El Chichón Volcano (Chiapas Volcanic Belt, Mexico) Transitional Calc-Alkaline to Adakitic-Like Magmatism: Petrologic and Tectonic Implications

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Abstract

The rocks of the 1982 eruption of El Chichón volcano (Chiapas, Mexico) display a series of geochemical and mineralogical features that make them a special case within the NW-trending Chiapas volcanic belt. The rocks are transitional between normal arc and adakitic-like trends. They are anhydrite-rich, and were derived from a water-rich, highly oxidized sulfur-rich magma, thus very much resembling adakitic magmas (e.g., the 1991 Pinatubo eruption). We propose that these rocks were generated within a complex plate tectonic scenario involving a torn Cocos plate (Tehuantepec fracture zone) and the ascent of hot asthenospheric mantle. The latter is supported by an outstanding negative S-wave anomaly widely extending beneath the zone, from 70 to 200 km in depth. The adakitic-like trend would be derived from the direct melting of subducting Cocos plate, whereas the transitional rocks would have resulted from the mixing of two poles, one reflecting a mantle source, and the other, the already mentioned adakitic melts. The basaltic source would also account for the high sulfur content and $\delta^{34}S$ values of the El Chichón system (about +5.8), as result of a contribution of SO_2 in fluids released from an underlying mafic magma.

Introduction

EL CHICHÓN VOLCANO belongs to the NW-trending Chiapas volcanic belt, which comprises three major centers (El Chichón, Tzomtehuitz, and Nicolás Ruiz; Capaul, 1987; Fig. 1A). In contrast with the typical Central America volcanic arc, the Chiapas volcanic belt follows an anomalous, oblique magmatic trend at ~30° with respect to the WNW-trending Middle America trench, an oddity only comparable to the also oblique E-W–trending Mexican volcanic belt (e.g., Márquez et al., 1999; Fig. 1A). Two major sinistral wrench fault systems separate the Chiapas volcanic belt from the westernmost Central American volcanoes and from the Mexican volcanic belt, respectively, thus bounding an isolated tectonic block, here named as the Yucatán block (Fig. 1A). Another key tectonic feature to be taken into account is the nearly perfect alignment defined by the NE-trending Tehuantepec fracture zone and El Chichón (Fig. 1A). El Chichón became famous in 1982, when a violent eruption caused the death of about 2000 people, and the emission of 7 million tons (Mt) of SO_2 into the atmosphere (compared with 20 Mt of SO_2 by Mount Pinatubo in 1991; Pasteris, 1996). Another remarkable feature of the El Chichón volcanic rocks is their anhydrite-rich character, exemplified by the 1982 eruption pumices.

