Pressure-temperature-time evolution of Paleozoic high-pressure rocks of the Acatlán Complex (southern Mexico): Implications for the evolution of the Iapetus and Rheic Oceans

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ABSTRACT

New thermobarometric and U/Pb and $^{40}Ar/^{39}Ar$ geochronologic data coupled with ages obtained from the Acatlán Complex, the basement of the Mixteco terrane of southern Mexico, reveal the existence of three distinctive high-pressure metamorphic events of early to middle Paleozoic age, each recorded in a separate lithological suite. Xayacatlán suite eclogites with oceanic affinity underwent peak metamorphism at 609–491 °C and 13–12 kb during the Early Ordovician (ca. 490–477 Ma, U-Pb zircon), followed by a partial overprint at 600 °C and ~9.6 kb and then at 500 °C and ~6.7 kb. An overprinting event at 525–500 °C and ~9.5 kb is ascribed to the Devonian. The pressure-temperature (P-T) path of the Xayacatlán suite indicates a subduction-exhumation process followed by tectonically related reburial. Ixcamilpa suite blueschists with oceanic affinity underwent epidote-blueschist metamorphism (T, 200–390 °C; P, 6–9 kb) and then epidote-amphibolite (T, 390–580 °C; P, 9–6 kb) events ascribed to the Late Ordovician–Early Silurian. Esperanza suite eclogites with continental affinity underwent peak metamorphism at 830–730 °C and 17–15 kb. Amphibole from eclogite yields a 430 ± 5 Ma $^{40}Ar/^{39}Ar$ age, dating the high-pressure (HP) event. P-T paths of high-temperature (HT) eclogites like those of the Esperanza suite have been related to the collision of continental blocks. Partial overprinting occurred at 690–640 °C and 14–10 kb prior to 374 ± 2 Ma ($^{40}Ar/^{39}Ar$, phengite). The three HP suites were tectonically juxtaposed at different times before the Mississippian Period, resulting in the closure of the Iapetus Ocean. Phengite $^{40}Ar/^{39}Ar$ geochronology reveals the existence of a widespread tectonothermal event between 345 and 323 Ma, which may be related to the juxtaposition of the HP-composed block and the Gondwanan-affinity Cosoltepec suite, causing the closure of the Rheic Ocean. The tectonothermal events in the Acatlán Complex coincide in time, physical conditions, and tectonic setting with events in the Appalachian-Caledonian orogen, suggesting their relation. On that basis the geology of the Acatlán Complex can lead to a more comprehensive understanding of the tectonic evolution of the Appalachian orogen and of the Gondwana-Laurentia interactions preceding the Pangean assembly.

Keywords: eclogite, blueschist, Paleozoic, Appalachian, Acatlán Complex, Mexico.

INTRODUCTION

Owing to their tectonic setting and viability for providing quantitative thermobarometric and geochronological measurements, high-pressure (HP) assemblages are frequently used to reconstruct the tectonic evolution of ancient orogenic chains (e.g., Ernst, 1977, 1988; England and Richardson, 1977; Godard, 2001). Moreover, these rocks commonly form distinctive petrotectonic assemblages that facilitate regional correlations and paleogeographic reconstructions.

The Acatlán Complex of southern Mexico (Fig. 1) contains the largest exposures of eclogites, HP garnet-amphibolites, blueschists, and eclogitized granitoids of Paleozoic age in Mexico. The complex is framed of tectonic slices containing Laurentian and Gondwanan affinity assemblages, and hence it may be useful for interpreting interactions between these paleocontinents during the Paleozoic. In this paper, we present detailed petrographic and thermobarometric data of HP suites as well as new U/Pb and $^{40}Ar/^{39}Ar$ ages of key rocks to define the ages of protoliths and metamorphic events in the Acatlán Complex. These data reveal the existence of three distinctive events of HP metamorphism, each with contrasting pressure-temperature (P-T) conditions that occurred at different times throughout the early-middle Paleozoic

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and in different lithological suites. Furthermore, this paper includes the first detailed description of Paleozoic blueschists in Mexico, which are uncommon around the world.

Our data, combined with previously published geochemical and geochronological data (Yañez et al., 1991; Ortega-Gutiérrez et al., 1999; Meza-Figueroa et al., 2003; Talavera-Mendoza et al., 2005; Murphy et al., 2006), help to define the Paleozoic evolution of the Acatlán Complex and provide the basis for establishing correlations with suites of coeval orogenic belts.

GEOLOGICAL SETTING

The Acatlán Complex is presently seen as a pile of thrust sheets containing Mesoproterozoic to Paleozoic petrotectonic suites with Laurentian or Gondwanan affinities juxtaposed during the Paleozoic (Talavera-Mendoza et al., 2005). The geology of the complex has been comprehensively treated by Ortega-Gutiérrez (1978), Ramírez-Espinosa (2001), and Talavera-Mendoza et al. (2005). At present, seven major thrust sheets have been recognized, each containing a lithological suite characterized by a distinctive stratigraphy (Figs. 1 and 2).

We briefly describe here the main stratigraphic, geochronological, and geochemical characteristics of each suite. The Xayacatlán, Ixcamilpa, and Esperanza suites include the HP rocks treated in the study and are emphasized.

The Tecolapa suite is the oldest assemblage recognized in the Acatlán Complex. It consists of megacrystic granitoids and tonalitic gneisses of Mesoproterozoic age (1165 ± 30 to 1043 ± 50 Ma; U/Pb; Campa et al., 2002;

