

# Absence of Cocos plate subduction-related basic volcanism in southern Mexico: A unique case on Earth?

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## ABSTRACT

The relationship between volcanism and subduction of the Cocos plate is examined on the basis of new as well as published Sr, Nd, and Pb isotopic and geochemical data on late Miocene to Holocene (ca. 9–0 Ma) basic volcanic rocks from southern Mexico and Central America. Basic rocks (with  $\text{SiO}_2 < 52\%$ ) were chosen in order to minimize the effects of crustal-assimilation processes and, therefore, to test the contribution from deeper sources: the subducted Cocos plate and the mantle wedge. By using fluid-mobile to relatively fluid-immobile elements and radiogenic isotope ratios for such rocks, I show that the subduction of the Cocos plate does not contribute to the basic volcanism in all of southern Mexico as opposed to that in Central America (from Guatemala to northwestern Costa Rica). South Mexican volcanism is related to ongoing rifting processes, inferred from field geology, seismology, gravity, tectonics, and volcano alignments. This lack of subduction relationship probably represents the first case on Earth where the ongoing subduction of an oceanic plate does not give rise to basic volcanism, such as is present throughout southern Mexico.

**Keywords:** Mexico, Central America, subduction, rift, volcanism, geochemistry.

## INTRODUCTION

The Cocos plate has been subducting beneath the North American plate (i.e., beneath southern Mexico; Fig. 1) along the northwestern part of the Middle America Trench and beneath the Caribbean plate (i.e., beneath Central America), along the southeastern part (Burbach et al., 1984; Pardo and Suárez, 1995; Protti et al., 1995). Miocene to Holocene volcanism in southern Mexico (Fig. 1) is distributed along the central and eastern parts of the Mexican volcanic belt and the Los Tuxtlas volcanic field, as well as isolated centers such as El Chichón volcano. The volcanic front of the Mexican volcanic belt is far away from the trench, at a distance of ~220 km in the west to ~450 km in the east along the volcanic

belt; the Los Tuxtlas volcanic field and El Chichón volcano are located ~350 km from the trench. Farther south in Central America (from Guatemala to Costa Rica; Fig. 1), however, the arc-trench relationship becomes “normal” because the volcanoes are subparallel to the trench and the volcanic front is only ~150–190 km away from it.

To explain these geometric differences between the Mexican and Central American volcanism, several explanations have been put forth; none of them is totally satisfactory. Earthquake hypocenter depths (Burbach et al., 1984; Pardo and Suárez, 1995) summarized in Figure 2A show that the slab can be traced to ~240 km depth beneath Central America (from Guatemala to Nicaragua); elsewhere, this depth is generally <80 km in most areas, with only a few deeper seismic events. In southern Mexico, the Cocos plate depth contours deeper than ~60 km (Fig. 1) and the Wadati-Benioff zone corresponding to the

Mexican volcanic belt are not clearly defined; volcanoes are far away from the terminus of this zone. The Wadati-Benioff zone is shallow (~60 km) and in a tensional regime (Singh and Pardo, 1993). No magmas are likely to be generated from a subhorizontal subducted slab at such a shallow depth. Such diminution or even cessation of arc-related volcanism has been proposed for subhorizontal subduction of the Nazca plate beneath the south-central Andes (Kay et al., 1987). However, widespread volcanism occurs throughout southern Mexico, particularly along the entire east-trending Mexican volcanic belt (Fig. 1). To overcome this problem, an extrapolation of the subducted Cocos plate to greater depths has been proposed (Pardo and Suárez, 1995), but this extrapolation has been shown to be controversial (Verma, 2001).

Geochemical data, including radiogenic isotopes, for basic volcanic rocks from a wide area of southern Mexico and Central America and from well-known rifts, as well as for mid-oceanic-ridge basalt (MORB) and sediments from the subducting Cocos plate, have been tabulated<sup>1</sup>. These data are used to better define the relationship between volcanism and this subduction and to show a unique case on Earth where the subduction process is not generating volcanism above a large part of the slab.

<sup>1</sup>GSA Data Repository item 2002129, Table DR1 (new data), Table DR2 (synthesis of all compiled data), Figures DR3–DR5 (Figs. 1–3 color versions), Figure DR6 (Fig. 4—multielement plot), and relevant references, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at [www.geosociety.org/pubs/ft2002.htm](http://www.geosociety.org/pubs/ft2002.htm).

