Synthesis and tectonic interpretation of the westernmost Paleozoic Variscan orogen in southern Mexico: From rifted Rheic margin to active Pacific margin

J. Duncan Keppie \textsuperscript{a,⁎}, Jaroslav Dostal \textsuperscript{b}, J. Brendan Murphy \textsuperscript{c}, R. Damian Nance \textsuperscript{d}

\textsuperscript{a} Depto. de Geología Regional, Instituto de Geología, Universidad Nacional Autónoma de México, México, Mexico
\textsuperscript{b} Department of Geology, St. Mary's University, Halifax, Nova Scotia, Canada B3H 3C3
\textsuperscript{c} Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia, Canada B2G 2W5
\textsuperscript{d} Department of Geological Sciences, 316 Clippinger Laboratories, Ohio University, Athens, Ohio 45701, USA

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Abstract

Paleozoic rocks in southern Mexico occur in two terranes, Oaxaquia (Oaxacan Complex) and Mixteca (Acatlán Complex) that appear to record: (1) Ordovician rifting on the southern margin of the Rheic Ocean, (2) passive drifting with Amazonia during the Silurian, (3) Devonian-Permian subduction beneath southern Mexico producing an arc complex that was partially removed by subduction erosion, subjected to HP metamorphism and Mississippian extrusion into the upper plate, followed by reestablishment of a Permian arc.

In the Oaxaquia terrane, the 920–1300 Ma basement is unconformably overlain by a ∼200 m uppermost Cambrian–lowest Ordovician shelf sequence containing Gondwanan fauna (Tiñu Formation), unconformably overlain by 650 m of shallow marine-continental Carboniferous sedimentary rocks containing a Midcontinent (USA) fauna.

In the Mixteca terrane, the low-grade Paleozoic sequence is composed of: (a) a ?Cambrian–Ordovician clastic sequence intruded by ca. 480–440 Ma bimodal, rift-related igneous rocks; and (b) a latest Devonian-Permian shallow marine sequence (> 906 m) consisting of metapsammites, metapelites and tholeiitic mafic volcanic rocks. High pressure (HP) metamorphic rocks in the Mixteca terrane consists of: (i) a Cambro-Ordovician rift-shelf intruded by bimodal rift-related intrusions that are similar to the low-grade rocks; (ii) periarultramafic rocks, and (iii) arc and MORB rocks. The Ordovician granitoids contain concordant inherited zircons that range in age from ca. 900 to 1300 Ma, indicating a source in the Oaxacan Complex. Concordant ages of detrital zircons in both the low- and high-grade Cambro-Ordovician metasedimentary rocks indicate a provenance in local Ordovician plutons and/or ca. 1 Ga Oaxacan basement, and distal northwestern Gondwana sources with a unique source in the 900–750 Ma Goiás magmatic arc within the Brasiliano orogen. These data combined with the rift-related nature of the Cambro-Ordovician rocks are most consistent with an origin along the southern margin of the Rheic Ocean. Latest Devonian-Permian deposition was synchronous with Mississippian extrusion of the HP rocks into the upper plate during extensional deformation. The HP Cambro-Ordovician rift-shelf rocks are inferred to have originated in the forearc region of the upper plate that was removed by subduction erosion, carried down the subduction channel, and then extruded into the upper plate in the middle of the Mixteca terrane. The presence of arc-related rocks in the HP assemblage suggests that the arc complex was also removed, whereas the MORB rocks may have been derived from the subducting slab. Detrital zircons in the Carboniferous rocks of both the Mixteca and Oaxaquia terranes contain Devonian detrital zircons and volcanic clasts that are inferred to have come from the removed Devonian arc on the western margin of the Mixteca terrane and/or from exhumed HP rocks. During the Permian, arc-related intrusions in both the Mixteca and Oaxaquia terranes were accompanied by dextral transtensional deformation and deposition of clastic rocks containing Permian detrital zircons and carbonates in periarul pull-apart basins. Empirical relationships between the dip of the Benioff zone and the widths of arc and forearc indicate that the Permian trench lay beneath the eastern edge of the Mesozoic Guerrero terrane.

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⁎ Corresponding author. Tel.: +52 555 622 4290.
E-mail address: duncan@servidor.unam.mx (J.D. Keppie).

