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Notes
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ABSTRACT

The Tierra Colorada area sits along the northern limit of the Xolapa Complex, where it is juxtaposed against the Mixteco (Paleozoic) and Guerrero (Mesozoic) terranes of southern Mexico, just north of Acapulco. This paper presents combined structural and geochronological data from Tierra Colorada area that show evidence of four deformational events and several episodes of arc magmatism during Mesozoic and Cenozoic time. The oldest magmatism is represented by ca. 165 Ma granitoids and was followed by intrusion of the foliated El Pozuelo granite (129 ± 0.5 Ma; concordant U-Pb zircon analysis). This intrusion postdates D1 metamorphism and migmatization in the Xolapa Complex. The next magmatic episode is represented by the peraluminous foliated El Salitre granite (55.3 ± 3.3 Ma; mineral–whole-rock Rb–Sr isochron) and the protomylonitic Las Piñas I-type granite (54.2 ± 5.8 Ma; lower intercept U–Pb zircon). Las Piñas granite is characterized by D2 ductile fabric with normal, top-to-north-northwest sense of shear, deformed at 45–50 Ma (Rb–Sr and K–Ar ages). The ca. 34 Ma undeformed granites correspond to the last intrusive pulse in the area, postdating both D2 south-southwest–verging thrusting of the Cretaceous Morelos Formation over sheared granites and Lower Cretaceous volcanic rocks, and open folding during D3. These four pulses of subduction-related magmatism in the Tierra Colorada area indicate a regular northeastward subduction at the Mesosamerican trench since Jurassic time, and alternate with contractile and/or extensional tectonic events. The gap in magmatic activity ca. 90–100 Ma roughly coincides with deposition of platformal limestones of the Morelos Formation during the middle Cretaceous. The stable conditions during deposition of the Morelos Formation may have resulted from a combination of back-arc extension and development of a passive margin during the Early–middle Cretaceous, which postdated the accretion of an exotic block, either the Guerrero terrane or the Chortís block. Following the Laramide orogeny in southern Mexico (roughly during the Late Cretaceous) the Paleocene–Miocene tectonic evolution in the Tierra Colorada area involved an alternation of magmatic pulses with extensional and contractile events. This was the result of a combination of several factors, including the geometry of the subducted slab, convergence rate, stress transmission between the subducting and overlying plates, and the rate of subduction erosion.

Keywords: southern Mexico, U–Pb geochronology, Xolapa Complex, Cenozoic tectonics, arc magmatism.

INTRODUCTION

Southern Mexico is composed of a mosaic of at least four different crustal terranes (Fig. 1) that have markedly different basement characteristics, including metamorphic grade, composition, ages, and tectonic histories. According to Cappa and Coney (1983), and as modified by Sedlock et al. (1993), these terranes are: (1) the Guerrero terrane, mainly composed of Mesozoic arc-related rocks (Centeno-García et al., 1993; Elías-Herrera et al., 2000); (2) the Mixteco terrane, consisting of the Mesozoic Acatlán Complex, which is characterized by an assemblage of high-grade oceanic and continental rocks faulted against low-grade pelites and psammites, and covered by late Paleozoic–Jurassic continental sediments (Ortega-Gutiérrez et al., 1999; Keppie et al., 2004; Talavera-Mendoza et al., 2005; Nance et al., 2006); (3) the Oaxaca terrane, the Grenvillian Oaxacan Complex basement of which comprises rift-related anorthosite-mangerite-charnockite-granite, paragneiss, volcanic-arc rocks, and calcisilicates metamorphosed to granulite facies (Keppie et al., 2003; Solari et al., 2003); and (4) the ~600 × 50–80 km Xolapa terrane, which bounds the other three terranes on the south (e.g., Herrmann et al., 1994; Corina-Chávez, 1997; Werrre-Keeman and Bustos-Díaz, 2001; Ducea et al., 2004; Corina-Chávez et al., 2006).

The Xolapa Complex, the basement of the Xolapa terrane, has been interpreted as an allochthonous, Jurassic–Cretaceous, deformed magmatic arc terrane (Ortega-Gutiérrez et al., 1995; Morán-Zenteno et al., 1996; Dickinson and Lawton, 2001; Schaal et al., 2002; Corona-Chávez et al., 2006), or an autochthonous magmatic arc (Herrmann et al., 1994; Meschede et al., 1996; Ducea et al., 2004; Keppie, 2004). The boundaries between terranes in southern Mexico are generally marked by regional shear
zones or faults (Fig. 1). (1) The Caltepec fault zone is a Permian dextral shear zone between the Mixteco and Oaxaca terranes (Elías-Herrera and Ortega-Gutiérrez, 2002). (2) The Tertiary Laramide Papalutla fault forms the boundary between the Guerrero and Mixteco terranes (e.g., Cerca et al., 2004). (3) The Chacalapa–La Venta shear system is an Eocene–Oligocene sinistral strike fault along the northern border of the Xolapa Complex (Ratschbacher et al., 1991; Riller et al., 1992; Tolson, 2005; this paper).

Mesozoic and Cenozoic reconstructions of southern Mexico need to be based upon the correct time assignment of significant geologic events, such Laramide shortening and Paleocene–Oligocene arc magmatism (e.g., Cerca et al., 2004; Morán-Zenteno et al., 2005; this study), the time of migmatization in the Xolapa Complex (66–46 Ma according to Herrmann et al., 1994; Jurassic–Cretaceous according to Ducea et al., 2004), and possible interactions between southern Mexico with the Guerrero terrane and the Chortís block. The Guerrero terrane occupies most of western Mexico, and has been interpreted as either an exotic intraoceanic terrane accreted to southwestern Mexico during the Early Cretaceous by the subduction of the Mezcalera plate and closure of the Arperos basin (e.g., Dickinson and Lawton, 2001, and references therein), or a continental basement of the northern part of Central America. Two alternative models have been proposed for the southern Mexico-Chortís connections. (1) The Chortís block was adjacent to southwestern Mexico until the middle Tertiary, when it started to move toward its current position along a transform fault parallel to the Middle America trench; this fault is now represented by the Acapulco trench and the Polochic-Motagua fault zone in Guatemala (Anderson and Schmidt, 1983; Pindell et al., 1988; Ross and Scotese, 1988; Herrmann et al., 1994; Schaaf et al., 1995; Morán Zenteno et al., 1996; Meschede et al., 1996). (2) Keppie (2004) also placed the Chortís block adjacent to southwestern Mexico in the Pangean reconstruction, but by Eocene time it was southwest of its current position. The Chortís block would have reached its present position rotating clockwise, covering a distance of ~1100 km during the Cenozoic about a pole near Santiago, Chile (Keppie and Morán-Zenteno, 2005).

