GEOFISICA INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA, AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 26 México, D.F., 1o de enero de 1987 Núm.1

MEXICAN VOLCANIC BELT: AN INTRAPLATE TRANSFORM?

S. E. CEBULL*
D. H. SHURBET*

RESUMEN

La evidencia temporal y "geométrica" sugiere que varios eventos regionales tectónicos fueron contribuyentes de mucha importancia durante la evolución del Cinturón Volcánico Mexicano (CVM). Estos incluyen (1) el desarrollo de una zona tectónica de debilidad en el área del actual CVM, seguido durante la época cenozoica por (2) actividad tectónica en la región caribe, que incluye la difusión a lo largo del fondo del mar en la depresión Caimán, (3) cesación progresiva de subducción hacia el Sur, a lo largo de la costa poniente de Norteamérica y Centroamérica, y (4) desarrollo del proto-Golfo, el Golfo de California, y fallas de tipo "basin-and-range" (extensional) al norte del CVM.

La zona de debilidad fijó el lugar y la orientación del CVM. Posteriormente, en correspondencia con la cesación de subducción por la costa de la América del Norte a la parte norte de la zona, se desarrollaron tectónicos extensionales. Al sur, por donde la subducción tipo chileno prevalecía, no fue posible el tectonismo extensional. De este modo, la zona de debilidad llegó a ser un cinturón de acomodación, quizás asociado con extensión interna, entre regiones de kinemáticos estructurales contrastantes. En breve, llegó a ser un transforme de tipo intraplaca (con fuga) [en el sentido de Davis, 1980], por donde fue posible y se localizó el volcanismo. Paradójicamente, esta interpretación implica que el volcanismo a lo largo del CVM está más aliado a la cesación de la subducción al norte del CVM que a la subducción continua hacia el Sur. También da a entender que el CVM es fundamentalmente diferente de los arcos volcánicos típicos del borde pacífico.

* *Department of Geosciences, Texas Tech. University, Lubbock, Texas 79409, USA.*

ABSTRACT

Temporal and "geometric" evidence suggests that several regional tectonic events were especially important contributors during the evolution of the Mexican Volcanic Belt (MVB). These include (1) development of a tectonic zone of weakness in the area of the present MVB, followed in Cenozoic time by (2) tectonic activity in the Caribbean region that includes sea-floor spreading in the Cayman Trough, (3) progressive southward cessation of subduction along the west coast of North and Central America, and (4) development of the proto-Gulf, Gulf of California, and basin-and-range (extensional) faulting north of the MVB.

The zone of weakness fixed the location and orientation of the MVB. Subsequently, in response to cessation of subduction along the coast of North America, extensional tectonics developed to the north of the zone. To the south, where subduction of Chilean-type prevailed, extensional tectonism was inhibited. Thus, the zone of weakness became a belt of tectonic accomodation, perhaps associated with internal extension, between regions of contrasting structural kinematics. In short, it became an (leaky) intraplate transform (in the sense of Davis, 1980) along which the volcanism was both permitted and localized. Paradoxically, this interpretation implies that volcanism along the MVB is more closely allied to the *cessation* of subduction north of the MVB than to on-going subduction to the south. It further implies that the MVB is fundamentally unlike the typical volcanic arcs of the Pacific rim.

INTRODUCTION

In an earlier paper we suggested that the Mexican Volcanic Belt (MVB) is serving the function of an incipient plate boundary between the North America plate to the north and a developing (or possibly aborted) microplate to the south (Shurbet and Cebull, 1984). This interpretation was based partly on seismic data, albeit limited, that permits the interpretation that the belt is presently in a transtensional regime, the nearly horizontal slip vectors being disposed at an acute angle to the trend of the belt (at an azimuth similar to those associated with the coastal seismic zone). Also, we indicated that the MVB does not appear to be related directly to contemporary subduction, as some others have suggested (e.g. Molnar and Sykes, 1969; Couch and Woodcock, 1981; and Uyeda, 1982). Our interpretations have been criticized recently by Suárez and Singh (in press).

Although there is a wide diversity of interpretations regarding the tectonic origin and subsequent development of the belt (e.g. Mooser, 1968; Molnar and Sykes, 1969; LePichon and Fox, 1971; Gastil and Jensky, 1973; Mooser and others, 1974; Couch and Woodcock, 1981; Urrutia-Fucugauchi, 1981a, 1981b; Anderson and Schmidt, 1983), we focused chiefly on the MVB as a contemporary entity. Here, we consider some aspects of its developmental history.

