Geologic evolution of the Xolapa Complex, southern Mexico: Evidence from U-Pb zircon geochronology

Mihai N. Ducea†
George E. Gehrels
Sarah Shoemaker
Joaquin Ruiz
Victor A. Valencia

University of Arizona, Department of Geosciences, Tucson, Arizona 85721, USA

ABSTRACT

The Xolapa Complex of southern Mexico is composed of mid-crustal arc-related gneisses of poorly resolved ages, intruded by undeformed Cenozoic calc-alkaline plutons. Twelve undeformed and deformed tonalitic/granodioritic samples from three transects across the Sierra Madre del Sur (Acapulco, Puerto Escondido, and Puerto Angel) were chosen for U-Pb zircon analysis. The measurements were performed on single crystals of zircons, using a multiple-collector laser-ablation inductively coupled plasma–mass spectrometer (MC-LA-ICP-MS). About 20–30 crystals were measured from each sample. Three gneisses and migmatites from the eastern transect (Puerto Angel), located 30–42 km from the coast yielded Grenville-aged zircons (970–1280 Ma), suggesting that the samples represent Oaxacan basement, not deformed Xolapa Complex. The central transect (Puerto Escondido) yielded Oligocene ages (25–32 Ma) on undeformed plutons as well as mid-Mesozoic and Permian ages on gneisses. Most samples along the Puerto Escondido transect contain inherited ca. 1.1 Ga xenocrystals of zircons. The western transect (Acapulco) yielded Late Jurassic–Early Cretaceous ages (160–136 Ma) on gneisses, and Paleocene (55 Ma) and Oligocene (34 Ma) ages on undeformed plutons, with no inherited Grenville ages. The older ages and xenocrystic zircons in arc-related Xolapa Complex mirror the crustal ages found in neighboring terranes (Mixteca and Oaxaca) to the north of the Xolapa Complex, suggesting an autochthonous origin of Xolapa with respect to its neighboring north-bounding terranes. The new data and previously published ages for Xolapa suggest that metamorphism and migmatization of the deformed arc rocks took place prior to the Cenozoic. Eocene and Oligocene plutons representing renewed arc-related magmatism in the area are common throughout Xolapa, and probably represent the more deeply exposed continuation of the Sierra Madre Occidental arc to the northwest. The available U-Pb data argue against the previously proposed eastward migration of magmatism between Acapulco and Puerto Angel during the Oligocene.

Keywords: Xolapa Complex, arc magmatism, U-Pb zircon, geochronology, deformation.

INTRODUCTION

Geometric arguments based on plate-tectonic reconstructions and inferred boundaries between various apparently unrelated terranes in Mexico indicate that most of Mexico is composed of crustal elements that were accreted to North America after the Carboniferous (Dickinson and Lawton, 2001). The southern slopes of the Sierra Madre del Sur range comprise primarily arc-related rocks of the Xolapa Complex (Campa and Coney, 1983), also known as the Chatino terrane (Sedlock et al., 1993). It is a 600 km long, relatively narrow (<70 km) strip of mostly arc-related rocks straddling the coastal Pacific margin of southern Mexico. The local geology of Xolapa is not known in detail, partly because of the thick vegetation cover and scarce access, and also because of the predominance of high-grade basement rocks, the age and origin of which are not resolved. Overall, Xolapa has Gondwanan affiliations, as do the neighboring terranes of Mixteca and Oaxaca (e.g., Dickinson and Lawton, 2001). It is plausible that Xolapa may not be a far-traveled terrane, but instead might simply be the west-facing magmatic arc for Pacific Mexico (Herrmann et al., 1994) presumably formed between the Jurassic and the Late Eocene.

Two of the key elements required in deciphering the tectonic history of Xolapa are (1) sorting out the age and origin of its basement and (2) resolving the timing of arc magmatism and relationship to the surrounding arc-related products in Central America. Both of these tasks require high-precision geochronology of basement rocks. There is evidence that the arc was active in the Mesozoic and continued throughout much of the Cenozoic (Ortega-Gutierrez, 1981). Unfortunately, most of the published Xolapa ages employed isotopic techniques (K-Ar, Rb-Sr) that yield cooling ages but not necessarily crystallization ages (Morán-Zenteno et al., 1999, for a compilation of ages and review). One of the major limitations of the few previous U-Pb zircon studies (e.g., Robinson et al., 1989; Herrmann et al., 1994; Schaaf et al., 1995) is that they employed multigrain fractions that commonly yielded discordant ages; thus the age interpretations are commonly nonunique.