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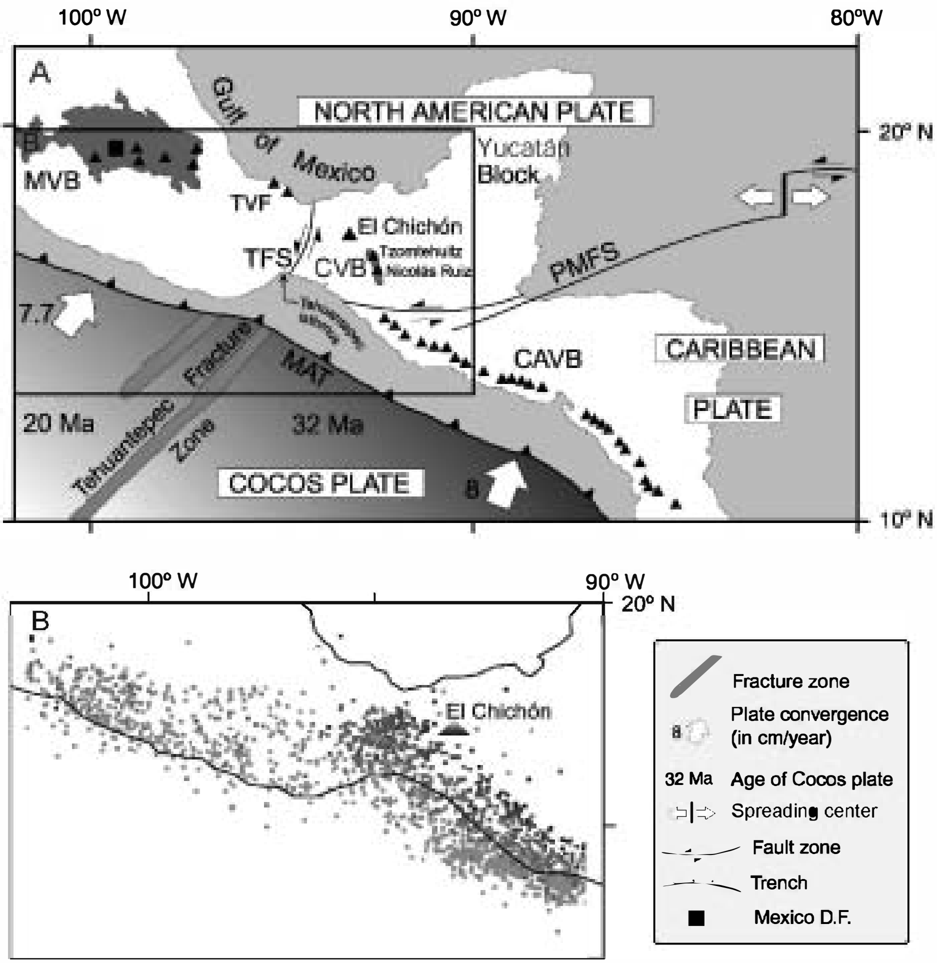

FIG. 1. A. Plate tectonic setting of volcanic belts in southern Mexico and Central America. See location of the Chiapas volcanic belt (including El Chichón at its northwestern tip). Abbreviations: CAVB = Central American volcanic belt; CVB = Chiapas volcanic belt; MAT = Middle America trench; MVB = Mexican volcanic belt; PMFS = Polochic-Motagua fault system; TFS = Tehuantepec fault syetem; TVF = Tuxtla volcanic field. B. Plan view of earthquake hypocenters deeper than 50 km (after USGS, 2001). Note the abrupt change from the Tehuantepec isthmus, with earthquake hypocenters decreasing and shallowing to the west.

The chemistry of El Chichón rocks shows transitional characteristics between calc-alkaline and adakitic-like magmatism. We argue that this transitional character is the result of the mixing of slab-derived and mantle-derived melts and may account for the highly oxidized character of the system.

Geologic Setting

The Chiapas volcanic belt (Capaul, 1987) is conspicuously separated from the WNW-normal Central American volcanic arc (Fig. 1A). Earthquake distribution from Guatemala to the Yucatán block does not show any significant change; thus, the change in direction of volcanism from WNW (Central American arc) to NW (Chiapas volcanic belt) cannot be related to subduction styles, and therefore must be associated with other tectonic features, e.g., the Motagua fault system (Fig. 1A). This major sinistral structure, together with the also sinistral Tehuantepec fault system, bounds the Yucatán block (Fig. 1A), thus forming an isolated, probably clockwise-rotated tectonic block (e.g., Delgado-Argote and Carballido-Sánchez, 1992) (Fig. 1A), which would account for the present NW direction of the Chiapas volcanic belt.

However, although this provides a plausible explanation for the clockwise rotation of the Chiapas volcanic belt, some geochemical (Luhr et al., 1984; Capaul, 1987; Espíndola et al., 2000) and mineralogical (anhydrite-rich volcanic facies) features of the El Chichón rocks still remain unusual compared to other volcanic centers of the belt (e.g., Capaul, 1987), or the Guatemalan volcanoes, which display calc-alkaline characteristics. What makes El Chichón different from the rest of the belt and from the Guatemalan volcanoes? There is a very large tectonic feature that may explain the singularity of this volcano: the Cocos Tehuantepec fracture zone, which separates 20 Ma– from 32 Ma–old subducting oceanic crust beneath southern Mexico and the Yucatán block, respectively. The fracture is interpreted to be an inactive linear bathymetric feature of the Cocos plate that is being subducted beneath the Yucatán block (Barrier et al., 1998). If the trend of the Tehuantepec fracture is projected onto the mainland, El Chichón lies almost perfectly above it (Fig. 1A).