The southern Mexico structural pattern was revised by Nieto-Samaniego et al. (2006), who proposed grouping deformation structures into three events (shortening, strike slip, and normal faulting), from the Late Cretaceous to the Miocene, progressively younging toward the east. Detailed structural observations and geochemistry of the Tierra Colorada area bear on the tectonic evolution of southern Mexico. Combining the new data presented here with those previously published (e.g., Riller et al., 1992; Herrmann et al., 1994; Meschede et al., 1996; Ducea et al., 2004; Nieto-Samaniego et al., 2006) provides a wider database for testing some of the previous models, such as the age of migmatization, the migration of structural patterns, and pulses of magmatism.

LITHOLOGICAL UNITS

In the fairly well exposed geologic record of the Tierra Colorada area (Fig. 2), the southernmost unit is represented by the Xolapa Complex, which is composed of high-grade orthogneiss
Figure 2. Geologic map of Tierra Colorada area, with stratigraphic column and section. Symbols are reported in the legend. Stereonets with main poles of S1 and S2 foliation, as well as L2 stretching lineation, are also shown. Structural measurements were performed in outcrops of ~2 km length, positioned as indicated by large arrows in the map.
and paragneiss and marbles that have undergone variable degrees of migmatization. The gneisises are generally fine to medium grained, and rarely reach augen gneiss texture. Representative minerals of these rocks are biotite, muscovite, and green hornblende; however, metasedimentary bands, most Al rich, also contain sillimanite, staurolite, and garnet. The gneissic banding consists of <3-mm-wide domains of oriented biotite, muscovite, and/or hornblende alternating with bands composed of an association of quartz, K-feldspar, and/or plagioclase. The mineral lineation is defined by oriented biotite and hornblende crystals.

A series of variably foliated granitoids is on top of the Xolapa gneisises (Fig. 2). The plutons occur along a west-northwest–trending band parallel to a complex structure that has been called the La Venta–Tierra Colorada shear zone (e.g., Riller et al., 1992). According to Campa and Coney (1983), this structure should mark the contact between the Mixteca and Xolapa terranes. The El Salitre granite crops out along Federal Road 95 just west of Xolapa town, west of the mapped area (Fig. 2). This is a peraluminous body mainly made up of quartz, plagioclase, K-feldspar, abundant muscovite, scarce garnet, and accessory apatite. The <5-mm-long muscovite crystals define the foliation, which is not a mylonitic fabric. In places the granite grades into a pegmatitic facies with the same mineralogy. Morán-Zenteno (1992) dated some pegmatites as 59 ± 1 Ma (Rb-Sr whole-rock–muscovite isochron) near El Salitre, although their relationships with the main granitic body are not described in detail. The El Salitre granite generally contains xenoliths of metamorphic rocks, as large as 20 cm, such as amphibolites, metagraywackes, and metapelites, likely derived from the Xolapa Complex. The westernmost contact of the El Salitre granite, outside the mapped area, is intruded by the ca. 29–34 Ma Xaltianguis granite (Schaaf et al., 1995; Deuce et al., 2004), whereas toward the east it grades into an unfoliated facies.

The El Pozuelo granite crops out in the western part of the studied area (Fig. 2), southeast of the El Salitre granite. Its best outcrop is located along the Mexico-Acapulco toll road, where it is a fine-grained, gray-greenish, foliated body that grades eastward into a porphyritic facies. It is made up of quartz, K-feldspar > plagioclase, and biotite intergrown with green hornblende. Zircon, apatite, and magnetite are the most common accessory minerals. Hernández-Pineda (2006) reported geochemical data for El Pozuelo granite as La/Nb > 4, subalkaline affinity, A/CNK index <1.1 (Maniar and Piccoli, 1989); together with absence of muscovite, the presence of biotite and green hornblende, these data indicate that it is a calc-alkaline I-type granite (according to the terminology of Kemp and Hawkesworth, 2004).

Foliation is penetrative toward the northern exposure along Highway 95, where it is mainly characterized by oriented biotite and stretched quartz, the latter forming a penetrative stretching lineation with constant north-northwest orientation (Fig. 3A). The El Pozuelo southernmost contact with the migmatites of the Xolapa Complex along the highway is a brittle normal fault; however, its original intrusive relationship is indicated by several dikes emanating from the main granitic body (e.g., Fig. 3B).

At the structural top of the Xolapa basement is a protomylonitic granite that we name Las Piñas (Fig. 2); it crops out continuously east of Highway 95. It is made up of plagioclase, quartz, K-feldspar, biotite, titanite, and secondary minerals such as chlorite and epidote. Zircon is a common accessory phase. Petrographically, it ranges between granite and granodiorite from west to east, and it has two main variants: a southern undeformed variety and a central-northern protomylonitic granite (Fig. 4A). Where the contacts are exposed and not affected by brittle faulting or ductile shearing, Las Piñas granite is intrusive into the Xolapa Complex and Chapolapa Formation (Fig. 2). Its geochemical character is strikingly similar to the El Pozuelo granite (Hernández-Pineda, 2006).