Such consideration is speculative and based on the work of many others. However, we offer a new suggestion, namely that the MVB has responded to regional stresses as an "intraplate transform" (in the sense of Davis, 1980) for at least the latter part of its long and enigmatic history. The term, as used here, refers to a linear zone that separates, and allows the "uncoupling" of, regions of contrasting tectonism. Although the history of the MVB doubtlessly is complicated, as suggested by the variety of evidence and the plethora of proposals put forth to explain it, four events are of particular importance to our proposal. These are summarized in the next section. We omit discussion of many other events important to the geologic development of Mexico and Central America, such as the possible development and role of the Mojave-Sonora megashear (Silver and Anderson, 1974), of continental truncation along the west coast (de Cserna, 1969; Kesler and Heath, 1970), and of rotation and/or reorganization of microplates (e.g. Pal and Urrutia-Fucugauchi, 1977; Anderson and Schmidt, 1983), because they are neither central to our proposal (applying Occam's Razor) nor incompatible with it.

FOUR IMPORTANT TECTONIC EVENTS IN THE REGION

The estimated ages and durations of these four major tectonic events are summarized in figure 1. The oldest, an event that may bear more directly on the character of the MVB than others, involves the development of a "zone of weakness" along the trace of the present MVB. For example, one hypothesis concerning the origin of this zone involves the segmentation of Mexico by three linear zones of apparent faulting. These fault zones, although the subject of continued uncertainty, are delineated on the basis of interpreted offset of Precambrian and Paleozoic rocks as well on geophysical data (de Cserna, 1970) and by the offset of subbelts of Mesozoic batholithic rocks and mineral deposits (Gastil and Jensky, 1973). The southernmost of these coincides with the MVB. De Cserna (1970, 1976) interpreted the zones as left-lateral strike-slip faults and suggested that they developed in Permian to Triassic time. Gastil and Jensky (1973) proposed that the southernmost zone was the site of two intervals of right-lateral strike-slip displacement, the first near the end of Mesozoic time, the second in Miocene or Pliocene time. In a somewhat different approach, Pal and Urrutia-Fucugauchi (1977) depict this zone as a late Cretaceous-early Cenozoic suture between a portion of the Farallon plate and the continent ("western cordillera") to the north, Urrutia-Fucugauchi (1981a, 1981b) suggests that it is a shear zone affected by rotations of adjacent blocks to the north and south, and Anderson and Schmidt (1983) regard it as a transform fault bounding the Yaki and Maya microplates, to cite but a few examples.

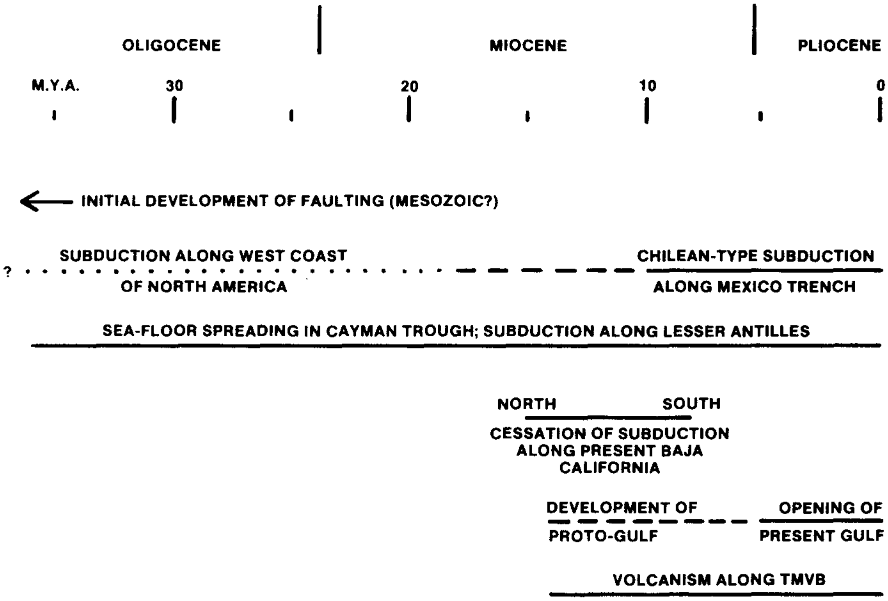

Fig. 1. Chronology of four major tectonic events that bear on the origin and development of the Mexican Volcanic Belt (MVB). See text for sources.