Petrology of El Chichón Rocks

The major volcanic centers of the Chiapas volcanic belt (El Chichón, Tzomtehuitz, and Nicolás Ruiz) are essentially described as dome fields overlain by pyroclastic deposits, comprising basalts (rare), porphyritic hornblende-andesites, trachyandesites, and minor rhyodacites and rhyolites (Duffield et al., 1984; Capaul, 1987; Espíndola et al., 2000). The petrographic features displayed by most of these rocks are in general those of the calc-alkaline suite—i.e., plagioclase, hornblende, pyroxene, and titaniferous magnetite phenocrysts in a micro- to cryptocrystalline groundmass for the andesites-trachyandesites, and quartz, biotite, plagioclase, and titaniferous magnetite phenocrysts in a glassy matrix for the rhyodacites and rhyolites. However, the El Chichón rocks display some unusual features for typical calk-alkaline rocks: phenocrysts of sphene, apatite, and anhydrite as well as the presence of only one pyroxene (augitic clinopyroxene) throughout the entire magmatic history of El Chichón (pre-1982 eruption rocks, Rose et al., 1984; Espíndola et al., 2000; and the 1982 eruption rocks, Luhr et al., 1984). Despite the fact that in some samples anhydrite phenocrysts have been leached, due to seasonal intense rainfall in the Chiapas region, this mineral is nonetheless preserved as inclusions in other phenocrysts (Rose et al., 1984); it was probably a ubiquitous phase in all the El Chichón samples.

The magma from El Chichón volcano is both mineralogically and geochemically distinct from the rest of the volcanoes of the Chiapas belt. Several outstanding features of El Chichón rocks are absent in the other volcanic centers of the Chiapas volcanic belt: (1) the enrichment in alkalis ($Na_2O + K_2O$) at a given SiO_2 content; (2) the presence of magmatic anhydrite; (3) the high sulfur contents; and (4) the high water and oxygen fugacities. The El Chichón rocks were derived from a water-rich (4–10 wt% H_2O), highly oxidized (fO_2 above the Ni-NiO buffer), sulfur-rich magma (Rye et al., 1984; see Fig. 2), thus very much resembling adakitic magmas. High water contents, high fO_2, and adakitic magmatism are closely related phenomena. The first two are connected via the equilibrium reaction: $H_2O = H_2 + ½ O_2$. Given the high diffusivity of H_2, fO_2 increases to maintain the equilibrium, and concomitant with this increase, the ratio SO_2/H_2S increases × 1000 or even more, which eventually results in an almost complete extraction of sulfur from the melt (Burnham, 1979). On the other hand, water in excess (>10%) of that structurally bound in minerals plays a vital role in achieving direct slab melts, i.e., adakitic magmatism (Prouteau et al., 1999). If fO_2 is buffered by an appropriate mineral assemblage (e.g., coexisting magnetite and hornblende), fH_2 increases to maintain the equilibrium, and therefore the ratio fSO_2/fH_2S in the vapor phase decreases with increasing fH_2O, with SH^- being the dominant sulfur-bearing species in the melt (Burnham, 1979). However, water solubility in silicate melts is directly controlled by pressure; thus during the emplacement of magmas, most of the sulfur in the melt exsolves as SO_2 (Burnham, 1979):

$$SH^-_{(m)} + 5\,OH^-_{(m)} \rightarrow 3O^{2-}_{(m)} + SO_{2(v)} + 3H_{2(v)}.$$

Given the high diffusivity of H_2 and the concomitant increase of fO_2, the ratio fSO_2/fH_2S also increases. However, at some point (e.g., the sulfur redox boundary) before eruption, the system is buffered by anhydrite formation. Regarding the El Chichón 1982 tuffs, even if pyrrhotite was one of the earliest minerals to crystallize, there is textural and isotopic evidence indicating near-equilibrium crystallization between pyrrhotite and anhydrite

