U–Pb geochronology of the Acatlán Complex and implications for the Paleozoic paleogeography and tectonic evolution of southern Mexico

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Abstract

Even though the Acatlán Complex in southern Mexico contains the largest exposure of Paleozoic rocks in Mexico, it is commonly ignored in reconstructions of Pangea because of poor geochronologic data. Presently, this complex is understood to be composed of metasedimentary units (Cosoltepec, Magdalena, Chazumba and Tecomate Formations), a major magmatic suite (Esperanza Granitoids), and a suite with eclogites and blueschists (Xayacatlán Fm). Sedimentary cover includes unmetamorphosed upper Paleozoic units. Here we provide single-crystal laser ablation U–Pb geochronology of the metasedimentary and magmatic suites of the Acatlán Complex and its upper Paleozoic sedimentary cover. The data reveal a complex geological evolution recording tectonic events from the assembly of Rodinia to the break-up of Pangea.

Data for the Esperanza Granitoids record three major tectonothermal events: (1) a Grenvillian (1165 ± 30 to 1043 ± 50 Ma), (2) a Taconian (478 ± 5 to 471 ± 5 Ma), and (3) a Salinian (Acatecan; 461 ± 9 to 440 ± 14 Ma). Eclogitic rocks from the Xayacatlán Formation of Neoproterozoic–Early Ordovician age contain detrital zircons derived most probably from the southwestern North America Grenville province. Data for the blueschists are consistent with a Middle Ordovician depositional age and derivation from Laurentian sources. The Tecomate Formation is composed of two unrelated units of contrasting age and lithology: a Neoproterozoic–Early Ordovician, arc- and rift-related volcanosedimentary unit containing detrital zircons derived from the southwestern North America Grenville province; and an essentially sedimentary unit containing Early Permian fauna. The Cosoltepec Formation has a maximum Devonian depositional age and contains detrital zircons consistent with derivation from South American sources. The age of the Magdalena and Chazumba Formations is established to be Late Pennsylvanian–Early Permian. These units contain detrital zircons indicating ultimate derivation from both North and South America crustal sources. The Late Paleozoic sedimentary cover contains detrital zircons shed mainly from Grenvillian sources with a significant contribution of Pennsylvanian magmatic rocks.

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The new U–Pb geochronologic data indicate that the traditional stratigraphic scheme used for the Acatlán Complex needs complete revision. Data further indicate that the earliest stages of the tectonic evolution of the Acatlán Complex are tied to the evolution of Rodinia and that the actual configuration of the Acatlán Complex was ultimately achieved by amalgamation of the Magdalena–Chazumba suite during the final stages of Pangea assembly. The Early Jurassic tectonothermal event affecting only the Chazumba and Cosoltepec units to produce the Magdalena Migmatite is related to the break-up of Pangea and the opening of the Gulf of Mexico.

The Acatlán Complex contains a section of the suture between Laurentia and Gondwana with some sediments arriving from Laurentia and others from Gondwana and mirrors the structure and evolution of the Appalachian–Caledonian chains of North America.

1. Introduction

Most paleogeographic reconstructions for Paleozoic time omit southern Mexico because of the scarcity of data concerning the origin, age and tectonic evolution of its Paleozoic suites. The overlap between South America and southern Mexico in most Pangea reconstructions (e.g., [1,2]) suggests that this region has many out-of-place terranes, whose origin and tectonic evolution would help to constrain the tectonic framework of southern North America before assembly of Pangea. The Acatlán Complex and its sedimentary cover contain the most complete succession of metamorphic, magmatic and sedimentary rocks of Paleozoic age in southern Mexico [3] and it is thought to record much of the tectonic evolution of southwestern North America from Rodinia to Pangea. Additionally, the location of the Acatlán Complex, between the Appalachian and the Colombian mountain chains may also constrain the interactions between Laurentia and South America during Paleozoic time and, hence, the paleogeography of the southwestern realms of the Iapetus and Rheic Oceans.

Here we use detrital zircon U–Pb geochronology in the metasedimentary units from the Acatlán Complex and its upper Paleozoic sedimentary cover to determine maximum depositional ages, depositional histories and the ages of parental rocks. These data, together with detrital zircon data from the Paleozoic sedimentary cover of the neighboring Oaxacan Complex [4], are used to place first order paleogeographic constraints on southern Mexico during Paleozoic time. These data are complemented with new U–Pb ages of selected plutonic rocks. These data together with available geochemical, isotopic and petrological data, provide the basis for a tectonic model for the evolution of the Acatlán Complex and southern Mexico during Paleozoic time.

2. Geological setting

Historically, the Acatlán Complex was understood to be a polymetamorphic complex composed of two major thrusted sequences of Early Paleozoic age (Fig. 1) [5]: (1) a high-pressure, allochtonous thrust sheet (Piaxtla Group) that includes basic eclogite and garnet-amphibolite of Xayacatlán Formation (416 ± 12 to 388 ± 44 Ma; Sm–Nd garnet-whole rock) [6] and the eclogitized Esperanza Granitoids (440 ± 14 Ma; U/Pb) [5], and (2) a low-pressure, parautochtonous thrust sheet (Petlalcingo Group) that includes migmatite of Magdalena Formation (204 ± 6 Ma, Sm–Nd garnet-whole rock) [6], biotite-schist of Chazumba Formation (167 ± 2 Ma; $^{40}Ar/^{39}Ar$) [7] and quartzite and phyllite of Cosoltepec Formation. The Cosoltepec Formation includes mountain-size blocks of massive and pillowed lavas that have yielded Ordovician (Rb/Sr whole rock) and Permian ($^{40}Ar/^{39}Ar$ whole rock) ages [5,8]. However, if Permian ages represent crystallization or reseted ages is uncertain. Anatectic granitic dykes of the San Miguel unit (175 ± 3 Ma; Rb–Sr and 172 ± 1 Ma; Sm–Nd) [6] cut the two lower formations of the Petlalcingo group. According to Ortega-Gutiérrez et al. [5], juxtaposition of the Piaxtla and Petlalcingo groups occurred during Late Ordovician–Early Silurian time. The Late Devonian (371 ± 34 Ma) La Noria stock and the earliest Permian (287 ± 2 Ma)
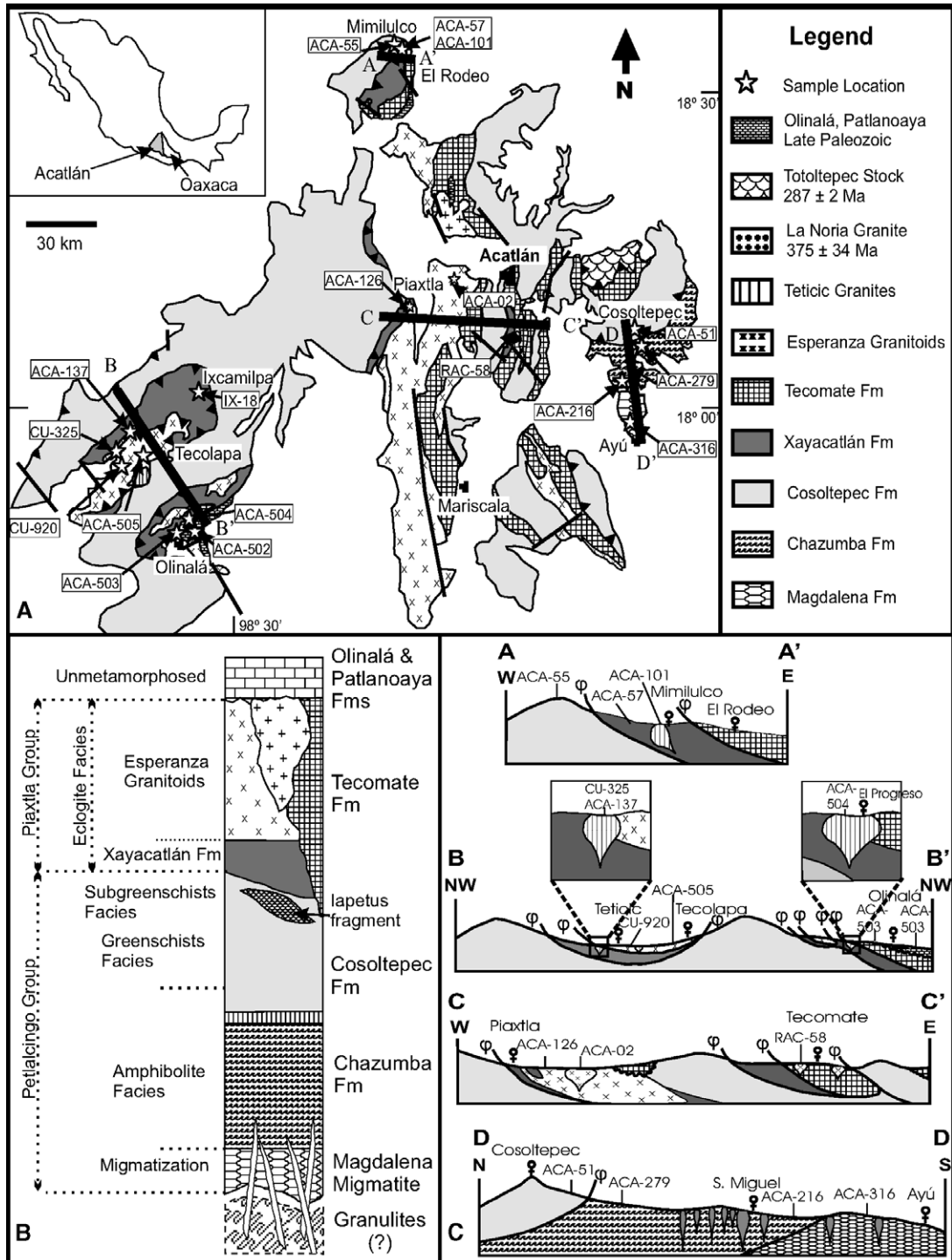
Fig. 1. (A) Geologic sketch map of the Acatlán Complex in southern Mexico showing location of analyzed samples. (from [9]). (B) Stratigraphy of the Acatlán Complex as proposed by Ortega-Gutiérrez et al. [5]. (C) Schematic cross-section of key areas showing stratigraphic-structural and intrusive relationships of Acatlán suites. Cross-sections not at scale.

