

*MEXICAN VOLCANIC BELT: PRESENT STATE OF KNOWLEDGE
AND UNSOLVED PROBLEMS*

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RESUMEN

Primeramente, se presenta una breve reseña de los estudios disponibles (hasta 1984) sobre el Cinturón Volcánico Mexicano (CVM). Esto se sigue con una síntesis de los resultados más importantes de los trabajos incluidos en el Volumen Especial sobre el CVM (*Geofís. Int.*, Vol. 24, Núm. 1 & 4; Vol. 26, Núm. 1 & 2). A pesar de que el Volumen CVM (con 28 trabajos) ha proporcionado un salto cuantioso en nuestro conocimiento de esta provincia volcánica, aún persisten muchos huecos grandes en él y existen muchas preguntas no-contestadas. Por lo tanto, un esfuerzo coordinado y sistemático es muy deseable y tal vez necesario si queremos lograr un progreso significativo (¡durante nuestras propias vidas!) concerniente a esta importante provincia circum-Pacífica.

ABSTRACT

A brief review is first given of the available studies (upto 1984) related to the Mexican Volcanic Belt (MVB). A synthesis is then presented of the most important results of the papers included in the Special Volume on the MVB (*Geofís. Int.*, Vol. 24, Nos. 1 & 4; Vol. 26, Nos. 1 & 2). Although the MVB Volume (containing 28 papers) has provided a quantum jump in our knowledge of this volcanic province, large gaps still persist and many unanswered questions exist. A coordinated and systematic effort is therefore very much necessary if we are to obtain a significant progress (during our own lifetimes!) concerning this important circum-Pacific province.

INTRODUCTION

The Mexican Volcanic Belt (MVB) is a 20-150 km-broad, ~1 000 km long structure (Fig. 1) which extends roughly east-west from near Puerto Vallarta in the west to Veracruz on the coast of Gulf of Mexico (Mooser, 1972; Demant and Robin, 1975; Robin, 1982a, b; López-Ramos, 1983). Although the MVB presumably belongs to the circum-Pacific volcanic chain, it can be seen from Fig. 1 that it is not parallel to the subduction zone (Middle American Trench, MAT) but makes an angle of about 20 degrees with it (Molnar and Sykes, 1969). The MVB is linked to Central American volcanic arc (which is parallel to the MAT) through a diffuse transition zone of Pliocene to Recent volcanic centers named as Chiapanecan Volcanic Arc (Damon and Montesinos, 1978).

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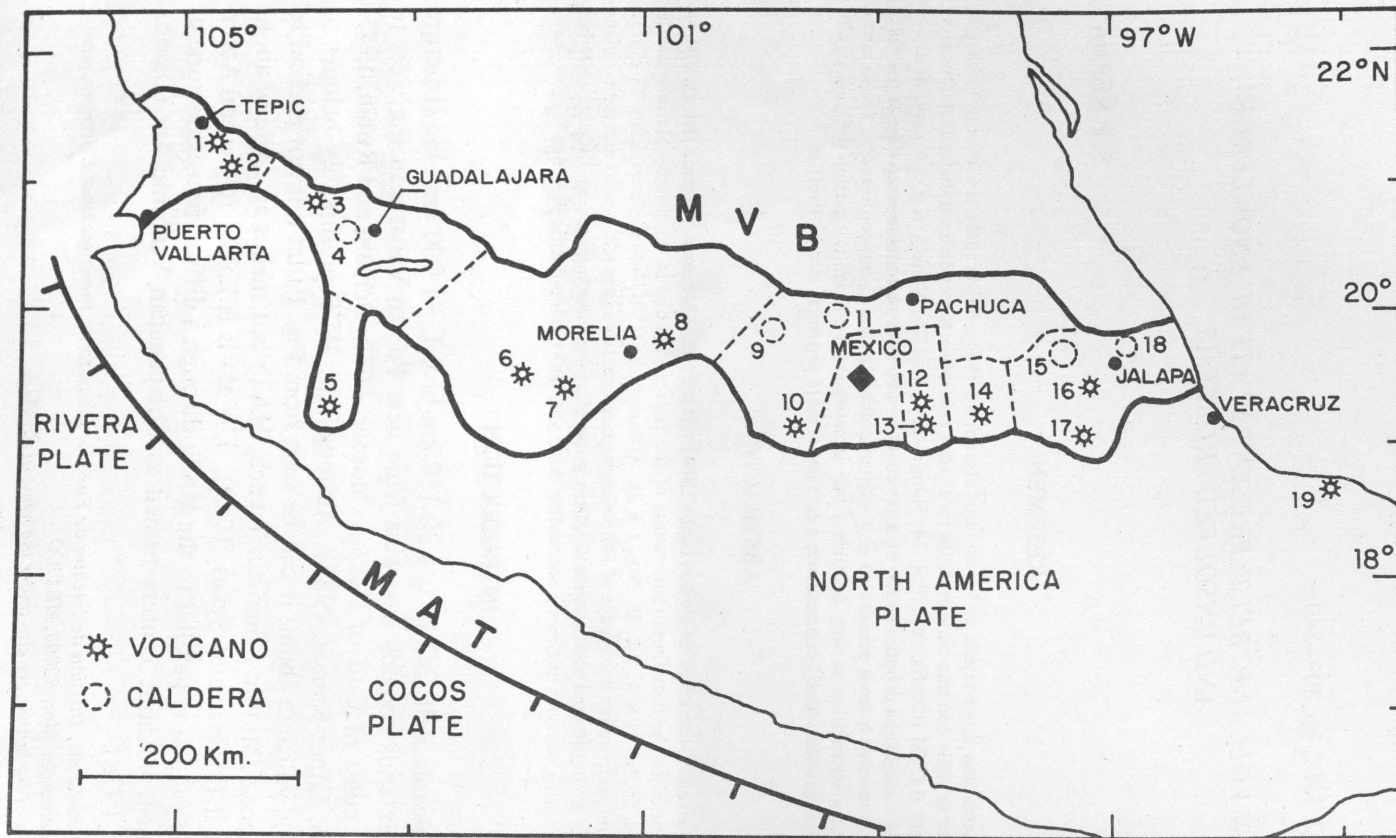