The purpose of this study was to acquire additional geochronological data on key locations within the Sierra Madre del Sur region. The strategy was such that we would fill gaps that remained after the publication of the previous zircon U-Pb geochronology studies, in order to obtain a more complete picture of the plutonic and metamorphic age distribution within Xolapa. The Xolapa zircons are commonly very complicated, and some record multiple ages even at crystal scale (Herrmann et al., 1994). We conducted our U-Pb study on small domains within single zircon crystals, via multicollector laser-ablation ICP-MS (MC-LA-ICP-MS),...
in order to efficiently sort out crystallization from inherited ages. MC-LA-ICP-MS U-Pb geochronology (Kidder et al., 2003; Dickinson and Gehrels, 2003; Ducea et al., 2003) is a new technique that allows rapid and inexpensive age determinations with a precision similar to secondary ion mass spectrometry. The technique can be used for both detrital zircon (provenance) studies and igneous geochronology.

Three key long-standing regional geologic questions are addressed in this study using U-Pb geochronology: (1) Is the Xolapa Complex a traveled terrane, i.e., was it largely assembled at a remote location relative to its neighboring blocks in southern Mexico? (2) When was the magmatic arc active in Xolapa? (3) Does the time-space distribution of Cenozoic magmatism in the Xolapa constrain the reorganization of plate boundaries in southwestern Mexico? We show that (1) inherited zircons suggest an autochthonous origin for the Xolapa Complex, (2) magmatism was active in distinct episodes with two major pulses in the Late Jurassic–Early Cretaceous and Eocene-Oligocene, and (3) magmatism ceased abruptly in Xolapa at ca. 25 Ma as the North American–Pacific plate boundaries were reorganized to form the modern Acapulco Trench. In addition, we use the regional geologic data to address some general questions on continental arc magmatism, specifically the causes of episodic high-flux magmatic events.

GEOLOGICAL BACKGROUND

Geology

All rocks studied here are part of the Xolapa terrane (Campa and Coney, 1983), which extends along the Pacific margin of southern Mexico in the states of Guerrero and Oaxaca and is ~600 km long and 50–70 km wide (Fig. 1). Although thought by many authors to represent an out-of-place terrane that may have docked to mainland Mexico by the Late Cretaceous (Dickinson and Lawton, 2001; Campa and Coney, 1983; Sedlock et al., 1993), some studies have argued that the geology of Xolapa, while somewhat distinctive from the neighboring terranes, represents a magmatic arc that formed in place during the Mesozoic and continued into the Cenozoic (e.g., Herrmann et al., 1994; Schaaf et al., 1995; Morán-Zenteno et al., 1999). Thus, the Xolapa Complex are referred to as the Xolapa Complex by Herrmann et al. (1994), a nongenetic terminology that we also adopt here.