Totoltepec stock are inferred to intrude units from both Piaxtla and Petlalcingo groups [5–7]. The Tecomate Formation is interpreted as an overlapping unit of the Piaxtla and Petlalcingo groups (Fig. 1) [5] and represents an arc- and continental rift-related volcanosedimentary succession capped by an upper, sedimentary sequence containing conglomerate, sandstone, shale and limestone [9]. Limestones from the upper levels yield Early Permian conodonts [7, Vega-Granillo unpublished data], which suggest that at least part of this formation together with the Patlanoaya, Matzitzi and Olinalá formations are the upper Paleozoic sedimentary cover [10].

3. Analytical methods

Seven to ten kilograms of each sample were processed for zircon extraction using standard heavy liquids and magnetic separation methods. A large fraction of the recovered zircons was mounted in epoxy resin and polished. For magmatic ages, at least fifty euhedral zircons were mounted by hand-picking at random. One hundred zircons were analyzed from each sedimentary or metasedimentary rock. The grains analyzed were selected at random from all of the zircons mounted from each sample. Core of grains were preferred to avoid possible metamorphic overgrowth. In magmatic rocks, 20–60 of the mounted zircons were analyzed at random.

The analytical procedure was described in detail by Dickinson and Gehrels [11]. U–Pb analyses were performed with a Micromass Isoprobe multicollector Inducted Coupled Plasma Mass Spectrometer (ICP-MS) equipped with nine Faraday collectors, an axial Daly collector, and four ion-counting channels. Zircons were ablated with a New Wave DUV 193 nm Excimer laser ablation system. All analyses were conducted in static mode with a laser beam diameter ranging from 25 to 50 μm. Contribution of Hg to the ^{204}Pb mass position was removed by subtracting measured background values. Isotopic fractionation was monitored by analyzing an in-house zircon standard, which has a concordant TIMS age of 564 ± 4 Ma [11]. This standard was analyzed once for every five unknowns in detrital grains and once for every three unknowns in magmatic zircons. Uranium and Thorium concentrations were monitored by analyzing a standard

(NIST 610 Glass) with ~500 ppm Th and U. The calibration correction used for the analyses was 2–3% for ^{206}Pb/^{238}U and approximately 2% for ^{206}Pb/^{207}Pb (2-sigma errors). The lead isotopic ratios were corrected for common Pb, using the measured ^{204}Pb, assuming an initial Pb composition according to Stacey and Kramers [12] and uncertainties of 1.0, 0.3 and 2.0 for ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb, respectively.

Ages are considered reliable if five or more analyses performed in different grains yield overlapping ^{206}Pb/^{238}U or ^{206}Pb/^{207}Pb ages. This strategy is used because of the low precision of ^{206}Pb/^{207}Pb ages for young grains, making concordance/discordance a poor criteria for determining reliability. Clustering is also a better criteria for reliability than concordance given that Pb loss and inheritance in young systems can create concordant ages that are significantly younger or older than the true ages. Such analyses could be concordant but would not define a cluster, and would accordingly be rejected as unreliable. Comparative studies using TIMS and LA-ICPMS techniques (e.g., [13]), have demonstrated that ^{206}Pb/^{238}U ages obtained with LA-ICPMS in young concordant zircons (<1.0 Ga) are close enough to TIMS ages to be considered reliable.

Gillis et al. [4] carried out a U–Pb single-crystal study of detrital zircons from the Paleozoic sedimentary cover of the Oaxacan Complex using both ID-TIMS and LA-ICPMS following the same analytical procedure and instrument used for this study. Their results indicate that with minor differences, data obtained with LA-ICPMS overlap within analytical error those obtained by ID-TIMS and that major detrital zircon populations are resolved accurately using LA-ICPMS in spite of the inherent larger error and apparent discordances (Fig. 2). In addition, we dated two magmatic samples from the Acatlán Complex previously dated by other authors: one sample from the Esperanza Granitoids in its type locality, which was dated at 440 ± 14 Ma by Ortega-Gutiérrez [5] using U–Pb TIMS; and, one granite from the San Miguel dykes, which was dated at 172 ± 1 and 175 ± 3 Ma by Yañez et al. [6] using Sm–Nd (garnet-whole rock) and Rb–Sr (white mica-whole rock), respectively, and at 171 ± 1 Ma by Keppie et al. [7] using U–Pb TIMS. Our results using LA-ICPMS yielded for the Esper-
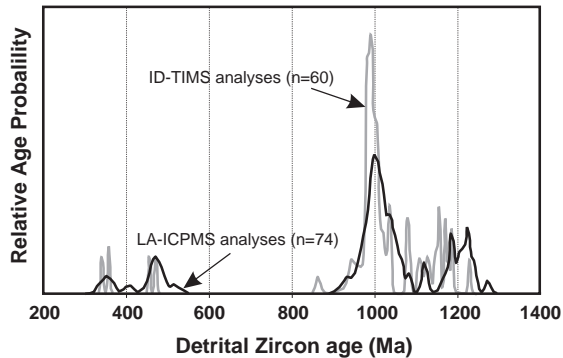
Fig. 2. Relative age probability plot of detrital zircons from the Oaxacan Complex (Mexico) analyzed by ID-TIMS and LA-ICPMS performed at the University of Arizona [4]. Analytical procedure and instrumentation for the LA-ICPMS ages are the same used in this study. Note that LA-ICPMS ages overlap within analytical errors those of ID-TIMS and that most zircon populations recorded by ID-TIMS are also recorded by LA-ICPMS.

anza Granitoid a weighted mean age of 442 ± 5 Ma ($n = 34$) in good agreement with the U–Pb TIMS age reported. Results for the San Miguel sample yielded a weighted mean age of 173 ± 3 Ma ($n = 20$), which is identical with the Sm–Nd, Rb–Sr and U–Pb ages previously reported.