Fig. 1. A simplified map showing the location of the Mexican Volcanic Belt (MVB) with associated major volcanoes and calderas, along with the Middle America Trench (MAT). Note the volcanic structures in the west are closer to the MAT than those in the east. These structures are: 1 = Sangangüey, 2 = Ceboruco, 3 = Tequila, 4 = La Primavera, 5 = Colima, 6 = Parícutín, 7 = Jorullo, 8 = Los Azufres, 9 = Amealco, 10 = Nevado de Toluca, 11 = Huichapan, 12 = Iztaccíhuatl, 13 = Popocatepetl, 14 = La Malinche, 15 = Los Hornos, 16 = Cofre de Perote, 17 = Pico de Orizaba, 18 = Chiconquiaco, 19 = Los Tuxtlas.

MVB has been the subject of a large number of studies ever since the times of *Alexander von Humboldt* who provided the first scientific explanation for the alignment of volcanoes in this province, by proposing the existence of a crustal fracture dissecting the continent along the 19th parallel from the Atlantic to the Pacific Ocean (Humboldt, 1808). The volcanic features of the Revillagigedo Islands in the Pacific, some 800 km to the west of the MVB (from Puerto Vallarta), were believed to belong to the same giant fracture. This pioneer hypothesis has been revived ever since with different kinds of modifications.

The main objectives of this review are to (A) present a very brief synthesis of our knowledge of the MVB upto 1984 when the publication of this Special Volume was initiated, (B) point out the most important results of the papers comprising this MVB Volume, and (C) indicate the most exciting problems that still remain to be solved. It should be mentioned, however, that although most of the published literature (upto 1984) has been included in this review, no claim is made regarding its exhaustive nature.

(A) STATE OF KNOWLEDGE UPTO 1984

This section presents a brief summary of the studies on the MVB, existing upto 1984 prior to the publication of the Special Volume. For the sake of convenience it is subdivided into four main subsections.

A-1. Geology There exists a geologic map of Mexico (López-Ramos and Sánchez-Mejorada, 1976) which assigns the rocks in the MVB from mid-Tertiary to Present. The geology of almost the entire region has been covered by 1:50 000 and/or 1:250 000 maps by DETENAL (a Mexican government agency). High-quality aerial photographs are also available from DETENAL. Furthermore, this agency has also published geologic maps of different parts of Mexico on a scale 1:1 000 000. Many mining areas have also been mapped by another agency, Consejo de Recursos Minerales. Similarly, the geology of geothermally potential areas has been worked out by Mexico's Comisión Federal de Electricidad (CFE). Some detailed geologic maps have also been elaborated by Instituto de Geología, UNAM as well as many individual researchers working in specific areas and institutions.

MVB is probably underlain by Precambrian and Paleozoic metamorphic rocks and Mesozoic igneous (granitic and granodioritic) intrusive bodies. Cretaceous sedimentary rocks also outcrop in some areas and have been encountered during drilling by

CFE and other organizations. Oligocene to Miocene rhyolitic and ignimbritic rocks of Sierra Madre Occidental (SMO) may also occur beneath the Mio-Pliocene to Recent volcanic rocks of the MVB province (see e.g., Verma, 1985a).

A-2. *Geophysics* This subsection is further divided into two main subjects.

(i) Plate motions

Plate tectonics is a unifying theory which combines surface geology with planetary evolution. In this broad concept, the MVB is a highly complex continental arc whose origin is presumably related to the subduction of the Cocos plate beneath the North American plate along the MAT (Fig. 1). Their convergence rate has been estimated as 6 to 7 cm a⁻¹ (Minster and Jordan, 1978; Nixon, 1982). Volcanism in the western portion of the MVB is also influenced by the waning, aseismic subduction of the Rivera plate. Prior to about 2 Ma, this small remnant of the Farallon plate was actively subducting into the MAT (Larson, 1972). Since that time, the Rivera plate has been accreting gradually to North America; convergence is now estimated as 2 cm a⁻¹ (Nixon, 1982). Furthermore, the present day plate motions are such that the net growth of the Cocos plate is negative (about -0.008 km²/yr) whereas the North American plate is growing at a rate of about 0.09 km²/yr (Minster and Jordan, 1978).

Atwater (1970) and Atwater and Molnar (1973) deduced the relative motion of the Pacific and North American plates from the magnetic anomalies and sea-floor spreading data. They concluded that a trench existed offshore from western North America during the mid-Tertiary time and that the Pacific-Farallon spreading center became very close to the North America after 38 Ma. The Pacific and North American plates were in contact by about 29 Ma. The average rate of motion between these plates was about 4 cm a⁻¹ between 29 and 21 Ma which reduced to about 1.3 cm a⁻¹ between 21 and 10 Ma. It increased to about 4 cm a⁻¹ between 10 and 4.5 Ma and then about 5.5 cm a⁻¹ since 4.5 Ma. A Miocene reorientation of spreading patterns in the eastern Pacific was proposed by Handschumacher (1976) as well as by Lynn and Lewis (1976). Their proposal was based on post-Eocene tectonic reconstructions and observed magnetic anomaly patterns.

