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On the nature and role of the lower crust in the volcanic front of the Trans-Mexican Volcanic Belt and its fore-arc region, southern and central Mexico

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ABSTRACT

With the main objective of further constraining models that debate how and where magmas are generated in the Mexican subduction factory, how they ascend through the overlying viscous layers, and how and where they interact with the traversed crust to produce the diversity of the magmas that compose the system, the nature of the lower crust and its immediate surroundings under the volcanic front of the Trans-Mexican Volcanic Belt (TMVB), as well as its fore-arc in southern Mexico, are analyzed and integrally characterized in this work. The study is mainly based on the analysis of geophysical and geological existing and new data, as well as on our new data obtained from deep-seated xenoliths. Taken as that part of the crust located from the Moho to a depth of 20–25 km below the surface, it is concluded from our analysis that all of the lower crust in the study area should be in the granulite facies, if geophysical modeling correctly predicted temperatures of 700–800ºC for its base, and a crustal thickness varying between 40 and 45 km. Xenoliths and surface geology information, when integrated to tectonic modeling, support the notion that most of the lower crust under the eastern and central sectors of the TMVB should be of Mesoproterozoic age, and tectonically overlapped by Paleozoic and Mesozoic juvenile crust in the central sector and its corresponding fore-arc region. It is also concluded in this work, in agreement with recent seismological high resolution studies, that the apparent differences existing between geophysical modeling and the P-T conditions required to generate the primary andesitic, dacitic and adakitic magmas that characterize the TMVB in the study area, may be resolved if the angle of the slab that extends northward and beyond the flat segment is increased substantially, thus creating optimal thermal and rheological conditions in a mantle wedge under the volcanic front much thicker than currently accepted. These conditions would increase the temperature of the entire subduction system to values that would permit the generation of such primary magmas by partial melting of the basaltic part of the subducting slab, the mantle wedge, and the mafic lower crust.

Key words: subduction factory, lower crust, xenoliths, Trans-Mexican Volcanic Belt, southern Mexico.

RESUMEN

Con el objetivo principal de contribuir a los modelos que debaten cómo y dónde se generan los magmas de la Faja Volcánica Transmexicana (FVTM), como ascienden atravesando la corteza viscosa, y cómo y dónde interaccionan con la corteza para producir la diversidad de magmas que integran ese sistema, en este trabajo se analizan e interpretan integralmente la naturaleza de la corteza inferior y su entorno inmediato debajo de la FVTM, así como de su región de antearco en el sur de México con base en la información geológica, geofísica y de xenolitos existente. Definida la corteza inferior como la parte de la corteza continental localizada entre el Moho y hasta un profundidad de 20–25 km bajo la superficie, se concluye de este análisis que toda la corteza inferior en el área de estudio debería estar en la facies de granulita, si los modelos geofísicos predicen correctamente una temperatura mínima de

700–800ºC para su base y un espesor cortical entre 40 y 45 km. La información procedente de xenolitos y de la geología superficial integrada a modelos tectónicos, a su vez, apoya la idea de que la mayor parte de la corteza inferior debajo de los sectores oriental y central de la FVTM es del Mesoproterozoico, y está tectónicamente sobrepuesta en su sector central y región de antearco correspondiente por corteza juvenil del Paleozoico y Mesozoico. También se considera en este trabajo, en armonía con estudios sismológicos recientes de resolución alta, que las diferencias aparentes que existen entre los modelos geofísicos y las condiciones P-T necesarias para generar los magmas andesíticos, dacíticos y adakíticos que caracterizan a la FVTM en el área de estudio, podrían resolverse si el ángulo de subducción de la placa que se extiende más allá de su segmento subhorizontal se incrementa sustancialmente, creando así las condiciones térmicas y reológicas óptimas en una columna de manto continental más amplia que la que se ha considerado debajo del frente volcánico del arco. Estas condiciones incrementarían las temperaturas a valores que permitirían la generación de esos magmas primarios por fusión parcial de la cubierta basáltica de la placa en subducción, la cuña del manto, o la corteza inferior máfica.

Palabras clave: corteza inferior, xenolitos, proceso de subducción, Faja Volcánica Transmexicana, sur de México.

INTRODUCTION

Active tectonics and arc volcanism in southern and central México have been a direct consequence of plate convergence of the Cocos and Rivera plates under the continental crust of México (North American plate) since the early Miocene (~20 Ma). The complex nature of this margin stems mainly from the inherent complexity of its pre-Miocene tectonothermal evolution, the geologic makeup of which in great measure should influence the nature and evolution of magmas generated in the subduction factory, as they migrate from their birthplace at mantle depths to the surface. Indeed, the interaction of these magmas with the traversed crust should be facilitated by the thermal regime and reactivity of the rocks composing that crust, as it is a well known fact (*e.g.*, Sachs and Hansteen, 2000; Dufek and Bergantz, 2005; Gerbi *et al.*, 2006) that a hot crust is essential to drive crust melting and assimilation followed by magma mixing. These processes would certainly affect the ascending magmas changing their primary composition and modifying their original routes of petrologic differentiation.

It is clear that the crust and probably the mantle subtending the Mexican Subduction Zone (MSZ) are anomalous in many aspects compared to many other arc regions of the world. For example, a very important feature of the MSZ is the diversity of crustal blocks or terranes that form the basement there (Figure 1), and it seems to be the only arc in the world that is substantially oblique (16º) to the corresponding trench. Also, the crust under the arc is one of the thickest found among all arcs of the world (Wallace and Carmichael, 1999). The Trans-Mexican Volcanic Belt (TMVB) extends about 1000 km across central México from the Atlantic to the Pacific margins astride at least five tectonostratigraphic terranes, which from east to west are dubbed (Campa and Coney, 1983; Sedlock *et al.*, 1993): Maya, Cuicateco, Zapoteco, Mixteco and Guerrero. In addition, the Chatino terrane, composed of high-grade metamorphic rocks and granites, integrates the southernmost continental crust of the TMVB fore-arc in southern México. The crystalline basement of these six provinces differ in age as well as in lithology and structure, rising the possibility that magmas ascending from the mantle may interact in different ways according to the geological constitution of the traversed crust. In fact, the extraordinary magmatic diversity of the TMVB (*e.g.*, Gómez-Tuena *et al.*, 2005, and references therein) must be substantially controlled by the structure and composition of the underlying crust, but specific details on the magnitude and nature of these interactions have been limited by the scarcity of deep-seated xenoliths in rocks of the TMVB and its fore-arc region.

In recent years, the multiplicity of igneous rocks and their geographic distribution in the TMVB have prompted a wealth of models to explain its complexity (Luhr, 1997; Wallace and Carmichael. 1999; Márquez *et al.*, 1999; Sheth *et al.*, 2000; Verma, 2002; Ferrari, 2004; Gómez-Tuena *et al.*, 2005, 2007), and yet essential aspects of the problem remain unsolved or under debate, such as the relative petrogenetic roles played by the mantle wedge, the subducted slab, the temporal evolution of the MSZ, and the structure and composition of the deep crust under the arc. However, in contrast with northern Mexico, where lower crustal xenoliths have been found in many places within Neogene basaltic fields (*e.g.*, Luhr and Aranda-Gómez, 1997, and references therein), only two places with proved lower crust xenoliths and two from the mantle have been reported from the TMVB, but none with mantle xenoliths from the fore-arc region of southern Mexico. For this reason, modeling the origin and evolution of magmas in the TMVB has been severely limited by the absence or paucity of crucial information about the nature of the lower crust, which constitutes one of the most important potential sources for generation of primary andesitic-rhyolitic magmas and an important contaminant for basaltic

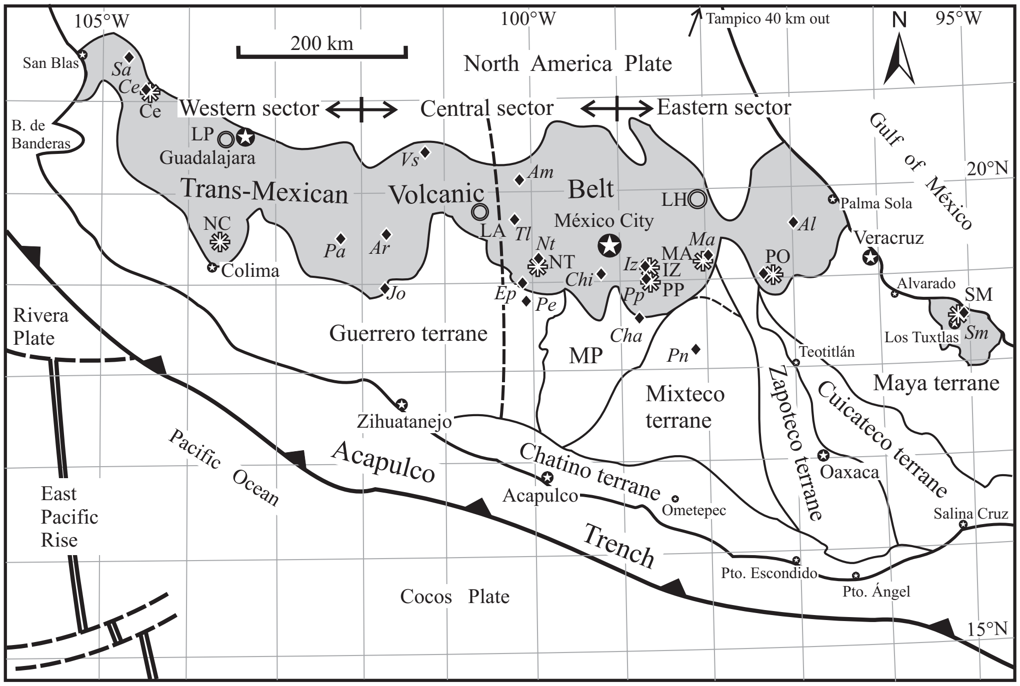

Figure 1. Tectonic map of southern México showing the Trans-Mexican Volcanic Belt and the tectonostratigraphic terrane boundaries (Sedlock *et al.*, 1993) in the fore-arc region. The Morelos Platform (MP) is added as a possible new tectonostratigraphic unit with a distinct very high-grade metamorphic basement revealed by metapelitic xenoliths at Chalcatzingo. The major stratovolcanoes (asterisk) are San Martín (SM), Pico de Orizaba (PO), La Malinche (MA), Iztaccíhuatl (IZ), Popocatépetl (PP), Nevado de Toluca (NT), Nevado de Colima (NC) and Ceboruco (CE). Open circles mark the active calderas: Los Humeros (LH), Los Azufres (LA) and La Primavera (LP). Localities with mantle and lower- and middle-crust xenoliths (filled diamond) are San Martín, Tuxtla (*Sm*), Alto Lucero (*Al*), Malinche (*Ma*), Puente Negro (*Pn*), Iztaccíhuatl (*Iz*), Popocatépetl (*Pp*), Chalcatzingo (*Cha*), Las Tetillas (*Lt*), Chichináutzin (*Chi*), Nevado de Toluca (*Nt*), El Peñón (*Ep*), Pepechuca (*Pe*), Amealco (*Am*), Tlalpujahua (*Tl*), Valle de Santiago (*Vs*), Arócutin (*Ar*), Jorullo (*Jo*), Paricutín (*Pa*), Ceboruco (*Ce*), and Sangangüey (*Sa*). The N-S trending dashed line represents the zone along which abrupt change in crustal thickness is deduced from Bouguer gravity data (see text for discussion). Other localities mentioned in the text are also shown.

melts ascending from the mantle.