The geology of the Xolapa Complex consists of high-grade orthogneisses and paragneisses as well as migmatises (Ortega-Gutierrez, 1981), intruded by generally undeformed tonalitic to granodioritic plutons (Herrmann et al., 1994; Meschede et al., 1997; Morán-Zenteno et al., 1999). Figure 2 is a geologic map of the Xolapa Complex in the vicinity of Acapulco (modified after Morán-Zenteno, 1992) and shows the overall geologic features of the complex. The orthogneisses are ductilely deformed and metamorphosed calc-alkaline diorites, tonalites, and granodiorites, and predominate over the paragneisses by a factor of at least 10. The orthogneisses represent a metamorphosed sequence of continental arc rocks, whereas the paragneisses are rare framework rocks of this arc (Ortega-Gutierrez, 1981). The protolith age for the gneisses and migmatites is ca. 1.0–1.3 Ga, based on Nd model ages and U-Pb ages (Herrmann et al., 1994), whereas metamorphism is thought to have occurred sometime between the Early Cretaceous and Eocene (Riller et al., 1992; Herrmann et al., 1994; Meschede et al., 1997; Morán-Zenteno et al., 1996, 1999). The undeformed plutons, calc-alkaline tonalites, and granodiorites are also characteristic of rocks formed in a continental magmatic arc setting (Martiny et al., 2000), and are Eocene-Oligocene in age: 36–23 Ma between Zihuatanejo and Puerto Angel (Schaaf et al., 1995; Morán-Zenteno et al., 1999; Herrmann et al., 1994). Trace element patterns in these plutons are characteristic of subduction-related magmatism, which suggests an enriched mantle source in the subcontinental lithosphere, modified by subduction fluids (Martiny et al., 2000). The
initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ values of these plutons suggest a relatively low degree of crustal contamination (Martiny et al., 2000). Herrmann et al. (1994) proposed that the Eocene-Oligocene magmatism has a distinct migration pattern from older in the west to younger in the east at a rate of 56 km/m.y.

The Xolapa Complex does not have an on-land sedimentary cover proper (Were-Keeman and Estrada-Rodarte, 1999; Castillo-Nieto and Rodriguez-Luna, 1996), in contrast to the adjacent terranes (e.g., Campa and Coney, 1983; Sedlock et al., 1993). The only sedimentary cover to Xolapa is represented by a narrow accretionary wedge of the modern Acapulco Trench, which represents the southern boundary of the Xolapa Complex, with the oldest sediments being Miocene in age (20 Ma, Watkins et al., 1981). The northern boundary of the complex is poorly known. This boundary is best studied in the Tierra Colorada region, north of Acapulco (Fig. 2), where it is marked by a zone of cataclastic rocks and mylonites, indicating sinistral shear and north-south extension (Meschede et al., 1997; Ratschbacher et al., 1991). In the Tierra Colorada region, mylonitization occurred between the Late Cretaceous and Paleocene-Eocene (Ratschbacher et al., 1991; Herrmann et al., 1994; Morán-Zenteno et al., 1999), and possibly later to the east near Puerto Angel (Morán-Zenteno et al., 1999).

**Tectonic History**

Since the middle Cretaceous, the relationship between the Farallon and North American plates changed several times (e.g., Engebretson et al., 1985): The plate boundary was predominantly convergent, with both periods of oblique subduction and periods when the margin was a continental transform boundary. By 20 Ma, the Farallon plate had fractured into the Cocos and Nazca plates (Meschede et al., 1997). The Cocos plate continued on a north-northeast trajectory with respect to the North American plate along the current southern Mexican border. Plate-tectonic reconstructions are subject to large errors for southern Mexico because the Farallon plate has been entirely subducted. The timing and patterns of migration of magmatic arcs on the continental Mexico side of this subduction zone are used to better understand the major changes in relative motion between the Pacific and North American plates in southern Mexico (Ferrari et al., 1999) especially in late Cenozoic time, for which numerous age data are available for volcanic and intrusive rocks.

The current southern margin of the North American plate has experienced truncation along the southern margin of the Xolapa Complex (Malfait and Dinkelman, 1972; Ross and Scotese, 1988; Ferrari et al., 1994; Herrmann et al., 1994; Schaaf et al., 1995). Though subduction has been occurring at most times since the early Mesozoic, the current margin displays none of the mature margin characteristics of other 100 Ma margins. The Middle America Trench today lies only ~75 km offshore, and thus the distance between the modern trench and the Eocene-Oligocene magmatic arc is much less than in other arc systems. The margin displays a very narrow upper slope and forearc basin when compared to other areas with long subduction histories (Karig-Cordwell et al., 1978). Structural trends of metamorphic rocks in the Xolapa Complex intersect the coast at steep angles, also indicating margin truncation (Malfait and Dinkelman, 1972). The lack of high-pressure/low-temperature rocks along the continental margin as well as the lack of an accretionary prism landward from the Middle America Trench add additional support for the hypothesis that truncation has occurred at some time (Schaaf et al., 1995; Meschede et al., 1997). The Middle America (Acapulco) trench along the southern Mexican margin has experienced accretionary sedimentation continuously since the Middle Miocene. The two mechanisms possibly responsible for truncation are (1) subduction erosion (Morán-Zenteno et al., 1996) and (2) lateral transport via transform faults, which may have removed the older wedges, the

Figure 2. Geologic map of the Acapulco transect (modified after Morán-Zenteno, 1992), showing the distribution of gneisses/migmatites and undeformed plutons in the area. The location of samples studied here from the Acapulco transect are also shown.
forearc, and even parts of the Xolapa Complex (Schaaf et al., 1995).