Structurally above the El Pozuelo, Las Piñas, and El Salitre granitoids is a 2–5-km-thick green volcaniclastic unit that was originally designated as Chapolapa Formation (De Cserna, 1965). Pelitic and psammitic metasedimentary bands are intercalated with andesitic and rhyolitic metavolcanic rocks with arc-related affinities (De Cserna et al., 1994). The Chapolapa Formation ranges from undeformed to mylonitic (Riller et al., 1992). Where contacts with the underlying granitoids are exposed, they are generally affected by ductile deformation. Undeformed metavolcanic rocks are characterized microscopically by the presence of plagioclase and quartz phenocrysts in a very fine grained matrix of plagioclase, chlorite, and epidote. Deformed portions show a complete range between protomylonite, mylonite, and ultramylonite (e.g., Figs. 3C and 4B–4D). U-Pb zircon geochronology on these rocks yielded crystallization ages of 126–133 Ma (Campa and Iriondo, 2004; Hernández-Treviño et al., 2004). Albion–Eocene–Oligocene limestones of the Morelos Formation (Fries, 1960; Hernández-Romano et al., 1997) are thrust over the Chapolapa Formation in the entire area (Figs. 3D–3G). The limestones are unconformably overlain by continental conglomerates of the late Paleocene–early Oligocene Balsas Formation (Fries, 1960; Cerca et al., 2004; Molina-Garza and Ortega-Rivera, 2006), and acid volcanic rocks of the Papagayo Formation, which is possibly the same age as the Alquitrán Formation, 22–24 Ma (Hernández-Treviño et al., 1996). The Balsas Formation was not observed in direct contact with the Xolapa Complex, as previously noted in other localities (e.g., De Cserna, 1965; Werre-Keeman and Bustos-Díaz, 2001).

The large Tierra Colorada granitic to granodioritic body (34 Ma, discordant U-Pb zircon age; Herrmann et al., 1994) intrudes the Las Piñas granite, Chapolapa Formation, Morelos Formation, and Xolapa basement. The Tierra Colorada granite is only affected by brittle deformation, and is intruded by diabase dikes,

Figure 3. Outcrop pictures representing main structures as described in text. (A) El Pozuelo granite, in its deformed facies, with visible S1, foliation (subvertical), and Lp, almost vertical white stretched quartz ribbons. Scale is indicated by white pencil in the middle left. (B) A pegmatite emanating from the El Pozuelo granite intruding migmatitic gneisses of the Xolapa Complex. Hammer is ~35 cm long. (C) F3 kink-like folds developed in the S1 mylonitic foliation in the Chapolapa Formation, just south of the Papagayo River dam. Top-to-the south-southwest sense of shearing is indicated by the black arrows. Scale is indicated by a ruler in the top left of the picture. Ruler is 30 cm long. (D) South-southwest–verging D3 thrust of the Morelos Formation on top of the sheared Chapolapa Formation, as observed along the Acapulco–Mexico Highway. Main thrust plane is drawn and indicated by black and white triangles. A circle in the bottom indicates the drag fold illustrated in Figure 3G. (E) Broken and thrusting chert lens into the Morelos Formation. D3 top-to-the south-southwest sense of shearing is indicated by black arrows. Coin is 25 mm in diameter. (F) Same contact represented in D, with Morelos Formation thrust over the Chapolapa Formation, as indicated by stair-stepping faults. Man is 1.60 m tall. (G) Folded beds at the bottom of the Morelos Formation. An F3 drag fold is developed near the contact with the underlying previously mylonitized Chapolapa Formation (bottom left). Sense of shearing is indicated by the white arrow. Notebook is 4 × 6 inches.
which represent the last intrusive event recognizable in the area.

**GEOCHRONOLOGY**

**Sample Preparation**

In order to constrain the ages of structures and igneous events in the Tierra Colorada area, two granitic samples for U-Pb geochronology, one El Pozuelo granite and one Las Piñas granite, were analyzed: 10–15 kg of rock sampled for dating were crushed and powdered to <500 μm. Heavy minerals were then concentrated using a Wilfley table, and further magnetic and nonmagnetic minerals were separated using a Frantz isodynamic magnetic separator. Zircons were concentrated and separated from other nonmagnetic minerals such as quartz, feldspars, andapatite using methylene iodide heavy liquid. Zircons were selected from the diamagnetic fraction at 2.0 amp by hand-picking under binocular microscope in ethanol. To assist interpretation, zircons were observed and imagined under cathodoluminescence, using an ELM 3R luminescope connected to a digital camera. One sample of El Salitre granite was also analyzed by Rb-Sr, and deformed micas of the protomylonitic portion of Las Piñas granite were dated by Rb-Sr and K-Ar. Micas were separated starting from 0.4 and 0.75 amp magnetic fractions, although final selection was performed by hand-picking under binocular microscope. Mica analyses follow analytical procedures described in the following and in Schaaf et al. (2000) for Rb-Sr, and in Ortega-Gutiérrez et al. (2004) for K-Ar.