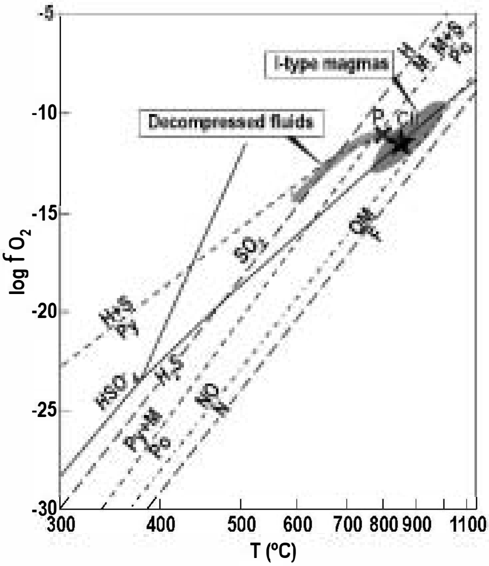

FIG. 2. Pre-eruption fO_2-T conditions (shaded area) of El Chichón anhydrite-bearing magma (after Whitney, 1984). Star represents the calculated fO_2 value (–11.0 bar) at 850°C. Pre-eruption conditions (P) of the Pinatubo magma erupted on June 15, 1991 (Imai et al., 1996) are also shown for comparison. The arrow indicates the probable path for hydrothermal fluids released from the magmatic system if a sudden decompression takes place (based on Rye, 1993). Abbreviations: H = hematite; M = magnetite; Po = pyrrhotite; S = sulfur (l); Py = pyrite; N = nickel; NO = nickel oxide, Q = quartz; F = fayalite.

(Luhr et al., 1984; Rye et al., 1984). For a crystallization temperature of 850°C, and given the occurrence of sphene instead of ilmenite in the tuffs, a reasonable log value of –11.0 bar is considered for fO_2 (Whitney, 1984) (Fig. 2), which is very close to the sulfur redox boundary. That value of log fO_2 and related values of fSO_2 (125 bar) and fH_2S (47 bar) are consistent with the isotopic data (Rye et al., 1984), indicating that sulfate in the eruption cloud came from an already oxidized sulfur phase present in the magma. Thus, most of the sulfur was outgassed as sulfate, and no oxidation of H_2S occurred in the volcanic plume contributed to form SO_2.

Some mineralogical and geochemical features of El Chichón magmas, such as the presence of magmatic anhydrite and high water contents, which are absent in normal-arc intermediate-to-acidic rocks, are nonetheless common in adakites. Adakites (*sensu* Defant and Drummond, 1990) are SiO_2-rich (≥56%), MgO-poor rocks (≤6%), with high Sr (≥400 ppm) and low Y contents (≤18 ppm) (among other features). The origin of these rocks is assumed to be related to direct partial melting of a subducting basaltic plate under high water fugacity conditions. This genesis explains three outstanding features of adakites: (1) high water fugacity in the source during partial melting, leading to high water activity and a very strong oxidized character of the magmas, and therefore to major production of anhydrite (e.g., Oyarzun et al., 2001); (2) the absence of plagioclase in the residuum during partial melting, which promotes high strontium contents; and (3) low Y contents due to the presence of garnet in the metabasaltic source. The El Chichón intermediate and acidic rock samples (Luhr et al., 1984; Rose et al., 1984; Capaul, 1987; Espíndola et al., 2000) can be grouped into two different kinds: one having high Sr (~ 1500 ppm) and very low Y (~ 10 ppm) contents, and another with slightly lower Sr (900–1000 ppm) and higher Y (15–25 ppm) contents. The latter defines a transitional trend between adakite-like rocks and the Chiapas volcanic belt "normal" calc-alkaline trend (with Sr contents between 200 and 700 ppm and Y contents between 30 and 45 ppm; Fig. 3).