This paper goes beyond a simple compilation of existing data, as we address the problem by focusing on the integration, analysis, and interpretation of the direct geological evidence (xenoliths and outcrops), and indirect data (geophysical modeling) known and provided in this work about the structure and composition of the lower crust that underlies the frontal region of the TMVB and its fore-arc in southern Mexico. However, this approach does not attempt to model the whole complexity of the region, but should be useful to constrain future and ongoing multidisciplinary studies that require some factual and integral knowledge about the geology of the local lower crust for the better understanding of how the MSZ has worked in the past 20 Ma.

GEOLOGIC SETTING

Definition and P-T conditions of the lower crust in the study area

The lower continental crust traditionally had been considered that part of the earth's crust below the Conrad discontinuity, a rather sharp seismic discontinuity present mainly in cratonic areas, and probably separating the granitic from the mafic components of the crust. However, deep continental drilling and detailed geophysical studies more recently have undermined this notion, and presently, the lower crust is usually placed at the transition from amphibolite to granulite facies rocks, a phase boundary that commonly occurs at minimum pressures around 5–6 kbar or about 18–22 km deep in extensional settings. Rudnick and Fountain (1995), for example, place the lower continental crust below 25 km, except in rifted margins, where the upper limit rises to 17–18 km (5 kbar) below the surface. Characteristic seismic wave velocities (V_P) of 6.7–7.5 km/s for the lower crust, or the brittle-ductile transition have been also used to separate the upper from the lower crust. The lower crust in this study is taken as that part of the continental crust extending from the local Moho to an uppermost depth of about 20–25 km (*ca*. 6–7 kbar). At the highest geothermal crustal gradient of 27.5ºC/km modeled for the Mexican region (*e.g.*, Manea *et al.*, 2005, 2006) the temperature at the top of this layer would be 550–687ºC, corresponding to the amphibolite metamorphic facies, where quartz, feldspar and hydrous phases still predominate. The underlying 20–25 km-thick lower crust of the study area,

Table 1. Depth-pressure relationships calculated for the Mexican crustal and mantle zones according to mean density of their dominant rocks.

Geologic system	Density (kg/m^3)	Equivalent depth (m/kbar)	Average (m/kbar)	Depth at the base (km)	Avg. pressure at the base (kbar)
Upper crust	2650 2700	3846 3775	3810	10	2.62
Middle crust	2750 2800	3707 3641	3674	25	6.70
Lower crust	2850 2900 3000	3576 3515 3397	3496	45	12.42
Normal mantle	3300	3088	3088	-	-
Garnetiferous mantle and eclogitic crust	3500	2912	2834	-	-

with temperatures of 800–1000ºC and pressures between 7 and 12 kbar, would lay mostly in the high T/P granulite facies, where probably garnet is not stable. On the other hand, for temperatures of 700–800ºC at the base of the crust previously modeled for the underlying volcanic front of the central TMVB (Currie *et al.*, 2002, Manea *et al.*, 2004), the entire lower crust would barely be in the granulite facies, but with garnet present at the deepest levels. A temperature of 800ºC predicted at the base of the crust for the Guerrero-Oaxaca fore-arc region (Currie *et al.*, 2002), seems to be more appropriate considering the high-temperature nature of the xenoliths found there (see data and discussions below). The depth-pressure relationships used in this work based on the mean density estimated for the crustal layers are shown in Table 1. The depth/pressure equivalence for the whole crust would be approximately 3660 m/kbar, (0.037 km/MPa) and about 3000 m/kbar (0.03 km/MPa) for the underlying mantle wedge.

Trans-Mexican Volcanic Belt

The TMVB is a continental volcanic arc of Miocene to Recent age located within the Circum-Pacific belt. It is oriented E-W extending from Palma Sola and Los Tuxtlas in the Gulf of Mexico Coastal Plain, to San Blas, Nayarit, and Bahía de Banderas, Jalisco, in the Pacific coast (Figure 1). The province is about 1000 km long and between 80 and 230 km wide, and is forming an angle of about 16º with the WNW trend of the Acapulco trench (Gómez-Tuena *et al.*, 2005) where the MSZ starts. Three plates are involved in the evolution of the TMVB (North America, Cocos, and Rivera) for which a vast literature exists about the nature of the structure and its temporal evolution that cannot be considered in this work. The latter plate moves slowly and subducts the North American plate with a steep angle of about 50º (Pardo and Suárez, 1993; DeMets and Wilson, 1997; Bandy *et al.*, 1999), whereas the Cocos plate in southern Mexico subducts at angles of 0 to 13º (Suárez, *et al.*, 1990; Pardo and Suárez, 1995), with velocities of 5 to 8 cm/year (*e.g.*, DeMets *et al.*, 1994).

The TMVB includes a great variety and large number of volcanoes (over 8000) such as stratovolcanoes, calderas, cinder cones, lava fields, shield volcanoes, and maars, the rocks of which are mainly of calc-alkalic composition, although minor volumes of coexisting alkalic and tholeiitic rocks are also found along the arc. The magmatic province has been subdivided in three sectors (Figure 1) approximately 330 km long each, which in this work correspond to the eastern (Long. W 96–99º), central (Long. W 99–102º) and western (Long. W 102–105º). These segments show distinct structural, compositional and volcanic features that have been genetically related to the nature of the underlying continental crust (Wallace and Carmichael, 1999), as well as to the geodynamic and age properties of the subducting plates. However, for the purposes of this work, the western segment, which is mostly associated with subduction of the Rivera oceanic plate, will not be considered any further.

Southern Mexico

The region that forms the fore-arc of the TMVB may be generally referred to as southern Mexico, although because of the obliquity of the arc relative to the trench, this region has a variable width from barely 60 km in the western sector to over 400 km in the central and eastern sectors. The geology of the area is extremely complex and rather poorly understood along the vertical dimension. The main geologic features of the six tectonostratigraphic terranes that compose this region are briefly summarized in Table 2, with some important references included in which more details may be found. Note that the TMVB intersects only four of the southern terranes (Maya, Zapoteco, Mixteco, and Guerrero) depicted in Figure 1, the former two underlain by Precambrian crust, and the Mixteco and Guerrero terranes composed of juvenile (Paleozoic and Mesozoic, respectively) and reworked (pre-Mesozoic) crust. On the other hand, the Cuicateco terrane, composed of juvenile (Mesozoic) and reworked (Precambrian and Paleozoic) crust, wedges out just before reaching the TMVB at the Pico de Orizaba volcano, and therefore it should not be represented in the crust underlying the volcanic province. The Morelos Platform, although is not considered a terrane by itself, the lack of exposed basement rocks in the region, and the major faults that delimit the province, make the boundary between the Mixteco and Guerrero terranes ambiguous (*e.g.*, Campa and Coney, 1983; Sedlock *et al.*, 1993). Nevertheless, the region intersects a large part of the central TMVB, and although its surface geology is well known (Fries, 1960; Hernández-Romano *et al.*, 1997; Molina-Garza and Ortega-Rivera, 2006) the nature of the buried crust under the platform supracrustal strata is only poorly characterized as probably Precambrian by the presence of high-grade metapelitic xenoliths in Neogene volcanic rocks at Chalcatzingo, Morelos (Gómez-Tuena *et al.*, 2008) and by isotopic geochemical inference (*e.g.*, Levresse *et al.*, 2007).

REGIONAL LOWER CRUST EXPOSED BY XENOLITHS AND OUTCROPS

Xenoliths

Xenoliths in the TMVB are common (Figure 1 and Table 3) but apparently most are of shallow origin except in five localities including three places with lower crustal mafic xenoliths (Valle de Santiago maars, Pico de Orizaba stratovolcano, and Amealco caldera), and two with mantle xenoliths (El Peñón, State of Mexico, and Alto Lucero, Veracruz). A summary of most important xenolith localities (18) in the TMVB is given in Table 3. On the other hand, deep-seated crustal xenoliths in the fore-arc of southern Mexico are only known in three places, but none contain mantle xenoliths: Pepechuca, State of México (Elías-Herrera and Ortega-Gutiérrez, 1997; Elías-Herrera, 2004), Chalcatzingo, Morelos (Ortega-Gutiérrez *et al.*, 2000) and Puente Negro, Puebla (Ortega-Gutiérrez *et al.*, 2004) (Figures 1 and 2). These fore-arc xenoliths differ from those in the TMVB because they consist mainly of granulite facies metapelites with common pyrope-rich garnet, sillimanite, rutile, spinel, corundum, cordierite, orthopyroxene, and Fe-Ti minerals, whereas quartz and feldspars are less common, thus probably imparting a relatively high density (>2.8 g/cm^3) to the buried forearc crust from which they were derived. Although many xenoliths in these places also originated in the deep middle crust under upper amphibolite facies, they consist of mafic, intermediate, and felsic gneisses and schists for which no exposures in the surrounding terranes are known. Granulite facies xenoliths can be distinguished by the presence of orthopyroxene in both mafic and metapelitic lithologies, rutile-bearing quartz and the apparent coexistence of ultrahigh temperature assemblages such as spinel-quartz and hypersthene-sillimanite (Figure 2). This type of metamorphism is unknown elsewhere in Mexico, and could represent a rather unique Proterozoic crust in the TMVB fore-arc of southern Mexico that was sampled by the Cenozoic magmas piercing the Morelos Platform.