**SAMPLES AND ANALYTICAL METHODS**

Samples were collected along three north-south transects in the Sierra Madre del Sur: Acapulco, Puerto Escondido, and Puerto Angel (Fig. 1). At each sample locality, we collected 1–2 kg of fresh whole rock. Samples were prepared for analysis using standard crushing and separation techniques, including heavy liquids and magnetic separation, at the University of Arizona. Inclusion-free zircons were then hand-picked under a binocular microscope. At least 50 zircons from each sample were mounted in epoxy and polished.

Single zircon crystals were analyzed in polished sections with a Micromass Isoprobe multicollector ICP-MS equipped with nine Faraday collectors, an axial Daly detector, and four ion-counting channels (Kidder et al., 2003). The LA-ICP-MS analyses involve ablation of zircon with a New Wave DUV193 Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 25 to 35 microns. The ablated material is carried in argon gas into the plasma source of a Micromass Isoprobe, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using Faraday detectors for 238U, 232Th, 208–206Pb, and an ion-counting channel for 208Pb. Ion yields are ~1 mV per ppm. Each analysis consists of one 20-second integration on peaks with the laser off (for backgrounds), 20 one-second integrations with the laser firing, and a 30-second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~20 microns in depth.

Common Pb correction is performed by using the measured 208Pb and assuming an initial Pb composition from Stacey and Kramers (1975) (with uncertainties of 1.0 for 206Pb/204Pb and 0.3 for 207Pb/204Pb). Measurement of 204Pb using the measured 208Pb and assuming an initial Pb composition from Stacey and Kramers (1975) (with uncertainties of 1.0 for 206Pb/204Pb and 0.3 for 207Pb/204Pb). Measurement of 204Pb in common Pb samples is generally ~3% (2-sigma) and preparation for the next analysis. The ablation pit is ~20 microns in depth.

Almost all zircons that yielded Cenozoic ages display igneous morphologies (e.g., euhedral zoned crystals) with no detectable optical zoning. The older zircons found are smaller rounded grains that indicate a detrital origin and/or corrosion in magma. For these zircons, we report the core ages, which are always older than rim ages. Rim ages typically have large errors (probably because the new rim growths are very narrow) and are not reported in Table DR1, but the ages are generally Cenozoic.

**Puerto Angel Transect**

Three samples collected from north of Puerto Angel (M01-11, M01-14, and M01-16) yield exclusively Precambrian ages (Fig. 4). Sample M01-11 (n = 31 zircons) has a bimodal distribution of U-Pb ages, with one group averaging 1252 ± 24 Ma (MSWD = 1.2), and a second group averaging 1109 ± 10 Ma (MSWD = 0.9). All zircons in M01-11 are concordant or nearly concordant within error (Fig. 4). M01-14 has an average age of 1092 ± 28 Ma (n = 29) and may also have a bimodal distribution of ages, although not as pronounced as M01-14. Peak ages are