A second event that bears on the development of the MVB is that of subduction along the coast of North and Central America. This subduction was established by Mesozoic time, but its relation to the fault zones that segment or otherwise cut across Mexico is unclear. Its northern limit ultimately became marked by the southern triple junction along the lengthening San Andreas transform, a junction which gradually moved southward during the latter half of the Tertiary (Atwater, 1970; Pal and Urrutia-Fucugauchi, 1977). Details of the pattern of the subduction zone(s) depend on the specific plate-tectonic reconstruction of microplate relationships. In the region of present Baja California, subduction ceased progressively from north to south during an interval of about 15 to 8-10 m.y. ago; at present it is confined to the region immediately south of the MVB, where it is marked by the Mexico and Guatemala trenches. Uyeda (1982) suggests that a present phase of subduction along Central America began about Early Miocene time, at about the time of inception of volcanism along the MVB, and that Chilean-type subduction, characterized by backarc compression, developed along the Mexican trench at least by the time interval of 19 to 10 m.y. ago.

A third event that may have had an effect on the development of the MVB is the sea-floor spreading that commenced in the Cayman Trough (Pindell and Dewey, 1982), perhaps initiated by clockwise rotation in Eocene time of the Caribbean plate with respect to the North America plate (MacDonald, 1974). This spreading began about 36 m.y. ago and was associated with the inception of left-lateral displacement between the Caribbean and North America plates and commencement of subduction along the Lesser Antilles.

A fourth important tectonic event is the development of the Gulf of California and of basin-and-range faulting, both occurring chiefly to the north of the MVB. The history of the Gulf comprises two phases. The first phase, postulated by Karig and Jensky (1972), was the development of a proto-Gulf of California in about mid to late Miocene time. It was associated with basin-and-range faulting, which is poorly dated. To the north, in the United States, this faulting probably began about 17 m.y. ago, although it could have begun earlier in Arizona and New Mexico (Stewart, 1978). Opening of the present Gulf of California began approximately four to six million years ago (Larson and others, 1968) at which time the southern part of what is now Baja California pulled away from the portion of the coast of Mexico as far south as the western end of the MVB. It was approximately at the beginning of this interval of proto-Gulf and Gulf development and of basin-and-range faulting that volcanism commenced along the MVB. Although the time of onset of volcanism has been variously estimated, Gastil and Jensky (1973) suggest that it began in about Middle Miocene time, possibly approximately 14 m.y. ago.

SEQUENCE OF MAJOR EVENTS

A simplified progressive, four-stage depiction of the events described above is shown in figure 2. In Paleogene time (Fig. 2A) the entire western margin of Central and North America was the site of active subduction. As indicated earlier, the pattern of subduction zones, which depends on the interpretation of microplate organization, doubtlessly was more complex than depicted here. The zones of crustal weakness, possibly old fault zones, that characterized the adjacent continent already had developed, and sea-floor spreading in the Cayman Trough had begun. Part of the spreading was westward (Fig. 2A). During Middle and Late Miocene (Fig. 2B) subduction along the coast of what is now Baja California ceased progressively from north to south. The proto-Gulf of California developed in conjunction with basin-and-range faulting, and volcanism along the MVB commenced. Subduction in the Mexico trench was, or had become, of Chilean type. By latest Miocene and earliest

