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Beyond Subduction and Plumes: A Unified Tectonic-Petrogenetic Model for the Mexican Volcanic Belt

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Abstract

The Mexican Volcanic Belt (MVB) is a major linear belt of Miocene to present-day volcanism in southern Mexico. Its origin has been controversial, although the majority opinion views it as a volcanic arc related to the subduction of the Cocos plate under the North American plate. Both calc-alkaline and alkaline volcanism characterize the belt; the latter has been previously cited as indicative of the role of a mantle plume. Here we present objections to these explanations, and conclude on the basis of geological, geochemical, and geophysical data that the MVB is unrelated to subduction or to a mantle plume, and is instead a rift-like structure experiencing active extension. Calc-alkaline or alkaline geochemistry of magmas is not useful for inferring tectonic setting, but reflects source parameters and petrogenetic processes. For the MVB, calc-alkaline geochemistry suggests crustal contamination, and the OIB-like geochemistry suggests an enriched mantle source. Our proposal of a heterogeneous mantle beneath the MVB comprising "normal" mantle and metasomatic, enriched veins, can explain the close association in space and time of calc-alkaline and alkaline volcanism throughout the belt.

Introduction

THE MEXICAN VOLCANIC BELT (MVB, Fig. 1) is a linear belt of Miocene to Recent volcanoes in southern Mexico, extending from Veracruz to Puerto Vallarta in an E-W direction for about 1000 km, with a width varying from 50 to 300 km. It comprises more than 8000 individual volcanic structures (Robin, 1982a), including towering stratovolcanoes, calderas, domes, and monogenetic cone fields. Several of the large stratovolcanoes (e.g., Ceboruco, Colima, Popocatépetl, and Citlaltépetl, Fig. 1) have been historically active.

Von Humboldt (1808) was the first to propose an explanation for this linear belt of volcanoes, in terms of a crustal fracture traversing the continent along 19° N from the Atlantic Ocean to the Pacific Ocean. He believed the Revillagigedo volcanic islands in the eastern Pacific, about 800 km to the west of Puerto Vallarta, to lie on an extension of the same major fracture. The crustal fracture model has had several followers since (e.g., Mooser and Maldonado, 1961; Mooser, 1969). A fracture zone of Permo-Triassic age, called the Mexico Fracture Zone, was proposed to underlie the MVB (De Cserna, 1971). When the Clarion Fracture Zone was discovered in the northeastern Pacific (Menard, 1955), the fracture-zone model received additional impetus, inasmuch as the MVB appears to be a continental extension of this oceanic feature.

Later, with the development of plate tectonics, the MVB was interpreted by most workers as a typical subduction-related magmatic arc related to the subduction of the Cocos plate beneath the North American plate along the Middle America trench (e.g., Molnar and Sykes, 1969; Mooser, 1972; Demant and Robin, 1975; Pal and Urrutia-Fucugauchi, 1977; Thorpe, 1977; Menard, 1978; Negendank et al., 1985). However, although the MVB has thus been widely postulated to be a part of the Circum-Pacific ring of volcanoes, it can be seen from Figure 1 that it is not parallel to the Middle America trench, but makes an angle of about 20° with it (Molnar and Sykes, 1969). The MVB links to the Central American volcanic arc (which is parallel to the Middle America trench) through a diffuse transition zone of Pliocene to Recent volcanism, called the Chiapanecan arc (Damon and Montesinos, 1978).

However, Shurbet and Cebull (1984) argued, based on seismic data, that the MVB is presently experiencing transtension, is not related directly to subduction, and is apparently serving the function

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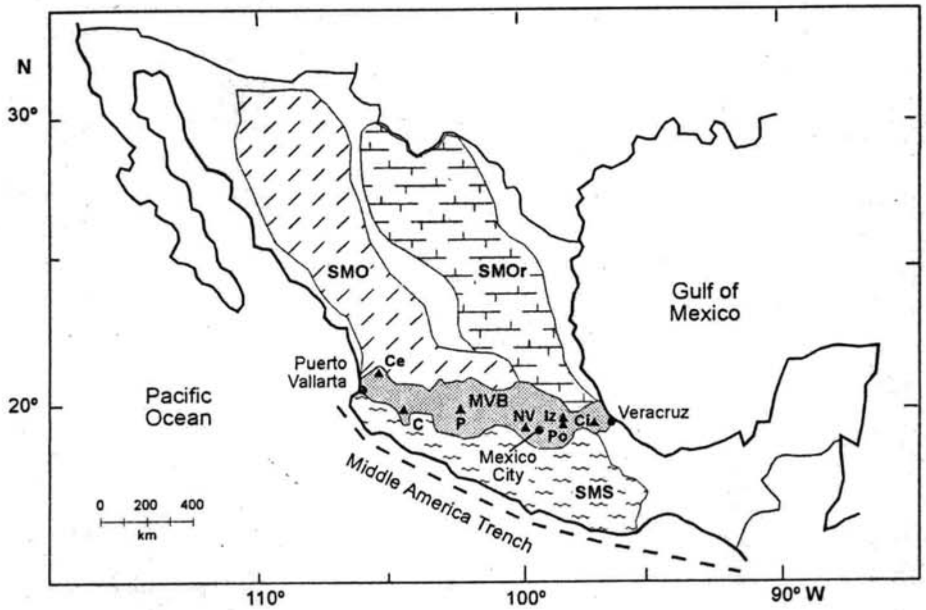

FIG. 1. The Mexican Volcanic Belt (MVB, shaded region) and other important geological provinces in Mexico. Abbreviations: SMO = Sierra Madre Occidental; SMOr = Sierra Madre Oriental; SMS = Sierra Madre del Sur. Major volcanoes are shown by filled triangles: C = Colima; Ce = Ceboruco; P = Paricutín; NV = Nevado de Toluca; Po = Popocatépetl; Iz = Iztaccíhuatl; Ci = Citlaltépetl (Pico de Orizaba).

of an incipient plate boundary between the North American plate to the north and a developing (or possibly aborted) microplate to the south. Their interpretations were criticized by Suárez and Singh (1986), who preferred to interpret the MVB as a product of subduction, but Shurbet and Cebull (1986) maintained that while subduction may be influencing the *character* of the volcanism, the *location* of the MVB was independent of subduction. Later, Cebull and Shurbet (1987) suggested that the MVB was acting as an "intraplate transform" (Davies, 1980) that accommodated differing tectonic conditions to the north and south (extension in the north and compression to the south). Verma and Aguilar-Y-Vargas (1988) showed that both calc-alkaline and alkaline magmas have erupted in the westernmost and easternmost parts of the MVB, calc-alkaline lavas (mostly andesites and dacites) dominate its central part, and there are no systematic variations in the alkali contents of the lavas along the length of the MVB related to the distance from the trench (measured along several perpendicular transects); this observation was inconsistent with generalized arc models.

Thus, the origin of the MVB has been highly controversial. Voluminous calc-alkaline magmatism characterizes the MVB, and this has usually been cited as evidence for a subduction origin (e.g., Negendank et al., 1985), and incompatible with an extensional-rift or fracture-zone origin (Márquez et al., 1999a). On the other hand, Moore et al. (1994) and Márquez et al. (1999a) noted and emphasized considerable volumes of alkaline, oceanic-island-basalt (OIB)–like magmatism found throughout the belt, and argued for its incompatibility with a purely subduction origin. These authors invoked an additional parameter to explain the OIB-type volcanism, namely a mantle plume beneath the Guadalajara area in the western part of the MVB (Fig. 2).

We demonstrate below, based on geological, geochemical, and geophysical data, that: (1) the MVB is indeed an intracontinental rift-like structure experiencing active extensile deformation; (2) the calc-alkaline and alkaline magmatism of the MVB is fully compatible with an extensional tectonic setting; and (3) the MVB is unrelated to either subduction or a mantle plume. We begin by highlighting problems with the subduction and plume explanations, and then describe how the geochemical signatures can be easily reconciled with our proposed rift setting.

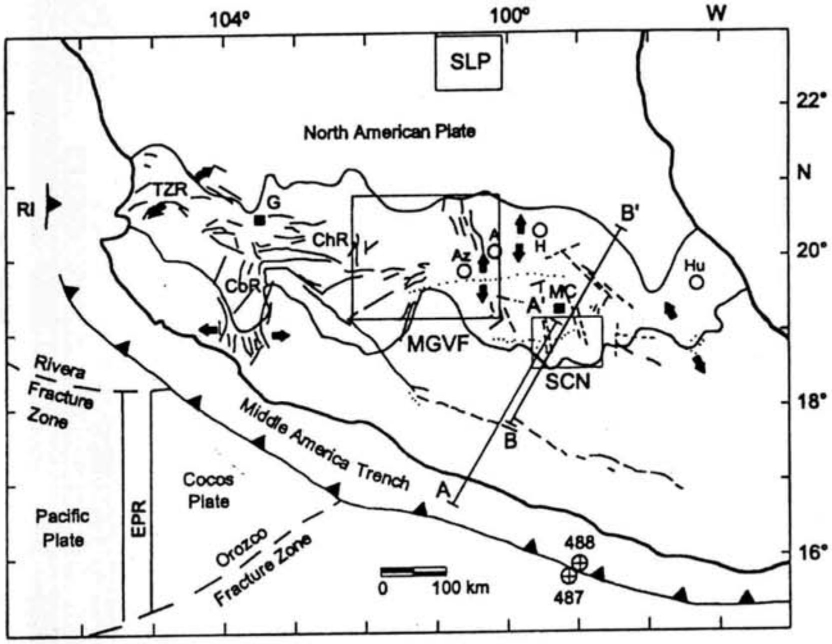

FIG. 2. The tectonic setting of the Mexican Volcanic Belt (modified after Verma, 2000a). Abbreviations: MC = Mexico City; G = Guadalajara; RI = Rivera Plate; EPR = East Pacific Rise. Thick arrows represent maximum horizontal tensional stress vectors, and continuous, dotted, and broken lines show regional fractures and faults (after Singh and Pardo, 1993). Important calderas: Az = Los Azufres; H = Huichapan; A = Amealco; Hu = Los Humeros. Other abbreviations: TZR = Tepic-Zacoalco rift; CoR = Colima rift; ChR = Chapala rift; SCN = Sierra Chichinautzin volcanic field; MGVF = Michoacán-Guanajuato Volcanic Field; SLP = San Luis Potosí area. Crossed circles depict the IPOD-DSDP Leg 66 Sites 487 and 488 (after Verma, 1999). A–A' and B–B' are locations of two seismic profiles across the MVB (see Fig. 3).

Problems with the Subduction Explanation

Numerous contradictions exist to the widely held belief that the MVB is a typical, subduction-related magmatic arc, and have been recently summarized by Márquez et al. (1999a, 1999c).