Menard (1978) proposed a complex fragmentation of the Farallon plate by pivoting subduction whereas Karig *et al.* (1978) observed that part of the continental margin along the west coast of Mexico has been removed during the process of sub-

duction, which probably occurred intermittently between late Cretaceous and late Miocene times. This lack of "maturity" normally associated with persistently convergent plate boundaries is quite anomalous in the case of the Mexican continental margin because plate convergence between the Mexican section of the North American plate and either the Cocos or other lithospheric plates within the Pacific Ocean has been occurring at least intermittently for more than 100 m.y. and probably for several times that long (De Cserna, 1960; Coney, 1972; Karig *et al.*, 1978; Clark *et al.*, 1982).

At present, a major complication arises because the Cocos plate is being subducted beneath the North American plate along the northwestern part of the trench and beneath the Caribbean plate in the southeast (see e.g., Verma, 1985a). Jordan (1975) estimated the present-day motion of the Caribbean plate and found that it might actually be almost fixed in the hot spot reference frame. In this connection, Sykes *et al.* (1982) showed that the relative motion between the North American and Caribbean plates is probably close to 4 cm a⁻¹. Since it is an unstable triple junction, this motion must alter the configuration of the trench with time.

(ii) Seismological and other studies

Stoiber and Carr (1973) and Carr *et al.* (1983) used the offsets in the volcanic chain to divide the Middle America zone into more than a dozen distinct surface regions 100-300 km long. On this basis, they postulated that each of these regions lay above a discrete segment of the subducted plate. However, such a large number of small-scale segmentation has not been favored from other seismic studies (Isacks and Barazangi, 1977; Burbach *et al.*, 1984). Hanuš and Vaněk (1978) used the seismicity in the region to point out a correlation of aseismic gap and the depth of generation of andesitic magmas. Recently, Burbach *et al.* (1984) used the best available teleseismic data to determine the large-scale structure of the subducted part of the Cocos plate. They concluded that this plate consists of only three major segments. Unfortunately, the structure of their segment III (from Orizaba to Rivera fracture zone) which corresponds to the MVB, is not very well defined.

Dean and Drake (1978) used fault plane solutions to show that focal mechanisms delineate tectonic activity (in the Middle America arc) which seems to be characteristic of a subduction zone. Moore *et al.* (1979) used the results of drilling, near MAT, by Glomar Challenger (IPOD-DSDP Leg 66; Watkins *et al.*, 1982) to show a seaward growth of continental margin. These results as well as those of magnetic (Karig *et al.*, 1978) and seismic reflection (Shipley *et al.*, 1980) studies indicate that

the Mesozoic to Precambrian basement approaches within 35 km of the trench axis and this limits the width and the volume of the off-scraped material.

It was shown by Ruff and Kanamori (1980) that the preferred trajectories of subducting slabs may, in fact, be related to the particular combinations of the lithospheric ages and convergence rates, thereby affecting Benioff zone geometry. If such a model is true, then given a young lithosphere of the Cocos plate (age <20 Ma) and a rather large convergence rate (6 to 7 cm a⁻¹), the angle of subduction should not be large (almost certainly less than 45 degrees). For the Cocos plate, the seismic activity suggests a shallower mode of subduction in the north (corresponding to the MVB) than to the south (Central America; e.g., Molnar and Sykes, 1969). This seems to be confirmed by the distribution of Quaternary volcanoes in the region as suggested by Stoiber and Carr (1973).

Large earthquakes along the northern Cocos plate have very similar focal mechanisms, source depths, rupture dimensions, and stress drops whereas events with more complicated body waves have been located in the vicinity of suspected triple junctions (Chael and Stewart, 1982). On the other hand, the existence of seismic gaps has been confirmed through relocation studies of large events by Singh *et al.* (1981). Thus, one important seismic gap - the Michoacan gap - might very well have existed but its possible relation to the volcanism in the MVB was not known.

Lomnitz (1982) claimed to have presented a direct seismic evidence of the presence of a subducted plate under southern Mexico. On the other hand, Nixon (1982) made an observation that the majority of volcanoes making up the MVB are located more than 50 km beyond the terminus of the inclined seismic zone; the latter extends to a depth of less than 150 km. The reasons of this discrepancy are far from clear, especially so because the Cocos plate has been subducting beneath the North American plate for at least the past 10 m.y. (Menard, 1978). In a recent study, Shurbet and Cebull (1984) used the geographical distribution of intermediate-depth earthquakes, analysis of Sn propagation, and a limited number of focal-mechanism solutions to suggest that the MVB is largely independent of subduction.

A-3. Geochemistry This subsection is further divided into several general topics or lines of research.

(i) Major-elements

There are quite a few studies involving petrography and major elements available for the MVB magmas. A compilation of the major element data on this belt was prepared by Pal *et al.* (1978). Almost all papers available at that time were included in this compilation. The only exception to this claim seems to be a report by Maupomé *et al.* (1975) on three chemical analyses of rhyolitic compositions. Furthermore, four analyses of Parícutín andesitic lavas reported by Williams (1950) were also left out for some mysterious reason. The most important result of this compilation (Pal *et al.*, 1978) was that the magmas in the western and central parts of the MVB were dominated by calc-alkaline compositions whereas those in the eastern part were largely alkaline in character.

Since this compilation many more studies have become available (e.g., Robin and Nicolas, 1978; Pérez-R. *et al.*, 1979; Silva-Mora, 1979; Demant, 1979, 1981; Luhr and Carmichael, 1980, 1981, 1982; Nelson, 1980, 1984; Cantagrel *et al.*, 1981; Mahood, 1981; Robin, 1982a, b, 1984; Robin and Cantagrel, 1982; Verma and López M., 1982; Combredet, 1983; Livieres, 1983; Nelson and Carmichael, 1984; Dobson, 1984; Ferriz and Mahood, 1984), which make another compilation very much desirable.