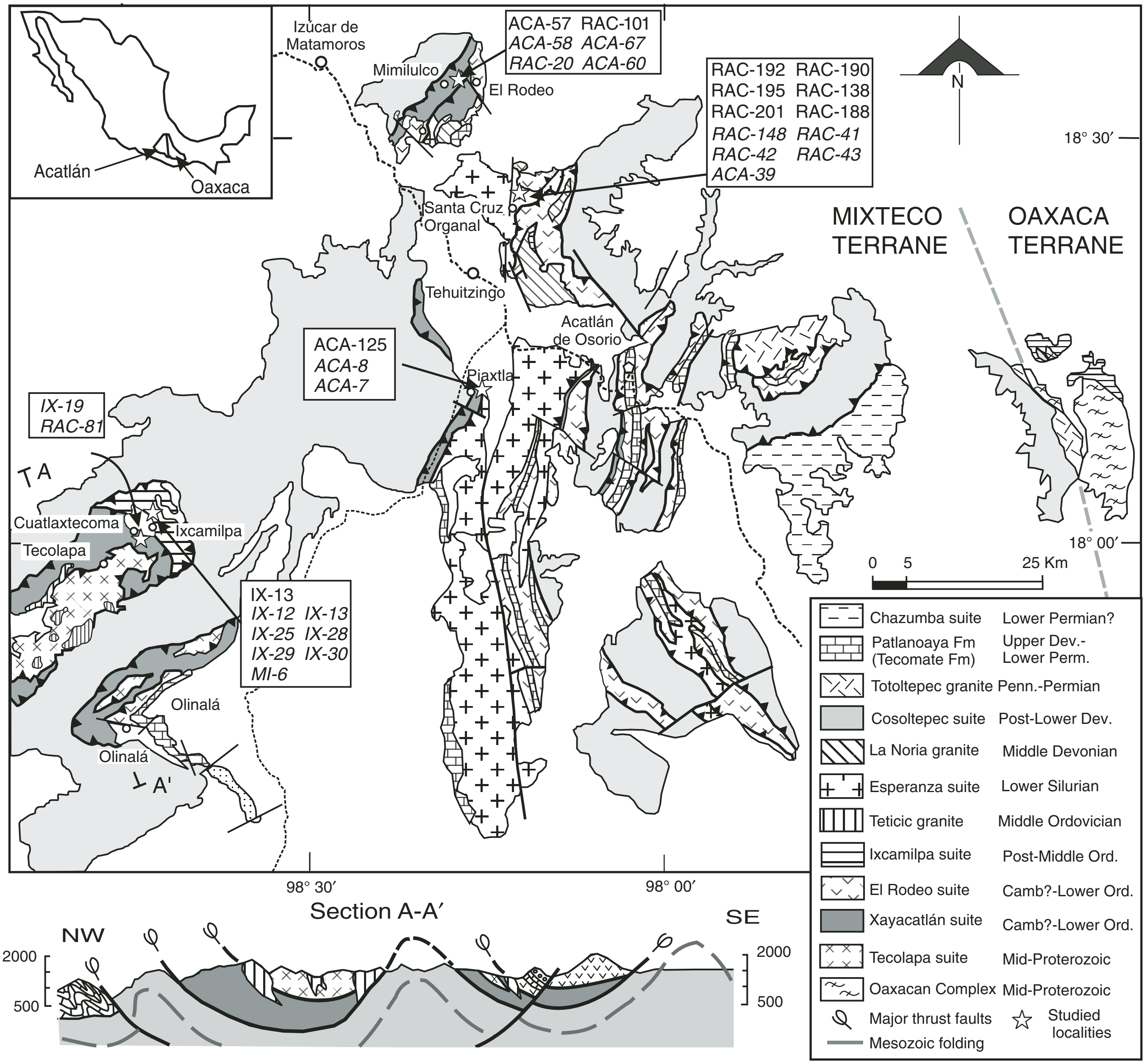

Figure 1. Geologic map of the Acatlán Complex, showing locations of studied samples. Samples in italics were analyzed by microprobe; samples in bold were dated by U/Pb or $^{40}Ar/^{39}Ar$ methods. Map modified from Ramírez-Espinosa (2001). Depth values in cross section are meters above sea level.

Talavera-Mendoza et al., 2005) that crop out in the southwestern region of the complex (Olinalá and Tecolapa areas in Fig. 1). The suite is cut by Early Ordovician leucogranites of 478 ± 5 to 471 ± 5 Ma (U/Pb, zircon; Campa et al., 2002; Talavera-Mendoza et al., 2005; Fig. 2).

The El Rodeo suite is a sequence of metabasites interbedded with quartzites and schists affected by greenschist metamorphism that crop out throughout the complex (Fig. 1). It is intruded by granitoids of Ordovician (476 ± 8 and 461 ± 7 Ma; Talavera-Mendoza et al., 2005), Devonian (371 ± 34 Ma; Yañez et al., 1991), and Early Permian (287 ± 2 Ma; Yañez et al., 1991) age (Fig. 2) (all U/Pb zircon ages). Geochemical and isotopic data of El Rodeo metabasites (Ramírez-Espinosa, 2001) indicate a continental-rift magmatic affinity. The ages of protoliths and metamorphism have been determined as Cambrian–Early Ordovician (Talavera-Mendoza et al., 2005, 2006).

The Xayacatlán suite is composed of eclogitic rocks and their retrogressed products that crop out in narrow NE-SW–trending belts in the western half of the complex (Fig. 1). A serpentinized ultrabasic sole is also ascribed to this suite. The suite is intruded by granites of Ordovician age (478 ± 5 to 461 ± 9 Ma; U/Pb; Campa et al., 2002; Talavera-Mendoza et al., 2005), which postdate the HP metamorphism (Fig. 2). Eclogitic rocks of a basaltic protolith show geochemical and isotopic characteristics of suites similar to mid-ocean-ridge basalt (MORB) (Yañez et al., 1991; Meza-Figueroa et al., 2003), although a continental affinity has also been proposed for rocks of this suite (Dostal et al., 2004). Protolith age has been ascribed to the Late Cambrian–Early Ordovician (Talavera-Mendoza et al., 2005).

The Ixcamilpa suite is a recently recognized unit (Talavera-Mendoza et al., 2002, 2005) that consists of blueschists with intercalations of pelitic-psammitic schists in the western realm of the complex (Figs. 1 and 2). Its maximum depositional age is Middle Ordovician (Talavera-Mendoza et al., 2006). There are no constraints for its minimum age.

The Esperanza suite is one of the most conspicuous assemblages of the complex and includes augen gneisses whose granitic protolith has an Early Silurian crystallization age (442 ± 5 to 440 ± 14 Ma; U/Pb; Ortega-Gutiérrez et al., 1999; Talavera-Mendoza et al., 2005). The granite locally intruded clastic rocks, whereas later mafic dikes cut both lithologies. The granitoids are peraluminous with a continental arc signature (Ramírez-Espinosa, 2001), and the basic rocks are continental tholeiites (Murphy et al., 2006). Traditionally, the Xayacatlán and Esperanza suites have been grouped as the Piaxtla Group (Ortega-Gutiérrez et al., 1999; Ramírez-Espinosa, 2001), which is considered to have undergone a single HP metamorphism event.

The Cosoltepec suite is the most widespread unit in the Acatlán Complex, forming up to 80% of the complex (Fig. 1). It consists of a monotonous succession of quartzite and phyllite with a greenschist facies metamorphism (Fig. 2). The unit contains meter- to kilometer-size tectonic slices of pillow basalts with oceanic affinity (Ramírez-Espinosa, 2001). The Cosoltepec suite has a maximum Early Devonian, ca. 410 Ma (U-Pb zircon), depositional age (Talavera-Mendoza et al., 2005).