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1. Introduction

Paleozoic rocks in southern Mexico are restricted to the Mixteca terrane and small outliers in the Oaxaquia terrane (Fig. 1). Knowledge of the Paleozoic geology of southern Mexico, especially in the Mixteca terrane (Fig. 2), during the twentieth century was hampered by generally poor preservation of fossils and a lack of reliable age dates. However, the last decade has seen a rapid increase in such data supplemented by geochemistry (Ortega-Gutiérrez et al., 1999; Elías-Herrera and Ortega-Gutiérrez, 2002; Vachard and Flores de Dios, 2002; Keppie et al., 2004a,b; Sánchez-Zavala et al., 2004; Vachard et al., 2004; Talavera-Mendoza et al., 2005; Keppie et al., 2006; Nance et al., 2006; Murphy et al., 2006a,b; Miller et al., 2007; Nance et al., 2007; Middleton et al., 2007; Elías-Herrera et al., 2007; Landing et al., 2007; Vega-Granillo et al., 2007; Keppie et al., 2008; Morales-Gámez et al., 2008; Ramos-Arias et al., 2008; Hinojosa-Prieto et al., in review; Grodzicki et al., in press). This has led to considerable revision of the geological history, which has recently been reviewed by Nance et al. (2006, 2007).

Nance et al. (in review) have compiled histograms of detrital zircon ages to give a broad overview of potential sources that they argued were of dominantly local and Gondwanan provenence. Here we try to refine these conclusions by focusing on concordant data (c.f. Anderson, 2005) (Figs. 3 and 4) from which emerges a suite of 900–750 Ma detrital zircons that has a unique source in the Goiás magmatic arc within the Brasiliano orogen of Amazonia (Pimental et al., 2000). We separate the zircon populations according to the age of the unit (Ordovician, Carboniferous and Permian). During the Ordovician both the Iapetus and Rheic oceans were in existence and the characteristics of these zircons test whether they had Gondwanan or Laurentian provenance. On the other hand, during the Carboniferous and Permian, the location of southern Mexico in Pangea implies that both continents may have contributed to the zircon populations. The earliest evidence of a southern source for flysch deposits in the Ouachita orogen occurs in the Mississippian (ca. 330 Ma: Arbenz, 1989). At about the same time, faunal interchange between Laurentia and Oaxaquia is documented with the appearance of Laurentian (Midcontinent USA) fauna in the Mississippian rocks of southern Mexico (Navarro-Santillan et al., 2002). Deformation associated with Laurentia–Gondwana collision started in the Pennsylvanian (Arbenz, 1989).

This paper, then, presents a tectonic interpretation of the Paleozoic geological record of southern Mexico, which

![Terrane map of southern Mexico](image)

Fig. 1. Terrane map of southern Mexico showing the locations of the Oaxaquia, Mixteca and Guerrero terranes and Permian arc intrusions (modified from Keppie et al., 2003c).
indicates that they formed on, and adjacent to, Oaxaquia on the northwestern margin of Gondwana (Amazonia) in two tectonic environments: (i) a Cambrian–early Silurian rift-shelf setting on the southern margin of the Rheic Ocean, and (ii) a latest Devonian-Permian active margin setting of the eastern Pacific Ocean (Fig. 5). However, southern Mexico, although it represents the western end of the Variscan–Alleghanian orogen, was not involved in the collisional stage typical of the rest of the orogen.

2. Review of the geological records of the Mixteca and Oaxaquia terranes

The Mixteca terrane (Acatlán Complex) is juxtaposed on its eastern side against the ca. 920–1300 Ma Oaxacan Complex of the Oaxaquia terrane (Figs. 1 and 2) along a Permian dextral flower structure where syntectonic migmatites have yielded an age of 276±1 Ma (Caltepec fault zone of Elías-Herrera and Ortega-Gutiérrez, 2002). These ~1 Ga rocks belong to the Middle American microcontinent, which lay along the northwestern border of Gondwana (i.e. Amazonia: Keppie, 2004).