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**TABLE 1. SAMPLE LOCATION AND PETROGRAPHY**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Petrography</th>
<th>U-Pb age summary</th>
<th>Other ages (Ma)</th>
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<tbody>
<tr>
<td>Puerto Angel transect</td>
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<tr>
<td>M01-11</td>
<td>15°56′40″</td>
<td>96°27′55″</td>
<td>Bt tonalitic gneiss</td>
<td>1252 ± 24, 1106 ± 10 Ma</td>
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<td>M01-14</td>
<td>15°58′38″</td>
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<td>Bi + Gt tonalitic gneiss</td>
<td>1029 ± 28 Ma</td>
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<td>M01-16</td>
<td>16°03′21″</td>
<td>96°30′22″</td>
<td>Hbl + Bi tonalitic gneiss</td>
<td>1119 ± 24</td>
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<td>Puerto Escondido transect</td>
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<tr>
<td>M01-17</td>
<td>15°54′55″</td>
<td>97°04′47″</td>
<td>Bt tonalitic gneiss</td>
<td>272 ± 10 Ma; 1100 Ma</td>
<td>27.9</td>
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<td>M01-19</td>
<td>15°59′46″</td>
<td>97°04′46″</td>
<td>Bi + Hbl granodiorite</td>
<td>158 ± 8 Ma; 1.1–1.2 Ga</td>
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<td>M01-26</td>
<td>16°12′54″</td>
<td>97°08′10″</td>
<td>Bi + Hbl diorite</td>
<td>25.4 ± 2.9 Ma; 1.1 Ga</td>
<td>16.2</td>
</tr>
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<td>M01-27</td>
<td>16°17′05″</td>
<td>97°08′41″</td>
<td>leucotonalite</td>
<td>31.2 ± 1.5 Ma; 1016 ± 28 Ma</td>
<td>16.2</td>
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<td>M01-28</td>
<td>15°51′28″</td>
<td>97°03′33″</td>
<td>leucogranodiorite</td>
<td>29.6 ± 4 Ma; 50–71 and 100–126 Ma</td>
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</tr>
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</table>

**Acapulco transect**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Petrography</th>
<th>U-Pb age summary</th>
<th>Other ages (Ma)</th>
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</thead>
<tbody>
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<td>M01-46</td>
<td>16°47′29″</td>
<td>99°49′43″</td>
<td>Hbl-syenite</td>
<td>54.9 ± 2.0 Ma</td>
<td>26.7</td>
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<tr>
<td>M01-02</td>
<td>16°22′37″</td>
<td>99°26′21″</td>
<td>Bi + Hbl tonalitic gneiss</td>
<td>140.9 ± 4.5 Ma</td>
<td>17.7</td>
</tr>
<tr>
<td>M002</td>
<td>17°13′53″</td>
<td>99°31′16″</td>
<td>Bi + Hbl tonalitic gneiss</td>
<td>136.6 ± 4.0 Ma</td>
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<tr>
<td>M01-04</td>
<td>16°46′26″</td>
<td>99°37′35″</td>
<td>Bi granodiorite</td>
<td>34.5 ± 1.2 Ma</td>
<td>37.6</td>
</tr>
</tbody>
</table>

**Note:** Bi—biotite, Hbl—hornblende, Grt—garnet.

†Crystallization ages are listed first; inherited ages, when determined, are shown in italics.

1Apatite fission track ages determined on the same samples by Shoemaker et al. (2002).

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GSA Data Repository item 2004xxx, U-Pb zircon analytical data, is available on the Web at http://www.geosociety.org/pubs/ft2004.htm. Requests may also be sent to editing@geosociety.org.
1244 ± 10 Ma (MSWD = 0.4), and 1163 ± 15 Ma (MSWD = 1.1). Most determined ages in M01-14 are concordant. Most zircons in sample M01-16 (21 out of 28) cluster around an average age of 1119 ± 24 Ma (MSWD = 0.4), although individual ages range from 950 to 1250 Ma. Most ages in this sample are also concordant (Fig. 4). There are no Phanerozoic zircons in these samples. Overall, these ages are identical to the ca. 1.0–1.2 Ga Grenville ages obtained on the high-grade basement of the Oaxaca terrane (Ruiz et al., 1988; Herrmann et al., 1994).

Puerto Escondido Transect

Tonalitic gneiss M01-17 collected south of Puerto Escondido has a 206Pb/238U age of 272 ± 10 Ma (MSWD = 0.4). Inherited zircons with middle Cretaceous (100–126 Ma) and latest Cretaceous–early Cenozoic (50–71 Ma) 206Pb/238U ages are found. One zircon has a 206Pb/238U age of 1051 Ma. Tonalite M01-27 has a 31.9 ± 1.5 Ma crystallization age (n = 22 zircons), MSWD = 5, as well as one Precambrian zircon (1016 ± 28 Ma). Finally, a quartz-diorite (M01-26) yielded a 25.4 ± 2.9 Ma crystallization age (n = 8 zircons), MSWD = 19. However, this sample contains complexly zoned zircons that yield discordant ages spanning the range between crystallization ages and an inferred inherited Grenville component, similar to the other samples collected along the Puerto Escondido transect.