Table 2. Main geologic characteristics of the tectonostratigraphic terranes of southern México.

Terrane	Main lithologies	Basement age (Ma)	Boundaries	References
Maya	*ca.*10 km of Jurassic to Recent mainly marine sedimentary rocks, and Permian to early Mesozoic granites intruding orthogneisses and paragneisses in the granulite facies	990-1000	Vista Hermosa thrust	1, 2
Cuicateco	Deformed and metamorphosed Mesozoic and Paleozoic volcanosedimentary rocks, covered by Cretaceous marine carbonates and clastics, and Paleogene volcanic units	Paleozoic	Vista Hermosa thrust and Oaxaca fault	3, 4
Zapoteco	Granulite facies gneisses covered by a Phanerozoic rock column that includes platform sedimentary rocks of early and late Paleozoic age, followed by a Jurassic-Cretaceous sequence, and volcanosedimentary units of Cenozoic age	975-1010	Oaxaca fault and Caltepec fault	5, 6, 7, 8
Mixteco	Polymetamorphic orogenic suites of Paleozoic age, covered by late Paleozoic mainly marine sedimentary rocks, Jurassic to Cretaceous marine and continental units, and volcanosedimentary sequences of Paleogene age	470-355	Caltepec fault and Papalutla thrust	5, 9,10, 11
Chatino	Amphibolite facies gneisses, schists, and migmatites (Xolapa Complex) intruded by Oligocene granites	Precambrian to Jurassic	Chacalapa-La Venta fault and Acapulco trench	5, 12, 13, 14
Guerrero	A complex assemblage of oceanic and continental margin arc-related volcanosedimentary sequences of Mesozoic age, covered by sedimentary and volcanic rocks of Cenozoic age	240-180	Papalutla thrust and Acapulco trench	15, 16, 17, 18

1: Weber and Kohler (1999); 2: Weber *et al.*(2006); 3: Ortega-Gutiérrez *et al.* (1990); 4: Ángeles-Moreno (2006); 5: Ortega-Gutiérrez (1981); 6: Ortega-Gutiérrez *et al.* (1995); 7: Solari *et al.* (2003); 8: Keppie *et al.* (2003); 9: Ortega-Gutiérrez *et al.* (1999); 10: Talavera-Mendoza *et al.* (2005); 11: Nance *et al.* (2006); 12: Ducea *et al.* (2004); 13: Corona-Chávez *et al.* (2006a); 14: Solari *et al.* (2007); 15: Campa and Coney (1983); 16: Centeno-García *et al.* (1993). 17: Elías-Herrera *et al.* (2000); 18: Mendoza and Suastegui (2000).

Table 3. Main xenolith localities reported for the TMVB with some features about their nature and data sources.

Locality	Volcanic unit	Type of xenolith	Observations	Ref.
San Martín, Tuxtla, Ver.	San Martín volcano	Dunite, peridotite, granulite, gabbro	Mantle and cumulate origin. Unstudied.	1, 15
Palma Sola, Ver.	Basaltos de Alto Lucero	Spinel lherzolite, pyroxenite, clinopyroxene megacrysts	Abundant in Pliocene basanites. Lower crust xenoliths not found. Unstudied.	1
Malinche, Pue.,	Malinche volcano	Aluminous granulite	Unstudied.	2
Llano Grande, Edo. Méx.	Iztaccíhuatl volcano	Aluminous granulite	Unstudied.	2
Popocatépetl, Edo. Méx., D.F.	Tutti Frutti tuff	Skarn, granitoids, gabbro, diorite, metasiltstone, marble, high-grade metapelite, deep-seated orthopyroxene xenocrysts	Diversity, abundance, and size of xenoliths are noteworthy. The tuff was dated at 14,000 a. Poorly studied.	3, 15
Chichinautzin series, D.F, Morelos	Tabaquillo lava flow, domes and cinder cones	Granitic to tonalitic, skarn, lamprophyres, rare plagioclase-orthopyroxene banded gneiss, common quartz and plagioclase xenocrysts	Poorly studied. Abundant, most are shallow and cogenetic with the andesitic host.	4, 15 18
Nevado de Toluca, Edo. Méx.	Volcanic complex	Gneiss, schist	Moderately studied. Isotopic signature similar to Mesoproterozoic Oaxaquia.	5
Tlalpujahua, Edo. Mex.	Ignimbrita Las Américas	Micaceous gneisses	Unstudied. Small (1–3 cm), rounded.	6, 15
El Peñón, Edo. Mex.	Basaltic lava flow	Amphibole lherzolites	Small and scarce, comprehensively studied.	7
Amealco, Qro.	Caldera de Amealco	Mafic orthogneiss	Well studied. Single granulite xenolith. It is considered of Precambrian age.	8
Valle de Santiago, Gto.	Maars: Rincón de Parangueo, Cíntora, Álvarez	Granulitic mafic orthogneisses, rare charnockite. Clinopyroxene megacrysts	Well studied: petrology geochemistry, geochronology, geothermometry.	9, 10, 12, 15
Paricutín, Mich.	Michoacán volcanic field	Granitic	Classical studies of magmatic evolution by assimilation-fractional crystallization.	11, 17
Jorullo, Mich.	Volcanic front of the TMVB	Granitic	Unstudied.	12
Arócutin, Mich.	Basaltic andesite breccias	Granitic	Poorly studied. Petrology.	13
Ceboruco, Nay.	Ceboruco, San Juan	Granitic	Unstudied. Extensive melting (pumicitic).	14
Sangangüey, Nay.	Volcanic complex	Gabbroic in alkalic basalts	Poorly studied.	14
Ayutla, Jal.	Lava flows	Phlogopite-clinopyroxene rock, gabbro	Well studied, cumulates, within coeval minettes.	16
Pico de Orizaba, Pue.	Stratovolcano	Mafic granulites	Poorly studied, show the assemblage Plg-Opx-Ol-Cpx	19

1: Nelson *et al.* (1995); 2: Nixon (1989); 3: Schaaf *et al.* (2005); 4: Martín-Del Pozzo (1990); 5: Martínez-Serrano *et al*. (2004); 6: Pantoja-Alor (1994); 7: Blatter and Carmichael (1998); 8: Aguirre-Díaz *et al.* (2002); 9: Uribe-Cifuentes and Urrutia-Fucugauchi (1995); 10: Urrutia-Fucugauchi and Uribe-Cifuentes (1999); 11: Wilcox (1954); 12: Righter and Carmichael (1993); 13: Corona-Chávez *et al.* (2006b); 14: Giosa and Nelson (1985); 15: this work; 16: Righter and Rosas-Elguera (2001); 17: McBirney *et al.* (1987); 18: Márquez *et al.* (1999); 19: Carrasco-Núñez *et al.* (2005).

Exposures of pre-Cenozoic lower crust and estimated densities

Figure 3 illustrates the lithologic columns and densities for the main exposed and buried inferred stratigraphic units for each of the terranes that compose the fore-arc of the Mexican Subduction Zone. Depth to the Moho is estimated from seismic and gravimetric data as discussed below, and reasonable densities are estimated on the basis of mineralogical extrapolations at depth from exposed formations, although considerations based on more complex petrophysical models for changes in porosity and hence density that take place at depth (*e.g.*, Tassara, 2006), and possible structural stacking of the crust are beyond the scope of this work.

Outcrops of old lower crust in southern Mexico extensively occur in the Mesoproterozoic Oaxacan Complex (Ortega-Gutiérrez, 1981, 1984; Solari *et al.*, 2003; Keppie *et al.*, 2003) and Guichicovi Complex (Weber and Kohler, 1999; Weber *et al.*, 2006) of the Zapoteco and Maya terranes, respectively, but may be also present in small portions of the Mesozoic Xolapa Complex in the Chatino terrane (Corona-Chávez *et al.*, 2006a). Lower crustal rocks of the Oaxacan and Guichicovi complexes consist of banded, granulite facies orthogneisses and paragneisses, the composition of which vary from quartz-feldspathic gneisses, calc-silicates and aluminous paragranulites, to mafic and intermediate orthogneisses with abundant anorthosite and