Accordingly, the age probability plots used in this study were constructed using the $^{206}Pb/^{238}U$ age for young (<1.0 Ga) zircons and the $^{206}Pb/^{207}Pb$ age for older (>1.0 Ga) grains. In old grains, analyses with >20% discordance or >10% reverse discordance are considered unreliable and were not used. Age probability plots, concordia ages and weighted mean ages were calculated using definition and criteria proposed by Ludwing [14]. The full set of analytical data is shown in Supplementary Tables 1 and 2.

4. Results

Eighteen samples from the Acatlán Complex and its upper Paleozoic sedimentary cover were selected for detailed U–Pb zircon geochronology including two samples reported previously by Campa et al. [15]. Locations of studied samples are indicated in Fig. 1. Nine samples belong to major metasedimentary units and the sedimentary cover and include samples from the Olinalá, Tecomate, Xayacatlán,

Cosoltepec, Chazumba and Magdalena Formations. Nine samples are granitic rocks and include samples from the Esperanza Granitoids and the Tetitic and Mimilulco leucogranites. We follow the commonly used stratigraphic nomenclature to describe the results. However, the data show that this stratigraphic scheme requires evaluation.

4.1. Olinalá Formation (ACA-502)

The Olinalá Formation unconformably overlies metabasites and metavolcaniclastics of the Tecomate Formation, with a basal conglomerate containing blocks of quartzite, micaceous schist and mafic schist (Fig. 1). Other formations of the upper Paleozoic sedimentary cover unconformably overly both Tecomate Formation and high pressure rocks of Xayacatlán Formation or Esperanza Granitoids. The analyzed sample is a quartz-rich calcareous sandstone from the middle stratigraphic level, collected from the type section east of the town of Olinalá. Ages from this sample range from 1546 ± 48 to 286 ± 16 Ma with a single grain at 2086 ± 83 Ma (Fig. 3). All analyzed grains show U/Th ratios <12 indicating a magmatic origin [16]. The cumulative age pattern is characterized by two major populations, one in the range 360–287 Ma (peak at ~297 Ma) and another in the range 1461–780 Ma with peaks at ~1203 and ~834 Ma (Fig. 4).

4.2. Tecomate Formation (ACA-503)

The Tecomate Formation consists of greenschist facies metabasites, metaconglometates and metavolcaniclastics, which are intruded by Early Ordovician leucogranites (ACA-504) and are unconformably overlain by the Middle to Upper Permian Olinalá Formation in the Olinalá region. The analyzed sample is a medium-grained volcaniclastic sandstone collected from the upper part of the section north of Olinalá (Fig. 1). Detrital zircon ages in this sample range from 1577 ± 47 to 896 ± 211 Ma (Fig. 3). All zircons show U/Th ratios <11 indicating a magmatic origin [16]. The cumulative age pattern of the sample consists of a single large population of Mesoproterozoic zircons with distinctive peaks at ~1171 and ~1471 Ma, and a few grains at ~988 Ma (Fig. 4).
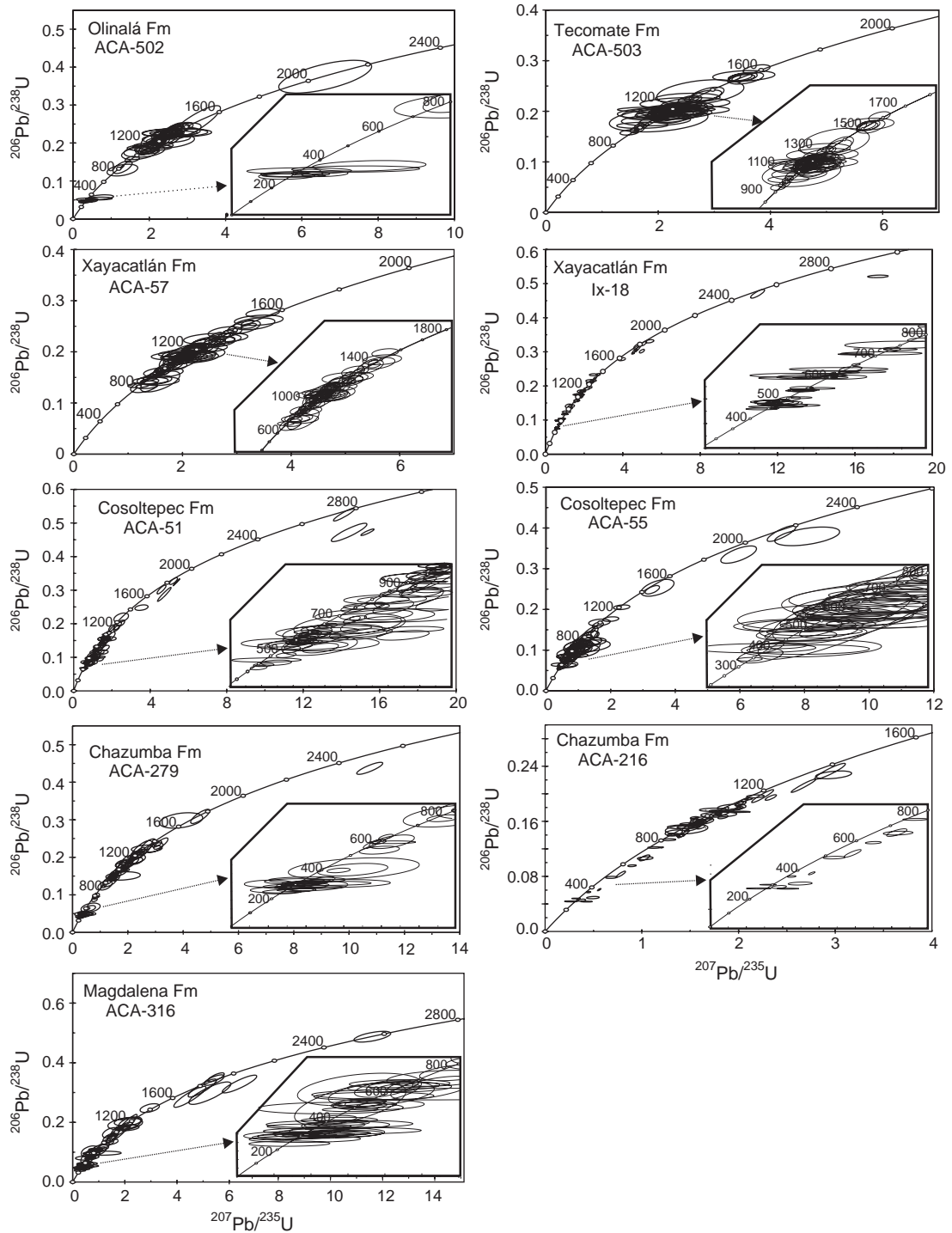
Fig. 3. Concordia diagram showing U–Pb age data of detrital zircons from metasedimentary units of Acatlán Complex and its late Paleozoic sedimentary cover. Ellipses are 2 sigma.
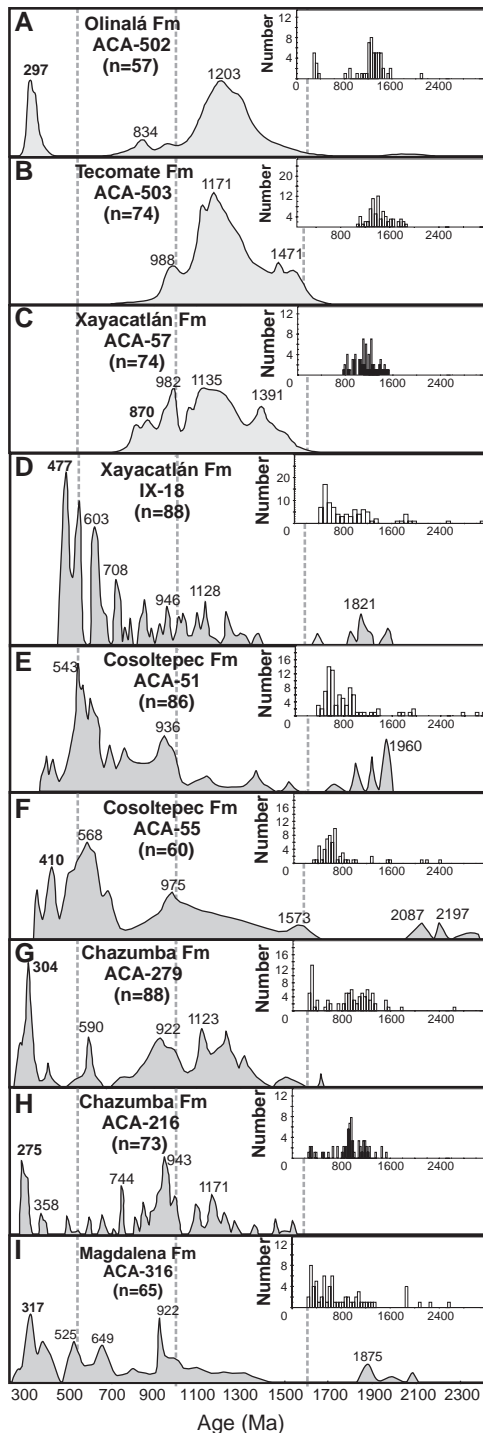
Fig. 4. Cumulative-age plots of metasedimentary units of Acatlán Complex and its late Paleozoic sedimentary cover. Vertical axis is relative age probability.