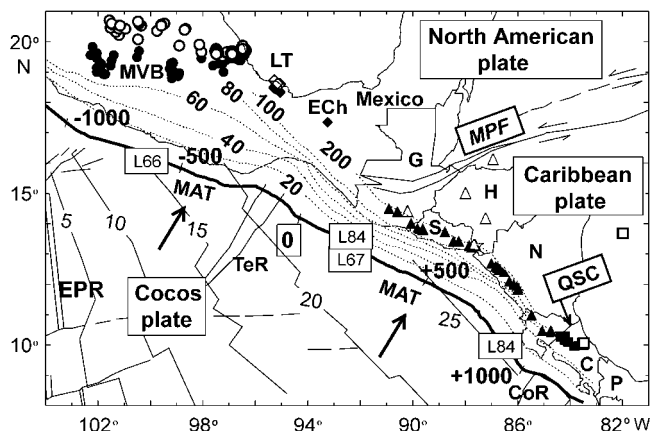
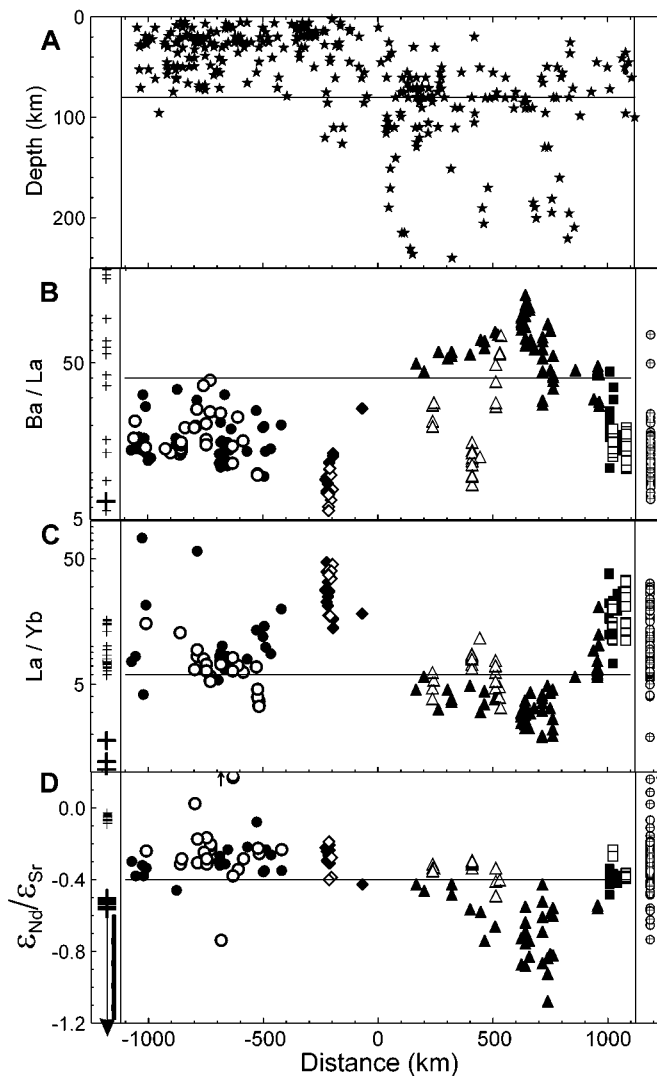


Figure 1. Simplified map of sample locations in southern Mexico and Central America. MAT—Middle America Trench; EPR—East Pacific Rise; TeR—Tehuantepec Ridge; CoR—Cocos Ridge; MPF—Motagua-Polochic fault system; QSC—Quesada sharp contortion; MVB—Mexican volcanic belt; LT—Los Tuxtlas volcanic field; ECh—El Chichón volcano. Central American countries: G—Guatemala; S—El Salvador; H—Honduras; N—Nicaragua; C—Costa Rica; and P—Panama. Approximate age (in Ma) of Cocos plate is shown schematically by contours marked 5, 10, 15, 20, and 25. In addition, depth contours (in km) on subducted Cocos plate, as inferred from earthquakes, are included for reference; note abrupt changes in depth contours (80 and 100 km depth) south of Quesada sharp contortion and absence of deep earthquakes in southern Mexico, especially below Mexican volcanic belt. Numbers (0, ±500, ±1000) along MAT are approximate distances (in km) as measured from central point (marked 0) close to Mexico-Guatemala border; these numbers refer to x-axis in Figure 2. Approximate locations of Deep Sea Drilling Project Legs 66 (L), 67, and 84 are also shown for reference. Solid and open symbols correspond to volcanic “front” and “behind front,” respectively.