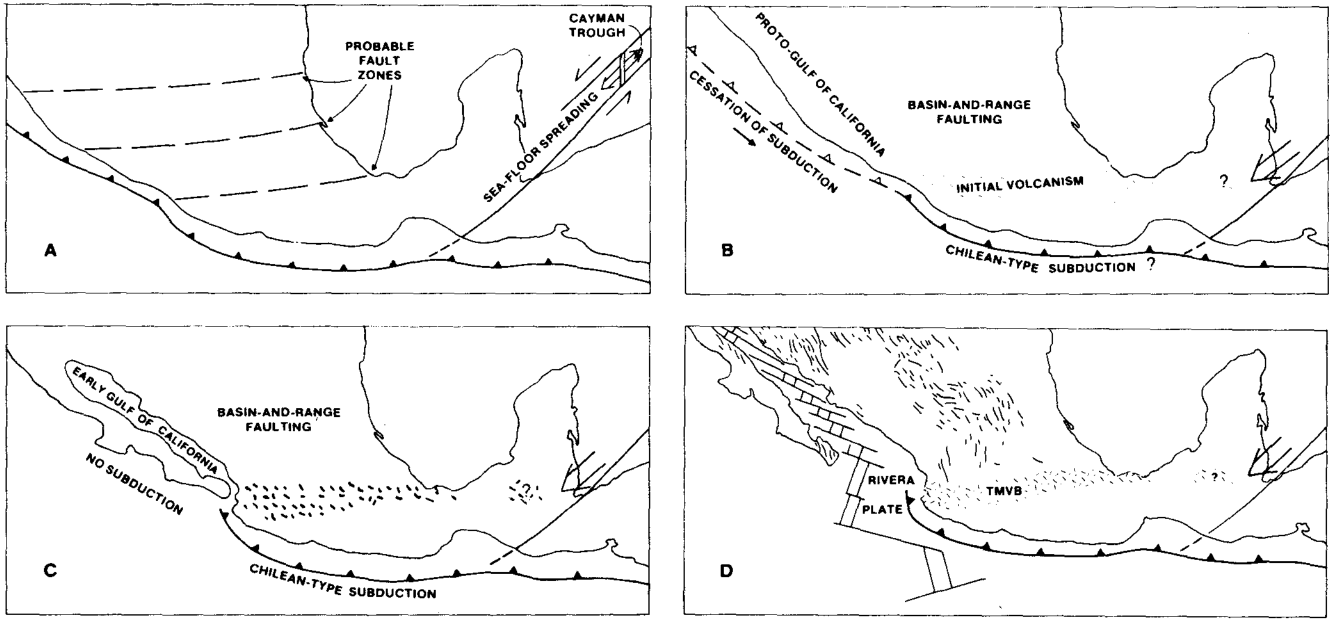

Fig. 2. Development of the MVB depicted at four generalized stages: (A) Paleogene, characterized by presence of a pre-MVB (Mesozoic?) zone of weakness, or fracture zone, along the trend of the present MVB, sea-floor spreading in the Cayman Trough, and subduction along the west coast of North and Central America. Early pattern of subduction, probably more complicated than depicted here, depends on specific interpretations of microplate relationships (not shown). "Probable fault zones" (*from* de Cserna, 1970) represent one of several proposals for development of the early-formed zone of weakness; (B) Middle to Late Miocene, marked by north-to-south cessation of subduction, possible development of the Proto-Gulf of California, early extensional tectonics north of the MVB, onset of volcanism along the MVB, and possible Chilean-type subduction to the south of the MVB; (C) latest Miocene and earliest Pliocene, characterized by termination of subduction, opening of the present Gulf of California, and continuing extensional tectonism north of the MVB along with Chilean-type subduction south the MVB; (D) present, showing "late Cenozoic extensional faults" of Stewart (1978).

Pliocene time (Fig. 2C) the present Gulf of California had begun to open. Subduction along the Mexico trench continued, and the current plate arrangement in the region (Fig. 2D) was established. This arrangement of plates is characterized not only by the well-known transform spreading of the Gulf of California, but also by delineation of the Rivera plate just west of the MVB. This plate is remarkable for its apparent tectonic inconsistency. To the north it is part of the North America plate (*see* Atwater, 1970), but to the south it may be undergoing subduction. Presently, this change in plate demeanor occurs at the western end of the MVB. The relationship between the Rivera plate and at least the western portion of the MVB has been discussed recently by Luhr and others (1985).

DISCUSSION AND INTERPRETATION

Theories concerning the origin and development of the MVB can be divided into two loosely delineated categories. The first relates this feature, and its origin, directly to the present subduction system, the second to various combinations of tectonic events that include the early development of a zone of weakness that fixes the position of the ensuing volcanism.

A basic premise of theories of the first category is that the MVB is fundamentally similar to most other volcanic arcs around the Pacific Ocean margin (except, of course, that the volcanic chain does not parallel the subduction zone). Such arcs are a direct result of subduction, which produces zones of generally calc-alkaline volcanism parallel to a trench and about 100 km immediately above the downgoing slab. These theories explain the peculiar geometry of the MVB as the result mainly of diminishing southward dip of the downgoing slab. Absence of a seismically well-defined Benioff zone beneath part of the arc is interpreted to mean that the downgoing slab is present but aseismic (e.g. Nixon, 1982). Variation in the products of volcanism along the length of the arc is explained, in part, by variations in the nature and age of the downgoing slab and/or by the presence of an "eastern alkaline province", the origin of the latter being unrelated to the MVB (e.g. Robin, 1982; Nixon, 1982). Overall, this is an attractive view, but elements of it cause us concern.