4.3. Xayacatlán Formation (ACA-57 and IX-18)

Two samples from the Xayacatlán Formation were analyzed. Sample ACA-57 is a chloritoid–phengite–garnet psamitic schist interbedded with retrogressed eclogites and garnet-amphibolites at Mimilulco (Fig. 1). At this location, eclogites are intruded by Middle Ordovician leucogranites (ACA-101). Sample IX-18 is a chlorite–phengite schist interbedded with blueschists at Ixcamilpa (Fig. 1). At both, Mimilulco and Ixcamilpa localities, the Xayacatlán Formation structurally overlies quartzite and phyllite of the Cosoltepec Formation and in the Mimilulco area, this formation is overlain by metabasite of the Tecomate Formation. The range of ages recorded in the two samples is quite different. Whereas in sample ACA-57 ages vary from 1522 ± 79 to 694 ± 51 Ma, in sample IX-28 they span from 3115 ± 16 to 447 ± 3 Ma (Fig. 3). With the exception of a few grains, zircons in both samples have U/Th ratios <14 typical of magmatic zircons [16]. Fig. 4 shows the age distribution patterns for samples from Mimilulco and Ixcamilpa. Sample ACA-57 is dominated by Mesoproterozoic–Neoproterozoic zircons in the range 1550–800 Ma with major peaks at ~1135, ~982, ~1387 and ~870 Ma. In contrast, sample IX-18 shows the largest zircon clusters at 550–447 Ma (peak at ~477 Ma) and 795–590 Ma (peaks at ~603 and ~708 Ma) with smaller but distinctive populations at 1400–800 Ma (peaks at ~946 and ~1128 Ma) and 1964–1651 Ma (peak at ~1821 Ma). A few grains occur in the range 3115–2550 Ma.

4.4. Cosoltepec Formation (ACA-51 and ACA-55)

Two quartzites from the Cosoltepec Formation were analyzed. Sample ACA-51 was collected from the type locality ~300 m from the contact with the underlying Chazumba Formation and sample ACA-55 was collected from the Mimilulco area close to the contact with the overlying Xayacatlán Formation (Fig. 1). With minor differences, the range of ages in both samples is similar extending from 3451 ± 7 to 341 ± 7 Ma (Fig. 3). All analyzed zircons have magmatic U/Th ratios (<14). The age probability plots (Fig. 4) are also very similar and characterized by major zircon clusters in the range

750–500 Ma (peaks at ~568 and ~543 Ma). Minor zircon populations occur in the range 450–341 Ma (peaks at ~410, ~394 and ~345 Ma), 1000–800 Ma (peaks at ~975 and ~936 Ma) and 2197–1780 Ma (peaks at ~1960, ~2087 and ~2197 Ma). A few zircons in the range 3451–2750 Ma occur in sample ACA-51. Peaks at ~394 and ~345 Ma have three or less zircon grains and are consequently not reliable. In contrast, the peak at ~410 Ma has five grains making it the youngest reliable age for the Cosoltepec Formation.

4.5. Chazumba Formation (ACA-279 and ACA-216)

Two samples from this formation were analyzed. Sample ACA-279 is a biotite–muscovite–garnet schist from the upper stratigraphic levels, and sample ACA-216 is a biotite–sillimanite schist from the lower stratigraphic levels of this unit (Fig. 1). Ages of the detrital zircons in both samples are similar ranging from 1772 ± 27 to 249 ± 10 Ma with a single grain at 2637 ± 13 Ma (Fig. 3). With the exception of a few grains, zircons show low U/Th ratios typical of magmatic zircons [16]. The cumulative age patterns of both samples are also similar and show dominant zircon clusters in the range 440–249 Ma (peaks at ~275 and ~304 Ma) and 1400–720 Ma (peaks at ~744, 943–922 and 1171–1123 Ma). Subordinate age peaks occur at ~1460 Ma in sample ACA-216 and at ~1515 and ~590 Ma in sample ACA-279 (Fig. 4).

4.6. Magdalena Formation (ACA-316)

The sample from this formation is a biotite–garnet–amphibole schist interbedded with amphibolites from the middle stratigraphic levels of this unit ~1.5 km north of Ayú (Fig. 1). Zircon ages in this sample range from 2250 ± 29 to 245 ± 13 Ma with a single grain at 2567 ± 27 Ma (Fig. 3). Only two zircons show U/Th ratios >14 indicating that nearly all zircons had a magmatic origin [16]. The age probability pattern (Fig. 4) shows that more than 90% of the analyzed zircons fall in the range 1500–245 Ma with major age probability peaks at ~317, ~525, ~649 and ~922 Ma. A smaller population of zircon ages occurs between 2250 and 1800 Ma (peak at ~1871 Ma).

4.7. Esperanza Granitoids (ACA-02, ACA-126, RAC-58, CU-920 and ACA-505)

The Esperanza Granitoids are the most voluminous magmatic suite in the Acatlán Complex and, together with the Xayacatlán Formation, constitute the high-pressure thrust sheet of Ortega-Gutiérrez et al. [5]. The most conspicuous lithology in this suite is megacrystic K-feldspar augen gneisses, which grades to microaugen schists and micaceous schists in highly sheared zones. Five samples from this unit were dated. Sample ACA-02 is a typical megacrystic K-feldspar granitoid containing garnet–biotite–muscovite–rutile collected at its type locality (Fig. 1). This sample yielded $^{206}Pb/^{238}U$ ages from 1296 ± 77 to 405 ± 15 to Ma with a major age cluster formed by thirty four grains yielding a weighted mean age of 442 ± 5 Ma (MSWD=1.3), which is interpreted as an igneous crystallization age for this unit (Fig. 5). This age is identical within analytical uncertainty to the 440 ± 14 Ma U–Pb age reported by Ortega-Gutiérrez et al. [5]. Twelve inherit zircons yielded Mesoproterozoic to early Paleozoic (1296–504 Ma) ages and broadly define a line of Pb-loss between the igneous crystallization age and a Grenvillian component.

Sample ACA-126 is a megacrystic K-feldspar granitoid containing biotite–muscovite–rutile, which is inferred to intrude eclogites at the locality of Piaxtla (Fig. 1). This sample yielded $^{206}Pb/^{238}U$ ages ranging from 1354 ± 49 to 290 ± 15 Ma. Fourteen grains define a cluster with a weighted mean age of 474 ± 16 Ma (MSWD=4.9), which is also considered a crystallization age (Fig. 5). Inherited ages range from 1354 to 500 Ma and yield a Pb-loss trend between the igneous crystallization age and a Grenvillian component. Zircon at 290 ± 15 Ma records Pb-loss during a younger tectonothermal event.