2.1. Oaxaquia terrane

The Oaxaquia terrane consists mainly of granulite facies rocks of the Oaxacan Complex, in which ages range from ca. 920 Ma to 1300 Ma. Important igneous and metamorphic events in this time interval occurred at ca. 1200–1300 Ma (intrusion of continental tholeiites: Keppie and Dostal, 2007), ca. 1160–1130 Ma (intrusion of bimodal igneous plutons), ca. 1106 Ma (Olmecan tectonothermal event, including migmatization), ca. 1004–978 Ma (Zapotecan orogeny, including granulite facies metamorphism and intrusion of an anorthosite–mangerite–charnockite–granite suite), and ca. 920 Ma ( intrusion of a calc-alkaline pluton) (Keppie et al., 2001, 2003a; Solari et al., 2003; Ortega-Obregón et al., 2003). In small outliers in southern Mexico, these Precambrian rocks are unconformably overlain by a thin (ca. 200 m) shallow marine, shelf sequence consisting of carbonates and clastic rocks (Tiñu Formation) containing latest Cambrian–earliest Ordovician fossils with Gondwanan affinity (Robison and Pantoja-Alor, 1968; Landing et al., 2007). The clastic rocks contain detrital zircons exclusively derived from the underlying Oaxacan Complex (Gillis et al., 2005) and show a geochemistry typical
of a rift-shelf origin (Murphy et al., 2005). These rocks are overlain by Carboniferous clastic and shallow marine rocks (Mississippian Santiago and Pennsylvanian Ixtaltepec formations: 200 m and 425 m thick, respectively) that contain a Midcontinental (USA) fauna (Navarro-Santillan et al., 2002) indicating proximity to Laurentia during in the initial stages of Pangea amalgamation. The Ixtaltepec Formation contains clasts of felsic volcanic rocks (Gillis et al., 2005). Whereas most of the detrital zircon ages from these two units indicate derivation from the Oaxacan Complex, there are a few Ordovician (447±17 Ma single grain TIMS analysis and several single grain LA-ICPMS analyses in the range ca. 470 to 475±4 Ma); and Devono-Carboniferous (340 and 358 Ma—single grain TIMS analyses and 339–405 Ma LA-ICPMS analyses: Gillis et al., 2005) ages (Fig. 4).

2.2. Mixteca terrane

The geological history of the Acatlán Complex has undergone rapid revision in recent years largely due to a rapidly improving geochronological and fossil database. As these changes have been recently reviewed by Nance et al. (2006, 2007) only a summary of the revised geological history is presented here (Fig. 5). The description is subdivided into low-grade and high pressure (HP) rocks.

2.2.1. Low-grade rocks

The low-grade sedimentary rocks underlie >60% of the Acatlán Complex (Fig. 2). They are predominantly arkoses, quartzites, psammites and pelites that were previously included in the Cosoltepec Formation (Ortega-Gutiérrez et al., 1999) which has since been shown to be a composite unit (e.g. Morales-Gámez et al., 2008; Ramos-Arias et al., 2008; Hinojosa-Prieto et al., in review; Grodzicki et al., in press). These clastic units may be subdivided into three age categories based upon the ages of the youngest detrital zircons and cross-cutting intrusions (Table 1): (1) younger than 900–650 Ma and pre-460–440 Ma; (2) Ordovician and pre-465–440 Ma; and (3) Devonian or younger, probably Carboniferous.
### 2.3. (?Cambrian–)Ordovician–earliest Silurian

Deposition of a the (?Cambrian–)Ordovician sequence was accompanied by intrusion of a 480–440 Ma bimodal igneous suite consisting of tholeiites (Keppie et al., 2008) and calc-alkaline megacrystic granitoids (Miller et al., 2007). The close association of these felsic rocks with tholeiitic mafic rocks indicates a rift origin (Keppie et al., 2008). Inherited zircons in the granitoid rocks indicate a source in a ca. 920–1300 Ga basement, probably the Oaxacan Complex (Fig. 6).

The absence of Ordovician detrital zircons in clastic rocks of the first category (Fig. 3) suggests that the strata were deposited either before, or synchronously with buried, Ordovician intrusions. Deposition of the rocks of the second category appears to be synchronous with these intrusions. Detrital zircon populations of both clastic suites (categories 1 and 2) indicate a wide range of concordant ages (490–2100 Ma: Fig. 3). However, those ranging from 900 Ma to 750 Ma are unusual, and the only known source that could provide such zircons is the Goiás magmatic arc of Amazonia (Pimental et al., 2000). Such ages are absent in Laurentia. The Goiás magmatic arc occurs within the Brasiliano orogen, which formed as a result of collision between the Sao Francisco and Amazonian cratons, and could also have provided the associated ca. 750–560 Ma detrital zircons. A drainage system originating in the Brasiliano orogen may have passed across Oaxaquia (which probably provided the ubiquitous 920–1300 Ma detrital zircons).