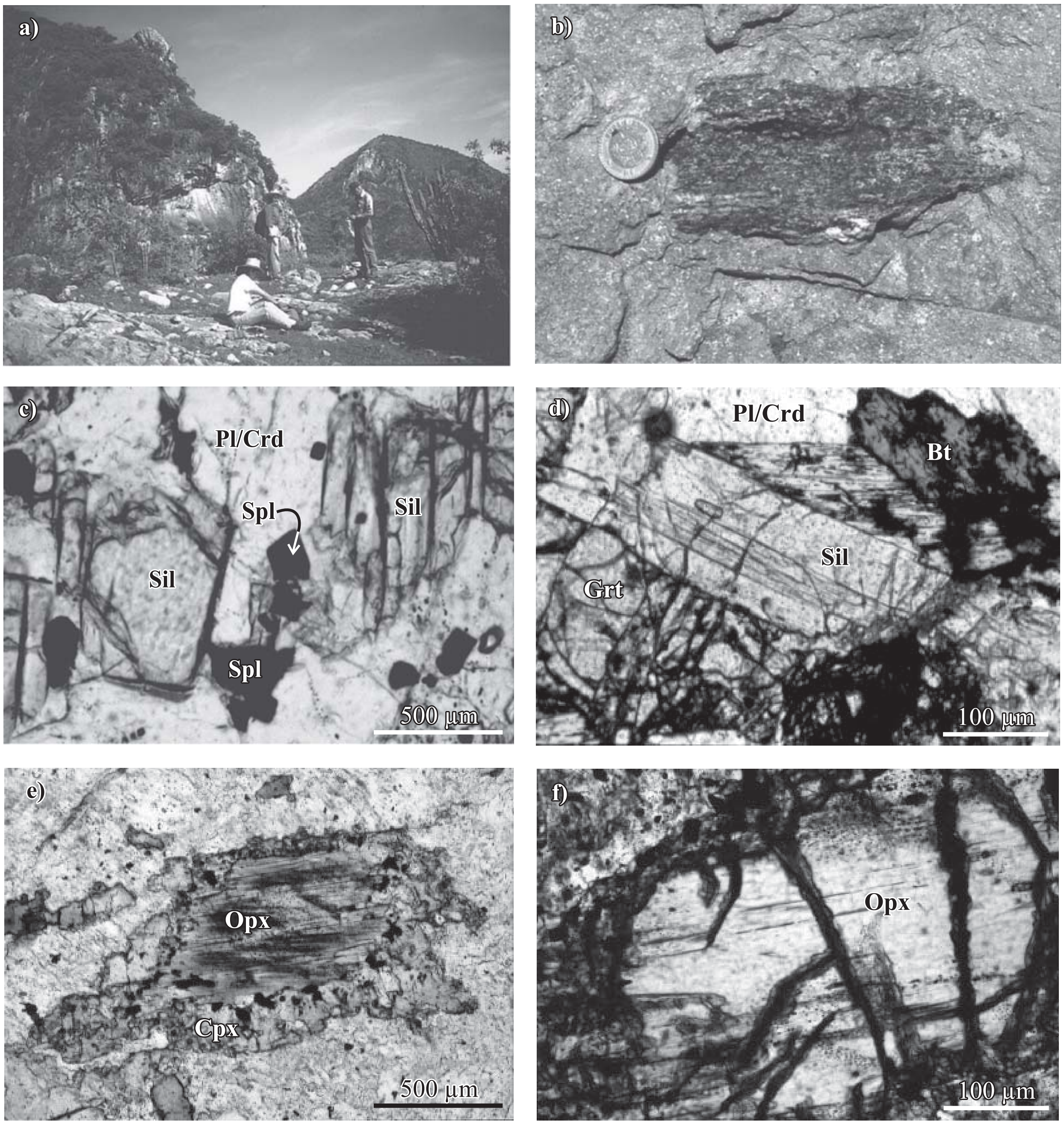

Figure 2. a: Main Chalcatzingo rhyolitic dome where xenoliths are common and diverse. b: One of the largest (coin measures 2.5 cm) xenoliths (hornblende-bearing two-pyroxene banded gneiss) found in the dome. c: Photomicrograph of the high-Al assemblage sillimanite (Sil)-spinel (Spl)-plagioclase/cordierite (Pl/Crd) in a granulitic metapelite. d: Photomicrograph of the high-Al assemblage sillimanite (Sil)-garnet (Grt)-biotite (Bt)-plagiclase/cordierite (Pl/Crd); garnet may be up to 60% mol pyrope, whereas biotite is reddish brown indicating high-Ti content and stability in the granulite facies. e: Orthopyroxene (Opx) with abundant magnetite exsolution lamellae, mantled by clinopyroxene (Cpx) and an opaque phase. The enclosing matrix is rich in plagioclase and strongly retrogressed. f: Hypersthene porphyroblast (Opx) replaced by opacite along the margin and fractures. The rock is a metapelite elsewhere containing quartz and sillimanite, an assemblage formed in the granulite facies at very high temperatures, which is consistent with the strongly pleochroic nature and high-Al content of the orthopyroxene.

rare ultramafic rocks. High-density phases such as garnet (3.58–4.32 g/cm^3) and pyroxenes (3.2–3.5 g/cm^3) are rather common in all mafic, felsic, and metapelitic lithologies, and compete in abundance with quartz (2.65 g/cm^3) and feldspar (2.62–2.76 g/cm^3). Biotite (2.8–3.2 g/cm^3) and hornblende (3.0–3.4 g/cm^3) are also abundant but moderate-density phases, except where retrogression has replaced them by chlorite group minerals (commonly <2.8 g/cm^3), muscovite (2.76 g/cm^3), and calcite (2.71 g/cm^3). This retrogression is local and represents low-temperature hydration of the granulites causing the density to decrease substantially. However, at certain depths under the present exposures, this low-grade retrogression may disappear. Thus, considering the mineralogy of granulites in the Zapoteco terrane of southern Mexico, a mean density for this crustal region may be closely estimated by taking the average of mafic and quartzo-feldspathic phases assuming that they constitute respectively approximately 50 % by volume. In this case, the average density of the lower crust (uncorrected for pore fluid contents) could be close to 3.0 g/cm^3 in this region. On the other hand, because abundant granitoids together with Precambrian granulites form outcrops (Guichicovi Complex) and subcrops in the buried basement of the Maya terrane, the mean density of the crust in this terrane may be estimated by considering equal parts of garnetiferous granulites (3.0 g/cm^3) and granite (2.65 g/cm^3), yielding a density of 2.82 g/cm^3. The Cuicateco terrane is not considered any further in this context because it wedges out before reaching the underpins of the TMVB (Figure 1). Nevertheless, its general geologic and density features are given in Figure 3.

The Mixteco terrane in outcrop includes eclogite and garnet amphibolite (>3.4 g/cm^3), but their added volume may represent only up to 10 % or less of the entire formation, which for the most part shows intense retrogression to garnet-free amphibolite or greenschist with lower densities. The structural depth to which the present Acatlán Complex extends is about 20 km, indicating that this lower limit marks the base of the middle crust. The underlying lower crust, about 20 km thick, probably is composed of granulite facies rocks, as evidenced by xenocrysts of metamorphic orthopyroxene contained in Jurassic granitoids emplaced in the middle crustal migmatites of the Acatlán Complex (Ortega-Gutiérrez, 1975). The main part of the exposed Acatlán Complex to structural depths of about 10 km is in fact formed by quartzite and quartzose phyllite, the mean (uncorrected) density of which would be about 2.65 g/cm^3. Because this sort of lithology continues down to the base of the Acatlán Complex, albeit changing to denser metamorphic phases such as biotite and some garnet, it is possible to predict the nature of rocks and minerals that compose the lower crust, provided that the Acatlán Complex continues down to this depth. At granulite facies, these rocks, because of the abundance of quartz and feldspar, would still preserve a mean density of about 2.75–2.8 g/cm^3, thus implying a total mean density for the crust underlying the Mixteco terrane of 2.73 g/cm^3.

The upper and middle crust of the Chatino terrane are dominated by garnet-poor, quartzo-feldspathic gneisses and intrusive granitic plutons, the mean density of which would by about 2.7 g/cm^3. The lower crust of the Chatino terrane is not exposed, although some granulite facies rocks are apparently cropping out in limited areas of the Xolapa Complex (Corona-Chávez *et al.*, 2006a). Thus, it may be safely assumed that most of the crust under the present exposures of the upper amphibolite facies Xolapa Complex is composed of granulitic and metapelitic gneisses with some garnet and pyroxenes, but with quartz, micas and feldspar constituting the great majority of that crust. A mafic lowermost crust may also be present if the source of the heat that generated the Xolapa Complex and its intrusive batholiths originated from underplated basaltic magmas. However, because garnet would not be stable in the relatively thin and hot crust of the continental margin of southern Mexico (10–30 km, see below), a garnet-free gabbroic rock in the granulite facies would have a density less than 3.0 g/cm^3. Thus, a mean density for the lower and middle crust in the continental margin of southern Mexico can be roughly estimated taking one quarter of this crust to be mafic and the other three quarters quartzo-feldspathic, yielding a value of about 2.72 g/cm^3.

Outcrops of the Guerrero terrane, considering a maximum exposed thickness of about 6 km in the Tejupiclo area (Elías-Herrera, 2004), consist of island arc and ocean floor volcanic and sedimentary assemblages generally metamorphosed at low grade (greenschist and sub-greenschist facies). Protoliths are dominantly slate, graywacke, and andesitic lavas and pyroclastic rocks, for which a mean density of 2.7 g/cm^3 may be safely assumed. Deeper structural levels include amphibolite facies schists and granitoids with densities estimated at 2.7–2.75 g/cm^3. The deep buried crust of the Guerrero terrane south of the Balsas River cannot not be much denser because even for crustal thicknesses calculated by seismology at 32 km (Domínguez *et al.*, 2006), the low-grade facies rocks would be hydrous quartzo-feldspathic schists and gneisses with minor amphibolites, where hornblende, some pyroxene, and epidote (3.3 g/cm^3) would be present. It is important to mention, however, that recent magnetotelluric experiments across two profiles in southern and central-northeastern Mexico (Jödicke *et al.*, 2006) concluded that the lower crust in these regions has been hydrated by fluids derived from the top of the subducting slab, and that porosities between 5 to 3 % may exist in this crust where excess water is being stored. Therefore, densities derived above were corrected down by a maximum factor of 5 % (Table 4) to account for the pores occupied by water (*ca.* 1 g/cm^3). Note that hydration of the granulitic lower crust to form amphiboles, biotite and probably epidote with mean densities similar to pyroxene, but with garnet remaining stable at those pressures and temperatures, would not change much an overall density of the lower crust estimated at 2.80 g/cm^3.