**Figure 2.** Selected parameters for basic rocks ( $\text{SiO}_2 < 52\%$ ) from southern Mexico and Central America plotted against distance along trench axis (Middle America Trench [MAT] in Fig. 1) as measured from close to Mexico-Guatemala border—marked 0 km distance. Distances corresponding to Mexico are expressed as negative values and those for Central America as positive ones. Data are plotted by using same symbol codes as in Figure 1 for sample locations. Also included are data for same parameters for basic rocks from six well-known rifts (crossed circle symbols at right part of diagrams), as well as for mid-ocean-ridge basalt (MORB) and sediments from subducting Cocos plate (crosses at left part of diagrams; large crosses are for MORB and small ones for overlying sediments). A: Depth of earthquake hypocenters from Mexico to Costa Rica (horizontal reference line is for depth = 80 km). B: Ba/La ratio, which when high indicates subduction signature (horizontal reference line is for Ba/La = 40). C: La/Yb ratio, which when high indicates mantle signature (horizontal reference line is for La/Yb = 6). D:  $\epsilon_{\text{Nd}}/\epsilon_{\text{Sr}}$ , which when high indicates mantle signature, where  $\epsilon = [(R_{\text{sample}} - R_{\text{CHUR}})/R_{\text{CHUR}}] \times 10^4$ ;  $R = {}^{143}\text{Nd}/{}^{144}\text{Nd}$  and  ${}^{87}\text{Sr}/{}^{86}\text{Sr}$  for  $\epsilon_{\text{Nd}}$  and  $\epsilon_{\text{Sr}}$ , respectively. Ratio of  $\epsilon_{\text{Nd}}/\epsilon_{\text{Sr}}$  was calculated by using  $({}^{143}\text{Nd}/{}^{144}\text{Nd})_{\text{CHUR}} = 0.512638$  and  $({}^{87}\text{Sr}/{}^{86}\text{Sr})_{\text{UR}} = 0.70475$  (horizontal reference line is for  $\epsilon_{\text{Nd}}/\epsilon_{\text{Sr}} = -0.4$ ). For Cocos plate, mixtures of MORB and sediments are also shown by using solid line and arrow.



## DISCUSSION OF GEOCHEMICAL DATA

Geochemical fingerprints of subducted slabs, i.e., fluid-mobile elements, and mantle wedges, i.e., relatively fluid-immobile elements, as well as ratios of these elements, are used to highlight significant differences in geochemical and isotopic characteristics of basic volcanism between southern Mexico and Central America and, therefore, in their petrogenetic sources.

A high Ba/La ratio (Ba, a large ion lithophile element [LILE], is fluid mobile and, therefore, indicative of slab; and La, a rare earth element [REE], is relatively fluid immobile and, therefore, indicative of mantle wedge) is considered an excellent subduction signal (e.g., Carr et al., 1990). In the basic rocks ( $\text{SiO}_2 < 52\%$ ) from southern Mexico and Central America, the Ba/La ratio shows a remarkable geographic variation (Fig. 2B). The Ba/La ratio is  $< 40$  in all of southern Mexico, increases to higher values (reaching  $\sim 130$ ) from Guatemala to northwestern Costa Rica, and decreases again to low values ( $< 45$ )