Acapulco Transect

Undeformed syenite sample M01-46, located in Acapulco Bay, has a crystallization age of 54.9 ± 2.0 Ma (MSWD = 3.3), which is similar to a 50 Ma K-Ar age on a nearby quartz-syenite (Morán-Zenteno, 1992). Twenty-four zircons from this sample yielded all crystallization ages, with no detectable inherited component (Fig. 6). Two garnet- and biotite-bearing tonalitic gneisses (M01-02 and M002) yielded early Cretaceous ages (Fig. 6), identical within errors: M01-02 has an age of 140.9 ± 4.5 Ma (n = 41 zircons, MSWD = 2.0), whereas M002 has an age of 136.6 ± 4.0 Ma (n = 33 zircons, MSWD = 1.1). There are no inherited zircons in this gneiss. Finally, sample M01-04, an undeformed hornblende- and biotite-bearing granodiorite that was collected along the new Highway 95, yields a 206Pb/238U age of 34.5 ± 2.2 Ma (n = 19, MSWD = 0.4) with no inherited grains, consistent with previously determined U-Pb ages on neighboring undeformed plutons (Herrmann et al., 1994).

INTERPRETATIONS

The Boundaries of the Xolapa Complex

Samples of the Puerto Angel transect are interpreted to represent basement rocks of the Oaxaca terrane, thus limiting the extent of the Xolapa Complex to less than 30 km from the coast along this transect. While most rocks investigated along this transect have a distinctive L-S tectonite fabric, they do not differ compositionally (tonalites, granodiorites) from most of the deformed rocks of the Xolapa Complex. In addition, one of the samples analyzed here (M01-16) is in fact a slightly deformed coarse biotite- and amphibole-bearing granodiorite, identical in both composition and fabric to a typical Xolapa postkinematic Eocene-Oligocene granitoid. This sample was collected just south of the Chacalapa shear zone, which is defined by some as representing the boundary between

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Xolapa and Oaxaca. The Xolapa Complex of Mesozoic-Cenozoic arc-related rocks becomes much narrower along the Puerto Angel transect than to the west, at Puerto Escondido, where it is 100 km wide (Campa and Coney, 1983). The narrowness of the Xolapa Complex at Puerto Angel compared to Puerto Escondido may be explained by the presence of a major fault orthogonal to the strike of the Xolapa Complex between Puerto Escondido and Puerto Angel, e.g., the Oaxaca fault (Nieto-Samaniego et al., 1995; Alanis-Alvarez et al., 1996). A significant late Cenozoic dextral strike-slip component on the Oaxaca fault could explain the change in the width of the Xolapa Complex east of that fault; however, field data can document only dip-slip displacements on the Oaxaca fault during the Cenozoic (Alanis-Alvarez et al., 1996; D. Morán-Zenteno, 2003, written commun.), whereas most of the strike-slip displacement is Mesozoic. Alternatively, the Grenville ages reported in this study may suggest that the basement of the Xolapa Complex and the Oaxacan basement are indistinct and that perhaps the deformed basement for the Xolapa Complex may be in fact Oaxacan basement at many other locales within the coastal Sierra Madre del Sur.

Evidence for Permian Magmatism

Sample M01-17, a tonalitic gneiss collected ~7 km north of the Pacific Coast at Puerto Escondido, yielded a Permian U-Pb zircon age (272 ± 10 Ma). This is an unusual age for the Xolapa Complex, as it predates the Mesozoic and Cenozoic metamorphism and magmatism that essentially define the Xolapa Complex. Plutons of Cenozoic ages are found both north and south of the location of M01-17. Therefore, sample M01-17 represents a framework rock of the Xolapa Complex. Similar Permian ages have been reported in the Acatlan basement of the Mixteca terrane (Yanez et al., 1991; Robinson et al., 1989; Elias-Herrera and Ortega-Gutierrez, 2002) and the Juchatengo terrane (Grajales-Nishimura et al., 1999). If the Mixteca terrane, which is located north of the Xolapa Complex at the longitude of Puerto Escondido, is in fact the basement for Xolapa, an out-of-place origin for the Xolapa Complex could be ruled out. Future data collection will be aimed at basement rocks of the Xolapa Complex (e.g., rare metasedimentary rocks) in order to further sort out the age distribution of the pre-arc Xolapa basement.