**Analytical Procedures**

Selected zircons were normally abraded for 6–8 h using pyrite crystals as the abrasive (Krogh, 1982), washed in warm 4M HNO₃ for ~20 min, followed by 10 min in an ultrasonic bath. Further hand-picking under binocular microscope was undertaken to avoid crystals with surficial contamination by pyrite remnants that could add common Pb to the analyses. Zircons were then weighed on a microbalance, with an error of ±1 μg, washed again in 8M HNO₃ on a hot plate for ~20 min, and put inside previously ultraclean Teflon microcapsules, together with concentrated HF + HNO₃ acids. As many as 9 microcapsules were stored in steel digestion vessels, and samples were digested in an oven for 4 days at 240 °C. Ultrapure acids are used through the digestion and chemical separation, and are normally obtained by Teflon distilling following the method described by Mattinson (1972). Digested samples are poured into ultraclean PFA Teflon beakers, spiked with a 280Pb/238U solution, evaporated until dry, and put again into a solution of 0.5M HBr acid. Chemical separation of U and Pb was performed in 40 μL Teflon microcolumns filled with ElChrom AGI X8 100–200 mesh anionic resin. The HBr-HCl chemical procedure is a modification of the original method (Krogh, 1973), and is similar to that described by Miller et al. (2006). Collected U and Pb aliquots are dried with a drop of 0.1M H₂PO₄, separately loaded on previously degassed Re filaments, and measured with a Finnigan MAT 262 mass spectrometer at the Laboratorio Universitario de Geología Isotópica (LUGIS) of the Universidad Nacional Autónoma de Mexico (UNAM). Pb is measured in static mode, using Faraday cups for 206Pb, 208Pb, 207Pb, and 208Pb beams, and an SEM (secondary electron multiplier) for the smaller 204Pb beam. Faraday-SEM counting gain was stable throughout the turret, with an error of 0.01%. Routine analyses of NBS 981, 983, and US50 standards were performed to check precision and to correct instrumental mass fractionation. Applied corrections are 0.12% ± 0.04% for Pb ratios, and 0.12% ± 0.05% for U ratios. Repeat analyses of 91500 zircon standard allow calculation of U/Pb errors at ±0.5%. The Pb ratios determined on concentrated feldspar separated from the same samples were used to correct for initial common Pb in zircons. Reduction of raw data was performed using Pbdat (Ludwig, 1991), whereas concordia plots were performed using Isoplot v.3.06 (Ludwig, 2004). Muscovite, K-feldspar, and whole-rock belonging to El Salitre, as well as biotite and whole-rock powder of Las Piñas, were also processed for Rb-Sr geochronology. Biotite from Las Piñas was also dated by K-Ar. The Rb-Sr samples were also analyzed at LUGIS, UNAM, Rb isotope ratios were measured with an NBS type single collector mass spectrometer (Teledyne Model SS-1290), whereas Sr isotopic measurements were performed in static mode on the Finnigan MAT 262. Samples were loaded as chlorides on double rhodium filaments and measured as metallic ions. K-Ar samples were analyzed at LUGIS, UNAM, as outlined in Ortega-Gutiérrez et al. (2004).

**Results**

**El Pozuelo Granite**

Zircons separated from the El Pozuelo granitic sample are small, generally euhedral, colorless or slightly yellow-amber, and prismatic to stubby, with a maximum elongation ratio of 4:1. Crystals >200 μm are generally full of inclusions, and thus not suitable for dating, so grains <200 μm were selected for analysis. Cathodoluminescence (CL) controlled images show a general predominance of igneous zoning in all the zircon morphologies; the zoning is sometimes developed around darker, oscillatory zoned xenocrystic cores (Fig. 5). We dated one large population of 50 prismatic grains, as...
Figure 5. Zircon photomicrographs and cathodoluminescence images of dated samples. El Pozuelo granite zircons are those labeled as XO0201, whereas Las Piñas zircons are labeled LV0321. Black and white bars indicate the scale. See also Table 1 for zircon descriptions.
TABLE 1. U-Pb ANALYSES FOR SELECTED SAMPLES IN TIERRA COLORADA AREA, SOUTHERN MEXICO

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Weight (g)</th>
<th>Atomic ratios</th>
<th>U (ppm)</th>
<th>Total Pb (ppm)</th>
<th>Pb/206Pb</th>
<th>Pb/207Pb</th>
<th>Pb/208Pb</th>
<th>Pb/206U</th>
<th>Pb/207U</th>
<th>Pb/235U</th>
<th>Pb/238U</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Pozuelo granite, sample XO0201-B 50 xls, sh prsm, clear, abr</td>
<td>0.100</td>
<td>10.1</td>
<td>22.5</td>
<td>0.0190</td>
<td>0.0584</td>
<td>1010.1</td>
<td>22.5</td>
<td>51</td>
<td>771.86</td>
<td>16.318</td>
<td>6.163</td>
</tr>
<tr>
<td>El Pozuelo granite, sample XO0201-H 3 xls, clear, sh prsm, abr</td>
<td>0.028</td>
<td>149.9</td>
<td>351.4</td>
<td>0.0207</td>
<td>0.0652</td>
<td>255.1</td>
<td>53</td>
<td>51</td>
<td>499.53</td>
<td>12.506</td>
<td>6.280</td>
</tr>
<tr>
<td>El Pozuelo granite, sample XO0201-I sng, prsm, abr</td>
<td>0.034</td>
<td>149.9</td>
<td>351.4</td>
<td>0.0207</td>
<td>0.0652</td>
<td>255.1</td>
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<td>499.53</td>
<td>12.506</td>
<td>6.280</td>
</tr>
<tr>
<td>El Pozuelo granite, sample XO0201-L 12 xls, prsm, clear</td>
<td>0.035</td>
<td>1419.8</td>
<td>28.6</td>
<td>18</td>
<td>540.90</td>
<td>18.295</td>
<td>7.304</td>
<td>20.9</td>
<td>797.8</td>
<td>20.9</td>
<td>6.690</td>
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<td>Las Piñas granite, sample LV0321-A 24 xls, byr, yellow</td>
<td>0.124</td>
<td>901.9</td>
<td>10</td>
<td>150</td>
<td>449.53</td>
<td>12.506</td>
<td>6.280</td>
<td>20.9</td>
<td>797.8</td>
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Note: Zircon sample dissolution and ion exchange chemistry are modified after Krogh (1973) and Mattinson (1987) in Parrish (1987) type microcapsules.

Weight uncertainties are ± 30%, due to the weight uncertainty.

Concentrations are known at ± 30%, due to the weight uncertainty.

Observed isotopic ratios are corrected for mass fractionation of 0.12% for Pb and Pb/206Pb ratios are <0.8%, generally better than 0.1%; uncertainties in the Pb/235U age uncertainties are 2 to 10 ppm.

Isotopic data were measured on a Finnigan MAT 262 mass spectrometer with Secondary Electron Multiplier Ion Counting at Universidad Nacional Autonoma de Mexico, Mexico City.