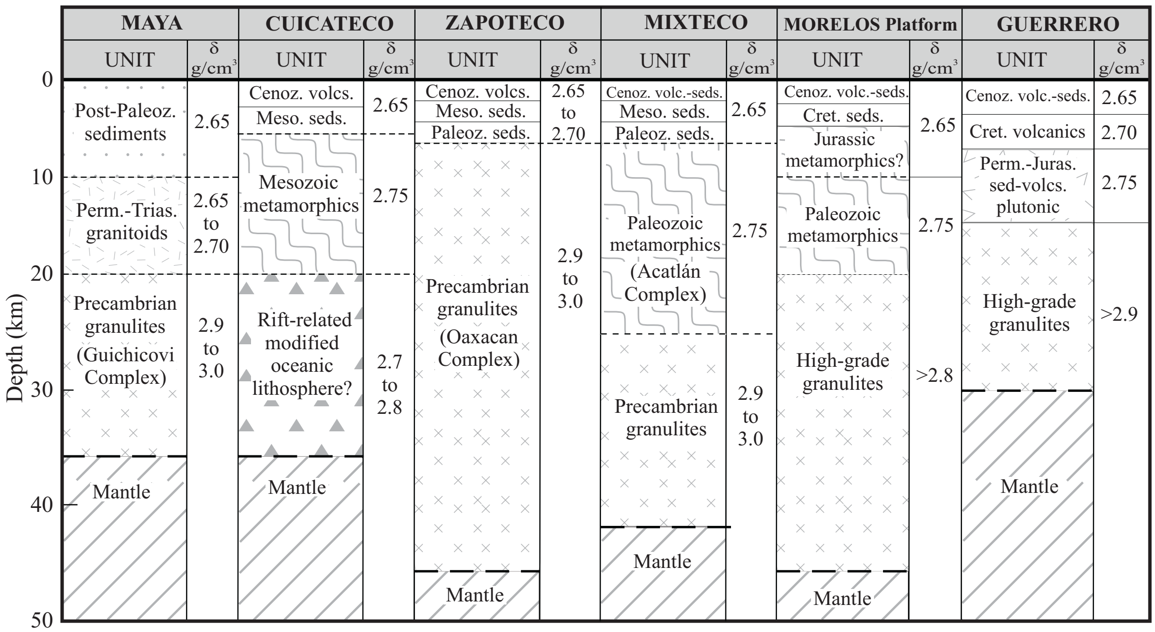

Figure 3. Lithologic columns and inferred densities for the main exposed and buried stratigraphic units that compose each of the terranes in the fore-arc of the Mexican Subduction Zone. The lithologic column of the Chatino terrane was omitted because, although it is part of the TMVB fore-arc, it is not involved as a possible source or contaminant of magmas of the arc.

GEOPHYSICAL MODELS

Gravity

Modeling of the crust by gravity methods requires some critical assumptions such as isostatic compensation and density profiles for a layered crust, which in turn rest on the adequate conversion of seismic wave velocities to densities. However, it should be borne in mind that the heterogeneous geology, active tectonics, and reduced width (<100 km) of many of the crustal blocks that compose the basement of the TMVB in some cases may not be isostatically compensated, thus somewhat weakening the models. The first comprehensive attempt to gravitationally picture the third dimension of the Mexican crust was made by Woollard *et al.* (1969) based on a survey of the Bouguer anomaly distribution in the country. The results, expressed in a map, proposed a close isostatic compensation of the Mexican crust given by the relation H = (BA-35)/0.079, where BA is the Bouguer anomaly in mgals and H the topographic height in meters (*e.g.*, Molina-Garza and Urrutia-Fucugauchi, 1993).

More recent modeling of the Bouguer anomaly in three N-S profiles representing the main part of the TMVB (Urrutia-Fucugauchi and Flores-Ruiz, 1996) determined a simple Bouguer anomaly pattern characterized by negative values between 200 and 250 mgals corresponding to a mean topographic height of about 2000 m (Figure 4). Maximum and mean crustal thicknesses of about 50 and 42 km and assuming mean crustal and mantle densities of 2.85 g/cm^3 and 3.30 g/cm^3, respectively, were pictured along the eastern profile, corresponding to the central region of the TMVB across Mexico City (see Figure 4a). The profile across the western part of the TMVB, on the other hand, showed a maximum crustal thickness of 41 km and an average of 38 km (Urrutia-Fucugauchi and Flores-Ruiz, 1996). Interestingly, the central profile across the Guanajuato-Michoacán volcanic field that contains the only granulitic xenoliths in the TMVB also yielded similar crustal thicknesses between 40 and 47 km. The thickness of the crust underlying the early Mesozoic Arteaga Complex in the TMVB fore-arc adjacent to the Michoacán monogenetic volcanic front, modeled by gravity and magnetics, was calculated at 28–32 km, assigning to the lower crust a density of 2.9 g/cm^3 and a thickness between 13 and 17 km (García-Pérez and Urrutia-Fucugauchi, 1997). However, considering the petrologic composition of the Guerrero terrane in its lower pre-Cretaceous levels, where quartz and feldspar-rich metasedimentary rocks predominate (Centeno-García *et al*., 1993, 2003; Elías-Herrera *et al.*, 2000; Elías-Herrera, 2004), the real density of the lower crust there is probably much lower. The thinnest crust found along the volcanic front of the TMVB occurs in its western sector beneath the Colima rift, where a maximum thickness of 18 km was measured by the gravity modeling (Figure 4a).

A detailed gravity interpretation of the crustal structure under the State of Oaxaca, southern Mexico (Mena *et al.*, 1995), based on two profiles along and across the continental margin from Ometepec, Guerrero to Salina Cruz, Oaxaca, and from Puerto Ángel to Teotitlán del Camino, Oaxaca, respectively, derived a complex crust consisting of six layers with densities ranging from 2.67 to 2.9 g/cm^3, and a constant Moho depth of 28–30 km along the Pacific coast of Oaxaca. The presence of this relatively thick continental crust adjacent to the deep oceanic trench is probably due to the Cenozoic truncation of the continental structure in southern Mexico.

Seismicity and magnetotellurics

Several seismic refraction profiles and other seismological local studies, or extending from the Pacific margin into the TMVB (*e.g.*, Meyer, 1961; Fix, 1975; Valdés *et al.*, 1986; Geolimex Working Group, 1994; Valdés-González and Meyer, 1996; Campillo, *et al.*, 1996; Campos-Enríquez and Sánchez-Zamora, 2000; Iglesias *et al.*, 2001), differ considerably in the crustal thickness estimates (*e.g.*, Cruz-Atienza, 2000) from the gravity results for the Moho depth in southern Mexico and under the TMVB. A crustal model based on magnetotelluric profiles of the Oaxacan continental margin (Arzate *et al.*, 1993) determined a relatively thin crust of about 35 km under the central part of the profile (Oaxaca city), contrasting with the maximum Moho depth of 44 km found on the basis of gravity modeling. This 10-km difference was attributed to the presence of fluids, porosity or fracturing of the lower crust, which shifted the magnetotelluric spectra towards lower values in relation to gravity and seismic modeling.

A more detailed magnetotelluric profile extending from Acapulco, in southern Mexico, to Tampico, in northeastern Mexico, across the TMVB, was designed to better understand the complex terrane structure, geometry of tectonic boundaries and constitution of the crust (Jording *et al.*, 2000). Results showed that some of the terrane boundaries are shallow structures that do not extend at depth, except for the case of the northern limit of the Xolapa Complex (Chatino terrane) along its entire length. It is rather surprising that this study did not consider the Oaxaca fault as a fundamental tectonic boundary, despite its 200 km rectilinear minimum extension separating the Proterozoic Oaxacan Complex from a Mesozoic tectonostratigraphic unit, which is formed by volcanosedimentary units partly deposited on oceanic lithosphere represented by mafic and ultramafic dismembered ophiolitic sequences in the Cuicateco terrane.

Similar magnetotelluric profiles across southern and central Mexico were studied with the main objective of depicting processes associated with fluid and melt release from the subduction zone and the influence of obliquity of the arc in relation to the trench (Jödicke *et al.*, 2006). In the central Mexico profile (Acapulco, Guerrero-Tampico, Tamaulipas) a high conductivity structure set astride the lower and middle crust boundary and extending over 300 km across the TMVB was interpreted as a partially molten zone produced by hydrous melting of the lower crust, whereas along the southern Mexico profile, which lacks volcanism (Puerto Escondido, Oaxaca-Alvarado, Veracruz) various high conductivity anomalies were explained only by the presence in the lower crust of fluids released from the shallow slab and trapped under an impermeable middle crust. The absence of melts in this case was ascribed to differences in the geometry and age of the deformed subducting plate, with a steeper angle of subduction in southern Mexico (13º) compared to the profile across central Mexico, where the slab is younger and less inclined (10º). Otherwise, the geothermal gradient along the trajectory of the subduction plane that best fitted the conductivity anomalies in relation to dehydration reactions of the downgoing plate was 8.5º/km for both regions.

Heat Flow

Surface heat flow measurements in southern Mexico or the TMVB are so few (*e.g.*, Prol-Ledezma and Juárez,

Table 4. Summary of the main properties of geologic systems involved in mantle-crust interactions in the TMVB volcanic front and fore-arc regions.

Province		**Maximum crust thickness (km)** (see text for references)	**Lower crust modeled mean density** (g/cm^3)	**Corrected mean density*** (g/cm^3)	**Xenoliths and xenocrysts**			**References for xenoliths** (see Table 3)
					UC	**LC**	**M**	
TMVB	Eastern	49	Undetermined	-	X	n. f.	X	1
	Central	47	Undetermined	-	X	X	X	2, 3, 4, 5, 6, 7
	Western	41	Undetermined	-	X	n. f.	X	14
Fore-arc terranes	Maya	35**	2.82	2.73	X	n. f.	X	1
	Zapoteco	45	3.0	2.90	n.f.	n. f.	n. f.	-
	Mixteco	40	2.8	2.71	X	X	n. f.	15
	Guerrero	32	2.85	2.76	X	X	n. f.	15
	Morelos Platform	45	2.79	2.65	X	X	n. f.	15
	Chatino	30	2.72	2.63	n. f.	n. f.	n. f.	-

X = Present. *Corrected to account for about 5 % porosity of the lower crust filled with aqueous fluids (*c.f.* Jödicke *et al.*, 2006). **Calculated from the hydrostatic equation $R = H*D_c/(D_m-D_c)$ assuming isostatic equilibrium, where R stands for the root of the mountain range, H the maximum height of non-volcanic mountains in the region, and D_m and D_c mean densities of the local mantle and crust respectively. A sea level crustal standard section 30 km thick is also assumed. UC: Upper crust, LC: Lower crust, M: mantle, n. f.: not found.