1. The MVB runs E-W, is not parallel to the trench, but makes an an angle of 15–20° to it (Molnar and Sykes, 1969); thus, while the western end of the MVB is about 150 km from the trench, the eastern end is 400 km away. Ruff and Kanamori (1980) argued that the preferred trajectories of subducting slabs may be related to the particular combinations of lithospheric ages and convergence rates, and thus may affect the Benioff zone geometry. Burbach et al. (1984), using teleseismic data to determine the large-scale structure of the subducted part of the Cocos plate, concluded that the plate consists of three major segments. However, the structure of the segment corresponding to the MVB is not well-defined. Suárez and Singh (1986) argued that the greater distance of the eastern part of the MVB from the trench reflects a progressively shallower subduction angle for the Cocos plate eastwards, which we consider a model-dependent modification of doubtful validity, especially in the absence of clear seismic imaging of the plate (see below).

2. Lomnitz (1982) claimed to have found direct seismic evidence for the presence of a subducted plate under southern Mexico. However, the Wadati-Benioff zone beneath the belt is seismically very poorly defined, and is completely absent beneath its central part (e.g., Singh and Pardo, 1993; Pardo and Suárez, 1995; Fig. 3A). The seismicity throughout the MVB is shallower than 60 km, and most earthquake focii are less than 20 km deep and are extensional (e.g., Suter et al., 1992, 1995; Singh and Pardo, 1993). Also, most of the MVB volcanoes are located more than 50 km beyond the terminus of the inclined seismic zone, which is the end of the down-going slab as defined seismically (Nixon, 1982; Fig. 3A).

3. The disappearance of earthquake focii 50 km before the volcanic front in the MVB may be argued as indicative of aseismic subduction (Demant, 1978), similar to the proposed aseismic subduction

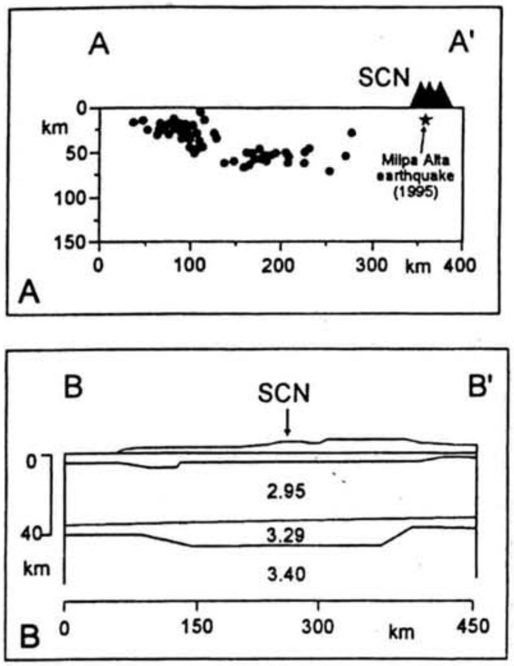

FIG. 3. A. Seismicity profile along the traverse A–A' (marked in Fig. 2) and the volcanic front (solid triangles). Simplified after Pardo and Suárez (1995). B. Crustal model for gravity profile along the traverse B–B' (marked in Fig. 2). Numbers indicate densities in g/cm^3. Simplified after Molina-Garza and Urrutia-Fucugauchi (1993).

of the Juan de Fuca plate under northwestern America (Weaver and Michaelson, 1985). In the present case, however, following the proposal of Defant et al. (1991), the Cocos plate would be expected to undergo melting and generate the silicic magmas of the central MVB. Paradoxically, there is no geochemical evidence for any role of the subducted Cocos plate in the petrogenesis of either the mafic magmas (Verma, 2000a) or the evolved magmas (Verma, 1999) at the volcanic front in the central part of the MVB (the Sierra Chichinautzin area, Fig. 2). Regarding the eastern part of the MVB, Verma (1983) has indicated that some magmas in the eastern MVB (e.g., from the Los Humeros caldera, Fig. 2) were generated in the upper mantle with very little, if any, contribution from the subducted oceanic crust, oceanic sediments, or continental crust.

4. A pronounced gravity low is observed over the entire MVB, and especially beneath its central part, which suggests the existence of an "anomalous," low-density (3.29 g/cm^3), low-velocity (V_p = 7.6 km/s) mantle layer at the base of the crust (40 km depth) (Molina-Garza and Urrutia-Fucugauchi, 1993; Fig. 3B). This is in marked contrast to Benioff zones such as the Aleutians, Japan, the Phillippines, or Central America (Gill, 1981).

5. A tensional regime, but not a compressional one, exists throughout the MVB, as known from, for example, studies by the UNAM and CENAPRED Seismology Group (1995), according to which the best-recorded event in the MVB, the Milpa Alta event (near Mexico City) of January 21, 1995 (M_c = 3.9, focal depth about 12 km), was a normal-faulting event with a significant (50%) strike-slip component.

6. OIB-like volcanic rocks, atypical of arc volcanism, are found throughout the MVB, have erupted throughout its history, and are voluminous. Thus, although much of the MVB volcanism is andesitic, a considerable volume is not, and most magmatism along both the eastern and western parts is alkaline (e.g., Luhr et al., 1985; Negendank et al., 1985; Cebull and Shurbet, 1987; Verma and Nelson, 1989; Luhr, 1997; Márquez et al., 1999a).

Problems with the Mantle Plume Explanation

Moore et al. (1994) were the first to invoke a mantle plume to explain OIB-type magmatism in the western MVB. More recently, Márquez et al. (1999a) emphasized the large volumes of OIB-type magmatism encountered throughout the belt, and extended the mantle plume model to the entire MVB, proposing that a plume could have upwelled at this active margin and caused the rift-rift-rift triple junction near Guadalajara (Fig. 2) as well. The three arms of this triple junction are the NW-trending Tepic-Zacoalco rift, the N-S–trending Colima rift, and the E-W–trending Chapala rift, which continues farther eastward as the main MVB (Fig. 2).

Although both the Guadalajara triple junction and voluminous OIB-type magmatism are real features, we do not think that a mantle plume is either necessary or appropriate to explain the same, for the following reasons.

1. OIB-type geochemistry is not evidence for mantle plumes but simply for enriched mantle sources, which could well lie in the shallow mantle (e.g., Bailey, 1983; Sheth, 1999a, 1999b; Verma, 2000b). We discuss this in detail below.

2. Most importantly, whether mantle plumes are real or not, and whether oceanic-island basalts themselves are derived from mantle plumes, are matters of debate. Thus, while most authors link

OIBs to mantle plumes, there is growing evidence that OIBs come from shallow enriched regions of the oceanic mantle, and the plume model is not consistent with data available for either OIBs or continental or oceanic flood basalt provinces (e.g., Smith, 1993; Anderson, 1999; Sheth, 1999a, 1999b; Smith and Lewis, 1999a, 1999b).

3. The broad regional uplift that a mantle plume is expected to produce in western Mexico is not observed (Ferrari and Rosas-Elguera, 1999). Márquez et al. (1999b) countered this objection with the argument that lateral spreading of low-density, unrooted plume material would avoid lithospheric uplift. In this case, one may ask how one would infer the existence of a plume at all (especially in the absence of geochemical requirements).

4. A mantle plume at the mouth of the Gulf of California has been widely hypothesized (e.g., Burke and Wilson, 1976; Crough and Jurdy, 1980), but Smith (1999) has shown that there is no geological, petrological, or geochemical evidence supporting it. It is unclear, however, whether the conjectured Gulf of California plume is the same as the one proposed by Moore et al. (1994) and Márquez et al. (1999a).

5. Márquez et al. (1999a) proposed a mantle plume as an "active" cause of the Guadalajara triple junction. The origin of the junction remains controversial. For example, Luhr et al. (1985) and Allan et al. (1991) argued that the extensional tectonics of these three grabens indicate active rifting of southwestern Mexico, which in turn is the result of an incipient eastward jump of the spreading East Pacific Rise beneath the continent. On the contrary, Rosas-Elguera et al. (1996) argued that Pliocene–Quaternary extensional faulting being experienced by these rifts is a basement-controlled intraplate deformation related to plate boundary forces, rather than to active continental rifting. In any case, the requirement for a plume is obscure.

Discussion

Having presented what we consider serious contradictions to both the subduction and mantle-plume explanations, we pursue below our interpretation that the MVB is a continental rift–like structure unrelated to either subduction or a mantle plume. First we discuss geological and geophysical data supporting our contention, and then present our interpretations of the calc-alkaline and alkaline geochemistry.

General geology and geophysics

The MVB is underlain by Precambrian and Paleozoic metamorphic rocks and Mesozoic granitic and granodioritic intrusions, in addition to Cretaceous sedimentary rocks of the Sierra Madre Oriental fold belt (SMOr, Fig. 1) in the east, and the Oligocene–Miocene rhyolitic and ignimbritic lavas of the Sierra Madre Occidental (SMO, Fig. 1) in the west (e.g., Verma, 1985; Pasquare et al., 1987; Ruiz et al., 1988; Rosas-Elguera et al., 1996). According to some workers, the MVB is the southernmost of three linear, E-W–trending fracture zones crossing southern Mexico, delineated on the basis of interpreted offsets of Precambrian and Paleozoic basement rocks and geophysical data (De Cserna, 1960), and on the basis of offsets of belts of Mesozoic batholithic rocks and mineral deposits (Gastil and Jensky, 1973). De Cserna (1960, 1976) interpreted these zones as left-lateral strike-slip faults and proposed that they developed in Permian to Triassic time. Gastil and Jensky (1973) proposed that the southernmost zone (i.e., the present MVB) experienced two events of right-lateral strike-slip faulting, the first at the end of the Mesozoic and the other in the Miocene or Pliocene. Pal and Urrutia-Fucugauchi (1977) designated this zone as a Late Cretaceous to Early Cenozoic suture between a portion of the Farallon plate and the continent to the north.

Thus, all these workers, and Cebull and Shurbet (1987), have related the orientation of the MVB to an early-formed, E-W–trending zone of weakness. Regarding why volcanism along the MVB was delayed until about Miocene time, when its underlying fracture zone was as old as Mesozoic or late Paleozoic, Cebull and Shurbet (1987) argued that the initiation of MVB volcanism was associated with extensional tectonism to the north of it, reflected in the development of the Gulf of California and faulting in the Basin and Range province of the western United States, roughly in middle Miocene time (Larson et al., 1968; Karig and Jensky, 1972).