The Las Piñas granite

Zircons separated from Las Piñas granite (LV0321) are generally elongate prisms, colorless or yellow-amber, with an elongation ratio as high as 6:1 (Fig. 5). Pyramidal terminations are also generally present, with well-developed euhedral facets (e.g., sample LV0321-8 in Fig. 5). CL images obtained from selected crystals mounted from this sample show a continuous oscillatory zoning indicative of a magmatic origin, sometimes around an inherited core (see CL images in Fig. 5). We dated four populations of zircons, one of which was abraded (fraction 8 in Table 1 and Fig. 5). These populations are composed of prismatic crystals, more or less elongated, sometimes with pronounced pyramidal terminations (LV0321-A, LV0321-6, and LV0321-7 in Fig. 6 and Table 1), and composed of colorless to pale yellow grains. In at least one case (LV0321-7) a clear inherited component represented by older ages (206Pb/238U age of 135.2 Ma) may indicate the presence of a xenocrystic core, possibly belonging to Xolapa-like zircons (cf. zircon data in Ducea et al., 2004). A further fraction, made up of abraded pyramidal tips broken off larger, euhedral crystals (LV0321-8 in Fig. 5 and Table 1) better constrains the lower intercept (Fig. 6B). All the data are discordant; however, the four populations define a chord with a lower intercept of 54.2 ± 5.8 Ma. Using just the lowermost three points yields a lower intercept of 57.6 ± 1.7 Ma (Fig. 6B and inset). Conservatively, we assume the age of 54.2 ± 5.8 Ma as representing the age of intrusion of the Las Piñas granite.

The El Salitre granite

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<td>0.0652</td>
<td>255.1</td>
<td>53</td>
<td>51</td>
<td>499.53</td>
<td>12.506</td>
<td>6.280</td>
</tr>
<tr>
<td>El Pozuelo granite, sample XO0201-L 12 xls, prsm, clear</td>
<td>0.035</td>
<td>1419.8</td>
<td>28.6</td>
<td>18</td>
<td>540.90</td>
<td>18.295</td>
<td>7.304</td>
<td>20.9</td>
<td>797.8</td>
<td>20.9</td>
<td>6.690</td>
</tr>
<tr>
<td>Las Piñas granite, sample LV0321-A 24 xls, byr, yellow</td>
<td>0.124</td>
<td>901.9</td>
<td>10</td>
<td>150</td>
<td>449.53</td>
<td>12.506</td>
<td>6.280</td>
<td>20.9</td>
<td>797.8</td>
<td>20.9</td>
<td>6.690</td>
</tr>
</tbody>
</table>
Table 2. Rb-Sr and K-Ar analyses for selected samples in Tierra Colorada area, southern Mexico

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral/whole rock</th>
<th>Concentration (ppm)</th>
<th>Isotopic dilution</th>
<th>$^{87}$Rb/$^{86}$Sr</th>
<th>$^{87}$Sr/$^{86}$Sr ± 1 SD</th>
<th>2 SE$_{W}$</th>
<th>n</th>
<th>K (%)</th>
<th>$^{40}$Ar $\times 10^{-5}$ (mol/g)</th>
<th>$^{40}$Ar* (%)</th>
<th>Age ± 2$\sigma$ (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Salitre granite, LV0136</td>
<td>17°08′52.7″ N, 99°38′00.0″ W</td>
<td>LV0136 Mu1 Muscovite &gt; 1 mm</td>
<td>556.1</td>
<td>10.9</td>
<td>149.6</td>
<td>0.827377 ± 45</td>
<td>15</td>
<td>35</td>
<td></td>
<td></td>
<td>55.3 ± 3.5 Ma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV0136 Mu2 Muscovite 0.5 mm</td>
<td>556.3</td>
<td>13.0</td>
<td>125.1</td>
<td>0.805748 ± 48</td>
<td>16</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV0136 KF Potassic feldspar</td>
<td>165.7</td>
<td>174.5</td>
<td>2.7</td>
<td>0.710537 ± 37</td>
<td>10</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV0136 WR Whole rock</td>
<td>133.8</td>
<td>119.5</td>
<td>3.2</td>
<td>0.711552 ± 39</td>
<td>11</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Las Piñas granite, sample LV0321</td>
<td>17°05′43″ N, 99°31′33″ W</td>
<td>LV0321 Bi Biotite</td>
<td>567.5</td>
<td>110.1</td>
<td>14.9</td>
<td>0.714466 ± 37</td>
<td>10</td>
<td>56</td>
<td>6.64</td>
<td>5.896</td>
<td>93.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LV0321 WR Whole rock</td>
<td>109.0</td>
<td>598.4</td>
<td>0.5</td>
<td>0.705210 ± 38</td>
<td>10</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Rb and Sr element concentrations and isotopic ratios were determined with the same run each consisting of 60 isotopic ratios. N—number of measured isotopic ratios. SD—standard deviation. SE—standard error. The values (1SD = ±1σ abs) refer to the error during measurement, in the last two digits.

2 SE$_{W}$ = 2σ abs/m. All Sr isotopic ratios were corrected for mass fractionation by normalizing to $^{88}$Sr/$^{86}$Sr = 0.1194. Laboratory values for standard NBS 987 (SrCO$_3$): $^{87}$Sr/$^{86}$Sr = 0.710237 ± 21 (±1σ abs, n = 317). Relative uncertainty (1σ) of $^{87}$Rb/$^{86}$Sr = ±2% (experience-based value for the LUGIS laboratory). Relative reproducibilities (1σ) for Rb and Sr concentrations at the laboratory are ±4.5% and ±1.8% respectively. Total procedure blanks during analyses of these samples were 0.06 ng Rb and 1.5 ng Sr.

$^{40}$Ar* is the radiogenic argon, expressed as moles/g and as percentage of radiogenic Ar from total Ar, respectively.

Numbers in italic are Rb-Sr mineral-WR cooling ages.

