 11). These observations are consistent with origins for both suites from a common mantle source-region in which veins of phlogopite – apatite – garnet pyroxenite cross-cut peridotite. As also argued earlier (Luhr *et al.* 1989, Wallace & Carmichael 1989, 1992, Carmichael *et al.* 1996, Hochstaedter *et al.* 1996), the primitive lamprophyres are envisioned to result mainly from melting of the veins (Fig. 12, no. 3). These veins appear to contain little B, perhaps because B is not easily accommodated in phlogopite. Nonetheless, these veins are enriched in Sr, Ba, La, Be and many other incompatible elements;

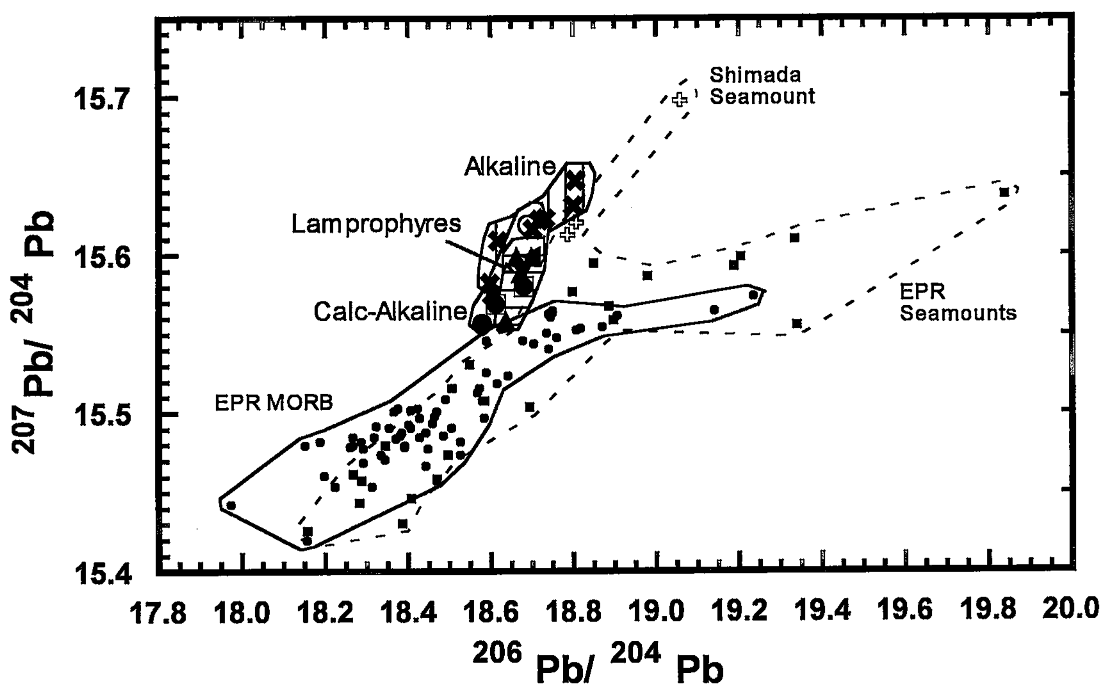

FIG. 11. Pb isotopic data for primitive volcanic rocks of the western Mexican Volcanic Belt. Samples plotted are from Table 2 (22E, 500, 511, 7E, S33, MAS–21, M.4A, Jor–44, Jor–46). Also shown are data for La Breña – El Jagüey basanites (Pier *et al.* 1992), mid-ocean ridge basalts from the East Pacific Rise (White *et al.* 1987, Prinzhofer *et al.* 1989), and basalts from East Pacific seamounts (Graham *et al.* 1988). Symbols as in Figure 10.

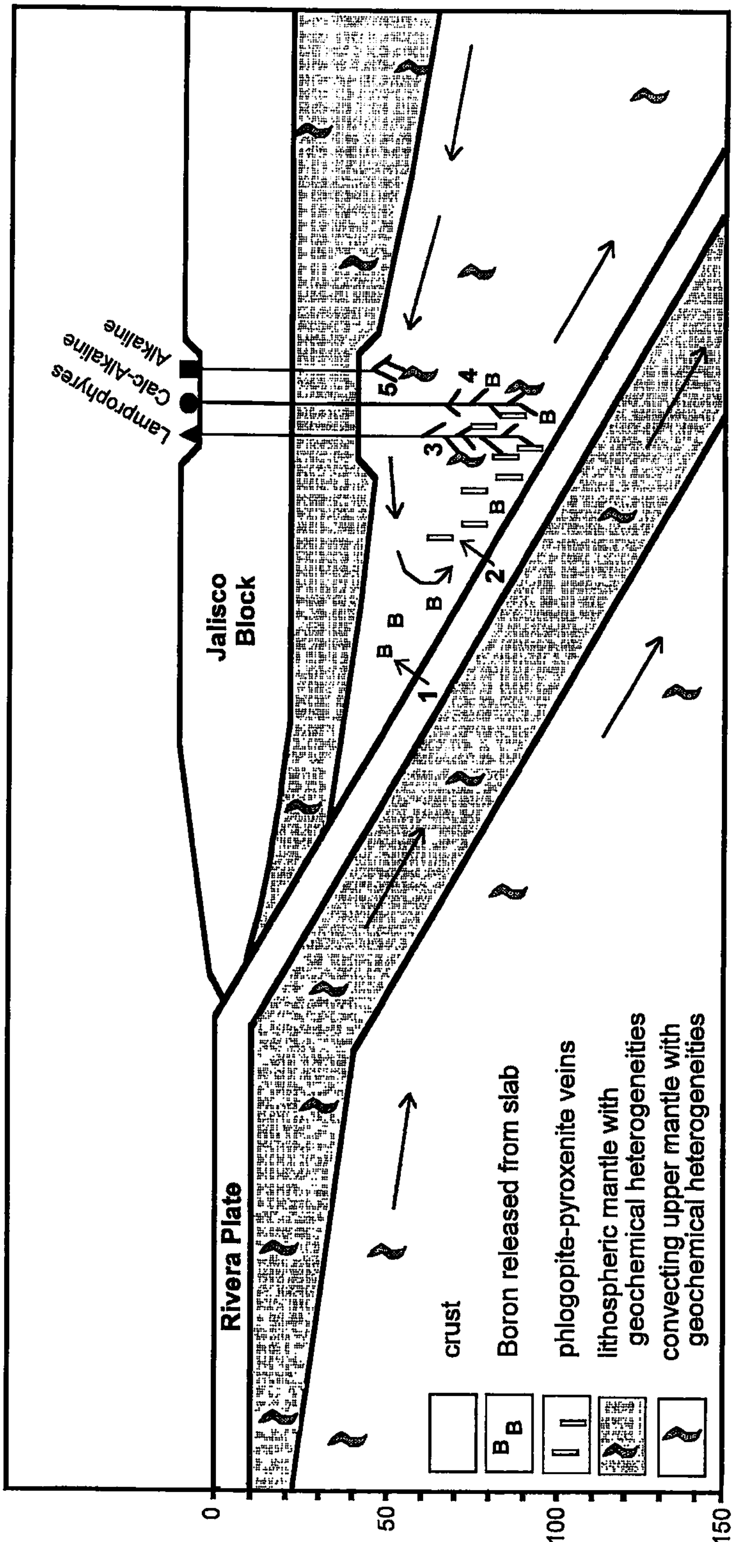

Fig. 12. Schematic illustration of Rivera plate subduction beneath the Jalisco Block (assuming a constant 30° angle of subduction) and important processes occurring in the subsurface. Modified from Davies & Stevenson (1992), Pearce & Peate (1995) and Hochstaedter *et al.* (1996). Details are discussed in the text.