First, and most obviously, is the lack of parallelism of the MVB and the Mexico trench. To the east, the MVB is progressively more distant not only from the Mexico trench but also from the clearly subduction-related coastal zone of seismic activity, thereby leaving an intervening area largely devoid of intermediate-depth seismicity (Shurbet and Cebull, 1984). Second, as Nixon (1982) noted recently, "most of the volcanoes of the MVB are located more than 50 km beyond the terminus of the inclined seismic zone" (*i.e.* the end of the downgoing slab as seismically defined). Third, the MVB apparently is characterized by considerable variation in its volcanic suites. Although much of the volcanism is andesitic, a good deal is not (e.g. Luhr and others, 1985), and most along the eastern portion of the belt is alkaline. Although the volcanic evidence is by no means definitive (anonymous reviewer), among some workers it has raised questions concerning the relation of the downgoing slab to the volcanism. For example, Robin (1982) suggests that the influence of a downgoing slab on the composition of the volcanic rocks is absent to modest and possibly increasing to the west, and Verma (1983) indicates that some magmas in the eastern part of the MVB (Los Humeros caldera) ". . . were generated in the upper mantle with very little, if any, contribution from the subducted oceanic crust, sediments or continental crust." Thus, on balance, it is difficult to assert that MVB volcanism, to the degree that it is understood, is typical of island arcs.

Theories of category two are mainly more "historically" oriented, more complex, and more diverse. They focus less on the configuration of the present downgoing slab beneath southern Mexico and more on past and/or regional tectonic events, part of which are recorded in the complexities of the pre-MVB basement. The number and diversity of these theories makes a review impractical here, but most have two elements. The first deals with orientation, or geometry, the second with volcanism.

In general, these theories suggest that the orientation of the MVB can best be attributed to the presence of an early-formed, east-west trending zone of weakness (e.g. de Cserna, 1970; Gastil and Jensky, 1973; Pal and Urrutia-Fucugauchi, 1977). Some have the advantage of explaining the orientation of the MVB with reference to features outside the belt, namely other linear structures to the north that essentially parallel the MVB, others refer to regional tectonic events that help to explain the overall development of the region. Whatever their nuance, such theories are free of the necessity of explaining an apparently long-term historical event, the development of the MVB, chiefly on the basis of the interpreted configuration of a currently subducting slab.

However formed, the proposed pre-existing zone of weakness, rather than the present subduction system, would control the location of the volcanism and, hence, the orientation of the MVB. This suggests that the volcanism is at least partly a response to tectonic activity associated with the fracture zone, activity that began in about Middle Miocene time, and not *directly* to subduction. Such an interpretation does not imply that volcanism along the MVB is wholly unrelated to subduction. It does imply that any magmatic-volcanic activity that is propagated by the downgoing slab is controlled by a fracture zone that exists independently of subduction. It also implies that the fracture zone may propagate volcanism that is independent of subduction processes.

A crucial question in this interpretation is why volcanism along the MVB was delayed until about Miocene time when the fracture zone may be as old as Mesozoic. Temporal relations (Figs. 1 and 2) suggest that initiation of volcanism along the MVB in some way was associated with extensional tectonism to the north of the MVB, as reflected by the development of the proto-Gulf and Gulf of California and by basin-and-range faulting. This tectonism is in contrast with that to the south, where compression prevailed in response to Chilean-type subduction (Uyeda, 1982) and possibly to westward sea-floor spreading in the Cayman Trough and subduction beneath the Lesser Antilles, both of which began earlier (MacDonald, 1974). Thus, we suggest that the MVB acted as an intraplate transform, a zone that accomodated the differing tectonic responses of the regions to the north and south. Strains within the zone were probably complicated but at least partly extensional, thereby allowing magmas to rise and volcanism to occur. The general scheme of the proposal is illustrated in figure 3.