(ii) Trace elements

There are several studies involving trace elements. Many of the above mentioned papers and theses also report data on several such elements. A few others (e.g., Pal, 1972; Pal *et al.*, 1974; Pal and Urrutia, 1977) are concerned with them, but there are not many attempts to use these data quantitatively for testing petrogenetic models. To the list of the recent studies (since 1978) given under the section of major-elements, one may add a few others that emphasize the use of trace elements in problems of petrogenesis (e.g., Richter and Negendank, 1976; Robin, 1982b; Verma, 1984a).

(iii) Radiogenic isotopes

The studies of radiogenic isotopes in the MVB are very scanty. Before the work of the present author (Verma, 1981a, 1981b, 1982, 1983a) only three papers (Whitford and Bloomfield, 1976; Moorbath *et al.*, 1978; Cantagrel and Robin, 1978) on $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios and one abstract (Carmichael and DePaolo, 1980) on $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were available in the literature. Besides, only one more abstract (Reid, 1983) has been published and one paper is in preparation (Negen-

dank *et al.*, written communication, 1984) concerning the isotopic data on the MVB. The available data seem to be compatible with the derivation of the MVB magmas from the upper mantle with little contribution from an altered oceanic crust, subducted sediments or sialic continental crust. These petrogenetic inferences are in contrast with those for the SMO province of Mexico (Verma, 1984b). Radiogenic isotope studies on Cocos and Rivera plates similar to those carried out on NE Pacific and Gulf of California (Verma, 1981c, 1983b) should be particularly useful for constraining the magma genesis in the MVB.

(iv) Stable isotopes

$^{18}\text{O}/^{16}\text{O}$ data in fresh whole-rock silicates and in mineral separates from them, in conjunction with $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes have proved quite effective in discriminating petrogenetic processes. However, no such stable isotope study has so far been carried out in the MVB. Nevertheless, a limited number of stable isotope ($\text{O}-18$, D or $\text{C}-13$) data has been reported for fluids or mineral separates in Los Azufres geothermal field situated in the MVB (Nieva *et al.*, 1983; Combredet, 1983; Dobson, 1984).

(v) Radiometric dating

Both K-Ar and C-14 methods have been employed successfully in dating of MVB magmas. K-Ar dates have been obtained by several workers (e.g., Watkins *et al.*, 1971; Steele, 1971; Cantagrel and Robin, 1979; Mahood and Drake, 1982; Ferriz and Mahood, 1984). There are also some reports on C-14 dates from the MVB. The earlier ones are included in compilations by Fries (1962) and Valencia and Fries (1965). Some of the more recent ones containing C-14 dates are by Bloomfield (1973), and Bloomfield and Valastro (1974).

It appears that most volcanic centers are associated with rather young dates (generally less than 1 m.y.) but the history of this volcanic Province should be traced back to at least several million years.

(vi) Paleomagnetic constraints

A few paleomagnetic studies have been carried out in the MVB (Steele, 1971; Mooser *et al.*, 1974; Urrutia and Pal, 1977; Herrero-B. and Pal, 1978; Pal, 1979; Böhnel and Negandank, 1981). Many of them provide constraints on the age of the volcanic flows studied.

A-4. Petrogenetic and tectonic models

As was stated in the "Introduction" section of this review, Humboldt (1808) was the first researcher to provide a scientific explanation for the alignment of volcanoes in the MVB. His hypothesis has been revived ever since with different kinds of modifications (e.g., Felix and Lenk, 1890; Mooser and Maldonado, 1961). Of particular interest was the discovery of the marine Clarión Fracture Zone (Menard, 1955); as a result, the alignment of the large volcanoes appeared to be the continental extension of an oceanic fracture.

Later, the MVB was visualized as the result of oblique crustal shearing along certain zones of weakness. Thus, Mooser and Maldonado (1961) considered the whole volcanic belt to be a flock-faulted "geotumor" subjected to shearing along two alignments: the Humboldt line and Chapala-Acambay line towards the north; the former was considered an extension of the Clarión fracture zone and the latter that of the San Andreas fault system prolonged southward into the Gulf of California. Based on the existing drainage patterns, Mooser and Maldonado (1961) also inferred a third alignment which was called the Balsas line. Mooser (1969) put forth a mechanism of differential crustal heating for formation of these fractures. A fracture zone called Mexico fracture zone (Permo-Triassic) is also shown to exist beneath the present location of the MVB (De Cserna, 1971; see his Fig. 11). Gastil and Jensky (1973) have presented evidence for strike-slip displacement beneath the MVB.

With the development of the theory of plate tectonics, the MVB was first visualized as a possible extension of the East Pacific Rise (EPR; Mooser *et al.*, 1970 cited in Mooser, 1972). Later, Mooser (1972) inferred that the MVB, a zone of weakness, has been reopened since the Tertiary and the lavas are derived from the subduction (of the Cocos plate) along the MAT. A direct relation of the MVB with the subduction has also been proposed by several other workers as well (Molnar and Sykes, 1969; Demant and Robin, 1975; Pichler and Weyl, 1976; Thorpe, 1977; Pal and Urrutia F., 1977; Urrutia F. and Del Castillo G., 1977; Demant, 1978; Negendank *et al.*, 1982). Some of these authors have also proposed different mechanisms and models in order to explain the non-parallelism of the MVB with the MAT.

Active rifting and graben structures have been proposed and interpreted in the western part of the MVB (e.g., Díaz C. and Mooser, 1972; Luhr *et al.*, 1984). Grabenlike tension in the coastal plain area (towards the Gulf of Mexico) has also been inferred by Robin (1976, 1982b).