thus the lamprophyres have low B/Be values (Hochstaedter *et al.* 1996). With increasing contribution from the wallrock peridotite, a transition to the primitive calc-alkaline basalts takes place (Fig. 12, no. 4). The slab-modified peridotite apparently contains significant B (Fig. 12, no. 1), and thus the calc-alkaline basalts have relatively high B/Be values (Hochstaedter *et al.* 1996).

The importance of compositionally distinct veins within the mantle was recognized more than 25 years ago from studies of composite mantle xenoliths (Wilshire & Trask 1971). Although these veins vary considerably in their mineralogy, pyroxenites are particularly common, as are minerals such as phlogopite, amphibole, and apatite, which carry K, P, H, F, and other elements that are not abundant in typical four-phase peridotites. Nicholls & Ringwood (1973) first suggested that hydrous siliceous melts, generated in subducted oceanic lithosphere, could migrate into the overlying mantle wedge and react with the peridotite to form hybrid zones of olivine pyroxenite. These were envisioned to give rise to calc-alkaline magmas following ascent and partial melting. The process of hybridization between hydrous siliceous melt and mantle peridotite was later investigated experimentally at high pressures by Wyllie and co-workers for equivalent synthetic systems (Sekine & Wyllie 1982a, b, Wyllie & Sekine 1982) and for natural peridotite–granite couples (Sekine & Wyllie 1982c, 1983, Wyllie *et al.* 1989). These studies demonstrated a variety of mechanisms for the production of olivine-free phlogopite pyroxenites with jadeitic clinopyroxene as products of the hybridization. Either buoyant diapiric ascent or induced convective motion was envisioned as carrying these phlogopite pyroxenites across their solidus to cause partial melting.

In a review of experimental and geochemical constraints on the origin of ultrapotassic volcanic rocks, Foley (1992a) showed that liquidus experiments on these rocks match poorly with results of partial-melting experiments on phlogopite-rich peridotites, a commonly suggested source composition. Rather, Foley favored phlogopite harzburgite or phlogopite pyroxenite domains in the mantle, with rare to absent olivine, as the source of potassic melts, although he noted that few relevant experiments have yet been conducted to test this hypothesis. In a companion paper, Foley (1992b) explored the partial-melting mechanisms for veins containing phlogopite, amphibole, apatite, carbonate, and titanates, cutting across garnet peridotite. Foley emphasized the importance of solid-solution behavior in phlogopite, amphibole, apatite, and other vein minerals in extending the temperature range of melting below the solidus temperature of the surrounding peridotite. Infiltration of the early vein-derived melts into the peridotite along grain boundaries could lead to strong dissolution of olivine and orthopyroxene, minerals out of equilibrium with the melt. This process was envisioned as responsible for raising the Mg# and Ni contents of the melts and giving them a "primitive" character. At a higher temperature, this dissolution grades into partial melting of the peridotite, which would act to further dilute the vein-derived melt. Foley noted that even where diluted, the geochemical signature of the vein would be evident in the pattern of relative enrichments of incompatible elements.

The vein-plus-wallrock melting mechanism advocated by Foley (1992b) is strongly supported by data for primitive lamprophyres and calc-alkaline rocks from the western Mexican Volcanic Belt. The lamprophyres, with their highly elevated K_2O/Na_2O values (Fig. 3), are likely to have formed primarily by partial melting of phlogopite pyroxenite veins generated by hybridization reactions between hydrous siliceous melts and peridotite above the subducting Rivera and Cocos plates. The lamprophyres have the highest Mg#, Cr, and Ni contents of all western Mexican Volcanic Belt rocks. Although these parameters were augmented in some rocks through accumulation of olivine with inclusions of chromian spinel (Luhr & Carmichael 1981), other melts may have been influenced by olivine and orthopyroxene dissolution in the wallrock peridotite. With increasing contribution of the wallrock, the vein-derived melt component is diluted toward compositions typical of calc-alkaline basalt. As emphasized by Foley (1992b), however, these still retain the isotopic and trace-element signatures of the vein component, although considerably diluted in element abundances. In this sense, the lamprophyres of the western Mexican Volcanic Belt represent the geochemical "essence" of subduction-zone magmatism. Following the terminology of the Basaltic Volcanism Study Project (1981), the western Mexican Volcanic Belt lamprophyres are viewed as "probes" of phlogopite pyroxenite veins in the mantle wedge above the subducted Rivera and Cocos slabs.

Lamprophyres in subduction zones

If minettes, kersantites, and other calc-alkaline lamprophyres [nomenclature: Rock (1991)] are the "essence" of subduction-zone magmatism, why aren't lamprophyres more commonly reported in active volcanic arcs? Similar veins of phlogopite pyroxenite may form above most subducted slabs, but the nearly pure lamprophyre-forming, vein-derived melts may rarely erupt to the surface in the typical compressive crustal stress regimes of subduction zones. More likely, these low-volume hydrous melts lose heat and water during ascent, crystallizing and stagnating in the upper mantle or crust to form lamprophyric dikes. As reviewed by Rock (1991), calc-alkaline lamprophyres, of which minette is the most common variety, are usually emplaced in convergent-margins settings as dikes intruding calc-alkaline granitoid rocks. Rock (1991) cited composite intrusions and other field and geochronological evidence indicating that lamprophyre-forming and granitic magmas were commonly coeval;

these are equivalent to the coeval lamprophyres and calc-alkaline rocks of the western Mexican Volcanic Belt.

The unusual extensional tectonic setting in western Mexico has apparently allowed a diverse suite of such lamprophyre-forming magmas to rise to the surface and erupt. Other examples of young lamprophyres erupted in active subduction-related arcs also can be cited, although the role of extensional tectonics is not generally so clear for these. The best analog is probably the 12.4–0.5 Ma trachybasalts reported by Hausback (1984) from the southern end of Baja California, which erupted at a stage in the rifting history of Baja similar to that proposed by Luhr *et al.* (1985) and Allan *et al.* (1991) for rifting of the Jalisco Block. Other equivalents are present in the Tabar–Feni arc of Papua New Guinea, where partial melts from the subduction-modified mantle wedge have risen along extensional faults that transect the remnant New Ireland forearc (McInnes & Cameron 1994, Herzig *et al.* 1994).