Although these latter ages overlap those of the Grenville orogen, the 980–920 Ma ages are limited to Oaxaquia (Keppie et al., 2003a: Fig. 3). The Maya terrane may also have contributed 540–560 Ma zircons, which have been recovered in ejects from the Chicxulub impact crater (e.g., Krogh et al., 1993). The interpretation that the zircon populations were derived from sources in Amazonia and Oaxaquia obviates the requirement of other sources for some of the suites (c.f. Talavera-Mendoza et al., 2005; Vega-Granillo et al., 2007).

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**Fig. 4.** Concordant detrital zircon ages from Carboniferous and Permian rocks of southern Mexico showing potential sources (see Fig. 2 for locations). $^{206}$Pb/$^{238}$U ages $\leq$ 1 Ga, and $^{207}$Pb/$^{206}$Pb ages $> 1$ Ga. Underlined ages are from the Ixtaltepec Formation. **Bold numbers** indicate TIMS analyses. Shaded areas indicate significant age ranges discussed in the text. Data sources: Olinala and Cosoltepec (Talavera-Mendoza et al., 2005); Canoas and Coatlaco (Grodzicki et al., in press); Ojo de Agua (Keppie et al., 2008); Salada (Morales-Gámez et al., 2008); Tecomate (Sánchez-Zavala et al., 2004); Ixtaltepec and Santiago formation (Gillis et al., 2005).
The mafic rocks associated with these Ordovician sedimentary rocks generally occur either as part of a dike swarm or are spatially associated with megacrystic granitoids plutons. The mafic rocks have a differentiated tholeiitic, within-plate chemistry, some of which indicate crustal contamination indicative of an origin in a rifted continental tectonic setting (Keppie et al., 2008). Only one grabbroic dike has been dated directly: 442 ±1 Ma (Keppie et al., 2008). The associated megacrystic granitoids have ages ranging from 478±5 Ma (Keppie et al., 2008; Morales-Gámez et al., 2008) and have a crustal signature. Their close spatial and temporal association with the rift-related tholeiites suggests the mafic magmas probably triggered melting of a crustal source. Inherited zircons in these megacrystic granitoids have ages ranging from ca. 910 Ma to ca. 1250 Ma (Table 1) consistent with a source in the Oaxacan Complex (Talavera-Mendoza et al., 2005; Miller et al., 2007; Morales-Gámez et al., 2008).

2.4. Late Paleozoic

Late Paleozoic events include deposition of latest Devonian (Strunian)-Late Permian, shallow marine carbonate and clastic rocks of the Patlanoaya Group and the Tecomate and Olinalá formations (Vachard et al., 2000; Vachard and Flores de Dios, 2002; Vachard et al., 2004; Keppie et al., 2004b; Ramos-Arias et al., 2008), psammites and pelites of the Salada, Cuatlaco/Canoas and type Cosoltepec units (The term Cosoltepec is here restricted to the type locality: Talavera-Mendoza et al., 2005; Morales-Gámez et al., 2008; Grodzicki et al., in press), and alluvial fan deposits of the Leonardian Matzitzi Formation (Weber, 1997). The Salada Unit is an along-strike continuation of the type Cosoltepec Formation (Fig. 2). The Salada, Cosoltepec (s.s.) and Cuatlaco units all contain mafic lenses of tholeiitic, within-plate affinity (Keppie et al., 2007; Grodzicki et al., in press). Compared with the Ordovician units, concordant detrital zircons in the Salada, Cosoltepec (s.s) and Cuatlaco units still show a strong preponderance of ca. 560–750 Ma and ca. 920–1250 Ma ages with relatively few ages in the ca. 775–900 Ma range (Fig. 4) indicating these strata are derived either directly from Amazonia and Oaxaquia or are recycled from older sediments which had Amazonian/Oaxaquian provenance. The ca. 440–480 Ma detrital zircons in these units indicate a local Mixtecan source, whereas units with detrital zircon ages of ca. 1.3–2.8 Ga suggest a source in the Amazon craton (Fig. 4). However, the appearance of detrital zircons with ages of ca. 350–390 Ma indicates a new Devonian source: such zircons also appear in the Carboniferous rocks of Oaxaquia. There are no igneous rocks of this age in either Mexico or in the Ouachita orogen, and only a few occur in massifs within the Andes (e.g. 394±23 Ma and 370 ±20 Ma in the eastern Cordillera: Alemán and Ramos, 2000). Another potential source is in a postulated Devonian arc on the western margin of the Mixteca terrane as discussed below.