Figure 6. U-Pb concordia diagrams and Rb-Sr isochron plots for the dated samples in the studied area. Ellipses for U-Pb concordia diagrams represent 2σ errors, whereas crosses in Rb-Sr isochrons are 1σ errors. Given errors in calculated ages are 2σ in both cases. MSWD—mean square of weighted deviates. Bi—biotite; WR—whole rock; Mu—muscovite; Kfs—K-feldspar.
Fig. 6C and Table 2) yielded a Rb-Sr isochron with an age of 55.3 ± 3.5 Ma. Although a Rb-Sr mineral–whole-rock isochron generally indicates mineral cooling age, the large size of muscovite analyzed, between 0.5 and >2 mm, together with the lack of deformation, suggests that the calculated age closely postdates the time of intrusion.

**STRUCTURAL EVOLUTION**

Four phases of deformation have been recognized in the area.

**D1: Migmatization and Deformation of the Xolapa Complex**

The oldest deformational fabric was only observed in the Xolapa gneisses, where it is a penetrative high-grade foliation defined by quartz + plagioclase ± K-feldspar microlithons alternating with biotite + hornblende foliated domains. Neosome lenses of quartz + plagioclase ± feldspar ± biotite generally develop parallel to S1, although they are not internally foliated. In the western part of the area, between Xolapa and El Papagayo towns (Fig. 2), S1 foliation is northwest trending and moderately southwest dipping, whereas in the east (Villa Guerrero to Omitlán, and west of El Zapote, Fig. 2) it is northeast trending, and gently to moderately southeast dipping. Neither mineral nor stretching lineation is present in the eastern area, and it is not pervasively affected by younger D2 or D3 events.

**D2: Mylonitization and North-Northwest–Vergent Listric Normal Faulting**

The S2 foliation is the dominant ductile fabric in the area, mainly affecting volcanic rocks of the Chapolapa Formation and metagranitoids such as El Pozuelo and Las Piñas granites. In the volcanic rocks of the Chapolapa Formation, foliation is west to west-southwest trending with gently northward dips north of the dam (just north of La Venta Vieja in Fig. 2), and close to the contact with the overlying Morelos limestones, whereas steeper dips are generally found south of the dam. In the El Pozuelo granite, S2 is southwest trending and moderately to steeply dipping toward the northwest (Fig. 2, stereonet).

In the Las Piñas protomylonitic granite, the few studied outcrops show a west- to northwest–trending, north to north-northeast moderately dipping S2 foliation. An accompanying, north-northwest– to northwest-trending, moderately plunging L2 stretching lineation is generally made up of stretched quartz ribbons. Locally, in the less deformed granitoids (e.g., El Pozuelo granite), the stretched quartz lineation is parallel to a mineral lineation made up of aligned biotite and hornblende crystals, indicating that while quartz was plastically stretched, both biotite and hornblende only underwent passive rotation toward the direction of maximum elongation.

Microstructures in the volcanic rocks of the Chapolapa Formation, also described in detail by Riller et al. (1992), show intracrystalline quartz deformation represented by deformation lamellae and subgrains, as well as undulose extinction (e.g., Fig. 4C). Zoned porphyroclasts present in the Chapolapa Formation have cores made up of Ca-rich plagioclase, and rims with more Na-rich plagioclase intergrown with sericite. A top-to-the-north-northwest sense of shear is indicated by: (1) the asymmetry in the zoned porphyroclasts of the Chapolapa Formation, as well as sigma and delta objects (Figs. 4F, 4G), combined with V pull-apart shear indicators (type 2b of Samanta et al., 2002) within plagioclase crystals (Fig. 4E); (2) S-C fabrics in the Las Piñas protomylonitic granite (e.g., Passchier and Trouw, 1996); and (3) deformed biotite fish in both the Las Piñas granite and Chapolapa Formation (Fig. 3H). Deformed quartz ribbons are present in both the Chapolapa Formation and Las Piñas granite, and their microtextures suggest bulging recrystallization processes (e.g., Passchier and Trouw, 1996; Stipp et al., 2002).

**D3: South-Southwest–Verging Thrusting and Folding**

A large, south-southwest–verging thrust places limestones of the Morelos Formation on top of volcanic rocks of the Chapolapa Formation. The main fault plane is north-northeast trending, with a 40°–60°NE dip (Fig. 3D). The contact is made up of fault gouge as thick as 5 m composed of both volcanic rocks and limestones. The S3 foliation in the Chapolapa Formation is deformed by west-trending, sub-horizontally plunging, decimeter- to meter-scale F3 folds, whose s-shaped asymmetry indicates a top-to-the south sense of shear (Fig. 3G). Other top-to-the southwest kinematic indicators are small thrusts developed in chert lenses (Fig. 3E) and stair-stepping indicators (Fig. 3F). F3 kink bands also affect the S3 mylonitic foliation in the Chapolapa Formation, just a few meters below the thrust contact, and their kinematics are compatible with D3 thrusting (Fig. 3C). The Morelos Formation lacks evidence of ductile shearing at its base, being only affected by brittle deformation. This is interpreted as further evidence that it was not in contact with the underlying Chapolapa Formation during D2 (cf. Riller et al., 1992).

**D4: Open Folding**

A kilometer-scale, west-northwest–trending, gently eastward-plunging, upright synclinal F4 fold affecting both the Chapolapa and Morelos Formations is present across the study area. It is truncated by the Tierra Colorada pluton (Fig. 2, map and section).

**INTERPRETATION**

The combination of mapping and structural data with the geochronology presented here allows the following evolutionary history for the Tierra Colorada area to be constructed.

1. The D1 deformation and low-pressure metamorphism in the Xolapa Complex is synchronous with migmatization, which predates intrusion of the 129 ± 0.5 Ma El Pozuelo granite. This is consistent with U-Pb zircon ages (laser-ablation–inductively coupled plasma mass spectrometer analyses) of ca. 130–140 Ma (Cretaceous) that Duca et al. (2004) interpreted as being syntectonic with the main deformation event in the Xolapa basement. This event can also be extrapolated to previous observations of Herrmann et al. (1994) that dated one migmatite belonging to the Xolapa Complex northwest of Puerto Angel, Oaxaca, as 131.8 ± 2.2 Ma, disregarded as being speculative (cf. Herrmann et al., 1994, p. 462, 467).