Major thrust faults juxtapose suites metamorphosed under contrasting P-T conditions. Thrusting produced overprinting of deformational phases, described in detail by Vega-Granillo (2006; see also Malone et al., 2002). The time of thrusting was determined from the ages of the rocks composing the suites and from the ages of intrusives cutting the thrust faults (Talavera-Mendoza et al., 2005).

SAMPLING AND ANALYTICAL METHODS

More than 130 thin sections of HP rocks and their retrogressed products from the Xayacatlán, Ixcamilpa, and Esperanza suites were studied in detail under the polarizing microscope. Twenty representative rocks were selected for electron

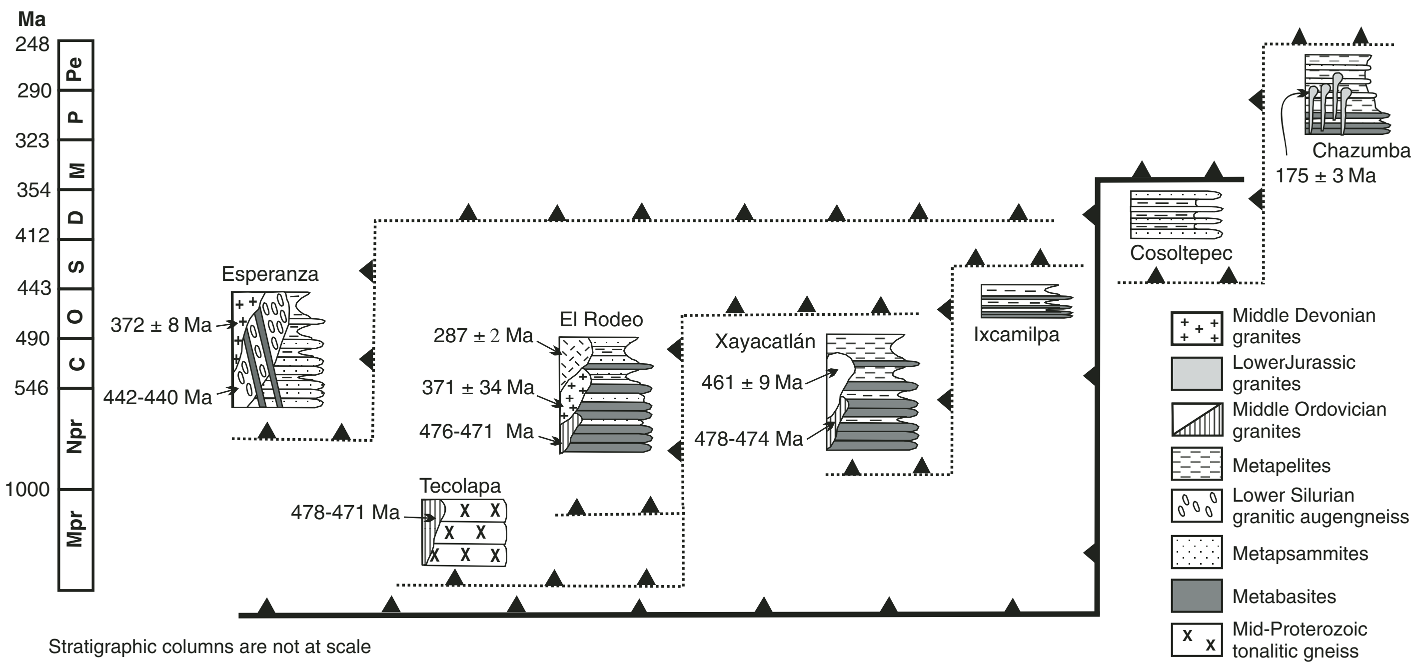

Figure 2. Stratigraphy of the suites of the Acatlán Complex, showing relative time and structural relationships. Upper levels of the thrusts indicate the estimated time for thrusting. Modified from Talavera-Mendoza et al. (2005). Mpr—Mesoproterozoic; Npr—Neoproterozoic; ascending abbreviations represent the Paleozoic periods.

microprobe analyses; ~1200 spot chemical analyses were performed. Besides, three samples were dated using the laser-ablation multicollector inductively-coupled plasma–mass spectrometry (LA-MC-ICP-MS) U/Pb method, and eight samples were dated by the $^{40}Ar/^{39}Ar$ method.

Mineral chemistry was performed using a CAMECA SX-50 electron microprobe at the Department of Lunar and Planetary Sciences at the University of Arizona. Analytical conditions consisted of a beam current of 20.0 nA and an accelerating voltage of 15 kV. Counting time was 10 s for sodium and 20 s for the rest of the elements. Under these conditions, contents below 0.1% are considered below detection limits. Microprobe analytical error varies roughly between ± 0.01 and 0.04 wt% (1 sigma [1σ]). Representative chemical analyses of metamorphic phases of the three studied suites are presented in the GSA Data Repository.[1]

Three samples from the Esperanza suite were studied by U/Pb geochronology at the Department of Geosciences at the University of Arizona, following the procedures described by Dickinson and Gehrels (2003) and Talavera-Mendoza et al. (2005). Zircons were extracted using heavy liquids and magnetic separation techniques. For detrital zircon studies, 100 grains were analyzed at random. Grain cores were preferred to avoid external parts of zircon that may have undergone Pb loss. For magmatic ages, at least 50 bipyramidal grains were randomly mounted. Analyses were performed on a minimum of 25 grains. Tips were preferred for determination of magmatic age, but cores were also analyzed to assess inheritance. Analyses were performed by LA-MC-ICP-MS in static mode with a laser beam ranging from 25 to 50 µm. Fractionation of U and Pb was corrected using an in-house zircon standard, with a concordant thermal-ionization mass-spectrometry (TIMS) age of 564 ± 4 Ma (Dickinson and Gehrels, 2003). This standard was analyzed once for every three unknowns in magmatic zircons and once for every five unknowns in detrital zircons. Uranium and thorium concentrations were monitored by analyzing a standard (NIST 610 glass) with ~500 ppm Th and U.

The age probability plot was 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 and weighted mean ages were calculated using the method of Ludwig (2003). The age error is calculated by quadratically adding the random or measurement error and the systematic error. All age uncertainties are reported at the 2 sigma (2σ) level.