The MVB itself includes six parallel, E-W–trending graben structures, which show active N-S extension and strike-slip faulting that have continued from the Miocene to the present (Márquez et al., 1999a). As noted, Molina-Garza and Urrutia-Fucugauchi (1993) presented a N-S gravimetric profile across the Sierra Chichinautzin area of the central MVB, with a regional anomaly linked to a low-density and low-velocity anomalous mantle layer at a depth of about 40 km. Such anomalous mantle cushions are most typical of areas of continental extension and rifting. Examples abound: the Rio Grande rift of the United States (Sinno et al., 1986); Gulf of California (Couch et al., 1991), the East African rift (Braile et al., 1995), and the Cambay rift of the Deccan volcanic province, India (Mahadevan, 1994; Kennett and Widiyantoro, 1999). Besides the anomalous mantle cushion, the shallow seismicity (Suter et al., 1992; Singh and Pardo, 1993; UNAM and CENAPRED Seismology Group, 1995), and the high heat flow in the MVB (Ziagos et al., 1995), all attest to the view that it is a rift-like structure experiencing active extension. There is a pronounced thinning of the crust beneath the western MVB (Wallace and Carmichael, 1999), and it is not surprising that primitive (high-MgO) volcanic rocks of diverse types are encountered in the western MVB (Luhr, 1997), their ascent and eruption having been facilitated by the thinned crust.

The meaning of calc-alkaline geochemistry

The dominant calc-alkaline chemistry of the MVB magmas usually has been cited as strong evidence for a subduction origin (e.g., Nixon et al., 1987). However, calc-alkaline lavas have been erupting in the U. S. Basin and Range province (Gans et al., 1989); the Gulf of California (Martin-Barajas et al., 1995; Paz Moreno and Demant, 1999), and the Rio Grande rift (McMillan and Dungan, 1986), all of which are undisputed areas of active continental extension. Therefore, if calc-alkaline magmas are profuse in continental rifts, then not only is calc-alkaline geochemistry no evidence for subduction, but it is also a question of whether calc-alkalinity or alkalinity of magmatic products is a useful indicator of tectonic setting at all.

We believe that the calc-alkaline or alkaline chemistry should more appropriately be related to *mantle sources and petrogenetic processes* than to tectonic setting. Thus, in our opinion, the calc-alkaline chemistry of MVB magmas simply reflects the process of crustal contamination undergone by mantle-derived magmas, and their fractionation mechanisms (i.e., early fractionation of clinopyroxene and olivine, as demonstrated by Rogers and Hawkesworth, 1999), rather than subduction. In fact, magma mixing between basaltic and dacitic magmas seems to have been a dominant magmatic process in volcanoes like Popocatépetl and Iztaccíhuatl (e.g., Robin, 1984; Nixon, 1988). In the Sierra Chichinautzin area of the central part of the MVB (Fig. 2), basaltic magmas appear to have been derived from the hot, upwelling mantle, and felsic magmas from melting of the granulitic lower crust (Verma, 1999). This magma mixing and crustal contamination are not only identifiable from the geochemical data, but there is ample petrographic evidence for the same (e.g., Kudo et al., 1985 on Pico de Orizaba [Citlaltépetl]; Márquez et al., 1999c on Sierra Chichinautzin; see also Robin, 1982b; Robin and Cantagrel, 1982). Indeed, some older Miocene rhyolites in the MVB are interpreted as crustal melts (Verma, 2000c), and combined crustal contamination and fractional crystallization processes have been invoked to explain the geochemical and isotopic data from several volcanic centers of the MVB (e.g., Verma and Nelson, 1989; Verma et al., 1991; Verma, 2000b, 2000c). It is well known that the volcano Paricutín contains granitic xenoliths, and crustal contamination is well demonstrated for Paricutín calc-alkaline lavas based on major and trace elements and isotopic ratios (McBirney et al., 1987), and based on B/Be ratios (Hochstaedter et al., 1996).

Melting of continental crust is also likely in the volcanism of the SMO province (Fig. 1) of western Mexico, which ended at about the time volcanism in the MVB began, and forms the largest continuous rhyolite province in the world (about 200,000 km^2) erupted in the short time interval between ~34 and 27 Ma (Lanphere et al., 1980). The traditional explanation for the SMO (e.g., Atwater and Molnar, 1973; Cameron et al., 1980) is that it is a mid-Tertiary magmatic arc associated with the subduction of the Farallon plate beneath the North American plate. While workers like Lanphere et al. (1980) argued for a purely mantle origin for some of these volcanics, Verma (1984) interpreted them in terms of mixing between mantle magmas and middle or upper continental crust. Ruiz et al. (1988) have argued, based on Nd-Sr isotope data for SMO volcanics, and for Paleozoic and Precambrian lower crustal xenoliths underlying the SMO, that the SMO silicic ignimbrites could comprise up to 100% lower crustal material. We maintain, therefore, that the calc-alkaline chemistry of MVB magmas is not, in itself, evidence for subduction.

We do not deny the fact that many lavas in real arcs are calc-alkaline, with tholeiitic lavas dominating the volcanic front and alkaline lavas dominating the back-arc regions. But we point out that the calc-alkaline chemistry of these true arc lavas is itself determined by the contamination of mantle-derived mafic magmas by overlying, often granitic, continental crust that usually characterizes such arcs as

Japan and the Andes (James et al., 1976; Aramaki and Ui, 1982). Thus, according to Aramaki and Ui, crustal contamination coupled with fractional crystallization is largely responsible for the predominance of andesite-dacite-rhyolite of the calc-alkaline series, most pronounced in southwest Japan. Calc-alkaline chemistry is therefore simply indicative of petrogenetic processes, and by itself is no evidence for subduction. Since the same magmatic-petrogenetic processes operate in arcs and in rifts, calc-alkaline magmatism is not incompatible with rift settings. The argument of Márquez et al. (1999c), that calc-alkaline volcanism cannot be explained by fracture-zone models, therefore is also incorrect. Márquez et al. (1999b) have corrected this error by pointing out that a volcanic suite cannot be characterized as subduction-related merely because it has calc-alkaline characteristics or because it includes andesites or dacites (e.g., Glazner, 1990). Calc-alkaline volcanism reflects petrogenetic processes, and is not useful for inferring the tectonic setting.

The case involving Nb anomalies is similar. Lavas with negative Nb anomalies are termed by many as subduction-related (e.g., Ferrari and Rosas-Elguera, 1999; Ferrari et al., 2000), but we suggest that the negative Nb anomalies, like calc-alkaline geochemistry, usually indicate contamination of mantle-derived magmas by granitic or granulitic continental crust depleted in Nb and similar high-field-strength elements (e.g., Ta, Ti). It is true that many arc lavas are characterized by negative Nb anomalies. But their Nb anomalies, like their calc-alkaline chemistry, could be the result of contamination of mantle-derived magmas by the granitic continental crust that forms the basement of the arcs (Wilson, 1989). Nb anomalies are not proof of subduction. In fact, if the SMO rhyolite ignimbrites underlie the western part of the MVB (Ferrari et al., 1999), arguments for a subduction origin of the MVB based on negative Nb anomalies in them (e.g., Ferrari et al., 2000) are in fact contradicted, inasmuch as the SMO volcanics provide an excellent Nb-poor, large-ion-lithophile-rich and light-rare-earth-element-rich contaminant for the MVB volcanics.

Moreover, negative Nb anomalies are not restricted to arc volcanics. In western India, the Deccan Traps form a large, rift-related flood basalt province. Lavas of the Bushe Formation of the Deccan show pronounced negative Nb anomalies in their mantle-normalized multielement patterns (e.g., Mahoney, 1988; Chandrasekharam et al., 1999; Mahoney et al., 2000). These are indicative merely of contamination of the basalts by the ancient (Precambrian or Proterozoic), granitic or granulitic, Indian basement crust; there is no argument on this point among Deccan specialists. It would be absurd to say that the Nb anomalies in the Bushe Formation of the Deccan Traps are indicative of subduction. Similar negative Nb anomalies are known from the Jurassic Central Atlantic tholeiites (Márquez et al., 1999b), and from the northern Gulf of California (Paz Moreno and Demant, 1999).

The meaning of OIB-type geochemistry

In nature, there are alkaline magmas and alkaline magmas, in the sense that an alkaline magma may owe its alkalinity to an enriched mantle source, to low degrees of melting of a mantle source, to pronounced differentiation from a more mafic magma, or, in fact, to crustal contamination (Mahoney et al., 1985). OIBs usually possess an enrichment in incompatible elements such as Rb, Ba, K, Nb, Ta, and Ti relative to mid-oceanic ridge basalts (MORB), and as a consequence of their higher Rb contents, for example, develop higher-than-MORB $^{87}Sr/^{86}Sr$ ratios. The elements Rb, Ba, K etc. are the so-called large-ion-lithophile elements (with large size/charge ratios), while the elements Nb, Ta, Ti etc. are the so-called high-field-strength elements (with small size/charge ratios). Many OIBs that are the products of low degrees of melting are characterized by large concentrations of incompatible elements such as Nb. Because of this, positive Nb spikes and/or absence of negative Nb anomalies, for example, in mantle-normalized diagrams of basalts are considered to be an OIB-type characteristic. In turn, based on the widely accepted view that OIBs come from mantle plumes, lavas with alkaline chemistry (high incompatible element abundances) or higher Sr isotopic ratios relative to MORB, are attributed to mantle plumes (e.g., Moore et al., 1994; Márquez et al., 1999a). However: (1) it is doubtful if mantle plumes exist at all (Anderson, 1999; Sheth, 1999a, 1999b; Smith and Lewis, 1999a, 1999b); and (2) the OIB-type geochemical characteristics can equally well be explained by shallow-level derivation from enriched mantle sources (Smith, 1993; Sheth, 1999a), as explained below.

Ionov and Hofmann (1995) have shown that amphibole is a very important host mineral for Nb and Ta in mantle xenoliths in alkali basalts, and probably in the shallow peridotite upper mantle in general. Amphibole has higher Nb, Ta, and Ti contents than coexisting mica. In K-enriched mantle rocks, phlogopite can also be an important host mineral for Nb and Ta. According to Ionov and Hofmann (1995), fluids and melts contributed by subducting slabs rise through the mantle wedge, and open-system crystallization of amphibole and phlogopite occurs. These minerals retain Nb and Ta, so island-arc lavas are depleted in Nb and Ta. The residual fluids carry the LILE. Another possible reason for these elemental depletions is the interaction of ascending magmas with mantle olivine (Kelemen et al., 1992). And, of course, still another well-known reason for the depletion of arc volcanics in these elements is crustal contamination, because the continental crust itself is depleted in HFSE relative to LILE.