Sample RAC-58 is a megacrystic K-feldspar granitic dyke intruding metabasites of the Tecomate Formation in the Tecomate area. This sample yields $^{206}Pb/^{238}U$ ages ranging from 1295 ± 13 to 443 ± 15 Ma. Thirteen zircons form a cluster with a weighted mean age of 461 ± 7 Ma (MSWD=0.99) also considered as the age of crystallization (Fig. 5). Eight grains yielded Neoproterozoic to Mesoproterozoic (585–1295 Ma) ages and define a trend that we interpret to reflect inheritance of a Grenvillian component.
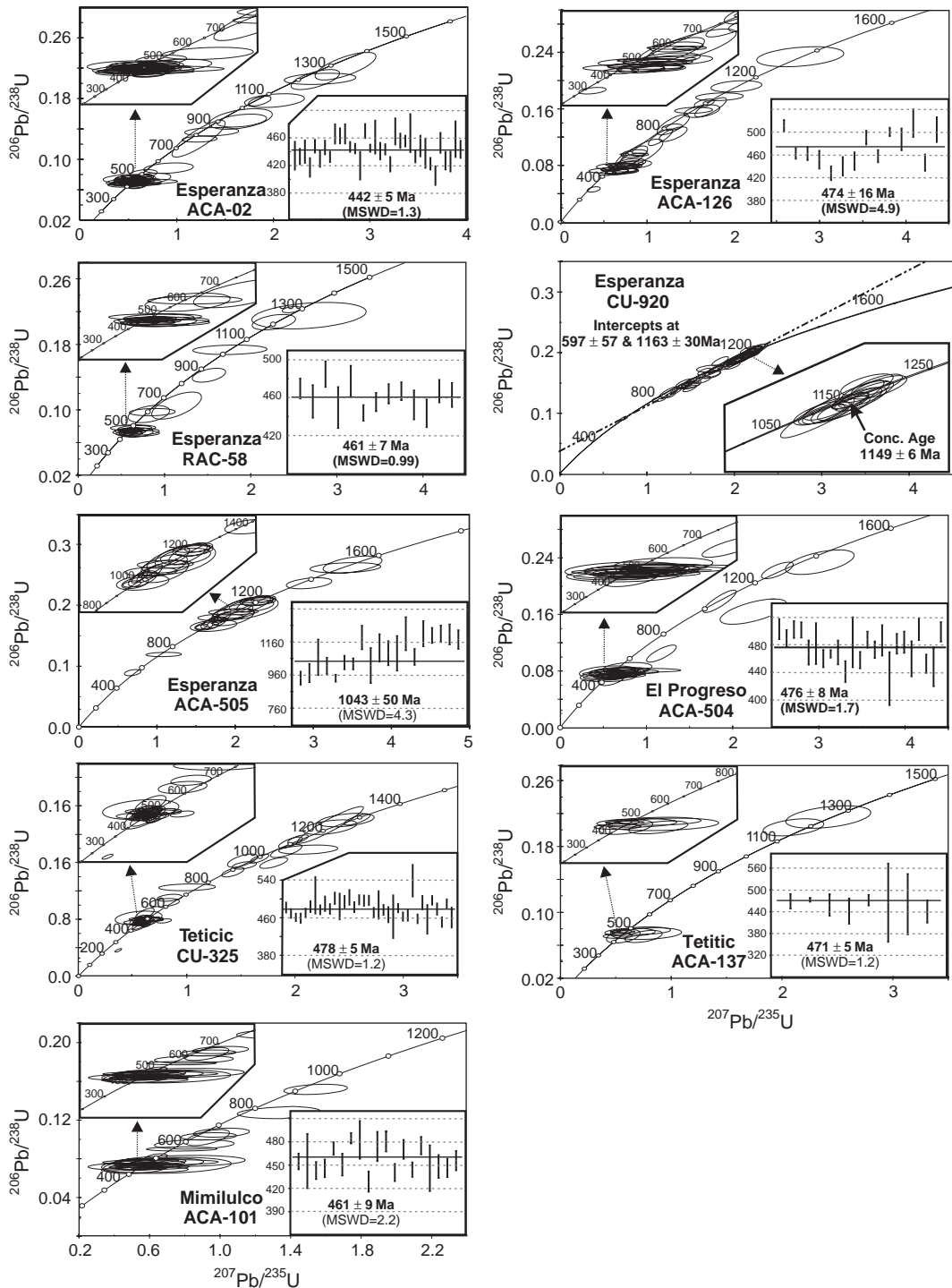
Fig. 5. Concordia diagram showing U–Pb age data of magmatic zircons from the Esperanza Granitoids and the Tetitic, El Progreso and Mimilulco leucogranites. Weighted mean ages are shown in insets. Ellipses and bars are 2 sigma.

Sample CU-920 is also a megacrystic K-feldspar granitoid collected northwest of Olinalá (Fig. 1). This sample yielded complex ages with $^{206}Pb/^{207}Pb$ ages ranging from 1454 ± 19 to 549 ± 27 Ma. They define a discordia with an upper intercept at 1165 ± 30 Ma (MSWD = 1.1), which is interpreted as the igneous age and a lower intercept at 597 ± 57 Ma, which is considered the time of Pb-loss (Fig. 5). Sixteen zircons concordant within analytical error yield a concordia age of 1149 ± 6 Ma (MSWD = 1.3) supporting the upper intercept as the igneous age. A few grains yielded ages from 1404 to 1454 Ma.

Finally, sample ACA-505 is an amphibole-rich, tonalitic gneiss collected around Tecolapa, northwest of Olinalá (Fig. 1). This sample yielded $^{206}Pb/^{207}Pb$ ages ranging from 1532 ± 58 to 806 ± 143 with a major cluster formed by nineteen grains with a weighted mean age of 1043 ± 50 Ma (MSWD = 4.3) interpreted as the igneous crystallization age (Fig. 5). Three grains yielded ages from 1532 ± 58 to 1435 ± 57 Ma. Grains younger than 1043 Ma record Pb-loss.

4.8. Tetitic and Mimilulco leucogranites (ACA-504, CU-325, ACA-137, ACA-101)

Four leucogranites with clear crosscutting relationships from key areas were dated to better constrain the age of country rocks as well as the age of metamorphism and deformation. Sample ACA-504 is a leucocratic granite intruding rocks of both Tecomate and Xayacatlán Formations at El Progreso in the Olinalá area (Fig. 1). $^{206}Pb/^{238}U$ ages in this sample range from 1354 ± 59 to 431 ± 39 Ma with twenty three grains defining a cluster giving a weighted mean age of 476 ± 8 Ma (MSWD = 1.7), which is considered the age of crystallization (Fig. 5). Five zircons yielded ages ranging from 641 to 1354 Ma, which may reflect inheritance.

Samples CU-325 and ACA-137 are highly-deformed leucogranites intruding rock from both the Xayacatlán Formation and the Esperanza Granitoids NW of Olinalá (Fig. 1). $^{206}Pb/^{238}U$ ages range from 1285 ± 33 to 229 ± 10 Ma in sample CU-325 and from 1259 ± 58 to 440 ± 31 Ma in sample ACA-137. The youngest clusters define weighted mean ages of 478 ± 5 Ma (MSWD = 1.2) and 471 ± 5 Ma (MSWD = 1.5) (Fig. 5). Older zircons in CU-325 range from

634 ± 25 to 1285 ± 33 Ma, whereas those of sample ACA-137 are exclusively Grenvillian (1259 ± 58 to 1193 ± 44 Ma). Finally, sample ACA-101 is a leucocratic, garnet-rich granitic pluton, intruding retrogressed eclogite, garnet-amphibolite and chloritoid–garnet schist at Mimilulco (Fig. 1). Zircons in this sample have $^{206}Pb/^{238}U$ ages ranging from 910 ± 22 to 429 ± 13 Ma. The youngest zircon cluster is formed by nineteen grains and yields a weighted mean age of 461 ± 9 Ma (MSWD = 2.2) (Fig. 5). Older zircons yield Neoproterozoic (557–910 Ma) ages.