Primitive intraplate-type alkaline basalts: decompression melting of the convecting upper mantle

The intraplate-type alkaline basalts of the western Mexican Volcanic Belt must have a distinct source in the mantle compared to the calc-alkaline types and lamprophyres, because of their differing Ba–Ti trends (Fig. 4), multi-element patterns (Fig. 7), and Sr–Nd isotopic compositions (Fig. 10). Worldwide, intraplate-type alkaline basalts are uncommon near the volcanic fronts of subduction-related arcs. As discussed by Gill (1981), Gill & Whelan (1989), and Reagan & Gill (1989), known post-Miocene examples are found where the descending plate is <25 Ma and deep Wadati–Benioff zone earthquakes are absent, and in many cases they overlie the edge of the subducting plate. Reagan & Gill (1989) discussed the case for Turrialba Volcano in Costa Rica, which marks the southeastern end of the Central American volcanic chain related to subduction of the Cocos plate. At the opposite, northwestern end of the Cocos–Rivera subduction system, the intraplate-type alkaline basalts of the western Mexican Volcanic Belt are virtually confined to the Tepic–Zacoalco Rift, which marks the northern boundary of the Jalisco Block and also overlies the northern edge of the subducting Rivera plate. Parallels between the western Mexican Volcanic Belt and Turrialba extend to Sr and Nd isotopic variations. Two samples analyzed from Turrialba (Reagan & Gill 1989) have similar ϵ_{Nd}, but the intraplate-type sample has a slightly lower $^{87}Sr/^{86}Sr$ value than the coeval calc-alkaline sample, just as seems to be the case for the western Mexican Volcanic Belt suites (Fig. 10).

Magmas with either pure or partial intraplate-type signatures have also erupted during and immediately following intra-arc rifting events (Gill 1981, Pearce & Peate 1995). The best described examples are the Sumisu Rift of the Izu–Ogasawara arc (Hochstaedter *et al.* 1990) and rifting events in the Volcano arc of the northern Marianas (Lin *et al.* 1990) and in Fiji (Gill & Whelan 1989). These cases of oceanic intra-arc rifting provide insight into mantle processes occurring beneath the continental rifts of western Mexico. Interpretations of the above authors indicate that lithospheric rifting is accompanied by advection of convecting upper mantle, unmodified by subduction and thus low in B and B/Be, into the sub-arc environment (Fig. 12, no. 5), to serve as the source of the intraplate-type magmas. As emphasized by Reagan & Gill (1989), however, the edge of the Rivera plate may be important to intraplate-type magmatism of the Tepic–Zacoalco Rift, perhaps channeling these melts to the surface. In either case, the convecting upper mantle ascends beneath the rifting lithosphere and partially melts during decompression. Because this occurs at relatively shallow levels in the mantle, where spinel peridotite is stable rather than garnet peridotite, the intraplate-type alkaline basalts are relatively rich in the heavy *REE* (Figs. 5–7).

Conclusions

In the western part of the Mexican Volcanic Belt, active rifting of the Jalisco Block is superimposed upon the compressive stress regime related to subduction of the Cocos and Rivera plates beneath the North American plate. This rifting has allowed an unusual diversity of primitive magmas to erupt at the surface. The primitive volcanic rocks are conveniently divided into three types: calc-alkaline, lamprophyres, and alkaline.

The primitive calc-alkaline rocks and lamprophyres are both clearly related to subduction. They have the high Ba/Ti values that are typical of subduction-zone rocks, similarly shaped patterns on multi-element plots, and overlapping Sr, Nd, and Pb isotopic ratios. They differ dramatically, however, in major-element compositions, proportions of normative minerals, mineral assemblages, and levels of incompatible-element enrichment. The lamprophyres and calc-alkaline rocks can be related to one another through a vein–wallrock melting mechanism in which the lamprophyres form by preferential partial melting of low-temperature veins of phlogopite pyroxenite, which carry the "geochemical essence" of subduction-zone magmatism. Rifting has allowed these low-degree hydrous melts to rise through the crust and erupt. Lamprophyre-forming melts are probably generated beneath most subduction-related arcs, but the compressive stress regimes in most arcs cause them to solidify in the upper mantle or crust as classic lamprophyric dikes. Higher degrees of partial melting, involving the wallrock peridotite, dilute this vein component and produce the calc-alkaline basalts that feed the volumetrically dominant andesitic subduction-zone volcanoes.

The primitive alkaline rocks erupted only in proximity to the Tepic–Zacoalco rift and show no geochemical evidence of a subduction-zone origin. Instead, they have the typical characteristics of intraplate-type magmas, with low Ba/Ti values. These alkaline magmas probably formed at relatively low pressures in the spinel peridotite field, during decompressive partial melting of convecting upper mantle that rose beneath the thinning sub-arc lithosphere.

ACKNOWLEDGEMENTS

Don DePaolo kindly permitted inclusion in this paper of results of his Sr and Nd isotopic analyses for volcanic rocks from western Mexico. The manuscript was improved considerably in focus and logic through reviews by James F. Allan, William P. Leeman, Robert F. Martin, an anonymous individual, and particularly Brian Cousens. I'm also grateful to Alfred G. Hochstaedter and Ian S.E Carmichael for discussions about the origins of western Mexican magmas, and to Genyong Peng, who tutored me in computer graphics during preparation of this manuscript.

REFERENCES

ALLAN, J.F. (1986): Geology of the northern Colima and Zacoalco grabens, southwest Mexico: Late-Cenozoic rifting in the Mexican Volcanic Belt. *Geol. Soc. Am., Bull.* **97**, 473-485.

________ & CARMICHAEL, I.S.E. (1984): Lamprophyric lavas in the Colima Graben, SW Mexico. *Contrib. Mineral. Petrol.* **88**, 203-216.

________, NELSON, S.A., LUHR, J.F., CARMICHAEL, I.S.E., WOPAT, M. & WALLACE, P.J. (1991): Pliocene-Holocene rifting and associated volcanism in southwest Mexico: an exotic terrane in the making. *In* The Gulf and Peninsular Province of the Californias (J.P. Dauphin & B.A. Simoneit, eds.). *Am. Assoc. Petrol. Geol., Mem.* **47**, 425-445.

ANDERS, E. & GREVESSE, N. (1989): Abundances of the elements: meteoritic and solar. *Geochim. Cosmochim. Acta* **53**, 197-214.

ARANDA-GÓMEZ, J.J., LUHR, J.F. & PIER, J.G. (1992): The La Breña – El Jagüey Maar Complex, Durango, México: I. Geological evolution. *Bull. Volcanol.* **54**, 393-404.

ATWATER, T. (1970): Implications of plate tectonics for the Cenozoic evolution of western North America. *Geol. Soc. Am., Bull.* **81**, 3513-3536.

BAN, M., HASENAKA, T., DELGADO-GRANADOS, H. & TAKAOKA, N. (1992): K–Ar ages of lavas from shield volcanoes in the Michoacán–Guanajuato Volcanic Field, Mexico. *Geofís. Int.* **31**, 467-473.