The ^{40}Ar-^{39}Ar analyses were performed at the Geochronology Laboratory at the Departamento de Geología, CICESE. Two instruments were used for the argon isotope analyses, a laser extraction system on line with a VG5400 mass spectrometer for single-grain experiments in phengite and amphibole, and an MS-10 mass spectrometer equipped with a Modifications Ltd. Ta-furnace for the bulk-sample analyses. The samples were irradiated in the U-enriched research reactor of McMaster University in Hamilton, Ontario, Canada. As irradiation monitors, TCR-2 (split G93) sanidine (27.87 ± 0.04 Ma) and internal standard CATAV 7–4 (88.54 ± 0.39 Ma) were irradiated alongside the samples. The argon isotopes were corrected for blank, mass discrimination, neutron interference reactions, radioactive decay of ^{37}Ar and ^{39}Ar, and atmospheric contamination. The analytical precision is reported as two standard deviations (2σ). The decay constants recommended by Steiger and Jäger (1977) were used in the argon data reduction procedures. The error in the plateau and the integrated and isochron ages include the scatter in the irradiation monitors. The equations reported by York et al. (2004) were used in all straight-line fitting routines of the argon data reduction. With the exception of sample IX-13, all the samples were step-heated with the laser extraction system, the Ta-furnace, or both.

RESULTS

Xayacatlán Suite

Lithology

Rocks of this suite were studied in the Piaxtla, Mimilulco, and Cuatlaxtecoma areas (Fig. 1). The succession is dominated by garnet-amphibolite intercalated with pelitic schist and minor eclogite and greenschist. Leucogranites of 476–461 Ma age cut the succession in the three studied localities (Talavera-Mendoza et al., 2005), engulfing xenoliths of the HP rocks. Eclogites that contain omphacite-garnet have been recognized in the Piaxtla and Mimilulco regions (Meza-Figueroa et al., 2003), but they are more common in the Piaxtla area, where they crop out as meter-size lenses included in amphibolites.

Petrography

Metabasites of the Xayacatlán suite show a well-developed, coarse-grained, continuous foliation with the diagnostic assemblages (abbreviations after Spear, 1995): $Omp_{(1)}$ + $Grt_{(1)}$ + Czo + Phe + Bar ± Qtz ± Rt, and Ab + Bar + $Grt_{(1)}$ + Czo + Phe ± Qtz ± Rt (Fig. 3A), whereas pelitic rocks develop the assemblage Phe + Qtz + $Grt_{(1)}$ + Ab ± Cld ± Rt ± Ilm ± Tur. Omphacite has compositions in the range $Jd_{29–34}$ $Ae_{10–18}$ Ca-$Cpx_{51–57}$ (Fig. 4A), whereas $garnet_{(1)}$ has almandine-rich compositions ($Prp_{10–11}$ $Alm_{58–62}$ $Grs_{23–27}$ $Sps_{1–5}$) (Fig. 4B). Both pyroxene and garnet compositions were obtained from inner to rim spots in different grains. $Garnet_{(1)}$ has a growth zoning typical of prograde garnet (Fig. 5). Amphibole is barroisite or Mg-katophorite (Fig. 6); phengite is characterized by high Si/Al (1.4–1.7) ratios.

HP minerals from most eclogites show reaction rims that indicate partial reequilibration. $Omphacite_{(1)}$ develops symplectitic overgrowths of Mg-Hbl + Ab ± $Omp_{(2)}$ (Fig. 3B). Retrograde $omphacite_{(2)}$ is richer in Ca and Fe^{3+} than prograde $omphacite_{(1)}$ (Fig. 4A). Garnet develops rims of pargasite or Fe-pargasite, whereas barroisite develops a zonation of Mg-hornblende-edenite ± clinozoisite (Fig. 6). Phengite is partly transformed to muscovite and to symplectites of biotite + albite. Sketches of rocks from this and other suites can be seen in the GSA Data Repository (see footnote 1).

Many garnet-amphibolites contain Mg-hornblende and actinolite following foliation planes associated with albite, $garnet_{(2)}$, chlorite, and clinozoisite. $Garnet_{(2)}$ appears as small, euhedral, and inclusion-free crystals, showing almandine compositions ($Prp_{5–7}$ $Alm_{56–58}$ $Grs_{31–34}$ $Sps_{3–6}$), slightly richer in the grossular end member than $garnet_{(1)}$ (Fig. 4B). These phases were produced by a later metamorphic event.

Geothermobarometry

For geothermobarometric studies, we analyzed rims of mineral pairs mostly in contact without reaction, which suggests equilibrium (Fig. 3A). We used large barroisite or Mg-katophorite crystals to define the HP conditions where calibrations included amphibole. The formation of eclogites has been constrained to 609–491 °C and 12 kb Cpx-Grt (Ellis and Green, 1979), Phe-Grt (Krogh and Raheim, 1978), Amp-Grt (Graham and Powell, 1984), and jadeite content in $omphacite_{(1)}$ (Holland, 1980) (Table 1). For garnet-amphibolites and chloritoid mica schists, temperatures were estimated between 599 and 486 °C, and minimum pressures of 12–11 kb Amp-Pl (Holland and Blundy, 1994), Phe-Grt (Krogh and Raheim, 1978), Amp-Grt-Pl-Qtz (Kohn and Spear, 1989), and Si in phengite (Massonne and Schreyer, 1987). These conditions coincide with those from the eclogites (Table 1).

Retrogression conditions range from ~600 °C and ~9.6 kb to ~500 °C and ~6.7 kb, estimated in

[1]GSA Data Repository item 2007192, Tables DR1–DR8 and Figures DR1–DR3, is available at http://www.geosociety.org/pubs/ft2007.htm or by request to editing@geosociety.org.