Mesozoic Arc Evolution and Ductile Deformation

Three of our deformed samples, M01-19 (Puerto Escondido), and M002 and M01-2 (Acapulco), Figure 4. U-Pb ages for Puerto Angel in concordia plots. A: Sample M01-11. B: Sample M01-14. C: Sample M01-16.
Figure 5. Zircon U-Pb ages along the Puerto Escondido transect. (A) $^{206}\text{Pb}/^{238}\text{U}$ ages of sample M01-17. (B) $^{206}\text{Pb}/^{238}\text{U}$ ages of sample M01-19. (C) $^{206}\text{Pb}/^{238}\text{U}$ ages of sample M01-26. (D) $^{206}\text{Pb}/^{238}\text{U}$ ages of sample M01-27. (E) $^{206}\text{Pb}/^{238}\text{U}$ ages of sample M01-28. (F) Concordia diagram for sample M01-19, showing the presence of inherited Grenville (ca. 1.1 Ga) ages as well as individual ages that lie on a mixing line between the inherited ages and the interpreted crystallization age of the rock.
yielded Late Jurassic–Early Cretaceous ages. Based on the zircon morphology (Pupin, 1983), we interpret these data to represent igneous crystallization ages. Field observations (this study and Morán-Zenteno, 1992) suggest that the timing of ductile deformation was concomitant with the intrusion (these are synkinematic plutons).

Several of the earlier geochronologic studies of the Xolapa Complex reported similar ages, based on U-Pb zircon geochronology (Fries and Rincon-Orta, 1965; Guerrero-Garcia, 1975; Robinson et al., 1989; Herrmann et al., 1994) and Rb-Sr whole-rock ages (Guerrero-Garcia, 1975; Morán-Zenteno, 1992). However, Herrmann et al. (1994) considered the pre-Cenozoic ages “speculative” and instead interpreted their U-Pb data to show evidence for an early Cenozoic (66–46 Ma) age of magmatism, ductile deformation, and metamorphism of the Xolapa Complex. The new data presented in this paper lend strong evidence to the previously postulated Late Jurassic–Early Cretaceous magmatic/deformational event.

The alkaline rock suite of Acapulco has a distinctively older age of ca. 55 Ma compared to other undeformed plutons in the region. It is part of a composite alkaline pluton extending ~15 km across Acapulco Bay (Morán-Zenteno et al., 1993), the eastern edges of which are only 30 km from gneissic sample M01-02, which yielded a Jurassic age. The emplacement depth for this suite was calculated by Morán-Zenteno et al. (1996) to be ~20 km, using Al-in-hornblende barometry. The emplacement of the Acapulco suite is coeval with the proposed Cenozoic metamorphic event (Herrmann et al., 1994), and the calculated depth of emplacement requires that these rocks would have been subject to crystal plastic deformation in such a metamorphic regime. The lack of plastic deformation in the Acapulco intrusive suite puts important constraints on the timing of metamorphism and ductile deformation of the Xolapa Complex; we interpret these data to strongly argue for a pre-Cenozoic age of metamorphism.