In a synthesis of the overall evidence against the mantle-plume model in general and as applied to the Deccan flood basalt province of India in particular, Sheth (1999b) argued that the high abundances of Nb in OIBs could indicate either low degrees of melting, or an enriched, metasomatized, Nb-rich source (with phlogopite and/or amphibole) in the shallow oceanic mantle. The sources must lie in the shallow mantle, because amphibole breaks down at a depth of about 80 km, although phlogopite is stable up to 250 km depth (Olafsson and Eggler, 1983). In fact, phlogopite actually has been argued to be the most characteristic mineral of the continental lithospheric mantle and shallow-level enrichment processes (Lightfoot and Hawkesworth, 1988; Hawkesworth et al., 1990). Sheth (1999b) also pointed out that the evidence for phlogopite and amphibole in the mantle sources of Hawaiian pre-shield volcanoes and the Comores hotspot volcanics (Class and Goldstein, 1997) is indicative of shallow, enriched, volatile-rich regions in the oceanic mantle and not of mantle plumes. Mantle plumes are supposed to be hotter than normal (e.g., Campbell and Griffiths, 1990). Ironically, in many OIB suites conventionally related to plumes, the amphibole and phlogopite are required to be *residual* phases, implying low temperatures of melting, far lower than even the coldest mantle plume conceivable (Smith and Lewis, 1999a).

Crustal contamination in the MVB: Actual examples

We elaborate below on our thesis that crustal contamination is widespread in the MVB, using multielement data (major- and trace-element data, including the rare-earth elements) and Nd-Sr isotopic data. Figures 4A–4D show MORB-normalized multi-element patterns for numerous, mostly mafic, volcanics from throughout the MVB.

Figure 4A shows MORB-normalized multi-element patterns for lavas from Ceboruco volcano and the Sanganguey area in the Tepic-Zacoalco rift (Verma and Nelson, 1989). SN-86 is a calc-alkaline basalt that shows a major peak at Ba and a corresponding trough at Nb, features typical of crustally contaminated melts. On the other hand, SN-66 and JH-109 are both alkali basalts and do not display negative Nb anomalies. Sample Jor-44 in Figure 4B is a calc-alkaline basalt from the Jorullo volcano in the Michoacan-Guanahuato volcanic field (MGVF; Luhr and Carmichael, 1985a), and shows similar features. Jor-46 is a lamprophyre from the MGVF with a pronounced Ba peak and a conspicuous Nb trough. Luhr (1997) described the MGVF lamprophyres as the "essence of subduction-zone geochemistry."

Figure 4C shows more numerous patterns for lavas from the Sierra Chichinautzin (SCN) monogenetic volcanic field (Verma, 1999, 2000a): CHI06 is a basaltic andesite, CHI09 is an andesite, and CHI10 is a dacite. Verma has argued that the basaltic magmas of the SCN were derived from hot, upwelling mantle, and the felsic magmas from melting of the granulitic lower crust. These multi-element patterns exhibit signatures typical of crustal contamination (e.g., peaks at Ba and troughs at Nb and other HFS elements such as P and Ti). On the other hand, CHI04 is an SCN basaltic trachyandesite with alkaline affinities and lacks a Nb trough. Toc1 is an andesitic pumice forming a Popocatépetl lahar (Siebe et al., 1999) and shows a similar pattern to most SCN lavas.

Figure 4D shows multi-element patterns for lavas from the eastern part of the MVB. NT48, NH12, and NH26 are an alkali basalt, basalt, and andesite, respectively, from the Citlaltépetl–Cofre de Perote area (Besch et al., 1995), with pronounced peaks at Ba and pronounced Nb troughs. CH56 and CH52a are a basaltic trachyandesite and a trachyte respectively, from Los Humeros (Verma, 2000b). CH52a in particular shows large Rb-Ba peaks and a small Nb trough, but major P-Ti troughs. Thus, overall, crustal contamination appears to have been a dominant process throughout the MVB, based on multi-element evidence.

We examine the evidence for crustal contamination further in Figure 5, using rare-earth-element

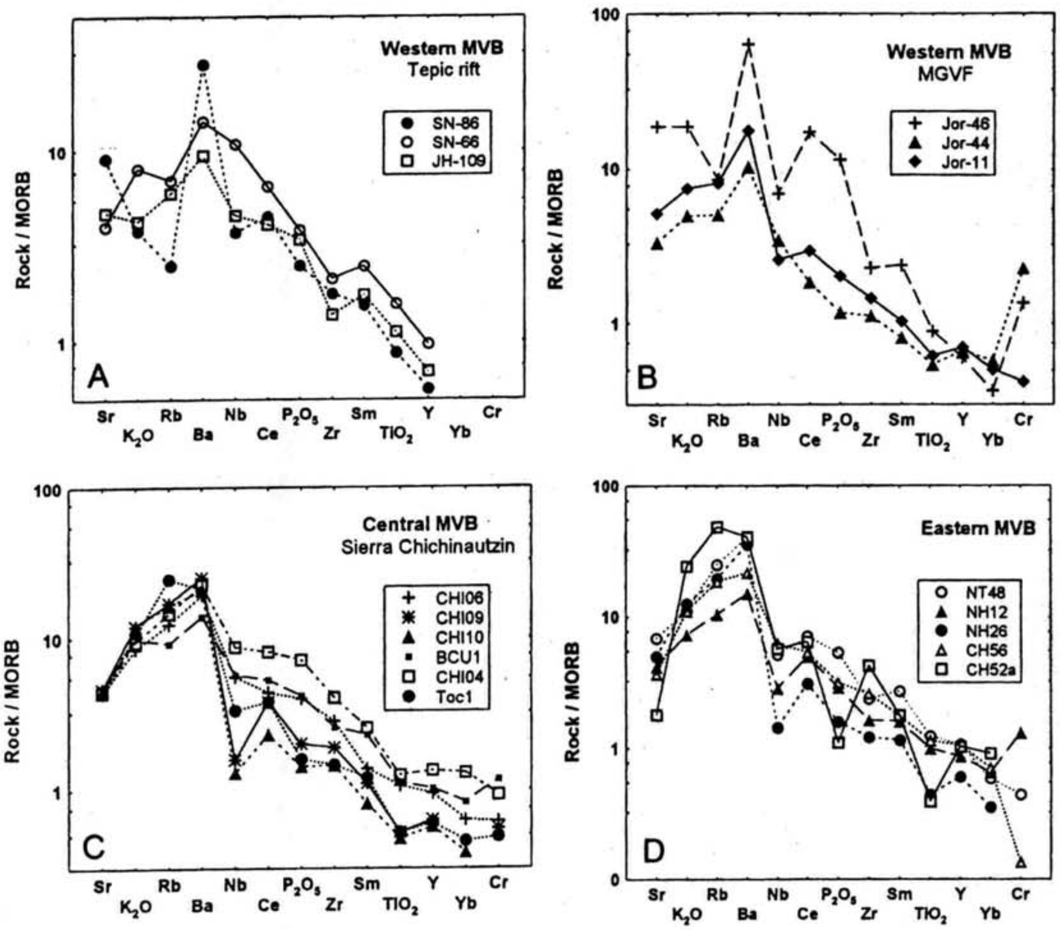

FIG. 4. A to D are MORB-normalized multi-element patterns of mafic rocks from the MVB. The MORB normalizing values are from Pearce (1982) and are in ppm unless otherwise specified: Sr = 120; K_2O = 0.15 wt%; Rb = 2; Ba = 20; Nb = 3.5; Ce = 10; P_2O_5 = 0.12 wt%; Zr = 90; Sm = 3.3; TiO_2 = 1.5 wt%; Y = 30; Yb = 3.4; Cr = 250. Sources of samples are as follows: SN-86, SN-66, JH-109 = Verma and Nelson (1989); Jor-46, Jor-44, Jor-11 = Luhr and Carmichael (1985a); CH106, CH109, CH110 = Verma (1999); BCU1, CH104 = Verma (2000a); Toc1 = Siebe et al. (1999); NT48, NH12, NH26 = Besch et al. (1995); CH56, CH52a = Verma (2000b). In C, Nb value is not available for Toc-1 but Ta value is, and the trough shown by the pattern of Toc-1 at Nb is actually a Ta trough. Normalizing value for Ta is 0.17 ppm (Pearce, 1982). See text for details.

(REE) data. Chondrite-normalized REE patterns for all samples plotted in Figures 5A to 5D exhibit enrichment in the light REE relative to the heavy REE by various degrees. The SiO_2 contents of these individual samples are also indicated, in addition to their REE patterns. An interesting feature observed from these plots is that the SiO_2 content and the LREE enrichment are not directly proportional to each other (i.e., samples with higher LREE enrichment are not necessarily high in SiO_2 content). In Figure 5A, Jor-46 is a lamprophyre with a trachybasaltic chemical composition, and is significantly enriched in the LREE but does not have particularly high SiO_2 (50.3 wt.%). If LREE enrichment were purely the result of greater degrees of fractionation, this would be accompanied by a corresponding increase in the SiO_2 values. These features seem to be related to the source characteristics, as explained in our proposed model below. The Popocatépetl andesitic pumices Toc-1, Ta-4Ap, and Ta-5p (Fig. 5B) are characterized by roughly the same SiO_2 values and LREE enrichments. Toc-3 is a dacitic pumice from Nevado de Toluca, characterized by substantially higher SiO_2 but similar LREE contents.