In addition to those in the older rocks, detrital zircons and granitic pebbles in the Permian Tecomate and Olinalá formations have concordant ages between ca. 325 and 290 Ma (Fig. 4). A source for these is provided by the Permo-Triassic arc that runs along the backbone of Mexico (Torres et al., 1999), with local representatives in the Mixtecan and Oaxaquia terranes (Fig. 1)(Totoltepec pluton dated at ca. 288 Ma: Yáñez et al., 1991; Keppie et al., 2004b, and La Carbonera stock dated at 275±4 Ma: Solari et al., 2001). The present width of the arc is 100–120 km (depending on whether a small
undated stock intruding the Patlanoaya Group is included or not). Using the empirical relationships between the widths of the arc and the dip of the Benioff zone (Fig. 7) one may estimate the width of the forearc to have been 180±40 km, a conclusion that places the Permian trench near the present eastern edge of the Mesozoic Guerrero terrane (Fig. 1). The Guerrero terrane was thrust over Mesozoic platformal carbonates during the Laramide orogeny, consistent with the inference that the Acatlán Complex underlies the Mesozoic platformal carbonates west of the Cenozoic Papalutla thrust (Centeno-Garcia et al., in press).

The latest Devonian–Carboniferous deposition was also synchronous with extensional deformation on listric normal shear zones (down-to the-east) that have yielded 40Ar/39Ar muscovite plateau ages of 347±2 Ma (Ramos-Arias et al., 2008). This greenschist facies deformation appears to have continued through ca. 330 Ma as indicated by cleavage development in other areas of the Acatlán Complex (e.g. Hinojosa-Prieto et al., in review). Furthermore, the Permian deposition coincided with a period of dextral transtensional deformation on N–S vertical shear zones (Morales-Gámez et al., 2006), during which local pull-apart basins and overthrust regions formed, depending on the location of releasing or restraining bends in the transcurrent faults. In the latter case, small clastic wedges up to Triassic in age were deposited in front of the advancing thrusts (Malone et al., 2002; Keppie et al., 2006).

2.4.1. High pressure rocks

A belt of high pressure (HP) rocks that strikes N–S occurs in the middle of the Acatlán Complex and is ≤ 15 km wide and 70 km in length. Although Vega-Granillo et al. (2007) argue for three periods of HP metamorphism in the Ordovician and Silurian in this belt, presently existing direct dating of the eclogite and blueschist metamorphism has only yielded Late Devonian–Mississippian dates (Middleton et al., 2007; Elías-Herrera et al., 2007; Keppie et al., 2008). This belt is bounded on either side by similar low-grade rocks. (Fig. 2). The HP rocks of the Acatlán Complex were originally inferred to be a nappe that was thrust over the low-grade rocks (Ortega-Gutiérrez et al., 1999 and references therein). However recent reexamination of the main central band reveals that contacts are generally steeply dipping dextral transcurrent shear zones/faults of Permian age. In contrast, in the Patlanoaya–Asis area (Fig. 8), the eastern contact of the HP rocks is a moderately east-dipping, listric normal shear zone with E-vergent kinematic.