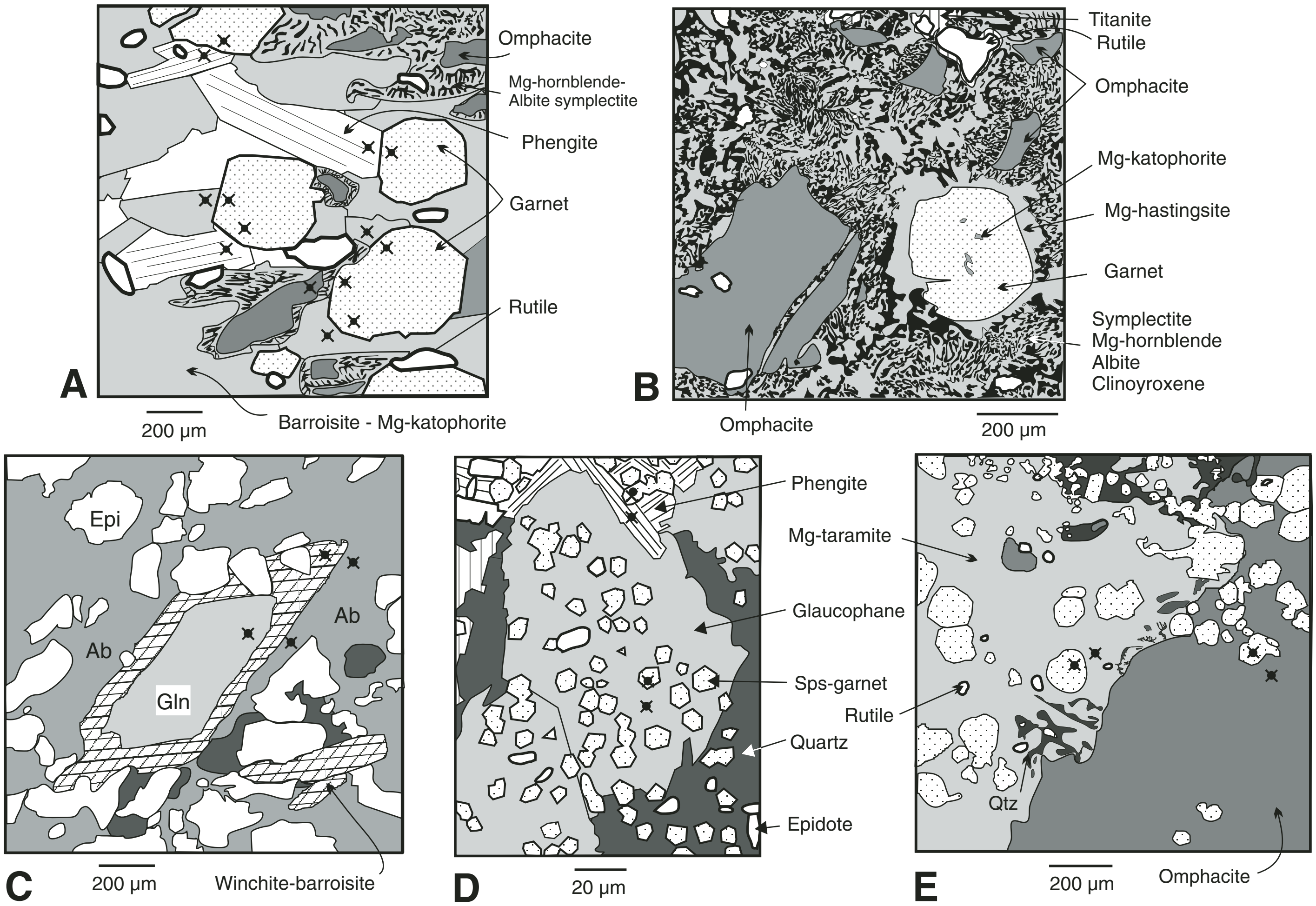

Figure 3. Sketches of the high-pressure (HP) rocks drawn from backscattered electron images. (A) Eclogite from the Xayacatlán suite. (B) Retrogressed eclogite from the Xayacatlán suite with development of symplectites made by Mg-hornblende, albite, and Ca-rich omphacite, as well as Mg-hastingsite coronas around garnet; these minerals were analyzed to define the retrogressive path. (C) Blueschist from the Ixcamilpa suite with a porphyroblast of glaucophane with a reaction rim of winchite. (D) Metachert with glaucophane and spessartinic garnet. (E) Eclogite from the Esperanza suite; amphibole is Mg-taramite. "x"s indicate typical sites for chemical analyses.

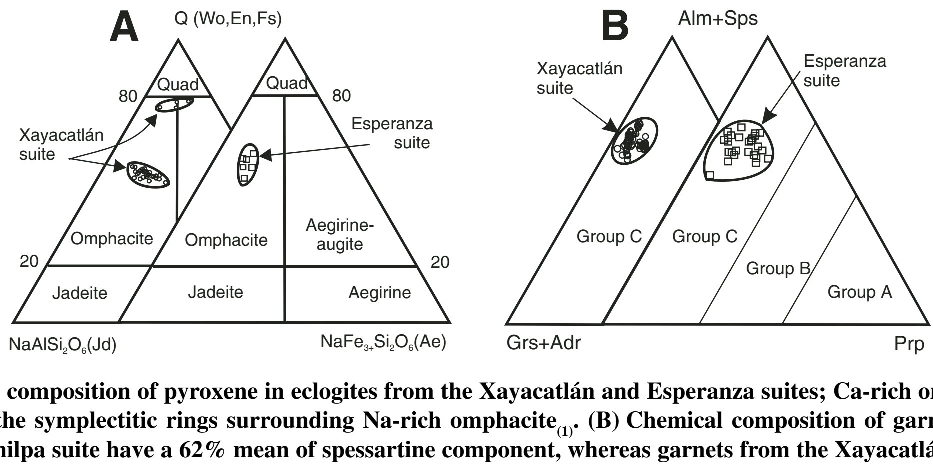

Figure 4. (A) Chemical composition of pyroxene in eclogites from the Xayacatlán and Esperanza suites; Ca-rich omphacite$_{(2)}$ of the Xayacatlán suite are from the symplectitic rings surrounding Na-rich omphacite$_{(1)}$. (B) Chemical composition of garnet from the HP suites; garnets from the Ixcamilpa suite have a 62% mean of spessartine component, whereas garnets from the Xayacatlán and Esperanza suites have 61% and 57% means of almandine component, respectively; garnets from the Esperanza suite are slightly richer in pyrope. Fields of eclogite types after Coleman (1965).