BANDY, W., MORTERA-GUTIERREZ, C.A. & URRUTIA-FUCUGAUCHI, J. (1993): Gravity field of the southern Colima graben, Mexico. *Geofís. Int.* **32**, 561-567.

________, ________, ________ & HILDE, T.W.C. (1995): The subducted Rivera–Cocos plate boundary: where is it, what is it, and what is its relationship to the Colima rift? *Geophys. Res. Lett.* **22**, 3075-3078.

BASALTIC VOLCANISM STUDY PROJECT (1981): *Basaltic Volcanism on the Terrestrial Planets.* Pergamon Press, Inc., New York, N.Y.

BEBOUT, G.E., RYAN, J.G. & LEEMAN, W.P. (1993): B–Be systematics in subduction-related metamorphic rocks: Characterization of the subduction component. *Geochim. Cosmochim. Acta* **57**, 2227-2238.

BOURGOIS, J. & MICHAUD, F. (1991): Active fragmentation of the North American Plate at the Mexican triple junction off Manzanillo. *Geo-Marine Lett.* **11**, 59-65.

________, RENARD, V., AUBOUIN, J., BANDY, W., BARRIER, É., CALMUS, T., CARFANTAN, J.-C., GUERRERO, J., MAMMERICKX, J., MERCIER DE LEPINAY, B., MICHAUD, F. & SOSSON, M. (1988): Fragmentation en cours du bord Ouest du continent Nord Américain: les frontières sous-marines du Bloc Jalisco (Mexique). *C. R. Acad. Sci. Paris* **307**, II, 1121-1130.

BURBACH, G.V., FROHLICH, C., PENNINGTON, W.D. & MATUMOTO, T. (1984): Seismicity and tectonics of the subducted Cocos Plate. *J. Geophys. Res.* **89**, 7719-7735.

CANTAGREL, J.-M. & ROBIN, C. (1979): K–Ar dating on eastern Mexican volcanic rocks: relations between the andesitic and the alkaline provinces. *J. Volcanol. Geotherm. Res.* **5**, 99-114.

CARMICHAEL, I.S.E. & GHIORSO, M.S. (1986): Oxidation–reduction relations in basic magma: a case for homogeneous equilibria. *Earth Planet. Sci. Lett.* **78**, 200-210.

________, LANGE, R.A. & LUHR, J.F. (1996): Quaternary minettes and associated volcanic rocks of Mascota, western Mexico: a consequence of plate extension above a subduction-modified mantle wedge. *Contrib. Mineral. Petrol.* **124**, 302-333.

CHAEL, E.P. & STEWART, G.S. (1982): Recent large earthquakes along the Middle American Trench and their implications for the subduction process. *J. Geophys. Res.* **87**, 329-338.

CHRISTIE, D.M., CARMICHAEL, I.S.E. & LANGMUIR, C.H. (1986): Oxidation states of mid-ocean ridge basalt glasses. *Earth Planet. Sci. Lett.* **79**, 397-411.

CHOU, I-MING (1978): Calibration of oxygen buffers at elevated P and T using the hydrogen fugacity sensor. *Am. Mineral.* **63**, 690-703.

CHURCH, S.E. (1973): Limits of sediment involvement in the genesis of orogenic volcanic rocks. *Contrib. Mineral. Petrol.* **39**, 17-32.

________ (1976): The Cascade Mountains revisited: a re-evaluation in light of new lead isotopic data. *Earth Planet. Sci. Lett.* **29**, 175-188.

________ & TILTON, G.R. (1973): Lead and strontium isotopic studies in the Cascade Mountains: bearing on andesite genesis. *Geol. Soc. Am., Bull.* **84**, 431-454.

CONNOR, C.B. (1990): Cinder cone clustering in the Trans-Mexican Volcanic Belt: implications for structural and petrologic models. *J. Geophys. Res.* **95**, 19395-19405.

DAVIDSON, J.P. (1987): Crustal contamination *versus* subduction zone enrichment: examples from the Lesser Antilles and implications for mantle source compositions of island arc volcanic rocks. *Geochim. Cosmochim. Acta* **51**, 2185-2198.

DAVIES, J.H. & STEVENSON, D.J. (1992): Physical model of source region of subduction zone volcanics. *J. Geophys. Res.* **97**, 2037-2070.

DELGADO-GRANADOS, H. (1993): Late-Cenozoic tectonics offshore western Mexico and its relation to the structure and volcanic activity in the western Trans-Mexican Volcanic Belt. *Geofís. Int.* **32**, 543-559.

________, URRUTIA-FUCUGAUCHI, J., HASENAKA, T. & BAN, M. (1995): Southwestward volcanic migration in the western Trans-Mexican Volcanic Belt during the last 2 Ma. *Geofís. Int.* **34**, 341-352.

DEMETS, C., CARMICHAEL, I.S.E., MELBOURNE, T., SANCHEZ, O., STOCK, J., SUÁREZ, G. & HUDNUT, K. (1995): Anticipating the successor to Mexico's largest historical earthquake. *EOS, Trans. Am. Geophys. Union* **76**(42), 417-428 (abstr.).

________, GORDON, R.G., ARGUS, D.F. & STEIN, S. (1990): Current plate motions. *Geophys. J. Int.* **101**, 425-478.

________ & STEIN, S. (1990): Present-day kinematics of the Rivera Plate and implications for tectonics in southwestern Mexico. *J. Geophys. Res.* **95**, 21,931-21,948.

DEPAOLO, D.J. (1981): A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California. *J. Geophys. Res.* **86**, 10,470-10,488.

________ & JOHNSON, R.W. (1979): Magma genesis in the New Britain island-arc: constraints from Nd and Sr isotopes and trace element patterns. *Contrib. Mineral. Petrol.* **70**, 367-379.

EISSLER, H. & MCNALLY, K.C. (1984): Seismicity and tectonics of the Rivera Plate and implications for the 1932 Jalisco, Mexico earthquake. *J. Geophys. Res.* **89**, 4520-4530.

FERRARI, L. (1995): Miocene shearing along the northern boundary of the Jalisco block and the opening of the southern Gulf of California. *Geology* **23**, 751-754.

________, PASQUARÈ, G. & TIBALDI, A. (1990): Plio-Quaternary tectonics of the central Mexican Volcanic Belt and some constraints on its rifting mode. *Geofís. Int.* **29**, 5-18.

________, ________, VENEGAS, S., CASTILLO, D. & ROMERO, F. (1994): Regional tectonics of western Mexico and its implications for the northern boundary of the Jalisco Block. *Geofís. Int.* **33**, 139-151.

________ & ROSAS-ELGUERA, J. (1997): Late Miocene to Quaternary extension at the northern boundary of the Jalisco Block, western Mexico: the Tepic–Zacoalco Rift revisited. *Geol. Soc. Am., Spec. Pap.* (in press).