Table 1

<table>
<thead>
<tr>
<th>Unit</th>
<th>Youngest detrital Zircon (206Pb/238U)</th>
<th>Cross-cutting intrusion</th>
<th>Overlying unit</th>
<th>Reference</th>
</tr>
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<tr>
<td>Upper Paleozoic</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Permo-Carboniferous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tecomate Fm</td>
<td>292±3 Ma</td>
<td>Late Penn</td>
<td></td>
<td>Keppie et al., 2004b</td>
</tr>
<tr>
<td>Tecomate Fm (type)</td>
<td>460±5 Ma (peak)</td>
<td></td>
<td></td>
<td>Sánchez-Zavala et al., 2004</td>
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<tr>
<td>Olinalá Fm</td>
<td>300±12 Ma</td>
<td></td>
<td></td>
<td>Talavera-Mendoza et al., 2005</td>
</tr>
<tr>
<td>Devono-Carboniferous</td>
<td></td>
<td></td>
<td></td>
<td>Vachard et al., 2004</td>
</tr>
<tr>
<td>Cosoltepec Fm (ss)</td>
<td>~399 Ma (mean of 4)</td>
<td></td>
<td></td>
<td>Talavera-Mendoza et al., 2005</td>
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<td></td>
<td>Permian</td>
<td>Morales-Gámez et al., 2008</td>
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<tr>
<td>Ojo de Agua Unit</td>
<td>466±25 Ma (peak)</td>
<td></td>
<td>Strunian</td>
<td>Keppie et al., in press</td>
</tr>
<tr>
<td>Mimilulco</td>
<td>~389 Ma (mean of 7)</td>
<td></td>
<td></td>
<td>Talavera-Mendoza et al., 2005</td>
</tr>
<tr>
<td>Cuatlaco Unit</td>
<td>357±35 Ma (mean of 8)</td>
<td></td>
<td></td>
<td>Grodzicki et al., in press</td>
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<tr>
<td>Canosas Unit</td>
<td>462±15 Ma (?interbedded with Cuatlaco)</td>
<td></td>
<td></td>
<td>Grodzicki et al., in press</td>
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<td>467±16 Ma</td>
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<td>Ordovician or older</td>
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<td>470–420 Ma</td>
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<td>Murphy et al., 2006ab</td>
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<td>Santa Cruz Orgonal</td>
<td>764±24 Ma (mean)</td>
<td>440±15 Ma (mean)</td>
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<td>Vega-Granillo et al., 2007</td>
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<td>Ixcamilpa</td>
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<td>441±11 Ma</td>
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indicators (Ramos-Arias et al., 2008). The western boundary of the HP rocks is a steeply dipping dextral fault (Barley, 2006).

The geological record is as follows (Fig. 5):

1. Post-700 Ma deposition of immature rift to shelf psammites and pelites derived from a continental source with a $T_{\text{DM}}$ age of 1.86–1.68 Ga (Murphy et al., 2006a,b; Vega-Granillo et al., 2007). Whereas the Asis/Santa Cruz Orgonal metasedimentary rocks yielded detrital zircons with ages of 705±8 Ma, 764±24 Ma, 888±18 Ma, 900–1200 Ma, and 1220–1500 Ma (Fig. 3), those along strike to the north at Mimilulco show an additional population between ca. 800 and 900 Ma (Fig. 3). The latter are similar to those occurring in blueschists in the western Acatlán Complex, which also contains an Ordovician population (460–490 Ma: Talavera-Mendoza et al., 2005; Vega-Granillo et al., 2007) (Fig. 3).

2. Ordovician intrusion of bimodal, megacrystic granitoids (~470–420 Ma U–Pb SHRIMP data: Murphy et al., 2006a,b; 440±15 Ma: Vega-Granillo et al., 2007) and continental rift tholeiites (SHRIMP age of 442±2 Ma from zircon cores: Elías-Herrera et al., 2004) from a 0.8–1.1 Ga mantle source ($T_{\text{DM}}$ age: Murphy et al., 2006a,b).

3. Latest Devonian–Mississippian eclogite facies metamorphism at ~750 °C at ≥14 kb was accompanied by polyphase deformation. A concordant TIMS zircon age of ~345–330 Ma zircon SHRIMP ages: Middleton et al., 2007, retrograde metamorphism, and polyphase deformation with westward extrusion fabrics (Middleton et al., 2007). The ~20 my older ages of 372±8 Ma (zircon LA-ICPMS mean U/Pb 206Pb/238U age) and 374±4 Ma (40Ar/39Ar phengite age from a foliated leucogranite dike at Santa Cruz Orgonal may indicate slightly earlier decompression melting (Vega-Granillo et al., 2007) The retrograde effects are constrained between ~350 and 335 Ma by a
351 ± 2 Ma $^{40}$Ar/$^{39}$Ar phengite plateau age (Middleton et al., 2007), the 347 ± 2 to 335 ± 2 Ma phengite ages of Vega-Granillo et al. (2007), and the ∼341 Ma phengite age recorded by Elías-Herrera et al. (2007).