5. Discussion

5.1. Depositional ages and stratigraphic implications

Although depositional ages of metasedimentary units in the Acatlán Complex are crucial in deciphering its tectonic evolution, no adequate geochronological data existed prior to this study and most ages were indirectly inferred limiting reliable regional correlations and leading to speculative stratigraphic and tectonic reconstructions.

The U–Pb geochronological data for the Esperanza Granitoids indicate a complex magmatic evolution for the complex and reveal the existence of three major magmatic suites: (1) A Mesoproterozoic (1165 ± 30 to 1043 ± 50 Ma) suite represented by the K-feldspar augen gneisses and tonalitic gneisses around Tecolapa, (2) an Early Ordovician (478 ± 5 to 471 ± 5 Ma) suite, which includes megacrystic granitoids and leucogranites from Piaxtla, Teticic and El Progreso, and (3) a Middle to Late Ordovician (461 ± 9 to 440 ± 14 Ma) suite, which includes megacrystic granitoids and leucogranites from the Esperanza Granitoids type locality, Tecomate and Mimilulco.

The youngest zircons in the volcanosedimentary units of the Tecomate Formation are around 834 Ma. At El Progreso and Tecomate, this formation is intruded by Early to Middle Ordovician granites (476 ± 8 and 461 ± 7 Ma) indicating a Neoproterozoic–Early Ordovician depositional age. This age disagrees with the Early Permian conodonts recently found in the upper stratigraphic levels of the Tecomate Formation [7, Vega-Granillo, unpublished data] and

indicates that this formation is really two independent units.

The youngest zircons in eclogitic rocks (ACA-57) from the Xayacatlán Formation are ~870 Ma. At Piaxtla, Teticic and Mimilulco, these rocks are intruded by granites of Early to Middle Ordovician age (478 ± 5 to 461 ± 9 Ma) indicating a Neoproterozoic–Early Ordovician depositional age. In contrast, the youngest zircon population in the sample interbedded with blueschists (IX-18) is ~477 Ma, which implies a maximum Middle Ordovician depositional age. Eclogitic rocks and blueshists show also contrasting zircon age patterns indicating derivation from distinct sources and although a shift in source or derivation from different depositional cycles cannot be completely ruled out, geochronological evidence indicated that eclogitic and blueschist suites are independent units.

In the Cosoltepec Formation, the youngest reliable zircon cluster is ~410 Ma, indicating a maximum Devonian depositional age. This age is substantially younger than the Cambrian–Ordovician age previously assigned to this formation [5,9].

Finally, the youngest zircon population in the Magdalena Formation is ~317 Ma indicating a maximum Early Pennsylvanian depositional age. In the lower stratigraphic levels of the overlying Chazumba Formation, the youngest zircon cluster is ~275 Ma, whereas in the uppermost levels it is ~265 Ma indicating a maximum Early Permian depositional age.

Crystallization and depositional ages reported here indicate a very different stratigraphic scheme for the Acatlán Complex than previously inferred and indicate that the subdivision of the complex into a high pressure, allochtonous thrust and a low pressure, parautochtonous thrust is too simplistic. Fig. 6 compares the classical stratigraphic scheme [6] with our new stratigraphic scheme.

Mesoproterozoic and Ordovician granitoids are clearly products of different orogenic cycles, and consequently, have no genetic relationships. Accordingly, Grenvillian metaigneous rocks must be treated as a separate unit and are referred here to as the Tecolapa suite. Ordovician granites will continue to be referred to as the Esperanza Granitoids, which are composed of two magmatic pulses: one of Early Ordovician age and another of Middle to Late Ordovician age.

Data from the former Tecomate Formation indicate that this formation is really two units: a volcanosedimentary unit of Neoproterozoic–Early Ordovician age metamorphosed at greenschist to lower amphibolite facies conditions, and an unmetamorphosed sedimentary unit of Early Permian age. In the new stratigraphic proposal, the Neoproterozoic–Early Ordovician unit is referred to as the El Rodeo Formation and the name of Tecomate Formation is only used for the Early Permian unit.

Similarly, our data indicate that the Xayacatlán Formation contains two different units: a sequence of Neoproterozoic–Early Ordovician age metamorphosed at eclogite facies conditions and another sequence with a maximum Middle Ordovician age affected by blueschist metamorphism. We will use Xayacatlán Formation for the older unit, whereas the younger unit will be referred as the Ixcamilpa blueschist suite.

The maximum depositional age for the Cosoltepec Formation is established as Devonian, whereas that for the Magdalena and Chazumba Formations is Early Pennsylvanian–Early Permian. These differences along with differences in the detrital zircon age patterns, which suggest provenance from contrasting crustal sources, indicate that the Cosoltepec and the Magdalena–Chazumba Formations were not sedimentologically related as previously proposed [5,6]. Our data further indicate that $^{40}Ar/^{39}Ar$ Permian ages reported by [8] for blocks of pillowed lavas included in the Cosoltepec Formation represent more likely reseted ages.

5.2. Zircon provenance and paleogeographic implications

The depositional ages of the Xayacatlán and the El Rodeo Formations have been bracketed between Neoproterozoic and Early Ordovician. With minor differences, both units contain similar Proterozoic detrital zircon populations suggesting provenance from similar parent sources. Grenvillian rocks are widespread in North America, South America and the Oaxacan Complex and represent the most probable sources. Plutonic rocks in the range 800–950 Ma have not been reported in the Oaxacan Complex and rocks older than 1260 Ma are scarce [4,17,18]. The southwestern Amazon craton contains abundant magmatic
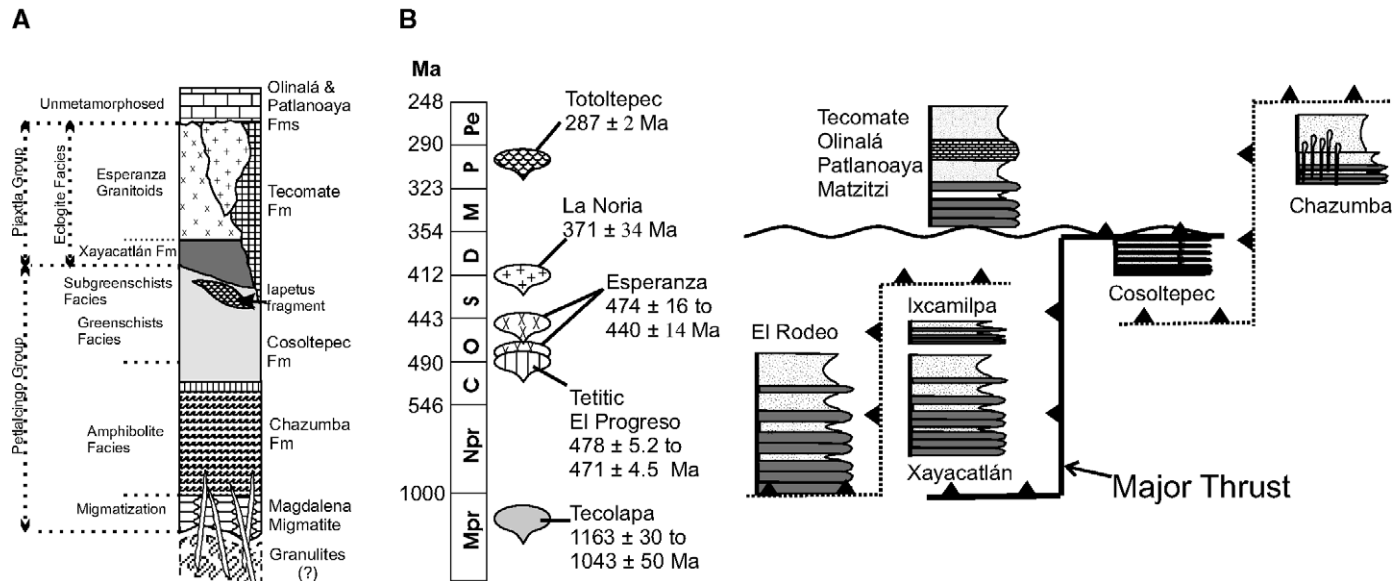
Fig. 6. Comparison of the classical stratigraphy of the Acatlán Complex after Ortega-Gutiérrez [5] and the new stratigraphic scheme proposed here. Beyond depositional ages constrained in this work, the main differences between the two stratigraphic schemes can be summarized as follows: the Esperanza Granitoids in the classical stratigraphy is separated into two magmatic suites; the Telocapa suite (Grenvillian) and the Esperanza Granitoids (Ordovician); the Tecomate Formation in the Ortega-Gutiérrez's stratigraphy is separated into the El Rodeo Formation (Neoproterozoic–Early Ordovician) and the Tecomate Formation (Early Permian); Xayacatlán Formation of Ortega-Gutiérrez et al. [5] is divided into the Xayacatlán Formation (Neoproterozoic–Early Ordovician) and the Ixcamilpa Blueschist suite (Middle Ordovician). For further details see the text.