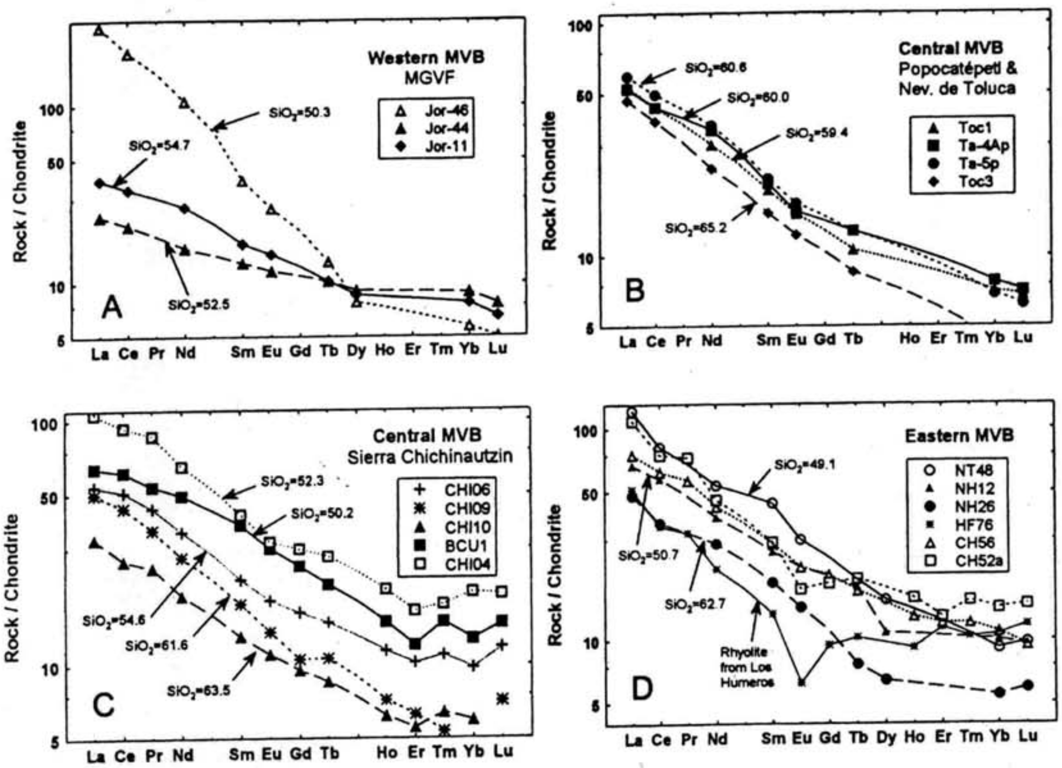

FIG. 5. A to D are chondrite-normalized REE patterns of (mostly) mafic rocks. Normalizing values are (in ppm): La = 0.329; Ce = 0.865; Pr = 0.112; Nd = 0.63; Sm = 0.203; Eu = 0.077; Gd = 0.276; Tb = 0.047; Dy = 0.343; Ho = 0.07; Er = 0.225; Tm = 0.03; Yb = 0.22; Lu = 0.0339 (after Haskin et al., 1968; Nakamura, 1974). Samples not appearing in Figure 4 are from the following sources: Ta-4Ap, Ta-5p, Toc-3 = Siebe et al. (1999). HF76 is a rhyolite from the Los Humeros caldera (Verma, 2000b). SiO_2 values are in wt% calculated on a dry basis. See text for details.

Figure 5C shows chondrite-normalized REE patterns for mafic and evolved volcanics from the Sierra Chichinautzin (Verma, 1999). The most notable feature of this plot is that the evolved lavas with SiO_2 values >60 wt% are less enriched in the LREE relative to the mafic rocks that have SiO_2 values around 50 wt%. Had these evolved rocks been derived by simple fractionation of these mafic lavas, they would have possessed higher LREE enrichment than the mafic lavas (and Eu anomalies concomitant on plagioclase fractionation as well). However, their consistently lower REE patterns, and absence of Eu anomalies in them, indicate that they were derived by melting of a LREE-depleted, possibly mafic granulite source in the lower crust, as argued by Verma (1999). Similar features can be seen in Figure 5D, which shows data for eastern MVB lavas. The rhyolite from Los Humeros (Verma, 2000b) shows a pronounced Eu trough, indicative of plagioclase fractionation from its parent magma. Similar Eu troughs are shown by rhyolite ignimbrites of the Huichapan caldera (Verma, 2000c).

Figures 6A to 6C present the Sr-Nd isotopic compositions of various MVB volcanics (all rocks are geologically recent eruptives). MVB lavas plot along the "mantle array," with the mafic lower crust (MLC) composition as the enriched end member of the mixing array. The point marked MLC is the average of eight analyses of granulite xenoliths from the San Luis Potosí area, analyzed by Schaaf et al. (1994). The field shown by dotted lines covers the entire compositional range of these granulite xenoliths. As shown by Verma (1999), evolved rocks of the Sierra Chichinautzin area plot almost completely within this xenolith compositional field, indicating that they may have been derived wholly from melting of the lower crust beneath the SCN. For lavas outside of the SCN, such as Popocatépetl and Nevado de Toluca, MLC remains a contaminant. The curve above the MVB array shows the compositions calculated by Verma (2000a) for various amounts of mix-

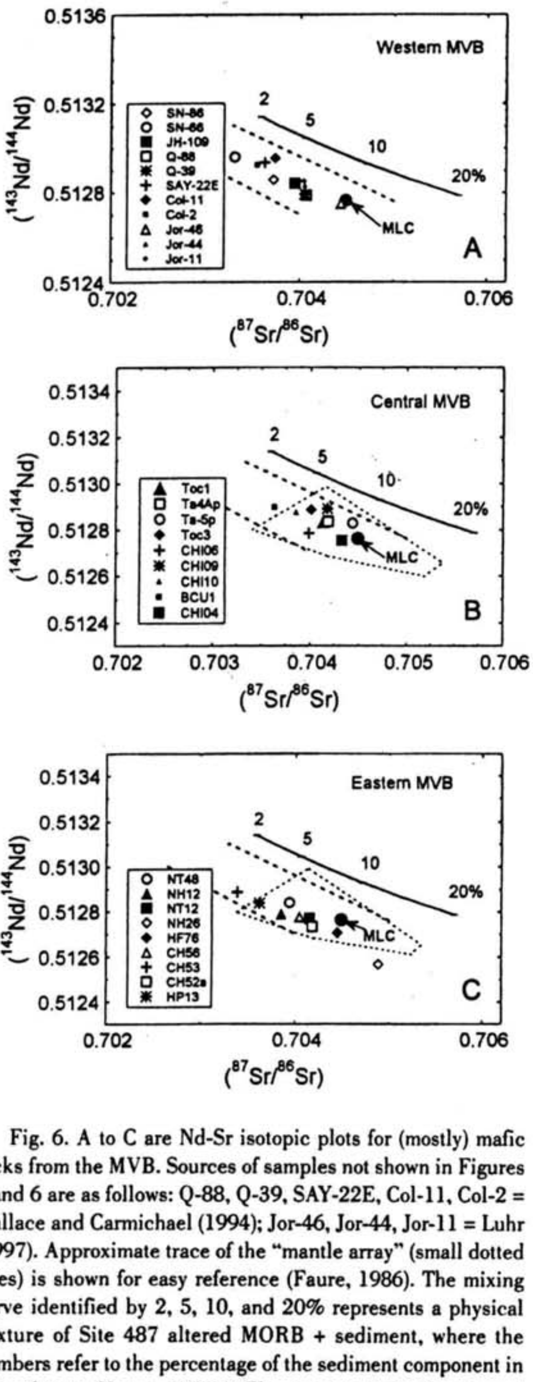

Fig. 6. A to C are Nd-Sr isotopic plots for (mostly) mafic rocks from the MVB. Sources of samples not shown in Figures 5 and 6 are as follows: Q-88, Q-39, SAY-22E, Col-11, Col-2 = Wallace and Carmichael (1994); Jor-46, Jor-44, Jor-11 = Luhr (1997). Approximate trace of the "mantle array" (small dotted lines) is shown for easy reference (Faure, 1986). The mixing curve identified by 2, 5, 10, and 20% represents a physical mixture of Site 487 altered MORB + sediment, where the numbers refer to the percentage of the sediment component in this mixture (Verma, 2000a). The average mafic lower crust composition (solid circle marked MLC) based on eight analyses of mafic granulites from the San Luis Potosí area is also shown for easy reference (from Schaaf et al., 1994).

ing (2, 5, 10, and 20%) of sediment with altered basalt from the Cocos plate. The fact that this mixing line trends completely away from the main MVB array is a major contradiction for explanations that suggest the MVB to be a direct consequence of Cocos plate subduction.

A new proposal: A veined mantle source

For the MVB, Márquez et al. (1999a) discounted heterogeneous mantle wedge models advocated for the Cascades by Hughes (1990) and Leeman et al. (1990) with the argument that because OIB-type volcanism in the MVB is very similar to that in Hawaii, the Galapagos etc., it can be explained as the result of a plume (assuming that Hawaii and Galapagos are plume related, which we consider debatable). In our opinion, however, the heterogeneous mantle models are in essence correct.

We propose that the mantle beneath the MVB is heterogeneous and contains kilometer-scale domains of peridotite with veins of amphibole and/or phlogopite, and vein-free peridotite. The extensional faulting prevalent throughout the MVB generates magmas from both normal unveined peridotite and veined peridotite. Magmas derived from unveined peridotite rising up and becoming contaminated by the continental crust develop calc-alkaline characteristics, whereas magmas formed by melting of the veined peridotite develop alkaline, OIB-type characteristics. Inasmuch as they are already rich in incompatible elements, they are expected to escape severe contamination from the continental crust, which is additionally aided by their arguably faster rise through the crust; therefore, they retain their OIB-type geochemistry. Support for our argument can be found in the observations of Hochstaedter et al. (1996) that, while the MVB calc-alkaline rocks show high B/Be ratios (where high B is indicative of crustal influence), none of the MVB alkaline rocks show significant amounts of B. In our interpretation, both calc-alkaline and alkaline compositions reflect characteristics of the mantle source and the petrogenetic processes, and do not indicate tectonic setting; i.e., neither does the calc-alkaline chemistry indicate or require subduction, nor does the alkaline volcanism necessitate a mantle plume. Besides, OIB-type volcanism is observed in restricted areas along active margins, including the Cascades, Central America, and the Andes, and we propose that it has a similar explanation in these areas. Our model is shown in Figure 7.

The source of the metasomatic fluids needs to be explained. If the MVB is sited along an ancient structure (e.g., De Cserna, 1960; Mooser, 1969;

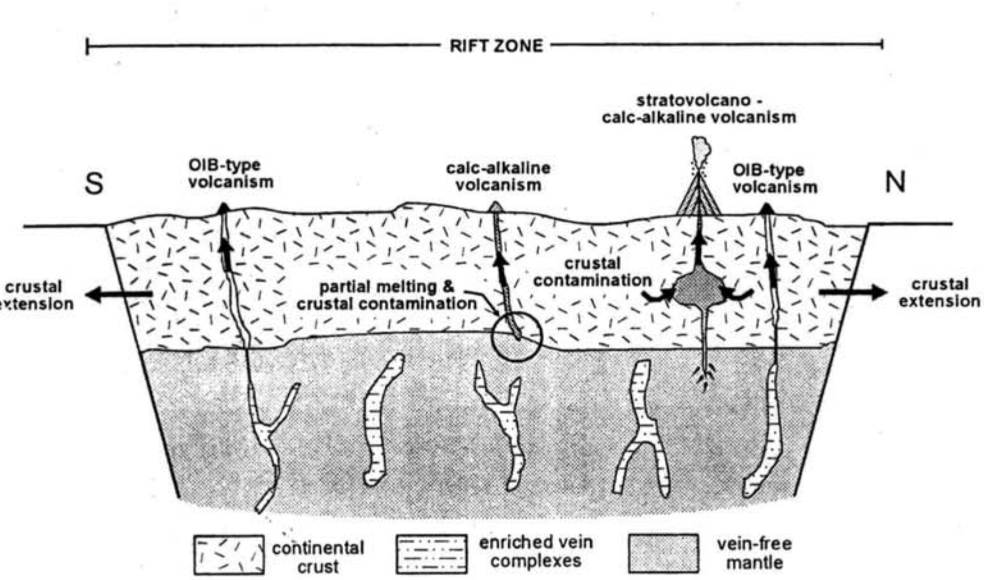

FIG. 7. Schematic diagram showing our proposed model of derivation of OIB-type magmas from metasomatically veined mantle, and calc-alkaline magmas from normal, vein-free mantle, followed by crustal contamination. See text for details.