FISHER, R.L. (1961): Middle America Trench: topography and structure. *Geol. Soc. Am., Bull.* **72**, 703-720.

FOLEY, S. (1992a): Petrological characterization of the source components of potassic magmas: geochemical and experimental constraints. *Lithos* **28**, 187-204.

________ (1992b): Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas. *Lithos* **28**, 435-453.

GARDUÑO, V.H. & TIBALDI, A. (1991): Kinematic evolution of the continental active triple junction of the western Mexican Volcanic Belt. *C.R. Acad. Sci. Paris* **312**, II, 135-142.

GASTIL, R. & JENSKY, W.A., II (1973): Evidence for strike-slip displacement beneath the Trans-Mexican Volcanic Belt. *Stanford Univ. Publ. Geol. Sci.* **13**, 171-180.

________, KRUMMENACHER, D. & JENSKY, W.A., II (1979a): Reconnaissance geology of west-central Nayarit, Mexico. *Geol. Soc. Am., Map and Chart Series* **MC 24** (scale 1:200,000).

________, ________ & ________ (1979b): Reconnaissance geology of west-central Nayarit, Mexico: summary. *Geol. Soc. Am., Bull.* **90**, 15-18.

GILBERT, C.M., MAHOOD, G.A. & CARMICHAEL, I.S.E. (1985): Volcanic stratigraphy in the Guadalajara area, Mexico. *Geofís. Int.* **24**, 169-191.

GILL, J.B. (1981): *Orogenic Andesites and Plate Tectonics.* Springer-Verlag, New York, N.Y.

________ & WHELAN, P. (1989): Postsubduction ocean island alkali basalts in Fiji. *J. Geophys. Res.* **94**, 4579-4588.

GRAHAM, D.W., ZINDLER, A., KURZ, M.D., JENKINS, W.J., BATIZA, R. & STAUDIGEL, H. (1988): He, Pb, Sr, and Nd isotope constraints on magma genesis and mantle heterogeneity beneath young Pacific seamounts. *Contrib. Mineral. Petrol.* **99**, 446-463.

GREEN, D.H. (1971): Compositions of basaltic magmas as indicators of conditions of origin: applications to oceanic volcanism. *Phil. Trans., R. Soc. London* **268**, 707-725.

HASENAKA, T. (1986): *The Cinder Cones of Michoacán–Guanajuato, Central Mexico.* Ph.D. dissertation, Univ. California, Berkeley, California.

________ & CARMICHAEL, I.S.E. (1985a): The cinder cones of Michoacán–Guanajuato, central México: their age, volume and distribution, and magma discharge rate. *J. Volcanol. Geotherm. Res.* **25**, 105-124.

________ & ________ (1985b): A compilation of location, size, and geomorphological parameters of volcanoes of the Michoacán–Guanajuato Volcanic Field, central Mexico. *Geofís. Int.* **24**, 577-608.

_______ & _______ (1987): The cinder cones of Michoacán–Guanajuato, central Mexico: petrology and chemistry. *J. Petrol.* **28**, 241-269.

HAUSBACK, B.P. (1984): Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico. *In* Geology of the Baja California Peninsula (V.A. Frizzell, Jr., ed.). *Pacific Section, Soc. Econ. Paleontol. Mineral.* **39**, 219-236.

HEATHERINGTON, A.L. (1988): *Isotopic Systematics of Volcanics from South-Central Rio Grande Rift and the Western Mexican Volcanic Belt: Implications for Magmatic and Tectonic Evolution of Cenozoic Extensional Regimes in Western North America.* Ph.D. dissertation, Washington Univ., St. Louis, Missouri.

HERRERA, C. (1967): *Geologia de los Volcanes de Colima.* Tesis Profes., Facultad de Ingenieria, Univ. Nac. Autón. Mexico.

HERZIG, P., HANNINGTON, M., MCINNES, B., STOFFERS, P., VILLINGER, H., SEIFERT, R., BINNS, R. & LIEBE, T. (1994): Submarine volcanism and hydrothermal venting studied in Papua New Guinea. *EOS, Trans. Am. Geophys. Union* **75**(44), 513-520 (abstr.).

HOCHSTAEDTER, A.G., GILL, J.B. & MORRIS, J.D. (1990): Volcanism in the Sumisu Rift. II. Subduction and non-subduction related components. *Earth Planet. Sci. Lett.* **100**, 195-209.

________, RYAN, J.G., LUHR, J.F. & HASENAKA, T. (1996): On B/Be ratios in the Mexican Volcanic Belt. *Geochim. Cosmochim. Acta* **60**, 613-628.

HUEBNER, J.S. & SATO, M. (1970): The oxygen fugacity – temperature relationships of manganese oxide and nickel oxide buffers. *Am. Mineral.* **55**, 934-952.

IDDINGS, J.P. (1895): Absarokite–shoshonite–banakite series. *J. Geol.* **3**, 935-959.

JOHNSON, C.A. & HARRISON, C.G.A. (1990): Neotectonics in central Mexico. *Phys. Earth Planet. Inter.* **64**, 187-210.

KAY, R.W., SUN, S.-S. & LEE-HU, C.-N. (1978): Pb and Sr isotopes in volcanic rocks from the Aleutian Islands and Pribilof Islands, Alaska. *Geochim. Cosmochim. Acta* **42**, 263-273.

KLITGORD, K.D. & MAMMERICKX, J. (1982): Northern East Pacific Rise: magnetic anomaly and bathymetric framework. *J. Geophys. Res.* **87**, 6725-6750.

KÖHLER, H., SCHAAF, P., MÜLLER-SOHNIUS, D., EMMERMAN, R., NEGENDANK, J.F.W. & TOBSCHALL, H.J. (1988): Geochronological and geochemical investigations on plutonic rocks from the complex of Puerto Vallarta, Sierra Madre del Sur. *Geofís. Int.* **27**, 519-543.

KRESS, V.C. & CARMICHAEL, I.S.E. (1991): The compressibility of silicate liquids containing Fe_2O_3 and the effect of composition, temperature, oxygen fugacity, and pressure on their redox states. *Contrib. Mineral. Petrol.* **108**, 82-92.

LANGE, R.A. & CARMICHAEL, I.S.E. (1990): Hydrous basaltic andesites associated with minette and related lavas in western Mexico. *J. Petrol.* **31**, 1225-1259.

_______ & _______ (1991): A potassic volcanic front in western Mexico: the lamprophyric and related lavas of San Sebastian. *Geol. Soc. Am., Bull.* **103**, 928-940.

LE BAS, M.J., LE MAITRE, R.W., STRECKEISEN, A. & ZANETTIN, B. (1986): A chemical classification of volcanic rocks based on the total alkali – silica diagram. *J. Petrol.* **27**, 745-750.

LEEMAN, W.P., CARR, M.J. & MORRIS, J.D. (1994): Boron geochemistry of the Central American volcanic arc: constraints on the genesis of subduction-related magmas. *Geochim. Cosmochim. Acta* **58**, 149-168.