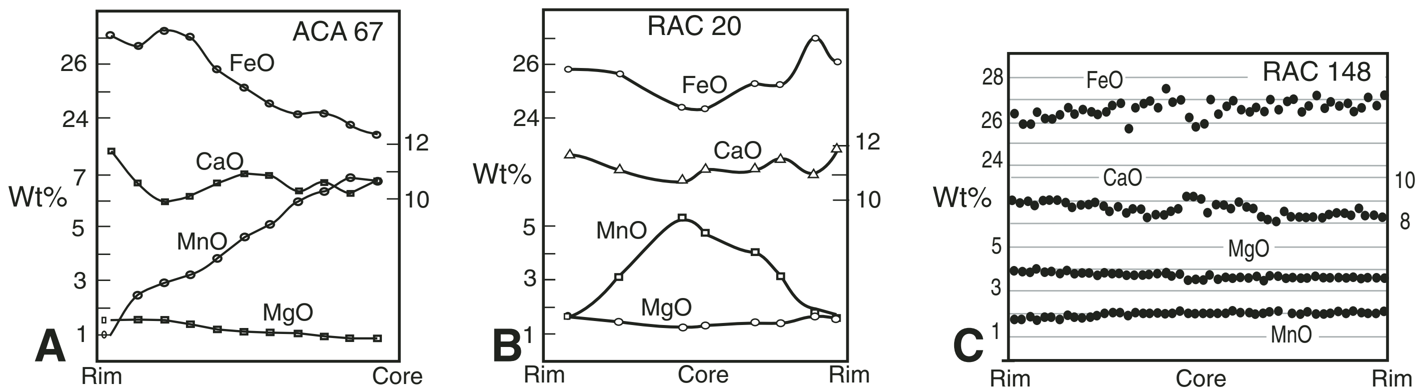

Figure 5. Garnet zonation in eclogites. (A, B) Garnets from the Xayacatlán suite eclogite, showing a typical bell-shaped profile commonly interpreted as zoning growth. (C) Garnet from the Esperanza suite eclogite, showing homogeneous distribution of elements typical of rocks metamorphosed at high temperatures. Vertical values are weight percents of oxides.

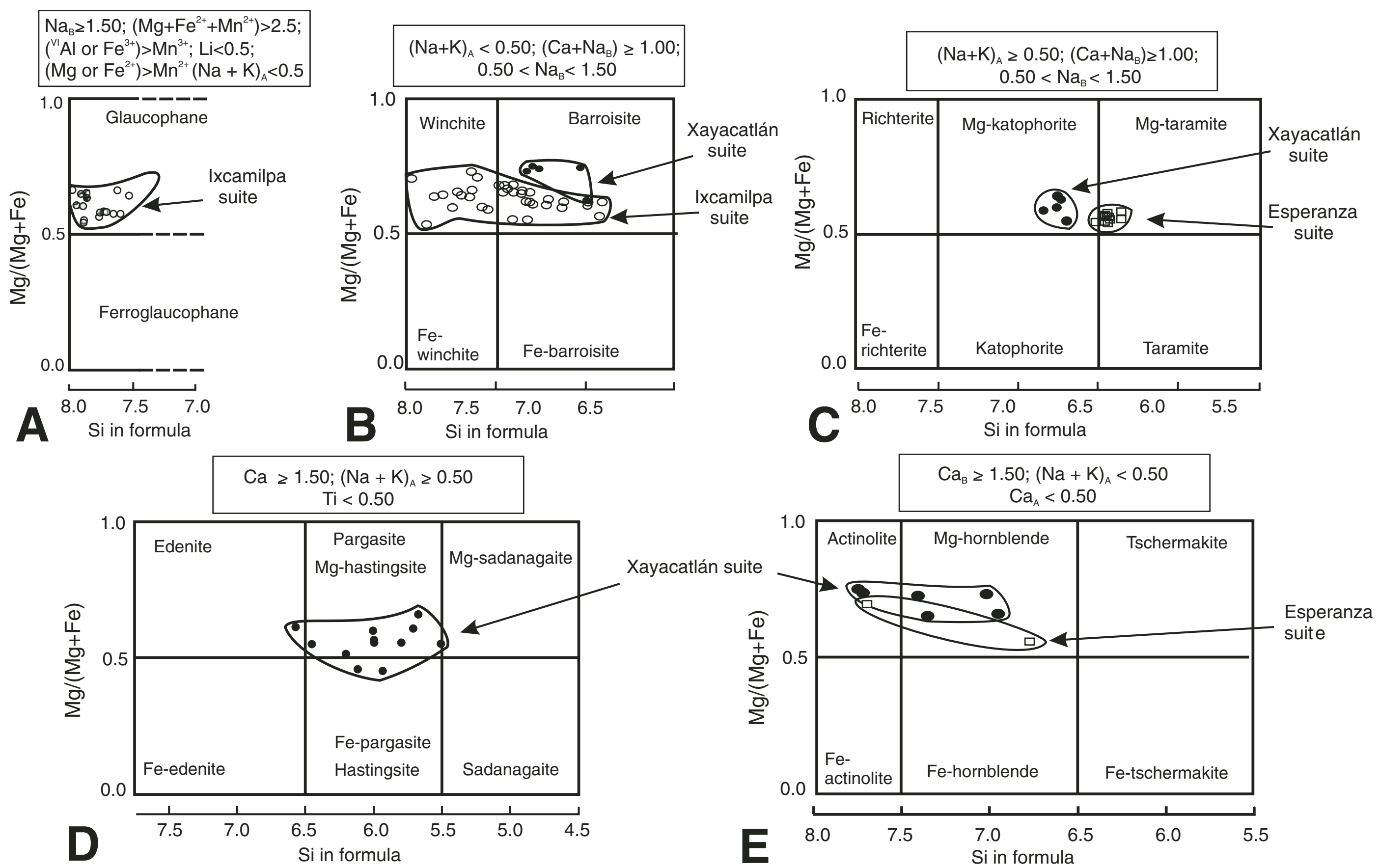

Figure 6. Chemical composition of amphiboles from the Xayacatlán, Ixcamilpa, and Esperanza suites, based on the chemical content of the standard amphibole formula. Classification diagrams and parameters from Leake et al. (1997). (a) Sodic amphiboles. (b, c) Sodic-calcic amphiboles. (d, e) Calcic amphiboles.