Evidence against Along-Strike Migration of Eocene-Oligocene Arc Magmatism

Our new data, together with previously published U-Pb zircon age data on the Eocene-Oligocene undeformed magmatic rocks within the Xolapa Complex, do not support the hypothesis of eastward migration of magmatism (Herrmann et al., 1994). Figure 7 shows that plutons with ages of 24–37 Ma were found within the western, central, and eastern transects described here, representing the eastern ~360 km along the strike of the arc. While it is possible that the cessation of magmatism was diachronous along the strike of the Oligocene Xolapa Complex, as a result of a change in the relative motion of the Farallon and North American plates and a transition from a subduction to transform margin, there is no obvious reason why the entire arc-related magmatic pulse should have migrated along the strike of the arc (Herrmann et al., 1994). In conclusion, our new data and

![Figure 6. 206Pb/238U ages for samples along the Acapulco transect. (A) Sample M01-46. (B) Sample M01-04. (C) Sample M01-02. (D) Sample M002.](image-url)
Timing poorly constrained

previously published data show that the Eocene-Oligocene magmatic pulse was not diachronous between Acapulco and Puerto Angel.

Episodicity of Magmatism

The Pacific margin of southern Mexico was a convergent margin after Middle Triassic time. Arc-related magmatism is therefore expected to have occurred at least intermittently for most of the last 200 m.y. However, our data and previously published data for the Xolapa Complex indicate a rather episodic record of magmatism consisting primarily of two volumetrically significant pulses: one in the Early Cretaceous (possibly extending into the Late Jurassic), and a second one that is Late Eocene–Oligocene (Fig. 8). Plutons of different ages, such as the Paleogene Acapulco composite intrusion, are present locally but appear to be volumetrically less significant in the Xolapa Complex. Other continental arcs in North and South America, such as the composite Sierra Nevada (Duea, 2001), Coast Mountains (Armstrong, 1988), and Peruvian batholiths (Pitcher, 1993), were not steady-state but were rather formed during short flare-up events separated by longer magmatic lulls. Available mapping and geochronologic data indicate that the Early Cretaceous arc is exposed to mid-crustal levels and represents some 40% of the exposed Xolapa Complex (Morán-Zenteno, 1992). This magmatic pulse is correlative with the Late Jurassic–Early Cretaceous flare-up of the California arc (Duea, 2001). Some 50% of the Xolapa Complex consists of large Eocene-Oligocene (35–25 Ma) calc-alkaline plutons. The match in age with the magmatic flare-up of the Sierra Madre Occidental to the north (Ferrari et al., 1999) suggests that these plutons may represent the southern continuation of that arc. Compositionally, the Eocene-Oligocene plutons of the Sierra Madre del Sur between Acapulco and Puerto Angel (Martiny et al., 2000) are remarkably similar to the average composition of the Sierra Madre Occidental arc. The deeper levels of exposure (Morán-Zenteno et al., 1996) of the Eocene-Oligocene plutons in the Xolapa Complex are due to relatively high erosion rates that characterize the Sierra Madre del Sur mountain range since the Miocene (Morán-Zenteno et al., 1996; Shoemaker et al., 2002).

Magmatism ended at ca. 25 Ma in the Sierra Madre del Sur. The Eocene-Oligocene continental margin was later truncated because the modern Middle America (Acapulco) trench is adjacent to the Eocene-Oligocene arc and oblique to it. The leading hypothesis for the late Cenozoic continental truncation in Pacific southern Mexico is tectonic erosion (or subduction erosion) (Morán-Zenteno et al., 1996).

CONCLUSIONS

A proposed synthesis of magmatic and deformation events that led to the development of the Xolapa Complex, based on our new results and previous data, is summarized in Figure 8. The main intrusive and deformational events that led to the development of gneisses in the Xolapa Complex are latest Jurassic–Cretaceous. The framework rocks to the Mesozoic arc may have been basement rocks of the Mixteca and Oaxaca terranes, suggesting, as did Herrmann et al. (1994), that the Xolapa Complex is not out of place with respect to these terranes. We also propose that renewed magmatism, not accompanied by deformation, took place in the Paleogene, and then again, more volumetrically significant, during the Eocene-Oligocene. The available data on the Eocene and Oligocene magmatism do not support the hypothesis of eastward migration of magmatism, but rather point to a regionally extensive, relatively short-lived (~10 m.y.)
flame-up episode that may be related to the development of the Sierra Madre Occidental arc. Magmatism ceased abruptly at ca. 25 Ma in the study area. Magmatism then migrated inland and resulted in the formation of the Trans-Mexican Volcanic Belt (Ferrari et al., 1999), which is oblique to the strike of the Xolapa Complex.

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