Several different hypotheses have been proposed for the origin of volcanism in the MVB. Gunn and Mooser (1971) considered possible mechanisms of magma generation including partial melting of oceanic tholeiitic or mantle pyrolytic material as well as crustal contamination and fractional crystallization but were unable to clearly discriminate between them. Negendank (1973a, b; 1976) and Richter and Negendank (1976) favored that the magmas in the Valley of Mexico (located in the central part of the MVB) were derived from the lower crust. Fractional crystallization and existence of magma chambers beneath strato-volcanoes in the western sector of the MVB have been proposed by Demant (1979). Mixing of magmas as an important mechanism of magma genesis has been advocated by Robin (1982b), and Robin and Cantagrel (1982).

Recent petrological and isotopic studies have shown that the magmas in many areas of the MVB may come directly from the upper mantle and not from an altered oceanic plate (Verma, 1982; 1983a, 1984a). Similar inferences have also been drawn by some geophysical data (Shurbet and Cebull, 1984). Verma (1984c) has shown that geochemical and thermal modelling can provide important constraints on subsurface magma bodies. Such inferences are particularly useful in the study of geothermal areas (Verma, 1984c, 1985b, c).

(B) ACHIEVEMENTS OF THIS SPECIAL VOLUME

The reasons for editing a Special Volume on the Mexican Volcanic Belt are enumerated by Verma (1985a) who also presents a brief review of the tectonics of the area. The present MVB Volume (in its four parts: 1, 2, 3A, and 3B) contains 28 papers written by 71 authors from 31 institutions. The publication was made possible by the help of a total of 55 reviewers. In this section, I present a brief review of the major achievements of the MVB Special Volume. In order to make an easy comparison with the state of knowledge in 1984, I have subdivided this section following the style of the earlier one.

B-1. Geology

As far as the problem of the nomenclature of this volcanic province is concerned, my own prejudices are (and ample evidence has been accumulated in this Special Volume) that the names like axis (eje, l'Axe) and adjectives like neo- are of lesser significance and perhaps neither necessary nor correct. Therefore, this volcanic province should simply be called as Mexican Volcanic Belt (MVB, following Mooser,

1969, 1972) or TransMexican Volcanic Belt (TMVB) and an equivalent in Spanish as "Cinturón Volcánico Mexicano" (CVM) or "Faja Volcánica Mexicana" (FVM).

Considerable advances concerning the geology of the belt are reported in several papers of the MVB Volume. Furthermore, a summary of abundant new petrographic data on the MVB volcanoes is also included here.

Venegas-S. *et al.* (1985) present simplified regional geologic and structural maps as well as lithologic columns in several geothermal areas situated in this volcanic province. On the basis of regional topography of Mexico as well as drill-hole geology in several geothermal fields, they conclude that the rocks from the Sierra Madre Occidental (SMO) - a major rhyolitic and ignimbrite province of Mexico - do not seem to underlie the volcanics associated with the MVB.

Lugo-H. *et al.* (1985) present an analysis of 77 topographic and geologic maps (scale 1:50 000) from DETENAL in the central part of the MVB. The study area with $\sim 73\ 000\ \text{km}^2$ has about 3 000 volcanoes (an average of 4 volcanoes/100 km^2). They point out the zones of major Quaternary volcanic activity, which contain 9, 12 or more volcanoes in 100 km^2 . This is contrasted by low volcano-concentration as well as stable zones.

In an attempt to review the on- and offshore morphotectonic features related to the continental margin structure in southern Mexico, Sandoval-O. (1985) proposes the existence of a major lineament, the Tecpan Regional Fault, that runs with a N17°E strike, from the inner slope of the MAT to the central part of the MVB.

The eastern part of the MVB has been studied in detail by Negandank *et al.* (1985). Using 1:50 000 DETENAL geologic maps, 1:200 000 LANDSAT images and 1:50 000 aerial photographs, these authors have prepared two petrographic geological overview maps of the area. They also identify some new caldera structures as well as give a map of structural lineaments in the study area.

Nieto-O. *et al.* (1985) present a discussion of the tectonically controlled morphological features related to the Río Grande de Santiago region in the western part of the MVB. They also include several Rose diagrams for the petrological suites of the study area. The fracture patterns are compatible with the presence of a large right-lateral fault system, which seems to control the geological limits of the SMO and the MVB.

A study of El Chichón volcanic products is reported by McGee *et al.* (1987). They show that among El Chichón rocks considerable variations exist in both total phenocryst contents (20 - 55%) as well as relative proportions. However, in all samples, plagioclase is the most abundant phenocryst, followed by hornblende, augite, and minor amounts (<5%) of magnetite, biotite, sphene, anhydrite and apatite. Concerning the controversy of the source of anhydrite, they argue on the basis of unaltered subhedral nature of both phenocryst and matrix anhydrite, in favor of a primary magmatic origin for this mineral.

Nixon *et al.* (1987) present several generalized geologic maps of various regions of the MVB and, in conjunction with radiometric dates, use them to construct the volcanic history of this province.

Pasquaré *et al.* (1987a) report a morphological and structural analysis of the central part of the MVB. They give an account of four categories of morphological units present in the area. These are: (a) reliefs pertaining to geological formations older than the MVB and characterized by Laramide orogenic deformations, (b) pre-MVB planar structural surfaces, (c) depositional surfaces of sedimentary or volcanoclastic infilling of post-orogenic tectonic depressions, and (d) surfaces of the MVB volcanoes themselves. Furthermore, the main morphogenetic stages are related to tensional tectonic phases and main volcanic events. On the other hand, Pasquaré *et al.* (1987b) present a morphological and structural model of the entire MVB. The main structural units recognized here were generated in several tensional phases since the Oligocene. The authors find three main sectors (western, central and eastern) inside the MVB and comment on their evolution and tectonic characteristics.