Cebull and Shurbet, 1987), then it is possible to conceive, following Bailey (1983), mantle metasomatism being triggered "passively" by the formation of the lesion in the overlying plate (the proto-MVB) and the development of a shallow, metasomatized, enriched mantle below the MVB, due to volatiles in a large region of the underlying mantle reservoir being drained through this narrow crack in the plate. Under the present extensional conditions, these enriched sources are undergoing melting to produce OIB-type volcanism all along the belt. Again, as far as direct evidence for mantle metasomatism and a shallow, enriched mantle is concerned, metasomatized, upper-mantle xenoliths of hornblende peridotite are known from central Mexico (Blatter and Carmichael, 1998), and Luhr et al. (1989) have presented evidence for the presence of phlogopite in the mantle wedge beneath the MVB based on trace-element data for lamprophyres and basanites. Also, metasomatic phlogopite and amphibole would be relatively rich in Ba-K-Sr compared to B-Cs-U (Ionov and Hofmann, 1995; Hochstaedter et al., 1996). Therefore, if the MVB alkaline magmas were deriving from such metasomatized mantle (our argument), they would be expected to be poor in B, which they in fact are (Hochstaedter et al., 1996).

In addition, there are reasons to doubt the usual (subduction) explanation as the source of the metasomatic fluids. While the lack of a well-defined Benioff zone beneath the MVB has been argued as evidence that the descending slab is hot, most of the fluids are expected to be released beneath the forearc region itself, well in front of the main volcanic front (Hochstaedter et al., 1996). These workers found, however, that the MVB appears not to be dry, but to be wet, at least at the volcanic front. We think that more diversified thinking—beyond subduction (and plumes)—is necessary if we are to correctly decipher the ultimate origin and tectonic setting of the MVB. Not only do we not see any evidence for a subduction origin of the MVB, but we feel that much of the current, confused literature with several ad hoc speculations (e.g., fluid movement and convection in the mantle wedge) is a consequence of forcing the MVB to be compatible with Cocos plate subduction.

Luhr and Carmichael (1985b) have described contemporaneous eruptions of calc-alkaline and alkaline magmas along the volcanic front in two separate areas within the western MVB (the Colima graben and the Michoacán-Guanajuato volcanic field, Fig. 2). Luhr and Carmichael were unable to explain these two contrasting magma suites by any simple mechanism. Indeed, these volcanics are impossible to explain with the thesis that they are the result of subduction and a mantle plume operating together. On the other hand, we suggest that they can be very well explained by our model involving a mantle source containing enriched, metasomatic veins on the scale of kilometers. The normal, unveined peridotite wall rock produces calc-alkaline magmas by melting and subsequent crustal contamination, and veined peridotite produces relatively low volume, OIB-type alkaline magmatism with a large contribution from the veins. The close association in both space and time of the calc-alkaline and alkaline magmatism in the MVB can be easily explained with this model. We consider the Luhr and Carmichael (1985b) study as strong evidence of relatively small scale, local, magmatic processes.

Conclusions

Based on geological, geophysical, and geochemical data, we conclude that the Mexican Volcanic Belt is related neither to subduction of the Cocos plate under the North American plate, nor to a mantle plume. Calc-alkaline or alkaline geochemistry of magmas is not useful to infer tectonic setting but reflects source parameters and petrogenetic processes. For the MVB, calc-alkaline geochemistry suggests crustal contamination, and the OIB-like geochemistry suggests an enriched mantle source. The MVB is an area of active extensional deformation; a heterogeneous mantle beneath the MVB made up of normal mantle and metasomatic, enriched veins, can explain well the close association in space and time of calc-alkaline and alkaline volcanism throughout the belt. It is only some misconceptions and naive tectonic interpretations of geochemical data, too often of questionable quality (see Verma, 1997; Márquez et al., 1999b), that are responsible for the current confused state of the voluminous literature pertaining to the ultimate origin of the MVB.

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REFERENCES

Allan, J. F., Nelson, S. A., Luhr, J. F., Carmichael, I. S. E., Wopat, M., and Wallace, P. J., 1991, Pliocene-Holocene rifting and associated volcanism in southwest Mexico: An exotic terrane in the making, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular province of the Californias: Amer. Assoc. Petrol. Geol. Mem. 47, p. 425–445.

Anderson, D. L., 1999, A theory of the Earth: Hutton and Humpty-Dumpty and Holmes, *in* Craig, G. Y., and Hull, J. H., eds., James Hutton – present and future: London: Geol. Soc. Spec. Publ. 150, p. 13–35.

Aramaki, S., and Ui, T., 1982, Japan, *in* Thorpe, R. S., ed., Andesites: Chichester, UK, John Wiley, p. 259–292.

Atwater, T., and Molnar, P., 1973, Relative motion of the Pacific and North American plates deduced from seafloor spreading in the Atlantic, Indian, and South Pacific Oceans: Stanford Univ. Publ. Geol. Sci., v. 13, p. 136–140.

Bailey, D. K., 1983, The chemical and thermal evolution of rifts: Tectonophysics, v. 94, p. 585–597.

Besch, T., Verma, S. P., Kramm, U., Negendank, J. F. W., Tobschall, H. J., and Emmermann, R., 1995, Assimilation of sialic crustal material by volcanics of the easternmost extension of the Trans-Mexican Volcanic Belt—evidence from Sr and Nd isotopes: Geofis. Int., v. 34, p. 263–281.

Blatter, D., and Carmichael, I. S. E., 1998, Hornblende peridotite xenoliths from central Mexico reveal the highly oxidized nature of subarc upper mantle: Geology, v. 26, p. 1035–1038.

Braile, L. W., Keller, G. R., Wendlandt, R. F., Morgan, P., and Kahn, M. A., 1995, The East African rift system, *in* Olsen, K. H., ed., Continental rifts: Evolution, structure, tectonics: Amsterdam: Elsevier, Developments in Geotectonics 25, p. 213–231.

Burbach, G. V., Frohlich, C., Pennington, W. D., and Matsumoto, T., 1984, Seismicity and tectonics of the subducted Cocos plate: Jour. Geophys. Res., v. 89, p. 7719–7735.

Burke, K. C., and Wilson, J. T., 1976, Hot spots on the Earth's surface: Sci. Amer., v. 235, p. 46–57.

Cameron, K. L., Cameron, M., Bagby, W. C., Moll, E. J., and Drake, R. E., 1980, Petrologic characteristics of mid-Tertiary volcanic suites, Chihuahua, Mexico: Geology, v. 8, p. 87–91.

Campbell, I. H., and Griffiths, R. W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth Planet. Sci. Lett., v. 99, p. 79–93.

Cebull, S. E., and Shurbet, D. H., 1987, Mexican volcanic belt: An intraplate transform?, *in* Verma, S. P., ed., Mexican Volcanic Belt: Geofis. Int., v. 26, p. 1–13.

Chandrasekharam, D., Mahoney, J. J., Sheth, H. C., and Duncan, R. A., 1999, Elemental and Nd-Sr-Pb isotope geochemistry of flows and dikes from the Tapi rift, Deccan flood basalt province, India, *in* Verma, S. P., ed., Rift-related volcanism: Geology, geochemistry, geophysics: Jour. Volcanol. Geotherm. Res., v. 93, p. 111–123.

Class, C., and Goldstein, S. L., 1997, Plume-lithosphere interactions in the ocean basins: Constraints from the source mineralogy: Earth Planet. Sci. Lett., v. 150, p. 245–260.

Couch, R. W., Ness, G. R., Sanchez-Zamora, O., Calderon-Riveroll, G., Doguin, P., Plawman, T., Coperude, S., Huehn, B., and Gumma, W., 1991, Gravity anomalies and crustal structure of the Gulf and Peninsular province of the Californias, *in* Dauphin, J. P., and Simoneit, B. R. T., eds., The Gulf and Peninsular province of the Californias: Amer. Assoc. Petrol. Geol. Mem. 47, p. 25–45.

Crough, S. T., and Jurdy, D. M., 1980, Subducted lithosphere, hotspots, and the geoid: Earth Planet. Sci. Lett., v. 44, p. 224–230.

Damon, P. E., and Montesinos, E., 1978, Late Cenozoic volcanism and metallogenesis over an active Benioff zone in Chiapas, Mexico: Arizona Geol. Soc. Dig., v. 11, p. 155–168.

Davies, G. A., 1980, Problems of intraplate extensional tectonics, western United States, *in* Continental tectonics: Washington, DC, Nat. Acad. Sci. Stud. Geophys., p. 84–95.

De Cserna, Z., 1960, Orogenesis in time and space in Mexico: Geol. Rund., v. 50, p. 595–605.

______, 1971, Precambrian sedimentation, tectonics, and magmatism in Mexico: Geol. Rundschau, v. 60, p. 1488–1513.

______, 1976, Mexico—geotectonics and mineral deposits, *in* Tectonics and mineral resources of southwestern North America. New Mex. Geol. Soc. Spec. Publ. 6, p. 18–25.

Defant, M. J., Richerson, P. M., De Boer, J. Z., Stewart, R. H., Maury, R. C., Bellon, H., Drummond, M. S., Feigenson, M. D., and Jackson, T. E., 1991, Dacite genesis via both slab melting and differentiation: Petrogenesis of La Yenuada volcanic complex, Panama: Jour. Petrol., v. 32, p. 1101–1142.

Demant, A., 1978, Características de eje neovolcanico Transmexicano y sus problemas de interpretación: Univ. Nac. Auton. Mex., Inst. Geol., Revista, v. 2, p. 172–187.

Demant, A., and Robin, C., 1975, Las fases del vulcanismo en México: Una síntesis en relación con la evolución geodinámica desde el Cretácico: Univ. Nac. Auton. Mex., Inst. Geol., Revista, v. 75, p. 813–860.

Faure, G., 1986, Principles of isotope geology, 2nd ed.: New York: John Wiley, 653 p.

Ferrari, L., Conticelli, S., Vaggelli, G., Petrone, C. M., and Manetti, P., 2000, Late Miocene volcanism and intra-arc tectonics during the early development of the Trans-Mexican Volcanic Belt, *in* Ferrari, L., Stock, J. M., and Urrutia-Fucugauchi, J., eds., The influence of plate interactions on the post-Laramide tectonics and magmatism in Mexico: Tectonophysics, v. 318, p. 161–185.