TABLE 1. THERMOBAROMETRIC DATA

Suite	Locality	Rock	Geothermometer	Grt-Cpx[a] T (°C)	Grt-Phe[b] T (°C)	Amp-Grt[c] T (°C)	Jd + Qtz[d] P (kb)	Amp-Pl[e] T (°C)	Phengite[f] P (kb)	
Xayacatlán suite	Piaxtla	Eclogite	Average	539 ± 27	539 ± 27	538 ± 30	12.4 ± 0.5	N.A.	N.D.	
			Std dev	40	9	15	0.10			
			Range	491–609	534–556	522–561	12.2–12.6			
			Number	12	6	7	27			
	Mimilulco	Garnet amphibolite/mica schist	Average	N.A.	511 ± 26	494 ± 30	N.A.	532 ± 40	N.D.	
			Std dev		13	12		29		
			Range		494–535	486–503		506–574		
			Number		16	2		4		
	Cuatlaxtecoma	Garnet amphibolite	Average	N.A.	570 ± 29	N.D.	N.A.	574 ± 40	11.7 ± 0.4	
			Std dev		24			35	0.4	
			Range		546–599			532–612	12.1–11.3	
			Number		6			5	5	
				Grt-Cpx[a] T (°C)	Grt-Phe[b] T (°C)	Amp-Grt[c] T (°C)	Jd + Qtz[d] P (kb)	Phengite[f] P (kb)	Bi-Grt[g] T (°C)	GPMB-Fe[h] P (kb)
Esperanza suite	Santa Cruz Organal	Eclogite	Average	796 ± 40	798 ± 40	701 ± 30	16.3 ± 0.5	N.D.	N.A.	N.A.
			Std dev	42	5	15	0.8			
			Range	763–853	794–803	673–717	15.3–17.2			
			Number	4	3	8	4			
		Mica schist	Average	N.A.	648 ± 32	N.A.	N.A.	N.D.	664 ± 20	13.8 ± 0.5
			Std dev		7				20	0.5
			Range		640–661				617–691	12.9–14.6
			Number		7				21	9
		Garnet augengneiss	Average	N.A.	694 ± 35	N.A.	N.A.	14.5 ± 0.7	737 ± 22	N.A.
			Std dev		36			0.6	15	
			Range		638–755			13.9–15.7	748–727	
			Number		9			11	2	
				Grt-Phe[b] T (°C)	Amp-Grt[c] T (°C)	Amp-Pl[e] T (°C)				Chlorite[i] T (°C)
						Glaucophane		Winchite:	Barroisite:	
						Inclusions:	Porphyroblasts:			
Ixcamilpa suite	Ixcamilpa	Blueschist/metachert	Average	388 ± 20	351 ± 30	225 ± 40	330 ± 40	439 ± 40	543 ± 40	319 ± 16
			Std dev	17	58	13	46	43	30	16
			Range	363–412	287–465	202–240	263–407	382–484	478–580	274–345
			Number	5	14	8	16	8	10	30

Note: N.A.—not applicable; N.D.—no data; Std dev—standard deviation. Mineral abbreviations after Spear (1995).
[a]Ellis and Green (1979)
[b]Green and Hellman (1982)
[c]Graham and Powell (1984)
[d]Holland (1980)
[e]Holland and Blundy (1994)
[f]Massonne and Schreyer (1987)
[g]Bhattacharya et al. (1992)
[h]Ghent and Stout (1981)
[i]Cathelineau (1988)

symplectites around omphacite$_{(1)}$ Amp-Pl (Holland and Blundy, 1994) and jadeite content in omphacite$_{(2)}$ (Holland, 1980) (Table 1; Fig. 3B). Later metamorphism occurred at temperatures of 527–505 °C and pressures of ~9.5 kb in the epidote-amphibolite facies Amp-Pl (Holland and Blundy, 1994) and Pl-Amp-Grt-Qtz (Kohn and Spear, 1989). However, thermobarometric data are not precise enough to clearly discriminate between both proposed epidote-amphibolite facies events. The assemblage Act + Chl + Ab + Czo ± Qtz ± Ttn indicates that retrogression followed under greenschist facies conditions.

Ixcamilpa Suite

Lithology

Rocks of this suite have been recognized only in the Ixcamilpa area in the southwestern part of the Acatlán Complex (Fig. 1). The suite consists of a succession of blueschist intercalated with greenschist and pelitic-psammitic schist with minor metachert, tectonically overlain by garnet-amphibolites of the Xayacatlán suite.

Petrography

Mafic rocks show a foliated fabric that contains the assemblage Gln + Ab + Czo + Phe + Chl + Qtz (Fig. 3C). Metacherts contain the same mineral assemblage plus fine-grained garnet with spessartine-rich compositions $Prp_{0–1}$ $Alm_{7–25}Grs_{6–19}Sps_{54–74}$ (Fig. 3D) (data from cores and rims in different grains). That assemblage is diagnostic of the epidote-blueschist facies (Evans, 1990). Winchite and barroisite generally rim the glaucophane crystals (Fig. 3C), and locally they occur in interlayered amphibolites without glaucophane. The latter rocks also may include actinolite (Fig. 6), forming assemblages typical of greenschist facies. Pelitic-psammitic rocks contain the assemblage Phe + Chl + Qtz ± Cld. Many syntectonic poikiloblasts of plagioclase have small lineated inclusions of Gln + Czo + Chl ± Ttn. Metabasites show an overprinted crenulation cleavage defined by actinolite and chlorite.

Geothermobarometry

The blueschist metamorphism occurred between temperatures of ~200–390 °C and pressures of 6–9 kb (Amp-Pl), Holland and Blundy (1994); Amp-Grt, Graham and Powell (1984); phengite, Massonne and Schreyer (1987). The partial replacement of glaucophane by winchite and barroisite indicates a temperature increase from ~390 to 580 °C (Holland and Blundy, 1994) coupled with decreasing pressure from 9 to 6 kb, defined with the geobarometer of Brown (1977). The pressure estimations consider a correction of +2 kb as suggested by Smith et al. (1999) (Table 1). Metabasites with actinolite, winchite, and barroisite, but without glaucophane, were formed in lower temperatures and pressures than were the garnet amphibolites. Those conditions and fabric relationships indicate a transition from epidote-blueschist to epidote-amphibolite and then a retrogression into greenschist facies.

Esperanza Suite

Lithology

In the Santa Cruz Organal area (Fig. 1) the Esperanza suite consists primarily of augen orthogneisses locally intruding a metasedimentary succession of quartz-feldspar schists, quartzites, and garnet mica schists. Eclogites appear as tabular bodies that cross both metasedimentary rocks and augen gneisses, indicating that protoliths were mafic dikes. Dikes of muscovite-bearing leucogranites of Late Devonian age (372 ± 8 Ma; U-Pb; this work) intrude the whole succession, postdating the HP event.