rocks of 950–1150 Ma and of 1300–1600 Ma but only a few of ~1150–1300 Ma [4], which are the ages of many zircons in the Xayacatlán and El Rodeo samples. In contrast, the southwestern realm of the Grenville province of North America contains widespread magmatic rocks of 1000–1500 Ma [19] and, therefore, represents a more likely source for both the Xayacatlán and El Rodeo Formations.

The Ixcamilpa blueschist suite has a maximum Middle Ordovician depositional age and contains Cambrian–Ordovician (550–447 Ma), Neoproterozoic (795–590 Ma), Mesoproterozoic (1400–800 Ma) and Paleoproterozoic (1964–1651 Ma) zircon populations. The largest population at ~477 Ma indicates that Early Ordovician magmatic rocks were the major source of detritus for this unit. Magmatic rocks of this age are widespread along the southeastern realm of North America (e.g., [20,21]) with more restricted equivalents in Gondwana [22,23] suggesting a Laurentian provenance. Moreover, Paleoproterozoic magmatism around 1800 Ma was widespread in Laurentia during the Trans-Hudsonian orogeny [24] and post-dates the Eburnean/Trans-Amazonian orogeny of Gondwana (1900–2300 Ma) and also suggests a Laurentian provenance for the Ixcamilpa blueschist unit. Grenvillian rocks are widely distributed in both Laurentian and Amazonian (Gondwana) orogens. Neoproterozoic zircons with peaks at ~603 and ~ 708 Ma are significant in the Ixcamilpa blueschist sample. Magmatic rocks of these ages are widely distributed in the Pan-African/Brasiliano orogens of Gondwana although silicic rocks related to the Laurentian margin rifting (760–570 Ma) have also been reported in the Appalachian [20]. The abundance of Taconian-age zircons and the presence of Trans-Hudsonian-age detritus suggest a Laurentian rather than a Gondwanan source for the Neoproterozoic population in the Ixcamilpa sample. Cawood and Nemchin [20] reported a comparable combination of Proterozoic zircons in rocks from the eastern Laurentia margin in the Newfoundland Appalachians.

Samples from the Cosoltepec Formation contain broadly the same zircon populations and similar age probability plots suggesting that much of this formation derives from similar parental sources. In this formation, the major zircon populations occur at ~543 and ~568 Ma, which correspond chronologically to the Pan-African/Brasiliano orogeny that characterizes the Amazonian and West African orogens (e.g., [24,25]) indicating a Gondwanan provenance. Paleoproterozoic zircons in the range 1780–2197 Ma are distinctive of the Trans-Amazonian orogeny (1900–2300 Ma) [13,26] and indicate also a Gondwanan provenance. The presence of Grenvillian zircons further suggests a South American rather than an African provenance since the West African craton was not involved in the Grenvillian orogeny (e.g., [27,28]).

The age of the Magdalena and Chazumba Formations has been established as Early Pennsylvanian–Early Permian. With minor differences, major populations in these formations are similar suggesting provenance from common sources supporting stratigraphic continuity [5]. They are dominated by Neoproterozoic–Mesoproterozoic (1600–500 Ma) zircons with significant Paleozoic (525–249 Ma) grains. Zircons in the range 2500–1800 Ma were only recorded in the Magdalena Formation. The Paleozoic, Neoproterozoic and Paleoproterozoic populations match with the Acadian–Alleghanian orogenies, the Neoproterozoic rifting of the Laurentia margin and the Trans-Hudsonian orogeny, respectively, favoring a Laurentian provenance [20]. However, Mesoproterozoic zircons in the Magdalena–Chazumba samples peak at 943–922 Ma post-dating the main magmatic and metamorphic pulse in the Grenville Province of North America (1.2–1.0 Ga) [19] suggesting additional or alternate sources. Rocks of appropriate age for this cluster have been reported in the Sunsas–Goias orogen of South America [13] and in the sedimentary cover of the neighboring Oaxacan Complex [4]. Alternatively, the main zircon populations in the Magdalena–Chazumba samples mostly coin-

Fig. 7. Simplified paleogeographic reconstructions showing probable locations of Acatlán units and their tectonic setting. Mesoproterozoic, Early–Middle Devonian, Late Pennsylvanian and Middle Permian reconstructions adapted after Keppie and Ramos [33]. Early Ordovician and Late Ordovician–Early Silurian reconstructions adapted after Niocaill et al. [31]. Oaxacan Complex position after Keppie and Ramos [33]. Te=Tecolapa; Co=Cosoltepec; Xa=Xayacatlán; Ix=Ixcamilpa; Cha=Chazumba; Ac=Acatlán Complex (Xayacatlán, Cosoltepec and Chazumba Formations already amalgamed); Ox=Oaxacan Complex. A=Avalonian blocks; F=Florida; NB=New Brunswick.
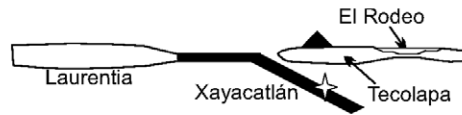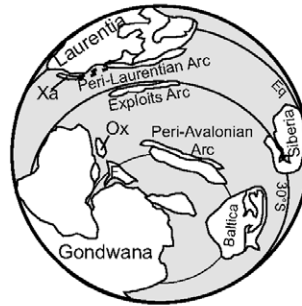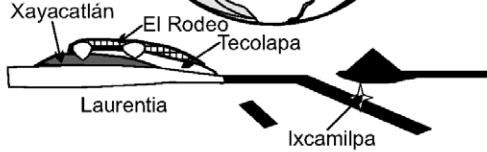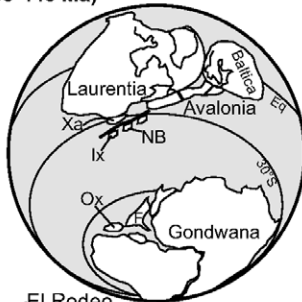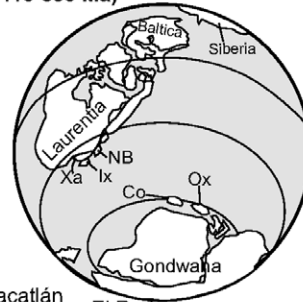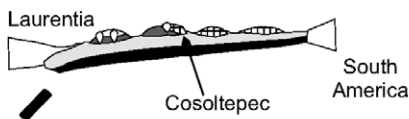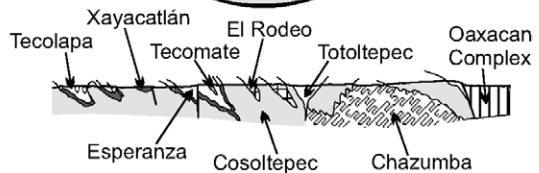
cide with major zircon clusters recorded in the Xaya-catlán and Cosoltepec Formations permissive of zircon recycling from the latter formations.