Historic pyroclastic flows from Volcán de Colima are studied by Martín Del Pozzo *et al.* (1987) who present a simplified geologic map and a brief petrographic description of the samples. They conclude high degree of fluidity as well as high temperatures associated with the flows studied.

B-2. Geophysics

(i) Plate motions

Unfortunately no paper was presented for publication in the MVB Volume, which could provide new data on motions of the Cocos, Rivera or North American plates.

(ii) Seismological and other studies

No paper was submitted on seismological studies leading to a better understanding of the plate tectonics of the area. However, two papers do consider other geophysical aspects of the Colima area (in the western part of the MVB). The first one by Allan (1985) presents estimates of sediment depth in the Colima graben from gravity data. He finds that a 20 mgal negative Bouguer gravity anomaly could be modelled in terms of at least 900 m of sediment depth in the northern Colima graben. He also gives estimates of a vertical offset of 2 1/2 km within the graben by combining the predicted sediment depth with the topographic relief. The second geophysical paper is by Medina-M. (1985) who presents an analysis of the relationship between volcanic events and large earthquakes in Colima area. He points out on the limited nature of the geophysical data which makes it difficult to draw definite conclusions from them.

B-3. Geochemistry

(i) Major-elements

Several studies report data on major-elements. Verma *et al.* (1985) present analyses of 10 samples (mostly basalts) from Arandas-Atotonilco area (western part of the MVB) and conclude that these rocks are dominantly calc-alkaline.

Los Humeros caldera situated in the eastern part of the MVB has been studied by Ferriz (1985) who reports whole-rock analysis of 4 samples of ignimbrites. On the other hand, he gives a detailed account of constituent mineral compositions for the different volcanic units. Using such data, Ferriz has obtained eruption-temperatures, oxygen-fugacities and H₂O concentrations in the magma. His temperature estimates range from ~1,070°C for olivine basalt down to ~800°C for the most-evolved magmas.

In a study of the volcanic stratigraphy of the Guadalajara area (located in the western part of the MVB), Gilbert *et al.* (1985) present wet chemical data on 8 samples on volcanic rocks ranging from basalt to rhyolitic ignimbrite. They also report microprobe analyses of feldspar and ferromagnesian phenocrysts and glasses from the older ignimbrite unit of intermediate composition. From these data they deduce pre-eruptive magma temperature of ~1,000°C and emplacement temperatures greater than 800°C.

Luhr and Carmichael (1985) present 3 whole-rock analyses from the southern Colima graben and 3 from the Jorullo area in the southern Michoacán-Guanajuato volcanic field. In both places, hypersthene- and quartz-normative calc-alkaline magmas with typical 'volcanic front' characteristics were erupted contemporaneously with hydrous, nepheline-normative, basic alkalic magmas. The authors conclude that this observation cannot be easily reconciled with the general models for subduction-related volcanic arcs.

Negendank *et al.* (1985) report a very large number (188) of whole-rock analyses of igneous rocks from the eastern part of the MVB. The rocks show from tholeiitic to calc-alkaline, high-K calc-alkaline and shoshonitic affinities. Further, monogenetic cone andesites seem to be less-evolved than the stratovolcano andesites. These authors also conclude that the MVB extends upto the coast of the Gulf of Mexico.

The Michoacán-Guanajuato volcanic field located in the central part of the MVB has been the area of interest for Hasenaka and Carmichael (1985) who present a catalog of over one thousand volcanic centers; 901 of which are lava or cinder cones, 43 domes, 22 maars or tuff rings, 13 shield volcanoes, and 61 lava flows not clearly associated with cones. These volcanoes lie between 200 km and 430 km from the MAT with the highest concentration at 250 km. The authors further deduce an average eruption volume rate of $0.8 \text{ km}^3/1,000 \text{ years}$ for the entire volcanic field.

Nieto-O. *et al.* (1985) report 9 whole-rock chemical compositions on samples of igneous rocks from the western part of the MVB adjacent to the SMO. Calc-alkaline affinity is evidenced during several volcanic episodes from the Oligocene to the Present. On the other hand, alkaline volcanic products were emplaced during tensional tectonic phases 14-12 m.y. ago (during the beginning of the aperture of the Gulf of California), and from 3 Ma to the Present in several localities along a shear zone.

Volcán Pico de Orizaba, the highest volcano of the MVB, has been studied by Kudo *et al.* (1985), who report the chemical compositions of 5 whole-rocks and 4 matrix-glasses. The data show typical calc-alkaline affinities for the samples studied. The authors also present microprobe mineral composition data and conclude that at least two different magmas were first evolved, an andesitic magma generated in the upper mantle or the lower crust, and a high-silica one originated by partial melting of the lower crust. These magmas have been contaminated by xenocrystic olivines and pyroxenes to form the rocks analyzed by them.

Luhr and Lazaar (1985) report whole-rock analyses on 9 samples from the southern Guadalajara Volcanic Chain in the western part of the MVB. They state that although the orientation of this volcanic chain is apparently related to a major crustal rifting event, the magmas erupted from these centers are typical calc-alkaline basaltic andesites.

On the basis of new chemical data on 7 samples of 1982 and 4 of pre-1982 eruptions in El Chichón, McGee *et al.* (1987) suggest that a chemical uniformity exists in the eruptive products during the 0.3 m.y. time span covered by the samples. The authors also provide abundant microprobe data on El Chichón rocks.