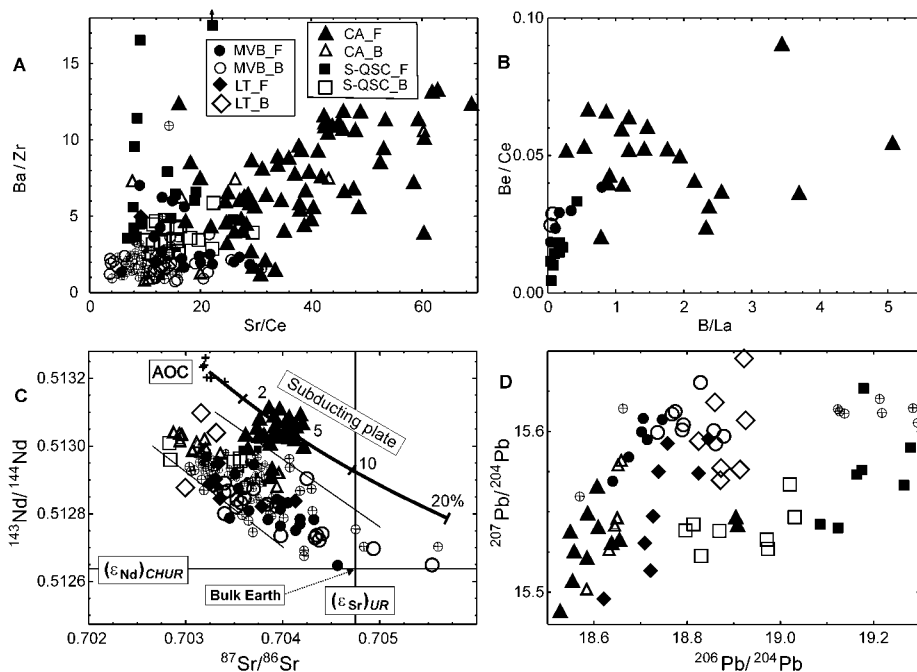
in southeastern Costa Rica (south of Quesada sharp contortion [QSC] in Fig. 1).

The La/Yb ratio (La, a light REE, is a highly incompatible element, and Yb, a heavy REE, is a less incompatible element; both are relatively fluid-immobile elements) is an excellent indicator of degree of enrichment or degree of melting of mantle sources (Fig. 2C). Compared to the Ba/La ratio, La/Yb shows an inverse behavior, as documented in the Central American volcanic arc (Carr et al., 1990). Low La/Yb ratios (generally  $< 6$ ) characterize the basic rocks from Guatemala to Nicaragua, but La/Yb increases to high values (to  $\sim 40$ ) in northwestern as well as southeastern Costa Rica. In southern Mexico, this ratio is elevated (generally  $> 6$ ), reaching values as high as  $\sim 75$ .

I propose the ratio of two isotopic ratios ( $\epsilon_{\text{Nd}}/\epsilon_{\text{Sr}}$ ; Fig. 2) as an excellent variable to highlight the differences between mantle sources and subducted slab inputs. In southern Mexico and southeastern Costa Rica, the basic rocks show values generally  $> -0.4$  ( $+0.458$  to  $-0.397$ , 49 data points; only three lower

values [ $-0.431$  to  $-0.735$ ] were found), whereas for the rest of Central America under study (Guatemala to northwestern Costa Rica), the rocks, especially those from the front-arc areas, have values (front arc:  $-1.086$  to  $-0.428$ , 36 data points; backarc:  $-0.491$  to  $-0.290$ , 17 data points) generally  $< \sim -0.4$  (Fig. 2D).

A comparison of geochemical and isotopic data from southern Mexico and Central America (Fig. 2; Table DR2, see footnote 1) with those from rifts as well as from the subducting Cocos plate provides petrogenetically useful information. Rift-like ratios are observed for basic rocks from all of southern Mexico and southeastern Costa Rica, whereas subduction-like signatures (similar to those of the Cocos plate) characterize rocks from other parts of Central America (Guatemala to northwestern Costa Rica). Another salient feature of the geographic distribution of the data (Fig. 2; Table DR2, see footnote 1) to be explained by any model, is that, for southern Mexico and to a lesser extent for southeastern Costa Rica, there are no significant differences between



**Figure 3.** Selected plots for basic rocks ( $\text{SiO}_2 < 52\%$ ) from southern Mexico and Central America. Data are plotted by using same symbol codes as in Figure 1 for sample locations. **A:** Subduction signals Sr/Ce vs. Ba/Zr (F—volcanic front, B—behind volcanic front or backarc; see Fig. 1). **B:** Subduction signals B/La vs. Be/Ce. **C:**  $^{87}\text{Sr}/^{86}\text{Sr}$  vs.  $^{143}\text{Nd}/^{144}\text{Nd}$  diagram; “mantle array” as well as CHUR and UR reference lines (“bulk Earth” value) are included; also included is composition of subducted Cocos plate (Verma, 2001; AOC—altered oceanic crust); basic rocks from rifts are shown (crossed circles) for comparison purposes. **D:**  $^{206}\text{Pb}/^{204}\text{Pb}$  vs.  $^{207}\text{Pb}/^{204}\text{Pb}$  diagram.