Discussion

The intermediate trend of El Chichón magmas mimic that of the Kamchatka–Aleutian Islands rocks (Yogodzhinski et al., 2001, Fig. 3), where there are also two distinctive groups of rocks with regard to their Sr-Y contents: (1) the Klyuchevskoy group, which represents a "normal" calc-alkaline arc; and (2) the Sheveluch group, comprising rocks that, in the Sr/Y versus Y diagram, plot between the Klyuchevskoy arc and the adakites from the Aleutian Islands (Fig. 3). Yogodzhinski et al. (2001) suggested that the character displayed by the rocks from the Sheveluch area is consistent with the possible presence of a slab-melt component in their source. Based on this, two subduction-related petrogenetic processes may have been implied in the genesis of El Chichón magmas: partial melting of the subducting plate, and partial melting of the mantle wedge overlaying it. The high Sr/Y, low Y samples from El Chichón (samples: CHI-9550 and CHI-9615; Espíndola et al., 2000, Fig. 3) could thus be derived almost exclusively by direct partial melting of the subducting slab, at conditions of ~ 20–30 Kb, 900–1100°C and high water contents (10 wt%, provided by the dehydration of serpentinite), in the

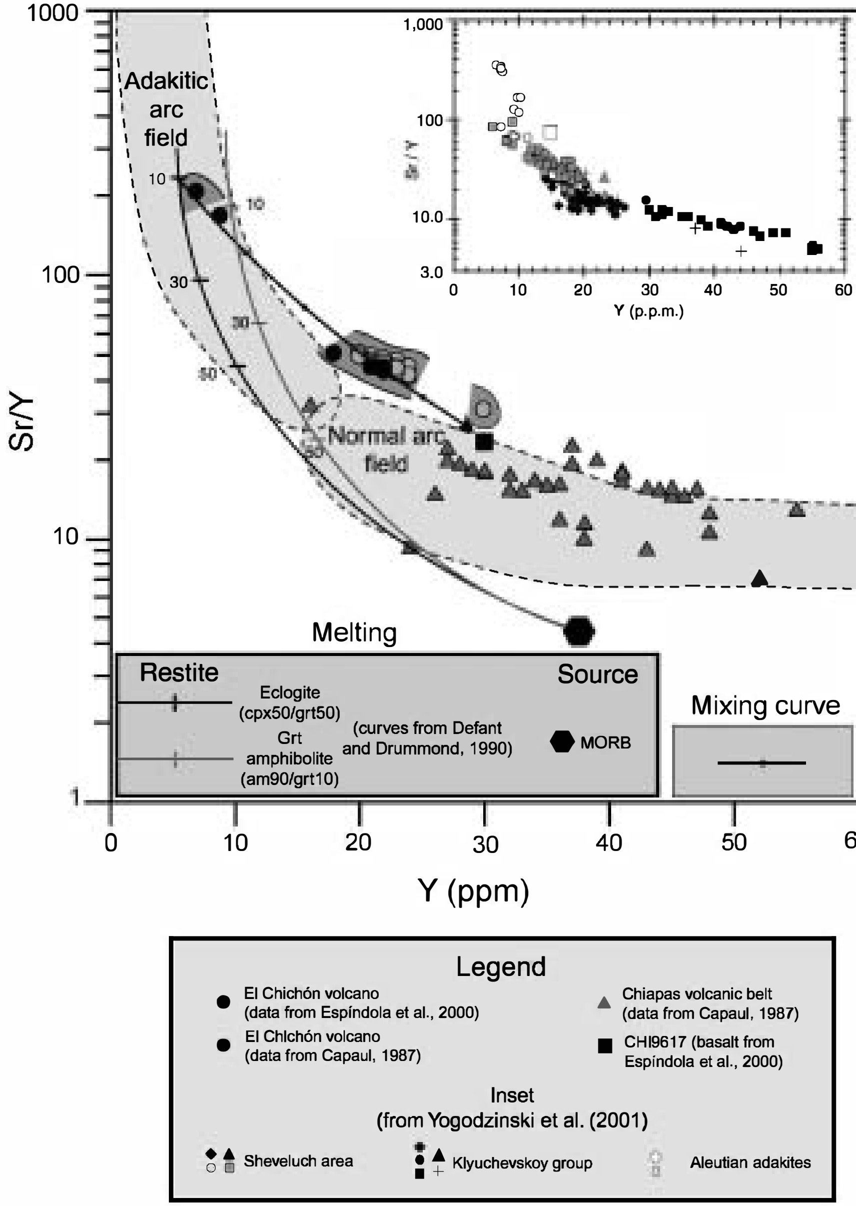

FIG. 3. Sr/Y versus Y diagram (fields after Defant and Drummond, 1990). Note the transitional (adakitic-like to calc-alkaline) character of most of the El Chichón rocks, which follows a similar trend to that displayed by the Sheveluch rocks, Kamchatka (see inset; samples after Yogodzinski et al., 2001). The adakitic-like rocks can be modeled in terms of the melting of basaltic source (solid hexagon). In turn, the transitional rocks can be modeled in terms of the mixing of an adakitic pole and a basalt cropping out in the El Chichón area (solid square).

garnet amphibolite-eclogite transition (Defant and Drummond, 1990; Prouteau et al., 2001). However, the majority of the transitional El Chichón rocks, can be modeled as mixing products between partial melts from the subducting plate (adakitic-like), and basaltic magmas such as those represented by sample CHI-9617 (Espíndola et al., 2000, see solid square in Fig. 3). Furthermore, Tepley et al. (2000)

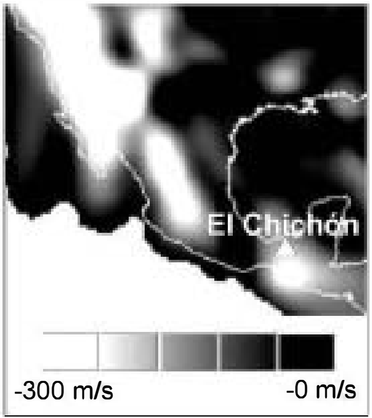