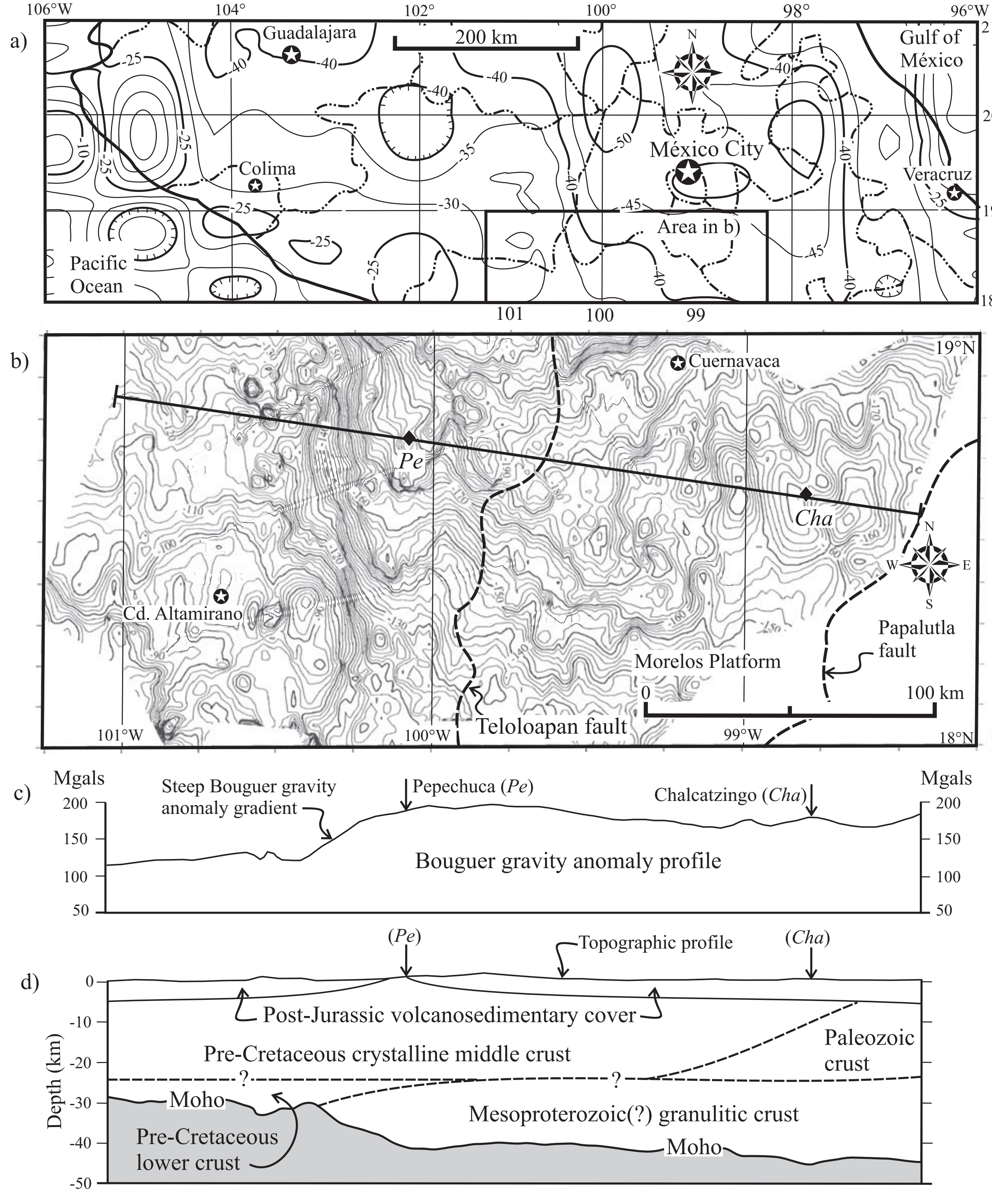

Figure 4. a: Regional crustal structure beneath southern-central México obtained from Bouguer gravity anomalies (Urrutia-Fucugauchi and Flores-Ruiz, 1996). The map was elaborated using an intermediate layer density of 2.63 g/cm^3. (b) Total Bouguer gravity anomaly map for the Balsas basin in the Cuernavaca, Morelos-Ciudad Altamirano, Guerrero region (García-Pérez, 1995) with a Bouguer gravity profile (c); and (d) the correspondent crustal profile calculated from the formula H = 2800h/500 assuming isostatic, single level (Airy model) compensation, where H stands for the thickness of crustal root in meters, and h for the topographic altitude in meters above sea level; the mean density of the crust is taken to be 2800 kg/m^3, and the density contrast between the mantle and the crust 500 kg/m^3. For the discussion, it is important to note in this figure the N-S trending steep gravity gradient located *ca.* 100° 15´, from which an abrupt change in crustal thickness is deduced, as indicated in (b). The granulite facies crustal xenolith localities of Pepechuca (*Pe*) and Chalcatzingo (*Cha*) are included, together with the boundaries between Guerrero, and Mixteco terranes as proposed by Campa and Coney (1983, Teloloapan fault) and Sedlock *et al.* (1993, Papalutla fault). Teloloapan and Papalutla faults delimit the Morelos Platform.

1985; Ziagos *et al.*, 1985), with the exception of the Texcoco site in the Valley of Mexico, of very shallow depth (100–350 m), that their use for constraining the thermal structure of the crust overlying the MSZ is severely limited. It should be mentioned, however, that the corrected geothermal gradients obtained from 15 sites along an area running from the fore-arc (8 sites), across the arc (2 sites), and into the backarc (5 sites) regions of the central and western segments of the TMVB (Ziagos *et al.*, 1985) yielded low values in the fore-arc (8.4–16.3ºC/km), but substantially higher (as expected) in the arc (36.9–56.5ºC/km), and the backarc (17.8–61ºC/km). In fact, these specific gradients and its large variations respond more probably to local and transient geologic conditions rather than to the secular heat field that should affect deeper levels of the underlying crust. On the other hand, the contoured heat flow for southern and central Mexico roughly depicts a fore-arc with values below 40 mW/m^2, which double in the arc and backarc regions to values between 40 and 80 mW/m^2. Averages for the fore-arc, arc, and back arc regions reported by Ziagos *et al.* (1985) were 26 ± 5 mW/m^2, 91 ± 26 mW/m^2, and 89 ± 27 mW/m^2, respectively, indicating contrasting thermal conditions, most probably related to the presence in the last two regions of stagnant magmas in the crust, or an underlying anomalous hot mantle. The fore-arc, on the other hand, appears to be refrigerated with respect to normal conditions in the continental crust of Mexico. Corresponding geotherms for the entire fore-arc crust of southern Mexico is extremely low at 5ºC/km, whereas it rises to 22.5ºC/km in the backarc region of the TMVB (Ziagos *et al.*, 1985, fig. 9).

DISCUSSION

Xenoliths age and pressure-temperature conditions in the local lower crust

The only data on the P-T conditions based on deep-seated xenoliths from the crust under the TMVB are reported in two studies. Aguirre-Díaz *et al.* (2002) reported one granulite xenolith from the Amealco caldera (Figure 1), State of Querétaro, that yielded entrainment pressures of 2.9–3.2 kbar (10–12 km) calculated from trapped fluid inclusions and assuming temperatures of 800 and 900ºC for the generation of the enclosing granulites. However, the original layer that provided the xenoliths, considering its high-grade metamorphism and relatively young Nd model age (683 Ma), more probably represents the actual lower crust buried at least 25 km, and from which the xenolith was carried up by a magma that stagnated in the upper crust (<12 km), where the fluids inclusions might have been formed. The Amealco caldera is located between extensive outcrops of the Mesozoic Guerrero terrane at El Oro-Tlalpujahua region in the south, and Guanajuato area in the north, and thus this terrane should underlie the caldera. Because a minimum structural thickness of about 6 km has been measured in the Guerrero terrane of southern Mexico (Elías-Herrera, 2004), the upper and middle crust underlying the southern edge of the central TMVB should be composed essentially of low-grade metamorphic rocks typical of that terrane, and the Precambrian granulites proposed by Aguirre-Díaz *et al.* (2002) may be present only in the lower crust. It should be pointed out, however, that the Precambrian age obtained by Aguirre-Díaz *et al.* (2002) for the xenolith is a Nd model age, but the true age of the buried basement should be younger.