“front” and “behind the front” rocks, whereas for Guatemala to northwestern Costa Rica these differences are generally statistically significant; the volcanic front rocks show a larger slab component.

All other useful chemical and isotopic parameters are consistent with these differences in geographic distribution; some typical ones are plotted in binary diagrams (Fig. 3) to highlight the significant differences between southern Mexico and Central America. Both Sr/Ce (Sr is a fluid-mobile LILE, and Ce is a relatively fluid-immobile REE) and Ba/Zr (Ba is a fluid-mobile LILE, and Zr is a fluid-immobile high field strength element [HFSE]) ratios are sensitive indicators of melting related to subduction. Basic rocks from Guatemala to northwestern Costa Rica show high values of both parameters, whereas all south Mexican and most southeast Costa Rican rocks are characterized by low values of both of these slab-fluid and/or melt-indicating parameters, with the exception of a few Costa Rican samples that have high Ba/Zr ratios (Fig. 3A). Although data are scarce, another binary plot (Fig. 3B), constructed by using two subduction-signal parameters (B/La and Be/Ce) (Leeman et al., 1994), shows that the subduction-related Central American rocks have high ratios, whereas the south Mexican and southeast Costa Rican rocks have low ratios. Other geochemical parameters, such as Zr/Y, Nb/Y, Sr/

P, Ti, and V, also show systematic geographic differences (plots not shown), consistent with the already stated observations. Similarly, on multielement MORB- or primitive-mantle-normalized diagrams (Fig. DR6, see footnote 1), basic rocks from southern Mexico, particularly those with high MgO contents and high Mg numbers, do not show HFSE depletion (e.g., Nb, Ta, and Th) compared to LILEs (e.g., Ba and Rb) and REEs (Verma, 2000, 2001). Therefore, these rocks contrast with similar rocks from Guatemala to northwestern Costa Rica; most of them, particularly those from the volcanic front, show such a depletion.

Such a geographic distinction is also clearly seen on two isotope-isotope diagrams (Figs. 3C, 3D). Subduction-related Central American rocks from the volcanic front show a marked tendency toward the subducting plate (mixing curve between altered oceanic crust and overlying sediments) in an isotope diagram plotting Sr versus Nd (Fig. 3C). All other rocks fall within or close to the “mantle array.” On a Pb-Pb isotope diagram (Fig. 3D), the rocks from southern Mexico define a field intermediate between the fields for the Central American arc and southeast Costa Rican samples, the latter probably being influenced from a HIMU component (HIMU = high  $\mu$  = high  $^{238}\text{U}/^{204}\text{Pb}$  ratio).

For rocks from Guatemala to northwestern

Costa Rica, the geochemical and isotopic characteristics clearly reflect the incorporation of a subducted-slab component in the mantle wedge before its melting. The basic rocks from southern Mexico as well as from southeastern Costa Rica (Fig. 1) define similar fields (Figs. 2 and 3) that are significantly distinct from the Central American subduction-related rocks. There is no consensus related to the origin of southeast Costa Rican volcanism. It has been attributed to a variety of processes: two-stage partial melting of subducted oceanic crust (Defant et al., 1992); lesser slab input from very young oceanic lithosphere (Harry and Green, 1999); slab-window formation (Johnson and Thorkelson, 1997); influence of the Galápagos mantle plume (Feigenson et al., 1996); flow of asthenosphere from South America (Herrstrom et al., 1995); and preferential melting of a veined mantle source (Feigenson and Carr, 1993).