________, SMITH, D.R., HILDRETH, W., PALACZ, Z.A. & ROGERS, N.W. (1990): Compositional diversity of late Cenozoic basalts in a transect across the southern Washington Cascades: implications for subduction zone magmatism. *J. Geophys. Res.* **95**, 19561-19582.

LIN, P.-N., STERN, R.J., MORRIS, J. & BLOOMER, S.H. (1990): Nd- and Sr-isotopic compositions of lavas from the northern Mariana and southern Volcano arcs: implications for the origin of island arc melts. *Contrib. Mineral. Petrol.* **105**, 381-392.

LUHR, J.F. (1978): Factors controlling the evolution of the pre-historic, pyroclastic eruption of Volcán San Juan, Mexico. *Geol. Soc. Am., Abstr. Prog.* **10**, 114.

________ (1993): Petrology and geochemistry of pre-caldera andesites and dacites from Volcán Colima, México. *Geofís. Int.* **32**, 592-603.

________, ALLAN, J.F., CARMICHAEL, I.S.E., NELSON, S.A. & HASENAKA, T. (1989): Primitive calc-alkaline and alkaline rock types from the western Mexican Volcanic Belt. *J. Geophys. Res.* **94**, 4,515-4,530.

________, ARANDA-GÓMEZ, J.J. & HOUSH, T.B. (1995): The San Quintín Volcanic Field, Baja California Norte, Mexico: geology, petrology, and geochemistry. *J. Geophys. Res.* **100**, 10,353-10,380.

________ & CARMICHAEL, I.S.E. (1980): The Colima Volcanic Complex, Mexico. I. Post-caldera andesites from Volcán Colima. *Contrib. Mineral. Petrol.* **71**, 343-372.

________ & ________ (1981): The Colima Volcanic Complex, Mexico. II. Late-Quaternary cinder cones. *Contrib. Mineral. Petrol.* **76**, 127-147.

________ & ________ (1982): The Colima Volcanic Complex, México. III. Ash- and scoria-fall deposits from the upper slopes of Volcán Colima. *Contrib. Mineral. Petrol.* **80**, 262-275.

________ & ________ (1985): Jorullo volcano, Michoacán, Mexico (1759–1774): the earliest stages of fractionation in calc-alkaline magmas. *Contrib. Mineral. Petrol.* **90**, 142-161.

________ & LAZAAR, P. (1985): The Southern Guadalajara Volcanic Chain, Jalisco, Mexico. *Geofís. Int.* **24**, 691-700.

________, NELSON, S.A., ALLAN, J.F. & CARMICHAEL, I.S.E. (1985): Active rifting in southwestern Mexico: manifestations of an incipient spreading-ridge jump. *Geology* **13**, 54-57.

________ & SIMKIN, T. (1993): *Parícutin: the Volcano Born in a Mexican Cornfield.* Geoscience Press, Phoenix, Arizona.

LYLE, M. & NESS, G. (1991): The opening of the southern Gulf of California. *In* The Gulf and Peninsular Province of the Californias (J.P. Dauphin & B.A. Simoneit, eds.). *Am. Assoc. Petrol. Geol., Mem.* **47**, 403-423.

MACDOUGALL, J.D. & LUGMAIR, G.W. (1986): Sr and Nd isotopes in basalts from the East Pacific Rise: significance for mantle heterogeneity. *Earth Planet. Sci. Lett.* **77**, 273-284.

MAHOOD, G.A. (1980): Geological evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Jalisco, Mexico. *J. Volcanol. Geotherm. Res.* **8**, 199-230.

________ (1981): Chemical evolution of a Pleistocene rhyolitic center: Sierra La Primavera, Jalisco, Mexico. *Contrib. Mineral. Petrol.* **77**, 129-149.

________ & DRAKE, R.E. (1982): K–Ar dating of young rhyolitic rocks: a case study of the Sierra La Primavera, Jalisco, Mexico. *Geol. Soc. Am., Bull.* **93**, 1232-1241.

________, GILBERT, C.M. & CARMICHAEL, I.S.E. (1985): Peralkaline and metaluminous mixed-liquid ignimbrites of the Guadalajara region, Mexico. *J. Volcanol. Geotherm. Res.* **25**, 259-271.

________ & HALLIDAY, A.N. (1988): Generation of high-silica rhyolite: a Nd, Sr, and O isotopic study of Sierra La Primavera, Mexican Neovolcanic Belt. *Contrib. Mineral. Petrol.* **100**, 183-191.

MAMMERICKX, J. & KLITGORD, K.D. (1982): Northern East Pacific Rise: evolution from 25 m.y. B.P. to the Present. *J. Geophys. Res.* **87**, 6751-6759.

MCBIRNEY, A.R., TAYLOR, H.P., JR. & ARMSTRONG, R.L. (1987): Parícutin re-examined: a classic example of crustal assimilation in calc-alkaline magma. *Contrib. Mineral. Petrol.* **95**, 4-20.

MCINNES, B.I.A. & CAMERON, E.M. (1994): Carbonated, alkaline hybridizing melts from a sub-arc environment: mantle wedge samples from the Tabar – Lihir – Tanga – Feni arc, Papua New Guinea. *Earth Planet. Sci. Lett.* **122**, 125-141.

MCNALLY, K.C. & MINSTER, J.B. (1981): Nonuniform seismic slip rates along the Middle America Trench. *J. Geophys. Res.* **86**, 4949-4959.

MICHAUD, F., BOURGOIS, J. & AUBOUIN, J. (1990): Fragmentation continentale en cours dans la zone d'affrontement entre le continent Nord-Américain et la ride d'accrétion océanique du Pacifique Est (Mexique). *Oceanologica Acta, Spec. Vol.* **10**, 87-96.

________, QUINTERO, O., BARRIER, É. & BOURGOIS, J. (1991): La frontière Nord du bloc Jalisco (ouest du Mexique): localisation et évolution de 13 Ma à l'actuel. *C.R. Acad. Sci.* **312**, *sér.* **II**, 1359-1365.

MINSTER, J.B. & JORDAN, T.H. (1978): Present-day plate motions. *J. Geophys. Res.* **83**, 5331-5354.

MOLNAR, P. & SYKES, L.R. (1969): Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. *Geol. Soc. Am., Bull.* **80**, 1639-1684.

MOORE, G., MARONE, C., CARMICHAEL, I.S.E. & RENNE, P. (1994): Basaltic volcanism and extension near the intersection of the Sierra Madre volcanic province and the Mexican Volcanic Belt. *Geol. Soc. Am., Bull.* **106**, 383-394.

MORRIS, J.D., LEEMAN, W.P. & TERA, F. (1990): The subducted component in island arc lavas: constraints from Be isotopes and B–Be systematics. *Nature* **344**, 31-36.

MORRISON, G.W. (1980): Characteristics and tectonic setting of the shoshonite rock association. *Lithos* **13**, 97-108.