FIG. 4, Map of the negative S-wave anomaly under the Yucatán block and Central America at 130 km depth, after Van der Lee and Nolet (1997). This anomaly persists in depth from 70 to 200 km, and most probably indicates the massive intake of hot asthenospheric mantle beneath the Yucatan block.

proposed, based on chemical (large variations in An contents) and isotopic compositions of Sr in plagioclases, both from pre-1982 and 1982-eruption samples, that chamber recharge and magma mixing processes, probably involving strong fluctuations in the volatile pressure of the system, triggered this volcanism. These authors discard other petrogenetic processes, such as AFC, as they cannot account for the low $^{87}Sr/^{86}Sr$ ratios in plagioclases. We propose that an alternative explanation for these data is the involvement of partial melts from the subducting plate, which would provide high Sr and low $^{87}Sr/^{86}Sr$ ratios.

Contrary to the normal, arc-related tholeiitic and calc-alkaline rocks that originate in the mantle wedge and later evolve by crystal fractionation or other phenomena, the adakitic rocks derive from direct partial meting of the subducted slab (Defant and Drummond, 1990); these authors relate the process to the melting of hot young (< 25 Ma) subducting lithosphere. Numerical and petrological models (Peacock et al., 1994) restrict the process to even younger subducting lithosphere (< 5 Ma) typically at 60–80 km depth. However, this would leave the important adakitic magmatism recorded in many places around the world unexplained, among them the Andean chain (Gutscher et al., 2000). Older oceanic crust (up to 50 Ma) can melt during prolonged flat subduction (Gutscher et al., 2000). Under these conditions, the plate will melt before undergoing dehydration, at the base of the lithosphere. The age of the subducting Cocos plate is 32 Ma beneath El Chichón (Nixon, 1982); however, seismic data rule out flat subduction (Fig. 1B). The recent paper by Yogodzinski et al. (2001) relates the presence of tranform faults to the generation of normal calc-alkaline (Klyuchevskoy Group) and transitional adakitic (Sheveluch area; El Chichón-like) rocks (Kamchatka; Russia), a trend that continues into the Aleutian arc with truly adakitic rocks. Given the nature of El Chichón volcanism (transitional calc-alkaline to adakitic-like), the observations from Yogodzinski et al. (2001) may prove useful in understanding magma genesis beneath the Chiapas volcanic belt.