## ORIGIN OF SOUTH MEXICAN VOLCANISM

### Failure of Prior Models

It seems that the origin of south Mexican volcanism should be attributed to a process that is unrelated to the subduction of the Cocos plate, but first an examination of the more conventional models is appropriate. The near absence of deep earthquakes (below 80 km, especially beneath the volcanic front in southern Mexico) and the relatively young age (10–20 Ma) of the subducting Cocos plate (Fig. 1) could be interpreted as though this plate is under melting conditions (Defant et al., 1992), a mechanism already rejected for the central part of the Mexican volcanic belt on combined geochemical and isotopic grounds (Verma, 2000) and because of the absence of “adakitic” rocks (probably slab melts) in southern Mexico. A subducted slab input (Harry and Green, 1999) could be argued from geochemical data for south Mexican rocks (Figs. 2 and 3). However, such an input should be stronger in the region closer to the trench than farther away from it (see sample locations in Fig. 1) and, therefore, should reflect significant differences between the “front” rocks (Mexican volcanic belt; F, Fig. 3) and the “behind the front” rocks (Mexican volcanic belt; B, and Los Tuxtlas volcanic field, B, Fig. 3). Such differences are clearly not observed for southern Mexico (Figs. 2 and 3). An explanation related to slab-window formation can also be ruled out because the rocks with unusual chemical characteristics, unrelated to subduction, occur throughout southern Mexico (Fig. 1). This explanation would require a very wide gate (almost half the size of the entire plate) rather than a window. Finally, although action of a mantle plume, first emplaced in the western

part of the Mexican volcanic belt, was also put forth to explain the unusual characteristics of the volcanic rocks (Márquez et al., 1999), this hypothesis was rejected on the basis of the geochemistry of the Mexican volcanic belt magmas and their distribution in space and time (Verma, 2001).

### Rift-Upwelling Model

The absence of a clear subduction signal in basic rocks from southern Mexico may mean that the slab-derived fluids, whether from subducted sediments, altered oceanic crust, or lower oceanic crust, are released too close to the trench and probably too shallow to cause mantle melting. Thus, given the shallow nature of the traceable subhorizontal slab and unusual tensional regime parallel to the Mexican Pacific coast (see seismic depth contours of 40–60 km in Mexico; Fig. 1), an absence of arc volcanism in Mexico related to the subduction of the Cocos plate could be hypothesized. In this scenario, the area where the tensional earthquakes occur (Singh and Pardo, 1993; see the area of depth contours of 40–60 km or more in Mexico; Fig. 1) could be considered already a backarc, without any arc activity. Some basin structures, such as the Balsas basin, are known in the area between the Mexican volcanic belt and the Pacific coast. Then, the lithospheric-mantle upwelling beneath the volcanic belt as well as beneath the rest of the south Mexican volcanic areas (Los Tuxtlas volcanic field and El Chichón area) could explain the unusual geochemical and isotopic characteristics. This upwelling requires a downflow (counterflow to the upwelling mantle), whose downwelling southern arm, probably located in the aseismic area south of the Mexican volcanic belt, would prohibit subducted fluids from flowing toward the area of mantle upflow where the south Mexican volcanoes are situated (Fig. 1).

Thus, partial melting of an upwelling heterogeneous mantle source and eruption of magma, both facilitated by ongoing rifting processes, could explain all the available evidence: (1) geologic data—e.g., nonparallelism of the volcanism with the trench, unusually large arc-trench distances, well-defined graben system throughout the belt, and intraarc extension and active normal faulting (Suter et al., 2001); (2) geochemical data—e.g., mantle-like isotopic signatures in the Mexican volcanic belt (known for the past 20 yr), origin of intermediate and acid volcanic rocks that have a significant involvement of the crust (Verma, 2001), insignificant  $^{10}\text{Be}$  values (within the lower limit of detection) for south Mexican rocks in contrast to the generally very high values for Central America (Tera et al., 1986), rift-like geochemical and isotopic signatures, and a lack of a clear subduction

signature in south Mexican basic rocks (shown in the present work); and (3) geophysical data—e.g., lack of well-defined Wadati-Benioff zone (Pardo and Suárez, 1995) coupled with presence of extensional and shallow seismicity below the Mexican volcanic belt (Suter et al., 2001) and in the forearc area (Singh and Pardo, 1993), high heat flow beneath the Mexican volcanic belt, a pronounced gravity low beneath the Mexican volcanic belt, and partial melts in the lower crust as interpreted from gravity data (Campos-Enríquez and Sánchez-Zamora, 2000). Despite all this evidence, none of the authors questioned the conventional subduction relationship of south Mexican volcanism.

The present interpretation, the best explanation for all the available data, shows at least one case on Earth—southern Mexico—where there is abundant and widespread volcanism (Fig. 1) that, instead of being related to the ongoing nearby subduction, owes its origin to ongoing rifting processes. Although volcanic gaps exist in many arcs around the world (e.g., the Andes; Kay et al., 1987), the Mexican example is probably the only one where almost half of the oceanic plate does not give rise to basic volcanism present in this region.

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