2.4.2. Comparison of low-grade and HP rocks

The geochemistry of the HP mafic rocks of the Asis area is almost identical to that in the overlying Ordovician rift tholeiites (Fig. 9a and b). In addition, the chemistry and detrital zircon age populations of the HP sedimentary rocks of the Asis area are comparable to those of the Cambro-Ordovician Tínu Formation of Oaxaquia (Murphy et al., 2005) (Figs. 8c and 6). Furthermore, the chemistry of the Ordovician megacrystic granitoids that underwent HP metamorphism is very similar to that of the low-grade Ordovician megacrystic granitoids (Fig. 9d and e), and their inherited zircons are very similar (Fig. 6). The similarity of all of these suites suggests that the HP rocks of the Asis area represent part of the (?Cambro-) Ordovician rift-shelf sequence that was subducted (Murphy et al., 2006a,b; Middleton et al., 2007). These data led Nance et al. (2006, 2007) and Keppie et al. (2007) to propose that the leading edge of the continental margin was subducted westwards and then extruded back up the subduction channel resulting in a nappe of HP rocks thrust eastwards (present coordinates) over the low-grade rocks (as envisaged by Ortega-Gutiérrez et al., 1999). However, it is now clear that the HP rocks lie structurally below the low-grade rocks on their eastern side and were extruded towards the west into the rift-shelf sequence of the upper plate (Fig. 8). These relationships suggest the opposite sense of polarity with the Benioff zone dipping towards the east. The similarity of the HP and low-grade, rift-shelf rocks may be interpreted in terms of subduction erosion of the leading edge of the upper plate, as a result of which the subducted continental margin material was subjected to HP
metamorphism and then extruded part or all of the way to the surface. If extrusion only occurred up subduction channel (Ernst et al., 1997), then its location would mark a suture between the plates. However, the central HP band lies in the center of the Acatlán Complex with similar low-grade rocks on either side (Fig. 2). This suggests that the HP rocks were extruded into the rift-shelf sequence of the upper plate and that the later stages of extrusion took place above the subduction channel into the overlying upper plate. Such a process is in accord with numerical models of a pre-collisional active margin undergoing subduction erosion (Stöckhert and Gerya, 2005), where upper crustal rocks were taken down to 70 km and returned to a depth of 10 km in <20 my by extrusion into the upper plate. The size and apparent coherency of the HP rocks is also consistent with the large slices observed in Cascadia and British Columbia (Monger and Price, 2002; Calvert, 2003). This contrasts with the piecemeal nature of fragments generally removed from the Middle American margin that would result in a melange (Ranero and von Huene, 2000).

Another component in the HP belt is the Tehuitzingo serpentinite (Figs. 2 and 5), which contains chromite with a periarc chemistry (Proenza et al., 2004). Other HP rocks with igneous protoliths have volcanic arc and MORB geochemistry (Meza-Figueroa et al., 2003). Although the protoliths ages of these rocks is presently unknown, it would follow if the Asis rocks underwent subduction erosion, that the arc and periarc, HP components were likewise subjected to subduction erosion and so might represent the vestige of a magmatic arc built on the leading (western) edge of the Mixteca terrane. The MORB rocks may represent fragments of the subducting crust. Allowing for at least 20 my for the cycle of subduction erosion and extrusion (Stöckhert and Gerya, 2005), the inferred arc could be as old as ca. 366 Ma (i.e. Middle Devonian) or older. The source of the 370–400 Ma detrital zircons in the Salada

![Diagram](image-url)

Fig. 10. Paleozoic evolution of southern Mexico shown as a series of cross-sections.
Unit and the Ixtaltepec Formation could then be attributed to the inferred arc, whereas the 330–360 Ma detrital zircons may have come from the exhumed HP rocks.

3. Tectonic implications

A series of schematic cross-sections show the sequence of events recorded in the Paleozoic of southern Mexico (Fig. 10). Interpretation from these sections are supplemented by paleogeographic reconstructions for the Ordovician and late Paleozoic (Fig. 11).