Two major tectonic features characterize the southern Mexico–Cocos realm: (1) the Tehuantepec fracture zone; and (2) the drastic change in plate configuration westward from the Tehuantepec isthmus. Westward of the isthmus, the plate subducts at a shallow angle (~10°) (Pardo and Suárez, 1995) and no important deep subduction-related seismic activity is recorded (Fig. 1B); eastward from the isthmus, Cocos is subducting at a contrasting higher angle (~ 30°) (Jiménez et al., 1999, Fig. 1B); further graphic information is provided by the Seismicity Map of North America (Engdahl and Rinehart, 1988), which also marks a major decrease in deep-seated hypocenters to the west of the Tehuantepec isthmus.

The tomographic characteristics of this realm (Van der Lee and Nolet, 1997) also indicate a drastic boundary; eastward from the isthmus a major negative S-wave anomaly extends in depth from Yucatán to Central America (Fig. 4). The data from Van der Lee and Nolet, (1997) indicate that the anomaly persists in depth from 70 to 200 km, most probably indicating the massive intake of hot asthenospheric mantle beneath the Yucatán block. If this assumption is correct, then the main question is the source of hot asthenospheric mantle. If the abrupt change from high angle (eastward from the Tehuantepec isthmus), to shallow subduction (westward from the Tehuantepec isthmus) truly represents the shape of the subducting Cocos plate (Fig. 1B), we may conclude that the plate is torn (along the fracture zones) and allows the eastward intake of asthenosphere beneath the Yucatán block (Fig. 5). This can induce the melting of the subducting plate in a way that resembles the mechanism proposed by Yogodzinski et al. (2001) for Kamchatka peninsula volcanism. If we accept this analogy, then the El

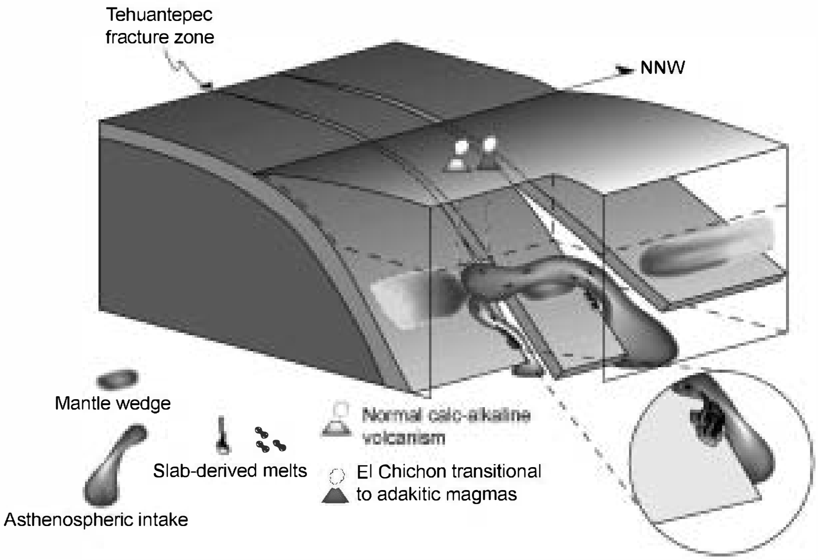

FIG. 5. Schematic 3D plate tectonic model for the El Chichón magmatism. Note the intake of asthenosphere along a torn Cocos plate, where direct melting takes place, giving rise to adakitic-like magmatism. The normal calc-alkaline rocks of the belt would originate from melting of the mantle wedge.