MYERS, J.D. (1988): Possible petrogenetic relations between low- and high-MgO Aleutian basalts. *Geol. Soc. Am., Bull.* **100**, 1040-1053.

NELSON, S.A. (1980): Geology and petrology of Volcán Ceboruco, Nayarit, Mexico. *Geol. Soc. Am., Bull.* **91**, 2290-2431.

________ & CARMICHAEL, I.S.E. (1984): Pleistocene to Recent alkalic volcanism in the region of Sangangüey volcano, Nayarit, Mexico. *Contrib. Mineral. Petrol.* **85**, 321-335.

________ & HEGRE, J. (1990): Volcán Las Navajas, a Pliocene–Pleistocene trachyte/peralkaline rhyolite volcano in the northwestern Mexican volcanic belt. *Bull. Volcanol.* **52**, 186-204.

________ & LIVIERES, R.A. (1986): Contemporaneous calc-alkaline and alkaline volcanism in the region of Sangangüey volcano, Nayarit, Mexico. *Geol. Soc. Am., Bull.* **97**, 798-808.

NICHOLLS, I.A. & RINGWOOD, A.E. (1973): Effects of water on olivine stability in tholeiites and production of silica-saturated magmas in the island arc environment. *J. Geol.* **81**, 285-300.

NIETO-OBREGÓN, J. (1989): Tectonic synthesis and seismic risk along the Rio Grande de Santiago fault, in Jalisco, Mexico. *Int. J. Mining Geol. Eng.* **7**, 37-51.

________, DELGADO, A.L. & DAMON, P.E. (1985): Geochronologic, petrologic, and structural data related to large morphologic features between the Sierra Madre Occidental and the Mexican Volcanic Belt. *Geofís. Int.* **24**, 623-663.

NIXON, G.T. (1982): The relationship between Quaternary volcanism in central Mexico and the seismicity and structure of subducted ocean lithosphere. *Geol. Soc. Am., Bull.* **93**, 514-523.

________, DEMANT, A., ARMSTRONG, R.L. & HARAKAL, J.E. (1987): K–Ar and geologic data bearing on the age and evolution of the Trans-Mexican Volcanic Belt. *Geofís. Int.* **26**, 109-158.

PARDO, M. & SUÁREZ, G. (1993): Steep subduction geometry of the Rivera Plate beneath the Jalisco Block in western Mexico. *Geophys. Res. Lett.* **20**, 2391-2394.

PASQUARÈ, G., FORCELLA, F., TIBALDI, A., VEZZOLI, L. & ZANCHI, A. (1986): Structural behavior of a continental volcanic arc: the Mexican volcanic belt. *In* The Origin of Arcs (F.-C. Wezel, ed.). Elsevier, New York, N.Y. (509-527).

PEARCE, J.A. & PEATE, D.W. (1995): Tectonic implications of the composition of volcanic arc magmas. *Annu. Rev. Earth Planet. Sci.* **23**, 251-285.

PIER, J.G., LUHR, J.F., PODOSEK, F.A. & ARANDA-GÓMEZ, J.J. (1992): The La Breña – El Jagüey Maar Complex, Durango, México. II. Petrology and geochemistry. *Bull. Volcanol.* **54**, 405-428.

PRINZHOFER, A., LEWIN, E. & ALLÈGRE, C.J. (1989): Stochastic melting of the marble cake mantle: evidence from local study of the East Pacific Rise at 12°50'N. *Earth Planet. Sci. Lett.* **92**, 189-206.

REAGAN, M.K. & GILL, J.B. (1989): Coexisting calcalkaline and high-niobium basalts from Turrialba volcano, Costa Rica: implications for residual titanates in arc magma sources. *J. Geophys. Res.* **94**, 4619-4633.

RIGHTER, K. & CARMICHAEL, I.S.E. (1992): Hawaiites and related lavas in the Atenguillo graben, western Mexican Volcanic Belt. *Geol. Soc. Am., Bull.* **104**, 1592-1607.

________, ________, BECKER, T.A. & RENNE, P.R. (1995): Pliocene-Quaternary volcanism and faulting at the intersection of the Gulf of California and the Mexican Volcanic Belt. *Geol. Soc. Am., Bull.* **107**, 612-626.

ROCK, N.M.S. (1991): *Lamprophyres.* Blackie and Sons, Ltd., Glasgow, U.K.

RYAN, J.G. & LANGMUIR, C.H. (1993): The systematics of boron abundances in young volcanic rocks. *Geochim. Cosmochim. Acta* **57**, 1489-1498.

SACK, R.O., CARMICHAEL, I.S.E., RIVERS, M. & GHIORSO, M.S. (1980): Ferric–ferrous equilibria in natural silicate liquids at 1 bar. *Contrib. Mineral. Petrol.* **75**, 369-376.

SATO, H. (1977): Nickel content of basaltic magmas: identification of primary magmas and a measure of the degree of olivine fractionation. *Lithos* **10**, 113-120.

SEDLOCK, R.L., ORTEGA-GUTIÉRREZ, F. & SPEED, R.C. (1993): Tectonostratigraphic terranes and tectonic evolution of Mexico. *Geol. Soc. Am., Spec. Pap.* **278**.

SEKINE, T. & WYLLIE, P.J. (1982a): Phase relationships in the system $KAlSiO_4 - Mg_2SiO_4 - SiO_2 - H_2O$ as a model for hybridization between hydrous siliceous melts and peridotite. *Contrib. Mineral. Petrol.* **79**, 368-374.

________ & ________ (1982b): Synthetic systems for modeling hybridization between hydrous siliceous magmas and peridotite in subduction zones. *J. Geol.* **90**, 734-741.

________ & ________ (1982c): The system granite – peridotite – H_2O at 30 kbar, with applications to hybridization in subduction zone magmatism. *Contrib. Mineral. Petrol.* **81**, 190-202.

________ & ________ (1983): Experimental simulation of mantle hybridization in subduction zones. *J. Geol.* **91**, 511-528.

SERPA, L., SMITH, S., KATZ, C., SKIDMORE, C., SLOAN, R. & PAVLIS, T. (1992): A geophysical investigation of the southern Jalisco Block in the State of Colima, Mexico. *Geofís. Int.* **31**, 475-492.

SINGH, S.K., ASTIZ, L. & HAVSKOV, J. (1981): Seismic gaps and recurrence periods of large earthquakes along the Mexican subduction zone: a reexamination. *Bull. Seismol. Soc. Am.* **71**, 827-843.

________, PONCE, L. & NISHENKO, S.P. (1985): The great Jalisco, Mexico, earthquakes of 1932: subduction of the Rivera Plate. *Bull. Seismol. Soc. Am.* **75**, 1301-1313.

TATSUMI, Y. & KOYAGUCHI, T. (1989): An absarokite from a phlogopite lherzolite source. *Contrib. Mineral. Petrol.* **102**, 34-40.