In the late Neoproterozoic, the Avalonian arc lay on the margin of northwestern Gondwana (Oaxaquia and Amazonia) (Keppie, 2004). Collision of a mid-oceanic ridge with the trench led to diachronous extinction of the arc and the development of a transform margin (Fig. 11a) (Keppie et al., 2003b). This produced a seaway (Excalibur sea—new name) between Avalonia and Oaxaquia leading to development of a distinct Avalonian fauna in the Early-Middle Cambrian (Landing, 1996). The reestablishment of a Gondwanan fauna in Avalonia during the Late Cambrian and lowermost Ordovician (Fortey and Cocks, 2003; Landing et al., 2007) indicates renewed...
proximity between Avalonia and northwestern Gondwana (Figs. 10a and 11b). However, during the rest of the Ordovician, faunal and paleomagnetic data indicate that Avalonia drifted across the Iapetus Ocean to collide with eastern Laurentia (Cocks and Torsvik, 2002), either by broadly orthogonal drift (Murphy et al., 2006a,b) or by further transcurrent motion (Keppie et al., 2003b). This drift was synchronous with rifting in southern Mexico, where the presence of 480–440 Ma bimodal rift magmatism suggests continuous active rifting on the southern margin of the Rheic Ocean long after the separation of Avalonia, Ganderia and Carolinia. Synchronous deposition is indicated by the presence of Ordovician detrital zircons in some of the units (Table 1, Fig. 10b). A modern analogue may be found in western North America where extensional deformation followed collision between the East Pacific Rise and the trench leading to the development of a slab window, core complexes and extensional Basin-and-Range tectonics (Dickinson, 2002). The absence of a true passive margin in southern Mexico suggests that thermal relaxation following stretching did not take place, a situation that is consistent with transient removal of Avalonia, Ganderia and Carolinia. The presence of a 900–750 Ma detrital zircon population in these Ordovician rocks indicates a unique source in the Goiás magmatic arc in the Brasiliano orogen (Fig. 11b), so it is likely that associated zircons of other ages also came from Amazonia and Oaxaquia.

Silurian rocks are absent in southern Mexico (Fig. 5). However, in northern Mexico, a Silurian shelf sequence rests unconformably upon Oaxaquia (ca. 1 Ga Novillo Gneiss) and contains a Gondwanan fauna (Stewart et al., 1999). This suggests that Oaxaquia drifted passively with Amazonia on the southern margin of the Rheic Ocean.

During the Devonian, it is inferred that a volcanic arc developed on top of the Ordovician rift-shelf sequence on the western edge of the Mixteca terrane (Fig. 5). 400–370 Ma detrital zircons and volcanic clasts in the Carboniferous rocks of the Mixteca and Oaxaquia terranes are inferred to have been derived from this arc because such rocks are absent in Mexico and southern Laurentia and rare in a few Andean massifs (Aleman and Ramos, 2000). This Devonian arc and its underlying rift-shelf sequence is inferred to have been removed by subduction erosion, such that it is represented only by vestiges in the extruded HP rocks in the center of the Mixteca terrane that were extruded during the Mississippian (Figs. 2, 10c and d, 11c). Exhumation of these HP rocks probably provided a source for the 330–360 Ma detrital zircons in some Carboniferous units. There appears to be an hiatus in arc magmatism during the Late Devonian and Carboniferous, a modern analogue for which occurs in the Cenozoic of southern Mexico where an hiatus between 30 and 20 Ma coincides with removal of a 260 km-wide forearc (Keppie et al., in press). The presence of similar rocks on either side of the HP belt suggests that the HP rocks were extruded into the upper plate. The extrusion produced heterogeneous deformation ranging from polyphase in the extruded rocks through polyphase-single phase in the adjacent cover, to listric faulting and basin development near the surface. This decrease in deformational complexity was accompanied by a similar decrease in the metamorphic grade.

During the Permian, arc magmatism occurred throughout the eastern Acatlán Complex and western Oaxacan Complex as part of an arc that extends along the backbone of Mexico produced by easterly dipping subduction with the trench lying near the present eastern Guerrero terrane boundary (Figs. 1, 10e and 11d). That this subduction was probably oblique is suggested by the accompanying dextral transtensional deformation. This produced pull-apart basins in releasing fault bends with deposition of the periac sedimentary rocks, and clastic wedges where constraining fault bends induced thrusting.

In conclusion, the Paleozoic rocks of southern Mexico appear to record rifting on the southern margin of the Rheic Ocean associated with its opening during the Ordovician followed by passive drifting with Amazonia during the Silurian. This was followed in the Devonian by subduction beneath southern Mexico along the paleo-Pacific margin that produced an arc, which, together with the underlying Cambro-Ordovician rift-shelf sequence, was removed by subduction erosion. HP metamorphism of these rocks was then followed by their extrusion into the upper plate during the Mississippian. The arc was reestablishment in the Permian with a trench estimated to lie just west of the boundary between the Mixteca and Guerrero terranes, which was thrust eastwards during the Laramide orogeny. The presence of a HP belt within the upper plate rocks of the Acatlán Complex indicates that the complex does not mark a suture zone between terranes originating in widely separated places on different plates (e.g. Talavera-Mendoza et al., 2005; Vega-Granillo et al., 2007). Thus, sutures defined by the presence of HP rocks in other orogens around the world, where extrusion back up the subduction channel is inferred, may require reexamination.

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