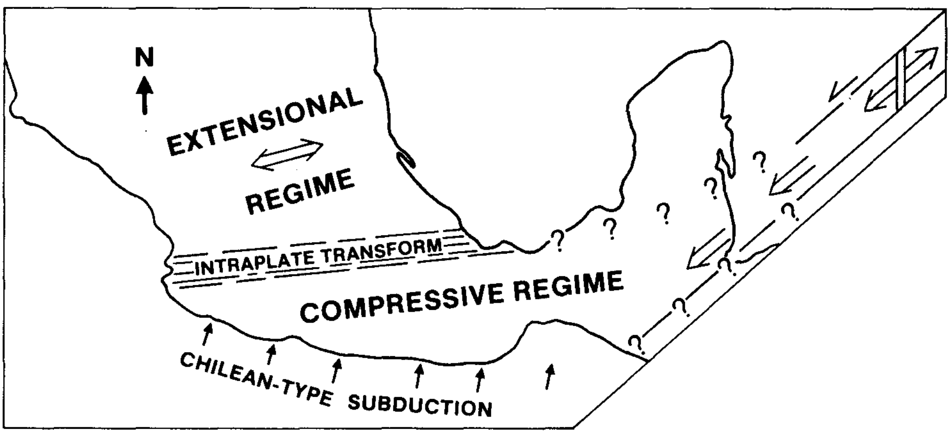

Fig. 3. Interpretation of the MVB as an (leaky) intraplate transform, a narrow zone that accomodates the development of differing tectonic regimes in immediately adjacent regions. Double arrow north of the MVB is approximately perpendicular to the trend of the late Cenozoic extensional fault pattern shown in figure 2d. Question marks indicate uncertainty of relationship of MVB to areas farther east.

The temporal relation between the progressive southward cessation of subduction along the west coast and the development of extensional tectonics north of the MVB is such as to indicate that the two are genetically related. Thus, we suggest further that the extensional tectonism is the product of the termination of subduction and, paradoxically, that the ensuing volcanism is not so much related to subduction as to the *cessation* of subduction. Where subduction continued, south of the MVB, highly developed extensional tectonism did not prevail.

CONCLUSIONS

As many others, we conclude that the orientation of the MVB probably is controlled by a fracture or zone of weakness of probable Mesozoic (and/or early Cenozoic) age but uncertain origin. Hence, its orientation need not be related to present subduction. However, unlike other workers, we suggest that volcanism along the zone was permitted by the tectonic response within the zone, at least partly extensional, to contrasting tectonism to the north and south. To the north, cessation of subduction promoted extensional tectonism, whereas, to the south, such tectonism was inhibited by Chilean-type subduction and, possibly, by westward sea-floor spreading in the Cayman Trough. If this proposal is correct, the MVB played the role of a "leaky" intraplate transform. Resulting volcanism probably was (and is) influenced by subduction, but was controlled chiefly by the fracture zone itself. Although this hypothesis, which certainly requires rigorous examination, does not necessarily support our earlier proposal of contemporary transtension along the MVB, it is both compatible with it and independent of it. It is also compatible with most of the broad tectonic syntheses of the region, such as that of Anderson and Schmidt (1983).

ACKNOWLEDGEMENT

We thank Dr. Lorum H. Stratton for his translation of our abstract into Spanish.

BIBLIOGRAPHY

ANDERSON, T. H. and V. A. SCHMIDT, 1983. The evolution of middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time. *Geol. Soc. Am. Bull.*, *94*, 941-966.

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

COUCH, R. and S. WOODCOCK, 1981. Gravity and structure of the continental margins of southwestern Mexico and northwestern Guatemala. *J. Geophys. Res., 86,* 1829-1840.

CSERNA, Z. de, 1969. Tectonic framework of southern Mexico and its bearing on the problem of continental drift. *Bol. Soc. Geol. Mex., 30,* 159-168.

CSERNA, Z. de, 1970. Mesozoic sedimentation, magmatic activity and deformation in northern Mexico, *in* The geologic framework of the Chihuahua tectonic belt. W. Texas Geol. Soc., p. 99-117.

CSERNA, Z. de, 1976. Mexico – Geotectonics and mineral deposits, *in* Tectonics and Mineral Resources of Southwestern North America. New Mex. Geol. Spec. Pub; No. 6, p. 18-25.

DAVIS, G. A., 1980. Problems of intraplate extensional tectonics, western United States, *in* Continental Tectonics, Nat. Acad. Sci. Stud. Geophys., p.84-95.