Xenoliths from Valle de Santiago, Guanajuato, although are abundant and have been geochemically well studied (Uribe-Cifuentes, 2006), their age and pressure-temperature conditions have been only poorly determined. Righter and Carmichael (1993) concluded that xenocrysts of olivine, pyroxene and plagioclase in the country lavas and pyroclastic rocks of this locality were taken from underplated bodies of gabbro and pyroxenite buried about 30 km. Thermobarometry on the granulite xenoliths yielded a pressure range of 5 to 10 kbar equivalent to lower middle and lower crust, although the mineral composition of granulites studied by us from Valle de Santiago consist of Opx-Cpx-Ol-Plg-Spl, showing all levels of concentration of the major phases from anorthositic to pyroxenitic in irregular bands or elongate zones, indicating that this part of the lower crust may represent intraplated basic magmas where fractional crystallization of plagioclase and pyroxene played a major role. The problem, however, is that some of these granulites show a foliation across the presumably magmatic banding, representing a tectonic event after crystallization, and therefore it is difficult to consider them equivalent to the magmas of the overlying TMVB, unless the deformation is associated with deep fault movements active in the Neogene. Considering that garnet-free, plagioclase-olivine, and orthopyroxene-spinel pairs coexist in textural equilibrium in most of the mafic granulites studied by us from that locality, maximum pressures between 5 kbar (olivine-plagioclase) and 8 kbar (orthopyroxene-spinel) may be estimated for the crystallization of these xenoliths based on petrogenetic grids for mafic and ultramafic rocks under granulite facies conditions (*e.g.*, Gasparik, 1984; Herzberg and Gasparik, 1991), and yet thermal models for the crust in the Michoacán sector of the Mexican subduction zone (*e.g.*, Currie *et al.*, 2002; Manea *et al.*, 2005) predict a temperature of 800ºC at the base of a 40 km thick crust. These conditions require a geothermal gradient of 20ºC/km and the stability of garnet for a mafic lower crust. Indeed, partial melting of the mafic lower crust (fluid absent), according to experimental data on MORB-type starting samples (Rapp *et al.*, 1991), at temperatures up to 1075ºC and between 8 and 32 kbar produces highly depleted HREE tonalitic to trondhjemitic melts, with garnet remaining in the residue at pressures above 8 kbar, but magmas or xenoliths with this composition are absent from Valle de Santiago volcanic field. Therefore, whether the mafic xenoliths come from underplated Mesozoic or Cenozoic subduction-related magmas, or were entrained well above the local Moho from an older crust, it is not known. If representing the lowermost crust under Valle de Santiago, a maximum thickness of about 30–36 km (8–10 kbar) would be suggested by the mineral assemblages in the garnet-free granulites, which is much thinner than the 40–45 km (11–12 kbar) suggested by geophysical methods (Urrutia-Fucugauchi and Molina-Garza, 1992; Campos-Enríquez and Sánchez-Zamora, 2000). Here we propose that these granulites may in fact represent the upper part (25–30 km depth) of probably Precambrian lower crust affected by Cenozoic thermal processes that include the coeval massive access of mafic magmas (underplating), granulite facies metamorphism, partial melting, and some mixing of the magmas evolved from these processes. Unfortunately, the age obtained for these xenoliths (Uribe-Cifuentes, 2006), of 1.6 Ga, and from high grade gneissic xenoliths of Nevado de Toluca at 1.2–1.3 Ga (Martínez-Serrano *et al.*, 2004) all are depleted mantle Nd model ages and therefore do not represent the real age of the correspondent basement, which is also the case for the Amealco granulite single xenolith (Aguirre-Díaz *et al.*, 2002).

Thermal structure

The thermal state of the lower crust plays a crucial role in the generation and modification of magmas by processes such as anatexis and assimilation. Thus, the understanding of the temperature distribution as a function of depth (geothermal gradient) constitutes an important factor for modeling geodynamic process associated with arc volcanism. In the absence of precise heat flow measurements along the TMVB and its fore-arc (Ziagos *et al.*, 1985), analogs of other similar arc settings in the world may be useful to assess the thermal structure of the lower crust under the TMVB, and compare it with data from recent numerical models mentioned above for the Mexican province. The young and hot Cascadia slab of the northwestern United States (8 Ma) shows a 13º angle of subduction and moderate temperatures of about 800ºC for the top of the slab at about 80–85 km depth under the volcanic front and maximum temperatures of 1050ºC for the overlying mantle (Hacker *et al.*, 2003; Preston *et al.*, 2003), yielding an integrated geothermal gradient for the slab of 10ºC/km (hot subduction). In contrast, the Costa Rica subduction zone, where steep slab angle only heats to 500ºC the upper plate boundary (Peacock *et al.*, 2005), developed a lower geothermal gradient of 7ºC/km (cold subduction).

On the other hand, the geometry of the Cocos plate west of the Tehuantepec ridge (Kostoglodov *et al.*, 1996) includes (Figure 5) a subhorizontal (13º) segment extending from the trench to the Pacific coastline, there it bends over and follows a horizontal trajectory for 150 km, plunging again to acquire its final angle of around 21º under the Popocatépetl volcano situated about 330 km from the trench. Based on this geometry and that of Pardo and Suárez (1995), Currie *et al.* (2002) carried out the first numerical thermal modeling of the MSZ along four profiles from Jalisco to Oaxaca in southern Mexico set across the fore-arc and into the TMVB. The most important result of that work was the definition of P-T fields for the four regions predicting maximum temperatures at the base of the local crust (mean of 40 km) between 700ºC for the Jalisco-Michoacán and 800ºC for the Guerrero-Oaxaca fore-arc sections. These data would yield a rather low geothermal gradient of 17.5 ºC/km and pressures of about 11 kbar for the base of the crust underlying the volcanic front at Popocatépetl volcano. Further thermal modeling of this subduction system, which considered the partly coupled nature of the slab interface (Manea *et al.*, 2004,), predicted fore-arc and volcanic arc surface heat flows of 28–35 mW/m^2 and ~60 mW/m^2 respectively, yielding a similar temperature of 700ºC for the Moho under Popocatépetl. In this case, the top of the subducting plate would be at 600ºC, and about 70 km deep (21 kbar) thus recrystallized in the wet (zoisite) eclogite facies, whereas maximum temperatures modeled for the mantle wedge under Popocatépetl volcano are about 750ºC. Clearly, these P-T conditions are not sufficient to melt the basaltic crust of the slab nor the mafic lower crust, and also are too low for melting (wet solidus at 980ºC at 70 km) of the overlying mantle peridotite (Peacock, 1990; Schmidt and Poli, 1998; Poli and Schmidt, 2002) to account for the primary andesitic and adakitic magmas that characterize the TMVB volcanic front.

However, when shear heating in the slab interface and a stress-temperature dependence of mantle viscosity are considered (*e.g.*, Manea *et al.*, 2005, 2006), temperatures dramatically rise to about 900ºC along the thrust plane, to a maximum of 1230ºC in the overlying mantle, and to 1100ºC at the base of the crust under Popocatépetl or Nevado de Toluca volcanoes, implying a mean crustal geothermal gradient of 27.5ºC/km. Under these conditions, hydrated mantle peridotite, eclogitic oceanic crust, and granulitic lower mafic crust would easily yield partial melts of andesitic composition, making it clear that frictional heating and a temperature-dependent olivine rheology of the mantle wedge are critical factors for the generation of intermediate and mafic magmas along the TMVB volcanic front. Another way to reconcile the actual presence of andesitic and adakitic volcanism in the frontal zone of the TMVB, would be to increase (beyond the flat segment) the present seismically unconstrained inclination of the slab from its proposed value of 19–21º (Manea *et al.*, 2004; Kostoglodov *et al.*, 1996) to much steeper angles (*e.g.*, Ferrari, 2006; Manea and Gurnis, 2007), which would then permit a thicker mantle column than the presently proposed value of only 32 km under Popocatépetl, and consequently also an intense asthenospheric heating of the wedge under the stratovolcano. In fact, an angle greater than 45º for the Cocos plate beyond the inflection point has been recently suggested from MASE (Middle America Subduction Experiments) receiver function data (Xyoli Pérez-Campos, unpublished data), thus creating optimal conditions within a mantle column 80 km thick (37 kbar at the slab interphase) for increasing the temperature of the entire subduction system to values that permit the generation of andesitic magmas. Note that adakites, if generated at these pressures, would have to be the product of coesite eclogite partial melting, where calcic or sodic amphiboles are no longer stable.

Measured surface and reduced heat flow in the study region, as described above (*e.g.*, Ziagos *et al.*, 1985), calculated a mean geotherm of 22.5ºC/km for the arc-backarc regions of the TMVB, which when translated to temperatures at a Moho buried 40–50 km, would yield values at the base of the local crust of 900–1125ºC. These temperatures, if the crust is indeed that thick, would also cause hydrous melting of the lower mafic crust and produce TMVB magmas of intermediate composition albeit without an adakitic signature because garnet or amphibole are not stable at those P-T conditions.

Precambrian lower crust under the TMVB?

Although outcrops of Precambrian rocks have not been found forming the basement of the TMVB volcanic rocks, it is quite possible that the eastern sector is underlain by Oaxaquian-type (*i.e*., Grenvillain) crust, which is widely exposed less than 100 km south of Pico de Orizaba volcano, and at a similar distance north of Los Humeros Caldera (Figure 1). The involvement of this crust is in fact shown by the higher radiogenic (Pb, Nd, and Hf) isotopic signatures measured for Pico de Orizaba (Schaaf *et al.*, 2005; Macías, 2005; Cai *et al.*, 2007) compared to the other sectors of the TMVB, and by the presence of granulite facies xenoliths in volcanic rocks at and around the Citlaltépetl (Pico de Orizaba) stratovolcano (Carrasco-Nuñez *et al.*, 2005).

Moreover, Precambrian Nd model ages (1.2–1.6 Ga) similar to those in Oaxaquia Mesoproterozoic crust have been documented from xenoliths, both in the front of the TMVB at Valle de Santiago (Urrutia-Fucugauchi and Uribe-Cifuentes, 1999) and Nevado de Toluca volcano (Martínez-Serrano *et al.*, 2004), as well as in the fore-arc region at Pepechuca (Elías-Herrera and Ortega-Gutiérrez, 1997; Elías-Herrera, 2004), which correspond to the central sector of the Mexican arc. Inherited zircons in latest Cretaceous granitoids of the Morelos Platform have been interpreted to come directly from underlying Grenvillian crust (Levresse *et al.*, 2007). On the other hand, the granulitic xenolith reported at Amealco (Aguirre-Díaz *et al.*, 2002) yielded a Nd model age of 683 Ma, probably indicating substantially less Precambrian crust contamination along the central sector of the TMVB. Although the thick crust (40–50 km) found by geophysical methods along the internal regions of the TMVB volcanic front, as presented above, would suggest the presence of lower crustal roots related to Paleozoic and Precambrian orogens, it is clear from Figure 1 that the distribution of terranes in the fore-arc of southern Mexico favors the existence of a younger middle crust (Paleozoic and Mesozoic) buried under the volcanic front along the central sector of the TMVB. The Bouguer gravity anomaly map and section across the tectonic boundary between the