The Olinalá Formation forms part of the sedimentary cover of the Acatlán Complex and has been dated at Middle to Late Permian (e.g., [10]). The latest Pennsylvanian (~296 Ma) zircon cluster recorded in this formation is consistent with such an age. This formation is dominated by Mesoproterozoic (1461–1011 Ma) with a few Neoproterozoic (942–780 Ma) zircons. Proterozoic populations in this formation are similar to those recorded in the Xayacatlán and El Rodeo Formations suggesting that Grenvillian rocks were the major source of detritus with likely recycling from these formations.

5.3. Tectonic evolution

Grenvillian metaigneous rocks of the Tecolapa suite are the oldest rocks in the Acatlán Complex and indicate that the earliest stage of its tectonic evolution is tied to the Grenville orogen. Although Grenvillian rocks are globally distributed, the close relationship of the Tecolapa suite with the Xayacatlán and El Rodeo Formations showing Laurentian affinities, suggests that they were most probably part of the North America Grenville Province.

Metabasites from the Xayacatlán Formation show OIB and MORB geochemical and isotopic signatures and have been affected by an eclogitic metamorphism [29]. Metavolcanic rocks from the El Rodeo Formation show arc and continental rift affinities [9]. This unit experienced metamorphism at greenschist to lower amphibolite facies conditions but shows no evidence of eclogitic metamorphism. At Olinalá, the contact between the Xayacatlán and El Rodeo Formations is intruded by El Progreso leucogranite dated at 476 ± 8 Ma, which, therefore, represents a minimum age for eclogitic metamorphism.

The close relationship of El Rodeo Formation with eclogitic rocks of the Xayacatlán Formation as well as the subduction-related geochemical and isotopic signature [9], suggest that the extensional event forming El Rodeo occurred within a subduction framework. Since convergence along the eastern margin of Laurentia began during Late Cambrian time (e.g., [30] and references therein), a Late Cambrian–Early Ordovician age for El Rodeo rifting seems reasonable.

Although no Late Cambrian–Early Ordovician paleopoles are available for the Xayacatlán or El Rodeo Formations, detrital zircon ages suggest that these units formed near Laurentia, likely south of the Avalonian blocks (Fig. 7). An east-directed subduction of the Xayacatlán basin is compatible with most proposed models for the Late Cambrian–Early Ordovician peri-Laurentian arc in the northern Appalachians (e.g., [30,31]). The resulting arc must have operated on a rifted Grenvillian block because it better explains the geochemical and isotopic signatures of the arc- and rift-related rocks and the detrital zircon provenance of the associated El Rodeo Formation. The closure of the Xayacatlán basin resulted in an arc-continent collision during Early Ordovician time, which produced the juxtaposition of the Tecolapa suite, the El Rodeo Formation and the eclogitic suite of the Xayacatlán Formation. The age of juxtaposition of these units is constrained by the intrusion of megacrysts granitoids (Piaxtla and Tecomate areas) and leucogranites (Teticic and El Progreso areas) (Fig. 7).

Blueschist protoliths in the Acatlán Complex show OIB and MORB geochemical affinities [29] and thermobarometric data indicate that they were metamorphosed to 300–350 °C and 5–7 kb. Although there are no constraints on the polarity for this subduction, an east-dipping subduction is preferred because it best explains the presence of detrital zircons deriving from Laurentian sources (Fig. 7). The coeval (460–440 Ma) magmatic and high pressure assemblages in the Blue Ridge, New Brunswick and northern Vermont regions attest to the existence of a regionally significant arc-trench system by this time (e.g., [32]). The tectonic emplacement of blueschists may occur during the Salinian (Acatecan) orogeny in Late Ordovician–Early Silurian time, which was accompanied by the syntectonic emplacement of 442–440 Ma granites.

By this time, the mid-Proterozoic Oaxacan Complex was located near Gondwana as indicated by faunal affinities from the overlying Ordovician–Silurian sedimentary units preventing its participation in the genesis of the Acatlán high-pressure suites as previously proposed [5,33]. Late Silurian–Devonian ages (416–386 Ma) obtained by Yañez et al. [6] in retrogressed eclogites and garnet-amphibolites most probably reflect overprint by an Acadian-age meta-

morphism, which was accompanied by the emplacement of La Noria granite (374 ± 34 Ma).

Our data for the Cosoltepec Formation are consistent with sedimentation along the northwestern margin of South America in a passive margin environment [9] during Devonian time. Available evidence suggests that juxtaposition of the Cosoltepec Formation with Laurentian suites (Tecolapa, El Rodeo, Xayacatlán and Ixcamilpa Formations) occurred after Devonian time, probably during the Carboniferous when South America was close to North America [28,31]. The emplacement of the Totoltepec stock at 287 ± 2 Ma may be related with this tectonic event (Fig. 7).

Sediments from the Magdalena and Chazumba Formations accumulated during Late Pennsylvanian–Early Permian time in a basin floored by oceanic crust [6]. This basin must have been located either between North America and South America or adjacent to the other suites of the Acatlán already amalgamated to explain the presence of Laurentian and South American detrital zircons (Fig. 7). The actual configuration of the Acatlán Complex was ultimately achieved by amalgamation of the Magdalena–Chazumba suite during the final stages of Pangea assembly at the end of the Permian.

Deposition of the Late Paleozoic sedimentary cover of the Acatlán Complex began by the Devonian–Mississippian boundary as indicated by the lower levels of the Patlanoaya Formation and continued until the Late Permian [10].

During Early Jurassic times, rocks from the Cosoltepec and Chazumba Formations were affected by a low P/T metamorphic event generating the Magdalena Migmatites [6]. This localized tectonothermal event has recently been interpreted as the result of a plume breaking up Pangea, and the opening of the Gulf of Mexico [7].

6. Conclusions

Single-crystal U–Pb geochronology of detrital and magmatic zircons from the Acatlán Complex and its upper Paleozoic sedimentary cover in southern Mexico provides important constraints on the stratigraphy, paleogeography and tectonic evolution of this region and leads to a refined evolution of southern Mexico during

Paleozoic time. Based on our U–Pb geochronology, depositional and magmatic ages for most units are substantially different than previously proposed requiring a different stratigraphic scheme. Our data suggest that the Acatlán Complex can be divided into: (a) a Laurentian zone, which includes the Grenvillian granitoids of the Tecolapa suite (previously part of the Esperanza Granitoids suite), the Neoproterozoic–Early Ordovician Xayacatlán and El Rodeo Formations (the latter previously part of the Tecomate Formation) and the Middle Ordovician Ixcamilpa blueschist suite (previously part of the Xayacatlán Formation); (b) a Gondwanan (South American) zone, which includes the Devonian Cosoltepec Formation; and, (c) a mixed zone represented by the Late Pennsylvanian–Early Permian Magdalena and Chazumba Formation containing detrital zircons deriving from both North and South American sources. Evidence from crosscutting granites strongly suggests that eclogitic metamorphism in the Xayacatlán Formation took place prior to or during Early Ordovician time, whereas blueschist metamorphism in the Ixcamilpa Formation occurred most probably during Late Ordovician–Early Silurian time. The succession of tectonothermal events recorded in the Acatlán Complex mirrors that of the Appalachian–Caledonian chains including Grenvillian, Taconian, Salinian (Acatecan), Acadian and Alleghanian events. Units from the Laurentian zone evolved independently at least until Devonian time and most probably until Carboniferous time. Amalgamation of the Magdalena–Chazumba zone achieved during final stages of Pangea assembly.

Thus, the Acatlán Complex represents a major zone of convergence between Laurentian and Gondwanan assemblages and globally resembles the configuration and tectonic evolution of the Appalachian–Caledonian chains of North America.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.04.013.

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