Chichón volcanism could be equated to that of Shiveluch (Fig. 3) in the southern realm of the Kamchatka Peninsula. Thus, we would expect contributions from the melting of the edge of the subducting Cocos plate (high Sr/Y–low Y samples: CHI-9550, CHI-9615; Espíndola et al., 2000) and from the mantle (e.g., basalt CHI-9617; Espíndola et al., 2000, Figs. 3 and 4). We propose that CHI-9617 may have originated from melting, by conductive heating of lithospheric mantle, during the intake of hot asthenospheric mantle along the torn Cocos subducting plate. Participation of mafic magmas is further supported by isotopic data from El Chichón. The $\delta^{34}S$ of the El Chichón system (melt + crystals + vapor) is ~5.8 ‰ (Rye et al., 1984), i.e., well above the range for primary magmas in continental regions (0 ± 3‰, Ohmoto and Rye, 1979). To explain that $\delta^{34}S$ enrichment, Rye et al. (1984) invoked an important loss of H_2S in the gaseous or fluid phase at depth prior to the eruption. Alternatively, the high $\delta^{34}S$ could be the result of a contribution of SO_2 in fluids released from an underlying mafic magma (Hattori, 1993). Furthermore, participation of mafic magmas provides a satisfactory explanation for the high sulfur content in the melt.

We also expect partial melting of the mantle wedge above the subducting Cocos plate within a complex plate tectonic scenario such as the one here suggested (Fig. 5). This would explain most of the Chiapas volcanic belt, because these rocks display a typical arc-related, calc-alkaline trend.

Conclusions

The El Chichón magmatism displays mineralogical and geochemical differences with respect to other major volcanic centers of the Chiapas belt: (1) higher Sr and lower Y contents; (2) presence of magmatic anhydrite; (3) high sulfur contents; and (4) high fO_2. These features reflect a transitional geochemical character between "normal" calc-alkaline and adakitic-like magmas for the El Chichón rocks (Figs. 2 and 3).

We suggest that generation of this calc-alkaline–transitional, adakitic-like magmatism can be related to a major change in plate configuration, which in turn would have been a consequence of the activity of major transform faults tearing apart the subducting Cocos plate. This would have favored the vigorous intake of asthenospheric mantle, triggering the direct melting of the subducting plate (e.g., see Yogodzinski et al., 2001), thus explaining the presence of high Sr/Y, low Y rocks in El Chichón (Figs. 3 and 5). Evidence supporting this scenario is provided by the distribution of hypocenters beneath the southern Mexico–Yucatán block (Engdahl and

Rinehart, 1988; USGS, 2001; Fig. 1B), and tomography (a major negative S-wave anomaly extending in depth from 70 to 200 km; Van der Lee and Nolet, 1997; Fig. 4).

The alignment of the El Chichón volcanic center with the Tehuantepec fracture zone, together with the existence of a drastic change in the subduction angle of the Cocos plate (10° to 30°) from W to E of the Tehuantepec Isthmus, indicates that the Cocos plate is torn; this would allow the eastward intake of asthenospheric mantle beneath the Yucatán block (Fig. 3). The intake of asthenosphere can account for the melting of a subducting slab (e.g., Yogodzhinsky et al., 2001), thus explaining the presence of adakitic-like rocks in El Chichón. Furthermore, mixing between these melts and basalts derived from an enriched mantle source (e.g., melting of lithosphere by conductive heating) would account for the peculiar mineralogical and geochemical features of the El Chichón transitional adakitic–adakitic-like rocks (Fig. 5). In turn, as indicated by their chemistry, the rest of the rocks of the belt (a rather typical calc-alkaline trend) would originate by normal partial melting of the mantle wedge above the subducting Cocos plate (Fig. 5). The lack of a complete dataset on REE concentrations of the available samples of El Chichón prevents the establishment of other necessary criteria for properly defining the presence of adakites in the El Chichón volcano (such as, for example, high La/Yb ratios; Drummond et al., 1996). However, the mineralogical, geochemical, and isotopic evidence strongly suggests that an adakitic component is actually involved in magma generation underneath the El Chichón volcano, as this component would satisfactorily explain the existing differences in mineralogy and geochemistry of the El Chichón rocks with respect to the rest of the Chiapas volcanic belt.

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