2. Intrusion of the El Pozuelo granite and extrusion of the volcanic rocks of the Chapolapa Formation occurred in the Cretaceous. Emplacement of El Pozuelo granite at 129 ± 0.05 Ma (cordillar U-Pb zircon age) provides a minimum age for the migmatization of the Xolapa Complex. This result is at odds with Herrmann et al. (1994), who inferred that migmatization in the entire Xolapa Complex took place between 46 and 66 Ma. The age obtained on El Pozuelo granite is similar to the 126–133 Ma U-Pb zircon ages for the volcanic rocks of the Chapolapa volcanic rocks reported by Campa and Iriondo (2004) and Hernández-Treviño et al. (2004), suggesting that they belong to the same association of subduction-related magmas.

3. Deposition of the Morelos Formation occurred during the Albian–Cenomanian.

4. Late Paleocene intrusion of both Las Piñas and El Salitre granites was ca. 55 Ma (U-Pb zircon lower intercept age, and Rb-Sr isochron, respectively).

5. Petrographic observations carried on the microtextures described in the D3 mylonites of the Chapolapa Formation and Las Piñas granite suggest that deformation took place at <300 °C. Given that deformed biotite crystals are ~150–300 μm, and assuming closure temperatures for Ar and Sr isotopic systems of ~270–290 °C, the
300 °C deformation should have opened the biotite isotopic system for both Ar and Sr systematics (Harrison et al., 1985; Shirley, 1991). The calculated ages of 45–50 Ma (Rb-Sr and K-Ar mineral ages), in spite of the slight age difference that could be explained by either excess Ar or probably disturbed systematics in the Rb-Sr whole rock used to construct the isochron, constrain mylonitization of the La Venta area. This event produced \( S_2 \) mylonitic foliation and \( L_1 \) mineral stretching lineation, with kinematic indicators giving a top-to-the north-northwest sense of shearing along a north-northeast–dipping fault. Our age limitations for mylonitization refine those inferred by Riller et al. (1992) of 90–34 Ma.

6. The late Paleocene–early Oligocene Balsas Formation was deposited on top of the allochthonous Morelos Formation. Because the Balsas Formation is only present on top of the Morelos Formation in the studied area, not covering the Tierra Colorada granite occurred at 34 ± 2 Ma (Herrmann et al., 1994).

7. Eocene \( D_1 \) southwest-directed thrusting and \( D_2 \) east-west–trending folding occurred between 45 and 34 Ma.

8. Late Eocene–early Oligocene intrusion of the Tierra Colorada granite occurred at 34 ± 2 Ma (Herrmann et al., 1994).

9. There is a post-Eocene, brittle, left-lateral strike-slip to extensional regime in the Tierra Colorada pluton aureole (fault striae from Riller et al., 1992).

**DISCUSSION AND SUMMARY**

The age data and structural reconstruction of the Tierra Colorada area allow integration of some of the previously reported data for the evolution of the Sierra Madre del Sur and provide a more coherent interpretation of the tectonics of southwestern Mexico (Fig. 7).

**Age of Migmatization of the Xolapa Complex**

In the Acapulco–Tierra Colorada transect, an Early Cretaceous upper limit on the age of migmatization in the Xolapa Complex is strongly delimited by the crystallization age of ca. 129 Ma obtained in the unmigmatized El Pozuelo granite, dikes of which cut across migmatitic gneisses.

**Timing of Arc-Related Magmatism, Magmatic Hiatus Circa 100 Ma, and Platformal Sedimentation**

We recognize two magmatic episodes in the Tierra Colorada area, at 129 ± 0.5 and ca. 55 Ma. Together with other magmatic episodes previously reported as ca. 158–165 Ma (Guerrero-García et al., 1978; Ducea et al., 2004) and 28–34 Ma (e.g., Herrmann et al., 1994; Schaaf et al., 1995; Ducea et al., 2004; Hernández-Pineda, 2006), they constitute an episodic sequence of subduction-related magmatic pulses roughly forming every 25–30 m.y. The hiatus ca. 90–100 Ma in the Tierra Colorada area and, in general, between Zihuatanejo to the west and Huatulco to the east (Fig. 1), corresponds to the deposition of the Morelos Formation (Albian–Cenomanian), as well as oceanic backarc magmatism at the Arcelia-Palmar Chico basin in the Guerrero terrane, just northwest of the studied area (93–103 Ma; Sánchez-Zavala, 1993; Elías-Herrera et al., 2000; Mendoza and Suastegui, 2000). Such features can be related to a series of geodynamic processes, the first of which would be the arrival of a continental block that choked the paleotrench, roughly during the Early Cretaceous. Such accretion and/or collision could have led to an interruption of subduction and hiatus in magmatism between ca. 130 and 60 Ma. Collision would also be coherent, with clockwise pressure-temperature-time paths necessary, according to Corona-Chávez et al. (2006), to develop high-grade fabrics and migmatization in the Xolapa Complex. This continental block could be the Guerrero terrane, which, according to Campa and Coney (1983) and Dickinson and Lawton (2001), was accreted to nuclear Mexico.
during the Early Cretaceous; however, such a hypothesis was criticized by Elias-Herrera and Ortega-Gutiérrez (1998), because of the absence of an exposed suture east of the Guerrero terrane. Alternatively, the continental block could have been the Chortís block, which, according to paleomagnetic data of Gose (1985), was located in front of southwestern Mexico ca. 140 Ma. A similar position for the Chortís block during the Early Cretaceous was proposed by Harlow et al. (2004), who studied coeval eclogites now found in the southern Motagua mélangé, Guatemala. According to Harlow et al. (2004), the exhumation of such eclogites would have occurred at 125–155 Ma, following collision of Chortís with southern Mexico, i.e., well before the onset of the Laramide orogeny. We propose that soon after its collision Chortís became an extensional arc that produced backarc rifting with a passive margin on its northeastern side ca. 100–110 Ma. Such development would have been in agreement with the backarc magmatism described here, and predated platformal sedimentation of the Morelos Formation.