Ferrari, L., López-Martínez, M., Aguirre-Díaz, G., and Carrasco-Nuñez, G., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt: Geology, v. 27, p. 303–306.

Ferrari, L., and Rosas-Elguera, J., 1999, Comment on "Alkalic (ocean-island-type) and calc-alkalic volcanism in the Mexican volcanic belt: A case for plume-related magmatism and propagating rifting at an active margin?": Geology, v. 27, p. 1055–1056.

Gans, P. B., Mahood, G. A., and Scremer, E., 1989, Synextensional magmatism in the Basin and Range Province: A case study from the Eastern Great Basin: Geol. Soc. Amer. Spec. Pap. 233, 53 p.

Gastil, R. G., and Jensky, W., 1973, Evidence or strike-slip displacement beneath the Trans-Mexican Volcanic Belt: Stanford Univ. Publ. Geol. Sci., v. 13, p. 171–180.

Gill, J. B., 1981, Orogenic andesites and plate tectonics: Berlin: Springer-Verlag, 358 p.

Glazner, A. F., 1990, Recycling of continental crust in Miocene volcanic rocks from the Mojave block, southern California, *in* Anderson, J. L., ed., The nature and origin of Cordilleran magmatism. Geol. Soc. Amer. Mem. 174, p. 147–168.

Haskin, L. A., Haskin, M. A., Frey, F. A., and Wilderman, T. R., 1968, Relative and absolute terrestrial abundances of the rare-earths, *in* Ahrens, T. H., ed., Origin and distribution of the elements: Oxford: Pergamon Press, p. 889–912.

Hawkesworth, C. J., Kempton, P. D., Rogers, N. W., Ellam, R. M., and van Calsteren, P. W., 1990, Continental mantle lithosphere, and shallow level enrichment processes in the Earth's mantle: Earth Planet. Sci. Lett., v. 96, p. 256–268.

Hughes, S. S., 1990, Mafic magmatism and associated tectonism of the central High Cascade Range, Oregon: Jour. Geophys. Res., v. 95, p. 19,623–19,638.

Hochstaedter, A. G., Ryan, J. G., Luhr, J. F., and Hasenaka, T., 1996, On B/Be ratios in the Mexican Volcanic Belt: Geochim. et Cosmochim. Acta, v. 60, p. 613–628.

Ionov, D. A., and Hofmann, A. W., 1995, Nb-Ta-rich mantle amphiboles and micas: Implications for subduction-related metasomatic trace element fractionations: Earth Planet. Sci. Lett., v. 131, p. 341–356.

James, D. E., Brooks, C., and Cuyubama, A., 1976, Andean Cenozoic volcanism: Magma genesis in the light of strontium isotopic composition and trace element geochemistry: Geol. Soc. Amer. Bull., v. 87, p. 592–600.

Karig, D., and Jensky, W. A., 1972, Proto-Gulf of California: Earth Planet. Sci. Lett., v. 17, p. 169–174.

Kelemen, P. B., Dick, H. J. B., and Quick, J. E., 1992, Formation of harzburgite by pervasive melt/rock interaction in the upper mantle: Nature, v. 358, p. 635–641.

Kennett, B. L. N., and Widiyantoro, S., 1999, A low seismic wavespeed anomaly beneath northwestern India: A seismic signature of the Deccan plume?: Earth Planet. Sci. Lett., v. 165, p. 145–155.

Kudo, A. M., Jackson, M. E., and Husler, J. W., 1985, Phase chemistry of recent andesite, dacite, and rhyodacite of volcan Pico de Orizaba, Mexican Volcanic Belt: Evidence for xenolithic contamination, *in* Verma,

S. P., ed., Mexican Volcanic Belt—Part 2: Geofis. Int., v. 24, p. 679–689.

Lanphere, M. A., Cameron, K. L., and Cameron, M., 1980, Sr isotopic geochemistry of voluminous rhyolitic ignimbrites and related rocks, Batopilas area, western Mexico: Nature, v. 286, p. 594–596.

Larson, R. L., Menard, H. W., and Smith, S. M., 1968, Gulf of California: A result of ocean-floor spreading and transform faulting: Science, v. 161, p. 781–783.

Leeman, W. P., Smith, D. R., Hildreth, W., Palacz, Z., and Rogers, N., 1990, Compositional diversity of late Cenozoic basalts in a transect across the southern Washington Cascades: Implications for subduction zone magmatism: Jour. Geophys. Res., v. 95, p. 19,561–19,582.

Lightfoot, P. C., and Hawkesworth, C. J., 1988, Origin of Deccan Trap lavas: Evidence from combined trace element and Sr-, Nd- and Pb-isotopic studies: Earth Planet. Sci. Lett., v. 91, p. 89–104.

Lomnitz, C., 1982, Direct evidence of a subducted plate under southern Mexico: Nature, v. 296, p. 235–238.

Luhr, J. F., 1997, Extensional tectonics and the diverse primitive volcanic rocks in the western Mexican Volcanic Belt: Can. Mineral., v. 35, p. 473–500.

Luhr, J. F., Allan, J. F., Carmichael, I. S. E., Nelson, S. A., and Hasenaka, T., 1989, Primitive calc-alkaline and alkaline rock types from the western Mexican Volcanic Belt: Jour. Geophys. Res., v. 94, p. 4515–4530.

Luhr, J. F., and Carmichael, I. S. E., 1985a, Jorullo volcano, Michoacán, México (1759–1774): The earliest stages of fractionation in calc-alkaline magmas: Contrib. Mineral. Petrol., v. 90, p. 142–161.

______, 1985b, Contemporaneous eruptions of calc-alkaline and alkaline magmas along the volcanic front of the Mexican Volcanic Belt, *in* Verma, S. P., ed., Mexican volcanic belt, Part 1: Geofis. Int., v. 24, p. 203–216.

Luhr, J. F., Nelson, S. A., Allen, J. F., and Carmichael, I. S. E., 1985, Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump: Geology, v. 13, p. 54–57.

Mahadevan, T. M., 1994, Deep continental structure of India: A review: Bangalore, Mem. Geol. Soc. Ind. 28, xv + 562 p.

Mahoney, J. J., 1988, Deccan Traps, *in* Macdougall, J. D., ed., Continental flood basalts: Dordrecht: Kluwer Acad. Publ., p. 151–194.

Mahoney, J. J., Macdougall, J. D., Lugmair, G. W., Gopalan, K., and Krishnamurthy, P., 1985, Origin of contemporaneous tholeiitic and K-rich alkalic lavas: A case study from the northern Deccan plateau, India: Earth Planet. Sci. Lett., v. 72, p. 39–53.

Mahoney, J. J., Sheth, H. C., Chandrasekharam, D., and Peng, Z. X., 2000, Geochemistry of flood basalts of the Toranmal section, northern Deccan Traps, India: Implications for regional Deccan stratigraphy: Jour. Petrol., v. 41, p. 1099–1120.

Márquez, A., Oyarzun, R., Doblas, M., and Verma, S. P., 1999a, Alkalic (OIB-type) and calc-alkalic volcanism in the Mexican volcanic belt: A case for plume-related magmatism and propagating rifting at an active margin?: Geology, v. 27, p. 51–54.

________, 1999b, Reply to Ferrari and Rosas-Elguera: Geology, v. 27, p. 1056.

Márquez, A., Verma, S. P., Anguita, F., Oyarzun, R., and Brandle, J. L., 1999c, Tectonics and volcanism of Sierra Chichinautzin: Extension at the front of the central Trans-Mexican Volcanic Belt, *in* Verma, S. P., ed., Rift-related volcanism: Geology, geochemistry, geophysics: Jour. Volcanol. Geotherm. Res., v. 93, p. 125–150.

Martin-Barajas, A., Stock, J. M., Layer, P., Hausback, B., Renne, P., and López-Martínez, M., 1995, Arc-rift transition volcanism in the Puertecitos volcanic province, northeastern Baja California, Mexico: Geol. Soc. Amer. Bull., v. 107, p. 407–424.

McBirney, A. R., Taylor, H. P., and Armstrong, R. L., 1987, Paricutín re-examined: A classic example of crustal assimilation in calc-alkaline magma: Contrib. Mineral. Petrol., v. 95, p. 4–20.

McMillan, N. J., and Dungan, M. A., 1986, Magma mixing as a petrogenetic process in the development of the Taos Plateau volcanic field, New Mexico: Jour. Geophys. Res., v. 91, p. 6029–6045.

Menard, H. W., 1955, Deformation of the northeastern Pacific basin and the west coast of North America: Geol. Soc. Amer. Bull., v. 86, p. 99–110.

______, 1978, Fragmentation of the Farallon plate by pivoting subduction: Jour. Geol., v. 86, p. 99–110.

Molina-Garza, R., and Urrutia-Fucugauchi, J., 1993, Deep crustal structure of central Mexico derived from interpretation of Bouguer gravity anomaly data: Jour. Geodyn., v. 17, p. 181–201.

Molnar, P., and Sykes, L. R., 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity: Geol. Soc. Amer. Bull., v. 80, p. 1639–1684.

Moore, G., Marone, C., Carmichael, I. S. E., and Renne, P., 1994, Basaltic volcanism and extension near the intersection of the Sierra Madre volcanic province and the Mexican Volcanic Belt: Geol. Soc. Amer. Bull., v. 106, p. 383–394.

Mooser, F., 1969, The Mexican Volcanic Belt – structure and development. Formation of fractures by differential crustal heating: Pan Amer. Symp. Upper Mantle, Mexico, v. 2, p. 15–22.

______, 1972, The Mexican Volcanic Belt: Structure and tectonics: Geofis. Int., v. 12, p. 55–70.

Mooser, F., and Maldonado, M. K., 1961, Pene-contemporaneous tectonics along the Mexican Pacific coast: Geofis. Int., v. 1, p. 1–20.

Nakamura, N., 1974, Determination of REE, Ba, Mg, Na and K in carbonaceous and ordinary chondrites: Geochim. et Cosmochim. Acta, v. 38, p. 757–775.

Negendank, J. F. W., Emmermann, R., Krawczyk, R., Mooser, F., Tobshall, H., and Werle, D., 1985, Geological and geochemical investigations on the Eastern Trans-Mexican volcanic belt, *in* Verma, S. P., ed., Mexican Volcanic Belt, Part 2: Geofis. Int., v. 24-4, p. 477–575.

Nixon, G. T., 1982, The relationship between Quaternary volcanism in Central México and the seismicity and structure of subducted ocean lithosphere: Geol. Soc. Amer. Bull., v. 93, p. 514–523.