________, SAKUYAMA, M., FUKUYAMA, H. & KUSHIRO, I. (1983): Generation of arc basalt magmas and the thermal structure of the mantle wedge in subduction zones. *J. Geophys. Res.* **88**, 5815-5825.

UNAM SEISMOLOGY GROUP (1986): The September 1985 Michoacán earthquakes: aftershock distribution and history of rupture. *Geophys. Res. Lett.* **13**, 573-576.

URRUTIA-FUCUGAUCHI, J. & MOLINA-GARZA, R.S. (1992): Gravity modelling of regional crustal and upper mantle structure of the Guerrero terrane. 1. Colima graben and southern Sierra Madre Occidental, western Mexico. *Geofís. Int.* **31**, 493-507.

VAN ANDEL, T.H., HEATH, G.R. & MOORE, T.C., JR. (1975): Cenozoic history and paleoceanography of the central equatorial Pacific Ocean: a regional synthesis of Deep Sea Drilling Project data. *Geol. Soc. Am., Mem.* **143**.

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

WALLACE, P.J. & CARMICHAEL, I.S.E. (1989): Minette lavas and associated leucitites from the western front of the Mexican Volcanic Belt: petrology, chemistry, and origin. *Contrib. Mineral. Petrol.* **103**, 470-492.

_______ & _______ (1992): Alkaline and calc-alkaline lavas near Los Volcanes, Jalisco, Mexico: geochemical diversity and its significance in volcanic arcs. *Contrib. Mineral. Petrol.* **111**, 423-439.

_______ & _______ (1994): Petrology of Volcán Tequila, Jalisco, Mexico: disequilibrium phenocryst assemblages and evolution of the subvolcanic magma system. *Contrib. Mineral. Petrol.* **117**, 345-361.

_______, _______, Righter, K. & Becker, T.A. (1992): Volcanism and tectonism in western Mexico: a contrast of style and substance. *Geology* **20**, 625-628.

Watkins, N.D., Gunn, B.M., Baksi, A.K., York, D. & Ade-Hall, J. (1971): Paleomagnetism, geochemistry, and potassium–argon ages of the Rio Grande de Santiago volcanics, central Mexico. *Geol. Soc. Am., Bull.* **82**, 1955-1968.

White, W.M., Hofmann, A.W. & Puchelt, H. (1987): Isotope geochemistry of Pacific mid-ocean ridge basalt. *J. Geophys. Res.* **92**, 4881-4893.

Wilcox, R.E. (1954): Petrology of Parícutin Volcano, Mexico. *U.S. Geol. Surv., Bull.* **965C**, 281-489.

Williams, H. (1950): Volcanoes of the Parícutin region, Mexico. *U.S. Geol. Surv., Bull.* **965B**, 165-279.

Wilshire, H.G. & Trask, N.J. (1971): Structural and textural relationships of amphibole and phlogopite in peridotite inclusions, Dish Hill, California. *Am. Mineral.* **56**, 240-255.

Wood, D.A., Tarney, J. & Weaver, B.L. (1981): Trace element variations in Atlantic ocean basalts and Proterozoic dykes from north-west Scotland: their bearing upon the nature and geochemical evolution of the upper mantle. *Tectonophys.* **75**, 91-112.

Wyllie, P.J., Carroll, M.R., Johnston, A.D., Rutter, M.J., Sekine, T. & Van Der Laan, S.R. (1989): Interactions among magmas and rocks in subduction zone regions: experimental studies from slab to mantle to crust. *Eur. J. Mineral.* **1**, 165-179.

_______ & Sekine, T. (1982): The formation of mantle phlogopite in subduction zone hybridization. *Contrib. Mineral. Petrol.* **79**, 375-380.

Zimmermann, J.-L., Stussi, J.M., Gonzalez-Partida, E. & Arnold, M. (1988): K–Ar evidence for age and compositional zoning in the Puerto Vallarta – Río Santiago batholith (Jalisco, Mexico). *J. South Am. Earth Sci.* **1**, 267-274.

Zindler, A., Staudigel, H. & Batiza, R. (1984): Isotope and trace element geochemistry of young Pacific seamounts: implications for the scale of upper mantle heterogeneity. *Earth Planet. Sci. Lett.* **70**, 175-195.

Received December 6, 1995, revised manuscript accepted November 28, 1996.

APPENDIX: PRIMITIVE SAMPLES INCLUDED IN THIS STUDY (Mg# > 62, MgO > 6 wt.%)

Tepic-Zacoalco Rift

Calc-alkaline:	Righter *et al.* (1995): 411
Transitional:	Moore *et al.* (1994): A-3, 3-106
Intraplate-type alkaline:	Nelson & Carmichael (1984): 1, 16, 34, 46, 66
	Nelson & Livieres (1986): 338
	Moore *et al.* (1994): A-2, A-30, A-73, 4-107, 48-166
	Righter *et al.* (1995): 396

Colima Rift

Calc-alkaline:	Luhr & Carmichael (1980): Col-13
	Luhr & Carmichael (1981): 22E
Lamprophyric:	Luhr & Carmichael (1981): 500, 501, 507, 508, 510, 511, 5A, 6A, 6D, 6E, 7E, 8G, 8H
	Luhr & Carmichael (1982): S33, S34
	Allan & Carmichael (1984): B43

Jalisco Block

Calc-alkaline:	Lange & Carmichael (1990): MAS-19, MAS-21, MAS-22, MAS-41, MAS-42, MAS-45, MAS-108, MAS-127, MAS-132, MAS-149, MAS-150, MAS-309
	Wallace & Carmichael (1992): 235
Lamprophyric:	Wallace & Carmichael (1989): 100, 113, 121, 154, 155, 166, 207, 211, 227, 231, 242
	Lange & Carmichael (1991): MAS-141, MAS-142, MAS-189, MAS-196, MAS-198, MAS-199
	Wallace & Carmichael (1992): 112, 114, 117, 120, 124-A, 125, 128, 143, 145, 164, 208, 218, 219, 220, 236, 243, 245, 246
	Carmichael *et al.* (1996): M.3A, M.4A, M.6, M.9, M.11, M.15, M.30, M.39, M.48, M.52, M.102, M.134, M.177b, M.177c, M.405
Intraplate-type alkaline:	Righter & Carmichael (1992): 243, 248

Michoacán-Guanajuato Volcanic Field

Calc-alkaline:	Luhr & Carmichael (1985): Jor-1A, Jor-2, Jor-15, Jor-16, Jor-19, Jor-25, Jor-26, Jor-29, Jor-31, Jor-39B, Jor-42, Jor-44
	T.B. Housh and J.F. Luhr (unpubl. data): 109089
	Hasenaka & Carmichael (1987): 416A, 426B, 517A, 534, 536L
Transitional:	Hasenaka & Carmichael (1987): 408A, 417A, 520, 542
Lamprophyric:	Luhr & Carmichael (1985): Jor-46, Jor-46d

Mexican Basin and Range Province

Intraplate-type alkaline:	Pier *et al.* (1992): 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 114, 115, 116, 117, 120