Time of Laramide deformation in Southern Mexico

The platformal sedimentation was followed by the Laramide orogeny, roughly bracketed between 93 and 87 Ma (Hernández-Romano et al., 1997; Lang and Frerichs, 1998), and 55–60 Ma, the age of postorogenic, subduction-related magmatism (González-Partida et al., 2003; Levresse et al., 2004; Cerca et al., 2004; this paper). By analogy with western North America, the origin of the Laramide orogeny in southern Mexico, expressed by contractile structures, can be a combination of several factors, such as flattening of the subducting slab (English et al., 2003, and references therein), or increasing convergence rate (e.g., Saleeby, 2003; English and Johnston, 2004).

Post-Laramide Magmatism

Paleocene granitoids that do not show any evidence of contractional deformation are widespread in southern Mexico. In the Tierra Colorada area these are represented by Las Piñas and El Salitre granites (ca. 55 Ma; this study), similar to the ca. 59 Ma in pegmatites reported by Morán-Zenteno (1992). In Acapulco, ~50 km southwest of the studied area, an undeformed syenitic granite was dated as ca. 54 Ma by zircon U-Pb (Duca et al., 2004). About 80 km north of the studied area, 63–66 Ma (zircon U-Pb and Ar-Ar), granitic to granodioritic postdeformation magmatism was described by Meza-Figueroa et al. (2003) and Levresse et al. (2004). Collectively, these events indicate a new onset of subduction and thermal perturbation in the continental margin, and a time of magmatism migration from the continent interior toward the coast. This could be indicative of a change in dip of the downgoing slab, which would increase from ca. 62 to 54 Ma.

Farther southeast, the cooling ages of Oligocene–Miocene plutons dated by Schulze et al. (2004) between Puerto Angel and Huatulco suggest a northward younging, i.e., in the opposite direction with respect to the Acapulco–Tierra Colorada segment. Thus, a decrease in the dip of the subduction zone during the Oligocene–Miocene southeast of Tierra Colorada might be indicated. As pointed out by Morán-Zenteno et al. (2005), the oblique convergence of the Farallon plate, its retreat during the Oligocene–Miocene (e.g., Nieto-Samaniego et al., 1999), and its shallowing (e.g., Morán-Zenteno et al., 1999) are all factors that can contribute to the migration of magmatic ages, and the formation and propagations of east-west, strike-slip left-lateral faults.

Tertiary Brittle Deformation

Our data indicate that D1, south-southwest-directed thrusting of the Morelos Formation on top of the Chapopala Formation postdates Laramide deformation and Paleocene subduction-related magmatism in southwestern Mexico. Such shortening is widespread in the eastern Morelos Guerrero platform, where it forms a wide range of folds and generally west-to-southwest-verging thrusts (e.g., Cerca et al., 2004, 2007). This contrasts with Riller et al. (1992) and Meschede et al. (1996), who did not recognize such thrusting event, but grouped the 40–70 Ma events as left-lateral movements on the Chacalapa–La Venta fault zone, in terms of an east-west subhorizontal σ1 and a north-south subhorizontal σ3. It also contrasts with Nieto-Samaniego et al. (2006), who did not consider the ca. 34–47 Ma shortening and southwest-verging event, and generalized that all the contractional structures were Laramide. Our structural and geochronology data indicate that normal-left lateral displacement along the La Venta shear zone predates such compressional event; i.e., they are kinematically different events.

Post-Laramide Tectonics

Post-Laramide widespread magmatism and deformation are present in Tierra Colorada and, generally, in Southern Mexico. We speculate that these features are the expression of major plate reorganization after the removal of the Chortís block. Previous work by Anderson and Schmidt (1983), Pindell et al. (1988), Ross and Scotese (1988), Herrmann et al. (1994), Schaaf et al. (1995), Meschede et al. (1996), and Nieto-Samaniego et al. (2006) suggests that Chortís displacement from southern Mexico occurred during the Eocene–Miocene, based on the presence of east-west left-lateral to transtensional faults, as well as the migration of magmatism. However, other data indicate that Chortís translation was characterized by a transpressional regime (e.g., Cerca et al.; Morán-Zenteno et al., 2005), and that its collision with the southern Maya block occurred between 65 and 73 Ma (e.g., Harlow et al.; Ortega-Gutiérrez et al., 2004). Moreover, Keppie and Morán-Zenteno (2005) argued that convergence of Chortís with the Maya block occurred by a translation from west-southwest to east-northeast, and that Chortís was located far southeast of southern Mexico during the Eocene.

If Chortís separated from southern Mexico before the Tertiary, those features developed during Paleocene–Miocene time, e.g., the 46–50 Ma detachment along the Tierra Colorada shear zone, as well as the southwest-directed thrusting of the Morelos Formation and other left-lateral to extensional structures, must be interpreted in a different way. In our view, they may be related to any combination of stress transmission during mechanical coupling between subducting and overlying plates associated with changes in dip of the subduction zone, as those evidenced herein (e.g., Fig. 7), combined with the irregular geometry of the subducted slab and the possible subduction of aseismic ridges as proposed by Keppie and Morán-Zenteno (2005). The same processes can be responsible for the supposed end of slightly diachronous magmatism along the margin of southern Mexico (cf. Duca et al., 2004), previously interpreted as evidence of the Tertiary migration of the Chortís block (e.g., Herrmann et al., 1994; Schaaf et al., 1995).

Plutonism in the Xolapa terrane and in the Tierra Colorada area ended by ca. 30 Ma and subduction erosion of the forearc led to exhumation of the present continental margin (e.g., Morán-Zenteno et al., 1996; Duca et al., 2005; Keppie et al., 2007).

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Cretaceous–Tertiary magmatic and structural evolution, Tierra Colorada area, southern Mexico