GASTIL, R. G. and W. A. JENSKY, 1973. Evidence for strike-slip displacement beneath the Trans-Mexico volcanic belt, *in* Proc. Conf. Tectonic Problems of the San Andreas Fault System, Stanford Univ. Pub. Geol. Sci., p.171-181.

KARIG, D. and W. A. JENSKY, 1972. Proto-Gulf of California. *Earth Planet. Sci. Lett., 17,* 169-174.

KESLER, S. E. and S. A. HEATH, 1970. Structural trends in the southernmost North American Precambrian, Oaxaca, Mexico. *Geol. Soc. Am. Bull., 81,* 2471-2476.

LARSON, R. L., H. W. MENARD and S. M. SMITH, 1968. Gulf of California: A result of ocean-floor spreading and transform faulting. *Science, 161,* 781-783.

LEPICHON, X. and P. J. FOX, 1971. Margin offsets, fracture zones and the early opening of the North Atlantic. *J. Geophys. Res., 76,* 6294-6308.

LUHR, J. F., S. A. NELSON, J. F. ALLEN and S. E. CARMICHAEL, 1985. Active rifting in southwestern Mexico: Manifestations of an incipient eastward spreading-ridge jump. *Geology, 13,* 54-57.

MacDONALD, W., 1974. Cretaceous-Tertiary evolution of the Caribbean, *in* Trans. VII Caribbean Geol. Conf., p.69-78.

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

MOOSER, F., 1968. The Mexican Volcanic Belt: structure and development. Formation of fractures by differential crustal heating. *Pan Am. Sympos. Upper Mantle, II,* 15-22.

MOOSER, F., A. E. M. NAIRN and J. F. W. NEGENDANK, 1974. Paleomagnetic investigations of the Tertiary and Quaternary igneous rocks: VIII. Paleomagnetic and petrologic study of volcanics of the Valley of Mexico. *Geol. Rundschau, 63,* 451-483.

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

PAL, S. and J. URRUTIA-FUCUGAUCHI, 1977. Paleomagnetism, geochronology and geochemistry of some igneous rocks from Mexico and their tectonic implications, *in* IV. Intern. Gondwana Sympos., Calcutta, Hindustan Pub. Corp., Dehli, p.814-831.

PINDELL, J. and J. F. DEWEY, 1982. Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. *Tectonics, 1,* 179-211.

ROBIN, C., 1982. México, *in* Andesites: Orogenic Andesites and Related Rocks, Wiley and Sons, New York, p.137-147.

SHURBET, D. H. and S. E. CEBULL, 1984. Tectonic interpretation of the Trans-Mexico Volcanic Belt. *Tectonophysics, 101,* 159-165.

SILVER, L. T. and T. H. ANDERSON, 1974. Possible left lateral early to middle Mesozoic disruption of the southwestern North American craton margin [abs]. *Geol. Soc. Am. Abstr. with Programs, 6,* 995.

STEWART, J. H., 1978. Basin-range structure in western North America: A review. *Geol. Soc. Am. Mem. 152,* 1-31.

SUAREZ, G. and S. K. SINGH, 1986. Comment on "Tectonic Interpretation of the Trans-Mexico Volcanic Belt". *Tectonophysics,* in press.

URRUTIA-FUCUGAUCHI, J., 1981a. Palaeomagnetism of the Miocene Jantetelco granodiorites and Tepexco volcanic group and inferences for crustal block rotations in central Mexico. *Tectonophysics, 76,* 149-168.

URRUTIA-FUCUGAUCHI, J., 1981b. Paleomagnetic evidence for tectonic rotation of northern Mexico and the continuity of the Cordilleran orogenic belt between Nevada and Chihuahua. *Geology, 9,* 178-183.

UYEDA, S., 1982. Subduction zones: an introduction to comparative subductology. *Tectonophysics, 81,* 133-159.

VERMA, S. P., 1983. Magma genesis and chamber processes at Los Humeros Caldera, Mexico – Nd and Sr isotope data. *Nature, 301,* 52-55.

(Received: April 15, 1985)
(Accepted: October 29, 1985)

It is recommended that reference to this paper be made as follows:

S. E. Cebull and D. H. Shurbet, 1987. Mexican Volcanic Belt: An intraplate transform? *Geofís. Int.,* Special Volume on Mexican Volcanic Belt - Part 3A (Ed. S. P. Verma), Vol. 26, pp. 1-13