______, 1988, Petrology of the younger andesites and dacites of Iztaccihuatl volcano, Mexico: II. Chemical stratigraphy, magma mixing, and the composition of basaltic magma influx: Jour. Petrol., v. 29, p. 265–303.

Nixon, G. T., Demant, A., Armstrong, R. L., and Harakal, J. E., 1987, K-Ar and geologic data bearing on the age and evolution of the Trans-Mexican Volcanic Belt, *in* Verma, S. P., ed., Mexican volcanic belt, Part 3A: Geofis. Int., v. 26-1, p. 109–158.

Olafsson, M., and Eggler, D. M., 1983, Phase relations of amphibole, amphibole-carbonate and phlogopite-carbonate peridotite: Petrologic constraints on the asthenosphere: Earth Planet. Sci. Lett., v. 64, p. 305–315.

Pal, S., and Urrutia-Fucugauchi, J., 1977, Paleomagnetism, geochronology and geochemistry of some igneous rocks from Mexico and their tectonic implications: Proc. IV Int. Gondwana Symp., Calcutta, Part II, p. 814–831.

Pardo, M., and Suárez, G., 1995, Shape of the subducted Rivera and Cocos plates in southern Mexico: Seismic and tectonic implications: Jour. Geophys. Res., v. 100, p. 12,357–12,373.

Pasquare, G., Vezzoli, L., and Zanchi, A., 1987, Morphological and structural model of Mexican Volcanic Belt, *in* Verma, S. P., ed., Mexican Volcanic Belt—Part 3B: Geofis. Int., v. 26, p. 159–176.

Paz Moreno, F. A., and Demant, A., 1999, The Recent Isla San Luis volcanic centre: Petrology of a rift-related volcanic suite in the northern Gulf of California, Mexico, *in* Verma, S. P., ed., Rift-related volcanism: Geology, geochemistry, geophysics: Jour. Volcanol. Geotherm. Res., v. 93, p. 31–52.

Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., ed., Andesites: Chichester, UK, John Wiley, p. 525–548.

Robin, C., 1982a, Mexico, *in* Thorpe, R. S., ed., Andesites: John Wiley, p. 137–147.

______, 1982b, Relations volcanologie-magmatologie-géodynamiques: Application au passage entre volcanismes alcalin et andésitique dans le sud Mexicain (Axe Trans-mexicain et Province Alcaline Orientale): Annal. Sci. l'Univ. Clermont-Ferrand II, v. 30, 503 p.

______, 1984, Le volcan Popocatepetl (Mexique): Structure, evolution pétrologique et risques : Bull. Volcanol., v. 47, p. 1–23.

Robin, C., and Cantagrel, J. M., 1982, Le Pico de Orizaba (Mexique): Structure et évolution d'un grand volcan andésitique complexe: Bull. Volcanol., v. 45, p. 299–315.

Rogers, N., and Hawkesworth, C. J., 1999, Composition of magmas, *in* Sigurdsson, H., ed., Encyclopedia of volcanoes: New York, Academic Press: p. 115–131.

Rosas-Elguera, J., Ferrari, L., Garduño-Monroy, V. H., and Urrutia-Fucugauchi, J., 1996, Continental boundaries of the Jalisco block and their influence in the Pliocene–Quaternary kinematics of western Mexico: Geology, v. 24, p. 921–924.

Ruiz, J., Patchett, P. J., and Arculus, R. J., 1988, Nd-Sr isotope composition of lower crustal xenoliths—evidence for the origin of mid-Tertiary felsic volcanics in Mexico: Contrib. Mineral. Petrol., v. 99, p. 36–43.

Ruff, L., and Kanamori, H., 1980, Seismicity and the subduction process: Phys. Earth Planet. Int., v. 23, p. 240–252.

Schaaf, P., Heinrich, W., and Besch, T., 1994, Composition and Sm-Nd isotopic data of the lower crust beneath San Luis Potosí, Mexico: Evidence from a granulite-facies xenolith suite: Chem. Geol., v. 118, p. 63–84.

Sheth, H. C., 1999a, A historical approach to continental flood basalt volcanism: Insights into pre-volcanic rifting, sedimentation, and early alkaline magmatism: Earth Planet. Sci. Lett., v. 168, p. 19–26.

______, 1999b, Flood basalts and large igneous provinces from deep mantle plumes: Fact, fiction, and fallacy: Tectonophysics, v. 311, p. 1–29.

Shurbet, D. H., and Cebull, S. E., 1984, Tectonic interpretation of the Trans-Mexican Volcanic Belt: Tectonophysics, v. 101, p. 159–165.

Shurbet, D. H., and Cebull, S. E., 1986, Tectonic interpretation of the Trans-Mexican Volcanic Belt—reply: Tectonophysics, v. 127, p. 158–160.

Siebe, C., Schaaf, P., and Urrutia-Fucugauchi, J., 1999, Mammoth bones embedded in a late Pleistocene lahar from Popocatépetl volcano, near Tocuila, central México: Geol. Soc. Amer. Bull., v. 111, p. 1550–1562.

Singh, S. K., and Pardo, M., 1993, Geometry of the Benioff zone and state of stress in the overriding plate in central Mexico: Geophys. Res. Lett., v. 20, p. 1483–1486.

Sinno, Y. A., Dagget, P. H., Keller, G. R., Morgan, P., and Harder, S. H., 1986, Crustal structure of the southern Rio Grande Rift determined from seismic refraction profiling: Jour. Geophys. Res., v. 91, p. 6143–6156.

Smith, A. D., 1993, The continental mantle as a source for hotspot volcanism: Terra Nova, v. 5, p. 452–460.

______, 1999, The Nd-Sr-Pb isotopic record in abyssal tholeiites from the Gulf of California region, western Mexico: No evidence for a Gulf mouth plume: INT. GEOL. REV., v. 41, p. 921–931.

Smith, A. D., and Lewis, C., 1999a, The evolution of scientific thinking in the mantle plume concept: Criticism and non-plume synthesis: Jour. Geol. Soc. China, v. 40, p. 1–40.

______, 1999b, The planet beyond the plume hypothesis: Earth Sci. Rev., v. 48, p. 135–182.

Suárez, G., and Singh, S. K., 1986, Tectonic interpretation of the Trans-Mexico volcanic belt—discussion: Tectonophysics, v. 127, p. 155–160.

Suter, M., Carrillo Martínez, M., Lopez Martínez, M., and Farrar, E., 1995, The Aljibes half-graben: Active extension at the boundary between the Trans-Mexican Volcanic Belt and the Southern Basin and Range: Geol. Soc. Amer. Bull., v. 107, p. 627–641.

Suter, M., Quintero, O., and Johnson, C. A., 1992. Active faults and state of stress in the central part of the Trans-Mexican Volcanic Belt, Mexico: 1. The Venta de Bravo fault: Jour. Geophys. Res., v. 97, p. 11,983–11,993.

Thorpe, R. S., 1977, Tectonic significance of alkaline volcanism in eastern Mexico: Tectonophysics, v. 40, p. 19–26.

UNAM and CENAPRED Seismology Group, 1995, The Milpa Alta earthquake of January 21, 1995: Geofis. Int., v. 34, p. 355–362.

Verma, S. P., 1983, Magma genesis and chamber proceses at Los Humeros Caldera, Mexico—Nd and Sr isotope data: Nature, v. 301, p. 52–55.

______, 1984, Sr and Nd isotopic evidence for petrogenesis of mid-Tertiary felsic volcanism in the mineral district of Zacatecas, Zac. (Sierra Madre Occidental), Mexico: Isotope Geosci., v. 2, p. 37–53.

______, 1985, Preface, *in* Verma, S. P., ed., Mexican Volcanic Belt, Part 1: Geofis. Int., v. 24, p. 7–18.

______, 1997, Sixteen statistical tests for outlier detection and rejection in evaluation of international geochemical reference materials: Examples of micrograbbro PM-S: Geostand. Newslett.: Jour. Geostand. Geoanal., v. 21, p. 59–75.

______, 1999, Geochemistry of evolved magmas and their relationship to subduction-unrelated mafic volcanism at the volcanic front of the central Mexican Volcanic Belt, *in* Verma, S. P., ed., Rift-related volcanism: Geology, geochemistry, geophysics: Jour. Volcanol. Geotherm. Res., v. 93, p. 151–171.

______, 2000a, Geochemistry of subducting Cocos plate and the origin of subduction-unrelated mafic volcanism at the volcanic front of central Mexican Volcanic Belt, *in* Delgado-Granados, H., Aguirre-Díaz, G., and Stock, J. M., eds., Cenozoic tectonics and volcanism of Mexico: Boulder: Geol. Soc. Amer. Spec. Pap. 334, Chap. 13, p. 195–222.

______, 2000b, Geochemical evidence for a lithospheric source for magmas from Los Humeros caldera, Puebla, Mexico: Chem. Geol., v. 164, p. 35–60.

______, 2000c, Geochemical and Sr-Nd-Pb isotopic evidence for a combined assimilation and fractional crystallisation process for volcanic rocks from the Huichapan caldera, Hidalgo, Mexico: Lithos, in press.

Verma, S. P., and Aguilar-Y-Vargas, V. H., 1988, Bulk chemical composition of magmas in the Mexican volcanic belt (Mexico) and inapplicability of generalized arc-models: Chem. Erde, v. 48, p. 203–221.

Verma, S. P., Carrasco-Nuñez, G., and Milán, M., 1991, Geology and geochemistry of Amealco caldera, Qro., Mexico: Jour. Volcanol. Geotherm. Res., v. 47, p. 105–127.

Verma, S. P., and 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: Jour. Geophys. Res., v. 94, p. 4531–4544.

Von Humboldt, A., 1808, Essai politique sur le Royaume de la Nouvelle Espagne: Paris : F. Schoell, 905 p.

Wallace, P. J., and Carmichael, I. S. E., 1994, Petrology of Volcán Tequila, Jalisco, Mexico: Disequilibrium phenocryst assemblages and evolution of the subvolcanic magma system: Contrib. Mineral. Petrol., v. 117, p. 345–361.

______, 1999, Quaternary volcanism near the valley of Mexico: Implications for subduction zone magmatism and the effects of crustal thickness variations on primitive magma compositions: Contrib. Mineral. Petrol., v. 125, p. 291–314.

Weaver, C. S., and Michaelson, C. A., 1985, Seismicity and volcanism in the Pacific Northwest: Evidence for the segmentation of the Juan de Fuca plate: Geophys. Res. Lett., v. 12, p. 215–218.

Wilson, M., 1989, Igneous petrogenesis: A global tectonic approach: London: Unwin Hyman, 466 p.

Ziagos, J. P., Blackwell, D. D., and Mooser, F., 1995, Heat flow in southern Mexico and the thermal effects of subduction: Jour. Geophys. Res., v. 90, p. 5410–5420.