Nixon *et al.* (1987) present the results of chemical analysis of 7 whole-rock samples which are also radiometrically dated by K-Ar. Three of them turn out to be basalts, 3 andesites and 1 rhyodacite.

Cathelineau *et al.* (1987) report major element chemistry of 18 samples of Quaternary volcanic rocks from Los Azufres geothermal field located in the central part of the MVB. They also give microprobe data on ortho- and clinopyroxene compositions on two samples. The authors conclude that the mineralogy and the calc-alkaline nature of the whole volcanic series are compatible with other suites of the MVB volcanoes.

Five new chemical analyses on Volcán de Colima are reported by Martín Del Pozzo *et al.* (1987). On this basis, they infer that both calc-alkaline andesites as well as alkaline basaltic magmas are present in the eruptive products of this volcano.

(ii) Trace elements

Verma *et al.* (1985) present data on alkali and alkaline earth elements on 8 samples as well as REE on 4 samples from Arandas-Atotonilco area in the western part of the MVB. They conclude that partial melting of a source with some residual garnet or of a LREE-enriched source coupled with the fractional crystallization of the observed modal phases dominated by hornblende and pyroxene are the main petrogenetic processes.

Ferriz (1985) reports trace element data on 4 samples of ignimbrites from Los Humeros caldera.

Luhr and Carmichael (1985) report trace element data on 6 representative lavas and scoria samples from the southern Colima graben and the Jorullo area. In conjunction with the Major-element compositions on the same samples, these data indicate that the contrasting alkalic and calc-alkaline magma suites cannot be related by any simple mechanism. Instead, they appear to record distinct melting events within the upper mantle.

The large number of samples of igneous rocks from the eastern part of the MVB studied by Nегendank *et al.* (1985) for major elements is also analyzed for the trace element contents. The authors test several petrogenetic models; the mantle wedge seems to be the most likely candidate for the source region of these magmas. They use several variation diagrams to further conclude that fractional crystallization of plagioclase and clinopyroxene is an important petrogenetic process.

Verma and Armienta-H. (1985) report alkali and alkaline earth element data on 9 samples from Chichinautzin Sierra, Valley of Mexico. The rocks studied are basalts, andesites and a dacite, all showing calc-alkaline affinity.

The trace element data on 9 samples of basaltic andesites erupted in the southern Guadalajara Volcanic Chain, studied by Luhr and Lazaar (1985) are compatible with their calc-alkaline nature as deduced from the major-elements.

(iii) Radiogenic isotopes.

Verma *et al.* (1985) report new $^{87}\text{Sr}/^{86}\text{Sr}$ data on 8 rock samples from Arandas-Atotonilco area, and Verma and Armienta-H. (1985) on 9 samples from Chichinautzin Sierra in the central part of the MVB, whereas Nегendank *et al.* (1985) present both Sr and Nd isotope data on 5 samples from the eastern part of the MVB. Verma and Armienta-H. (1985) also include one measurement of Nd isotopes on an olivine basalt sample from their study region. As a whole, it can be concluded that the sialic continental crust has not played an important role in the evolution of these magmas.

(iv) Stable isotopes

Unfortunately, no stable isotope data ($^{18}\text{O}/^{16}\text{O}$, D/H, $^{13}\text{C}/^{12}\text{C}$, etc.) are reported in the papers that constitute the MVB volume. However, Polak *et al.* (1985) use $^3\text{He}/^4\text{He}$ data on geothermal fluids from the MVB and an established correlation of world-wide helium isotopes with regional heat flow to compute heat flow values in

the MVB. The authors state that their "helium" heat flow data are in general agreement with the few published, directly measured values in the volcanic belt.

(v) Radiometric dating

The papers that report new K-Ar dates or present a compilation are: Verma *et al.* (1985), Venegas-S. *et al.* (1985), Gilbert *et al.* (1985), Nieto-O. *et al.* (1985), and Nixon *et al.* (1987).

Verma *et al.* (1985) report 4 dates from Arandas-Atotonilco area in the western part of the MVB, three of which are consistent at 11 ± 1 Ma, whereas the fourth is considerably higher (~ 32 Ma), the latter, however, may be in error due to an anomalous inherited ^{40}Ar component. Thus this volcanic region can be taken to be about 11 m.y. old.

Venegas-S. *et al.* (1985) present a compilation of radiometric dates from the MVB, 26 of them lie between 6 and 21 Ma whereas 57 samples are younger than about 5 Ma. Their compilation also includes 8 dates (older than 22 Ma) from the SMO. On this basis, they postulate the existence of volcanic hiatus in different sectors of the MVB.

Fifteen new K-Ar dates on volcanics from the Guadalajara area are reported by Gilbert *et al.* (1985). They range from 7.7 m.y. to 0.5 m.y.

Nieto-O. *et al.* (1985) present a compilation of K-Ar dates for the region between the SMO and the western part of the MVB. They also include 8 new dates, ranging from 26.7 m.y. to 0.88 m.y.

A compilation of K-Ar dates as well as 7 new dates are reported by Nixon *et al.* (1987). Although the compilation shows that the ages range from about 21 Ma to 0.03 Ma, the authors focus on the Plio-Quaternary evolution (1.7 m.y. to the Present) of the belt, during which time its development is intimately related to the contrasting subduction regimes of the Rivera and Cocos plates. The authors conclude that the width of the active arc has decreased appreciably during the Quaternary such that andesitic volcanism is presently focused nearest the trench. The average eruption rates for major Quaternary volcanoes are estimated at $0.2 - 0.3 \text{ km}^3/1000$ years.