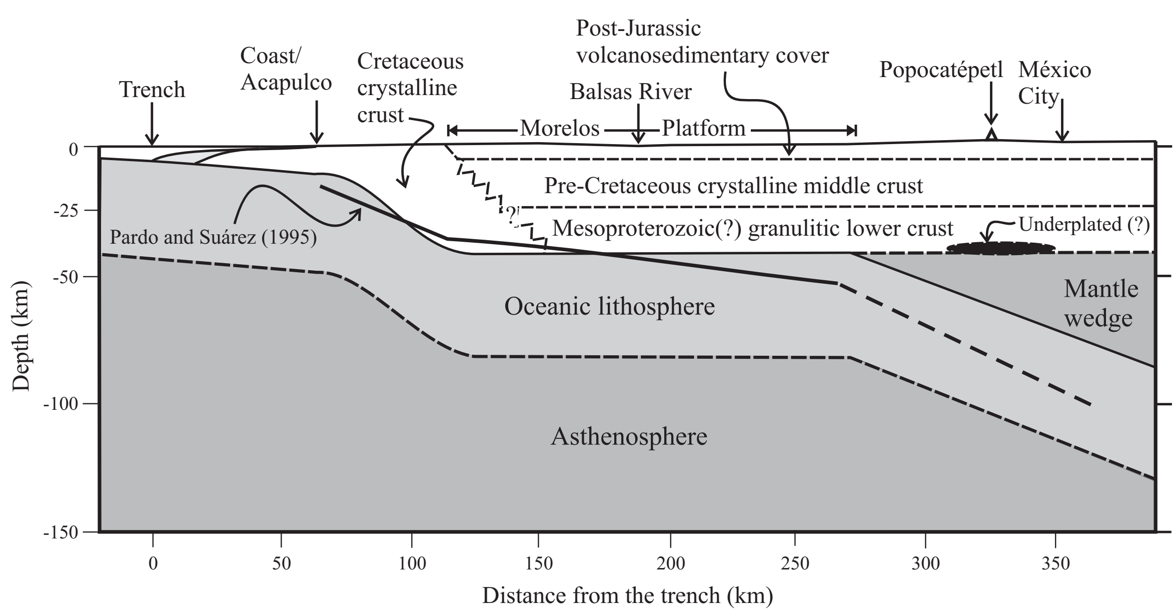

Figure 5. Mexican Subduction System showing the Cocos plate geometry as proposed by Kostoglodov *et al.* (1996), where the previous profile of Pardo and Suarez (1995) was added. The crust above is modeled in our work as composed of three main layers, consisting of a probable Mesoproterozoic lower crust overlain by middle crust crystalline rocks of Jurassic and older age, covered by unmetamorphosed post-Jurassic supracrustal sedimentary and volcanic units. The frontal part of the continental fore-arc is characterized by high-grade rocks of the Xolapa Complex, essentially of Cretaceous age, and a sedimentary Miocene-Recent accretionary prism. Note the possible presence, proposed here, of underplated mafic rocks at the base of the lower crust beneath the volcanic front (Popocatépetl volcano) of the TMVB.

Guerrero (Mesozoic) and Mixteco (Paleozoic) terranes (García-Pérez, 1995) between west longitudes 98 and 101º (Figure 4b and c) show a marked gradient trending N-S along 100.3º Meridian evidently dividing a thicker crust (Figure 4d) to the east (probably Mesoproterozoic lower crust) from a thinner crust to the west (essentially Mesozoic crust). Major geologic structures aligned with this trend are the Arcelia graben in southern Mexico and the Querétaro fault in the TMVB (Alaniz-Álvarez and Nieto-Samaniego, 2005). The tectonic significance of this feature constitutes a central issue because the contact between the Mesozoic Guerrero and the Paleozoic Mixteco terranes would lie 40 km (Campa and Coney, 1983) or 200 km (Sedlock *et al.*,1993) east of the gravity gradient trend. The thickening of the crust across this boundary may indicate thrusting of the Mesozoic rocks over the Paleozoic terrane and its possible Precambrian substrate (Figure 4d), and therefore the extension of pre-Mesozoic crust and Mesozoic thrusting for more than 240 km west of its outcropping limit in the Papalutla fault. In conclusion, however, the lack of Precambrian outcrops or properly dated xenoliths showing that age in the crustal structure of the western and central sectors of the TMVB requires extreme caution and further studies are needed before the presence of Precambrian crust under the arc is considered a valid assumption.

Role of the lower crust as a contaminant and potential source of andesitic and adakitic magmas in the TMVB

The chemical influence of the crust in the petrogenesis of the TMVB has been a constant subject of discussion, and many authors (*e.g.*, Verma, 1999, 2000; Chesley *et al.*, 2002; Verma and Carrasco-Núñez, 2003) have shown that crustal assimilation in some places of the TMVB had a central role in the process, whereas many others (Wallace and Carmichael, 1999; Gómez-Tuena *et al.*, 2007; Blatter *et al.*, 2007) tend to minimize this role in the studied areas (Chichinautzin, Zitácuaro), placing the main controls in processes affecting the mantle wedge and subducted slab. However, given the continental setting of the TMVB and the thickness of the underlying crust as discussed above, crustal assimilation should be an important process in the petrogenesis of its magmas, which in many places is clearly indicated at least for shallow levels by the thermal and chemical interaction of upper crustal xenoliths with the magma (*e.g.* Wilcox, 1954; McBirney *et al.*, 1987; Márquez *et al.*, 1999; Luhr, 2001; Schaaf *et al.*, 2005). And yet, with the exception of some volcanoes in the eastern sector, the great majority of the andesitic and basaltic magmas so far studied show little if any isotopic evidence of contamination by an evolved crust.

On the other hand, adakites which may be generated by partial melting of a thickened or delaminated lower crust (Chung *et al.*, 2003; Kay *et al.*, 2005), have been identified in the TMVB in several places, varying in age from Miocene to the present (Luhr, 2000; Gómez-Tuena *et al.*, 2003, 2006, 2008; Martínez-Serrano *et al.*, 2004). However, these rocks and following Defant and Drumond (1990), have been geochemically explained by melting the mafic crusts of the young Rivera plate (Luhr, 2000) or due to prolonged flat subduction episodes of the Cocos plate (*e.g.*, Mori *et al.*, 2007). For crustal thickness of 45–50 km (12–14 kbar) as modeled by gravity and seismology in the central and eastern sectors of the TMVB, and temperatures of 700ºC at the base of this crust (calculated by isoviscous modeling of the thermal structure of the MSZ, as discussed above), garnet granulites of gabbroic composition and Mg# <60 should compose most of the lower crust underlying the Mexican stratovolcanoes in those sectors. This sort of crust, even if wet, cannot melt at 700ºC to produce andesitic magmas, but it certainly would do so for temperatures above 1000ºC as modeled using temperature-stress dependent mantle rheologies. Abundant garnet in this case would be absent in the residue because pressures above 15 kbar are required to generate it at those temperatures, thus yielding ordinary andesitic-dacitic magmas. Nevertheless, Nevado de Toluca stratovolcano shows adakitic signature (Martínez-Serrano *et al.*, 2004), whereas it seems to be absent in the Popocatépetl and Pico de Orizaba volcanoes despite the fact that the crust there is thicker and probably cooler. If the adakitic signature of Nevado de Toluca was acquired by partial melting of the wet eclogitic top of the Cocos plate at pressures around 20 kbar (2 GPa, or 70 km deep), minimum temperatures should be of the order of 700–750ºC, which may occur if the slab and mantle wedge were sufficiently coupled to produce frictional heating. Indeed, higher temperatures in the mantle wedge and steeper plate geometry models (*e.g.*, Ferrari *et al.*, 2004) would have a major impact on the thermal conditions of the lower crust to make it a potential contaminant or a source for some magmas of the TMVB.

It should be noted that melting of eclogites, where garnet and rutile remain in the source, not always generates the adakitic signature, as melting of zoisite and apatite-rich eclogites at high and ultrahigh pressures in the slab (*e.g.*, Nagasaki and Enami, 1998; de Hoog *et al.*, 2007) will not produce a high Sr/Y ratio because zoisite and apatite retain some Sr and Y leaving behind a refractory kyanite-bearing eclogite at temperatures that must exceed 800ºC. Therefore, melting of the oceanic subducted crust recrystallized to zoisite eclogite may commonly occur in arc regions without imprinting a clear adakite signature. Popocatépetl and Pico de Orizaba could represent such case.

An additional model recently proposed for the origin of the high-magnesium andesites with an adakitic signature at Mount Shasta of the Cascades arc (Streck *et al*., 2007) is the mixing of dacitic (>50%) and basaltic (40–30%) magmas contaminated by ultramafic rocks (5–7%) from preexisting ophiolites. The adakitic signature of the high-Mg andesites was considered to be inherited from the more strongly adakitic dacites presumably produced by melting of the lower crust. A similar scenario may be entertained for some of the

TMVB lavas with a weak adakitic signature, because the traversed thick crust underlain by the Mixteco and Guerrero terranes flooring the arc front contains ultramafic bodies and the pressure-temperature conditions at the base of that crust may in some cases permit the stability of garnet, rutile, and hornblende in the granulite facies.

CONCLUDING REMARKS

The main conclusion that may be derived from this work is that much more geology-based information is required to really understand the nature and evolution of the lower crust under the TMVB and the fore-arc region before its role in the evolution of the magmas composing the province is properly assessed. In particular, the prospecting and petrologic study of a lot more deep-seated xenolith localities should be undertaken, as these objects can provide first hand information about the age and many physical and chemical parameters of the crust that are required for modeling the origin, ascent, modification and emplacement histories of the TMVB magmas. Also, the differences among geophysical (thermal, seismologic, magnetotelluric, and gravimetric) and petrologic models regarding the true geometry, structure and composition of the lower crust in the study area, will be better resolved once interdisciplinary research is designed more closely and considering the geologic data provided by xenoliths and basement outcrops. Ongoing research such as MASE (*e.g.*, Ferrari, 2006) will undoubtedly provide a high-resolution picture of the subducted Cocos plate, as well as the topography of the Moho, which will determine the thickness of the entire crust. Together, these data will certainly influence and constrain models that debate how and where magmas are generated in the subduction factory, how they ascend through the overlying viscous and fractured layers, and how and where they interact with the crust and mantle to produce the diversity that characterizes the magmas that compose the TMVB. In particular, the role of melts provided by the subducting slab (adakitic) and their interaction with peridotites of the metasomatized mantle wedge, should be examined more carefully in order to assess in great detail the ultimate origin of primitive magmas in the TMVB and to distinguish them from the more evolved products of fractionation, magma mixing, and of melting-assimilation processes in the lower and upper crust.

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