(vi) Paleomagnetic constraints

The only paleomagnetic study presented is by Steele (1985) who, on the basis of normal directions of remanent magnetization observed for 24 lava flows from Iztacihuatl volcano, concludes that its present edifice was formed during the Bhunhes Chron, consistent with the recent K-Ar data on this volcano. Furthermore, he points out that the lavas studied were extruded during a period long compared to that of the secular variation of Earth's magnetic field.

B-4. Petrogenetic and tectonic models

Cebull and Shurbet (1987) present a modified intraplate transform version of their earlier microplate model (Shurbet and Cebull, 1984). Although admitting speculation in their treatment, they base their discussion on four major tectonic events. The oldest one (Mesozoic and/or Early Cenozoic) is taken to be responsible for the development of a "zone of weakness" along the trace of the present MVB. The next event (since Mesozoic) bearing on the MVB concerns the subduction along the west coast of North America. A third event is the beginning of sea-floor spreading in Cayman trough about 36 m.y. ago. A fourth important event to the north of the MVB is the opening of the Gulf of California and the development of basin-and-range faulting. Thus the lack of parallelism of the MVB and the MAT is explained in terms of the volcanic and tectonic activities associated with the zone of weakness resulting from the above mentioned events. They also argue that the fracture zone may help propagate volcanism that is independent of subduction processes.

Cameron *et al.* (1987) present a synthesis and a detailed comparison of the geochemistry of volcanic rocks of the SMO and the MVB. Comparison of the two dominantly calc-alkaline provinces shows distinct characteristics. Evolution of the volcanic suites at individual eruptive centers appears to have been controlled largely by crystal fractionation. The limited Sr and Nd isotope data suggest a significant interaction of parental magmas with old radiogenic crust for the SMO volcanics, but relatively minor interaction in the MVB area.

Close to 1 800 bulk-chemical analyses of volcanic rocks from the MVB have been compiled by Aguilar-y-Vargas and Verma (1987), who infer their geologic significance by subdividing the large data-set in terms of 10 morphological blocks and using a series of histograms and bivariate and ternary diagrams. They show that both calc-alkaline and alkaline magmas have erupted in the western and eastern extremes

of the MVB, whereas calc-alkaline products dominate in the central part of the belt. Thus, the MVB does not show a lateral systematic variation in its volcanic products, because a gradual increase is not observed in their alkali-contents as the distance between the magmatic arc and the MAT increases from west to east. The magmatic evolution of all the important strato-volcanoes appears to be rather similar, suggesting magmatic differentiation dominated by fractional crystallization and accompanied by magma mixing at some stage of their development.

Other petrogenetic deductions are already mentioned in earlier sections on geology and geochemistry.

Finally, although unrelated to the present section, we must mention the work on silica geothermometry by Prol and Juárez (1985), who use geochemical analyses of 176 thermal springs to prepare isotherm map of the MVB. The authors suggest that the highest maxima ($T > 150^{\circ}\text{C}$) are related to centers of high volcanic risk. On the other hand, temperature minima ($T < 110^{\circ}\text{C}$) within the volcanic belt belong to samples collected from areas underlain by Cretaceous sedimentary formations.

The paper by Manzanilla and Serra (1987) also needs to be mentioned. This presents a historical record of biological resources of the Cuenca de México. Its inclusion in an Earth Science journal is unusual but rather important as it deals with the problems of Mexico City, the area with perhaps the highest population in the world today. This work gives an indication of the availability of abundant food and raw materials needed for construction as well as communication facilities between the period of 2 500 A.C. to 1 500 D.C.

(C) UNSOLVED PROBLEMS

Although there is a considerable improvement in our knowledge of this important circum-Pacific geologic province of Mexico, there still remain many unsolved problems related to the MVB. Furthermore, there exist techniques and methods that are not yet applied in the study of this volcanic province.

(1) We still need detailed geologic mapping of many areas. The graben structures, major faults and calderas need to be paid a special attention in this respect.

(2) Accurate estimates of crustal thickness are very essential constraints for understanding the evolution of the volcanic belt. The actual nature of the crust and its chemical composition are equally important.

- (3) Possible effects of seismic gaps and fault planes on the magma types need to be addressed.
- (4) Changes in chemical and isotopic signatures of the magmas within the MVB, in both space and time, are to be explored in a comprehensive manner.
- (5) Both chemistry and isotopic compositions of contemporaneous calc-alkaline and alkaline activities constitute a major problem to be studied in detail.
- (6) More radiogenic (Sr, Nd, Pb, Hf, etc.) isotope and trace element data pertaining to the origin of volcanoes in the MVB have to be acquired and quantitatively tested for petrogenetic models. The use of stable isotopes for problems of petrogenesis should also be undertaken.
- (7) Radiometric dating has to be carried out on a systematic basis in order to better elucidate the geological evolution on a local as well as a regional scale. The problems of the age connotation and the nomenclature and definition of the MVB are also very significant and should be addressed in a Workshop/Seminar on the Mexican Volcanic Belt.
- (8) Further data on the chemistry of igneous rocks and sediments from the Cocos and the Rivera plates should be obtained in order to test their relation with the lavas from the MVB.
- (9) The role of subducted sediments in the magma genesis should also be addressed using better and modern isotopic techniques, especially through the study of ^{10}Be in them as well as in historic lavas from the belt.
- (10) Chemical and physical characteristics of subsurface magma chambers and accurate inferences on the heat source(s) in geothermal areas of the MVB are also of major relevance in the study of the belt.
- (11) A catalog of the volcanoes that comprise the MVB along with their physical and chemical characteristics may also be of immense value in further improving our knowledge in this volcanic province.
- (12) Finally, the question of non-parallelism of the MVB and MAT should be addressed in the light of the new evidence.

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