Petrography

Rocks of this suite show nearly isotropic to well-foliated fabrics. Both metasedimentary rocks and augen gneisses contain the assemblage Ab + Phe + Grt + Qtz ± Bt ± Kfs ± Czo ± Rt, which is stable at amphibolite to eclogite facies conditions. Mafic rocks show isotropic fabric except those situated in the outer zones of lenses, which display a mildly foliated fabric. Eclogites are generally coarse grained (0.1–0.5 cm), but in some zones minerals reach lengths up to 5 cm. They contain the assemblages Omp + Grt + Amp + Phe + Ab + Rt and Amp + Grt + Ab + Phe + Rt (Fig. 3E). Omphacite has compositions in the range $Jd_{29–36}AeAu_{8–10}Ca\text{-}Mg\text{-}Fe_{53–62}$ and is comparable to prograde omphacite in the Xayacatlán rocks (Fig. 4A). Garnet is common in all rock types and shows almandine compositions ($Prp_{8–16}Alm_{54–65}Gr_{17–28}Sps_{1–5}$) (Fig. 4B) regardless of the lithology. Garnet from eclogites is generally fine grained and compositionally homogeneous (Fig. 5C), suggesting chemical homogenization during peak conditions, although larger garnets were not analyzed and may be zoned. Amphibole has calc-sodic composition and varies from Mg-taramite to Mg-katophorite (Fig. 6).

In general, HP phases show little or no evidence of retrogression, which may be related to a rapid exhumation or absence of fluids and deformation during uplift. Irregular contacts between Mg-taramite and omphacite (Fig. 3E) and the common inclusion of pyroxene within amphibole suggest a later growth of the amphibole. Scarce omphacite grains show symplectitic overgrowths of Mg-Hbl + Ab ± Qtz (Fig. 3E), whereas Mg-taramite has external zones of edenite (Fig. 6). Garnet shows partial transformation to clinozoisite. These reaction phases suggest an incipient reequilibration in amphibolite facies conditions.

Geothermobarometry

Peak metamorphic conditions of eclogites range from 830 to 768 °C and 17–15 kb (Cpx-Grt), Ellis and Green (1979); jadeite content in omphacite, Holland (1980). Slightly lower temperatures (717–673 °C) were obtained using the Amp-Grt geothermometer (Graham and Powell, 1984), which confirms that amphibole equilibrated later than omphacite, as suggested by the textures. In pelitic schist, metamorphic conditions were constrained to 699–617 °C and 14.7–13.2 kbar (Bt-Grt), Bhattacharya et al. (1992); (Ms-Grt), Green and Hellman (1982); (Ms-Bt-Pl-Grt), Ghent and Stout (1981). In augen gneisses, peak metamorphic conditions were constrained to 748–638 °C and 15.50–13.7 kb (Ms-Grt), Green and Hellman (1982); (Bt-Grt), Bhattacharya et al. (1992); phengite, Massonne and Schreyer (1987) (Table 1).

P-T conditions obtained from augen gneisses and mica schists (Ms-Grt), Green and Hellman (1982); (Si in phengite), Massonne and Schreyer (1987) indicate a partial reequilibration of these minerals in amphibolite facies conditions and define an almost isothermal transition from middle temperature eclogite to amphibolite facies, and a later retrogression to epidote-amphibolite facies conditions.

GEOCHRONOLOGY

In this section, we report new U/Pb and $^{40}Ar/^{39}Ar$ ages obtained in rocks from the Xayacatlán, Ixcamilpa, and Esperanza suites, as well as from granitic dikes crosscutting them. Only the HP event in the Esperanza suite can be dated precisely ($^{40}Ar/^{39}Ar$ in amphibole), because later thermal events reset the phengite $^{40}Ar/^{39}Ar$ system in most of the HP suites, as will be discussed afterward. However, the data obtained, combined with previous ages, help to define three different HP events and permit establishment of the metamorphic evolution of the Acatlán Complex.

U/Pb Geochronology

Three rocks from the Esperanza suite were dated, one quartzite from the metasedimentary succession, one augen gneiss, and one leucogranitic dike that postdates the HP metamorphic event (Fig. 7). The geochronologic data are available in the GSA Data Repository (see footnote 1).

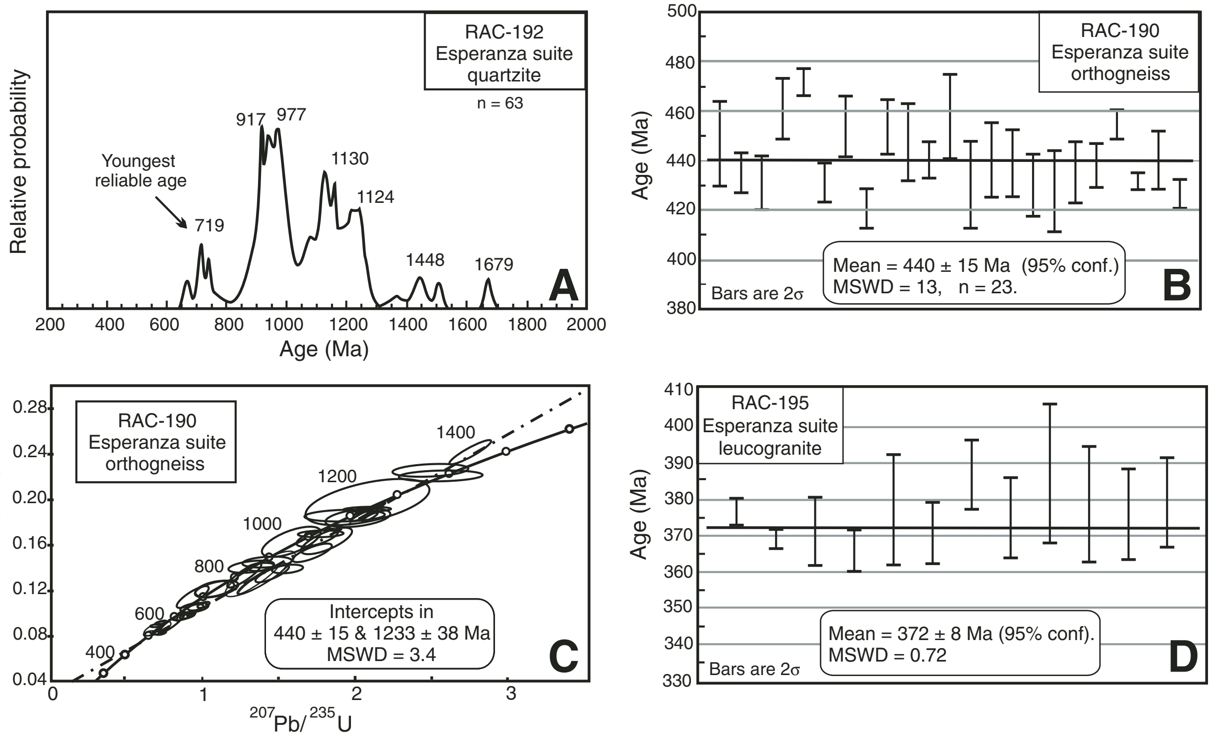

Figure 7. U-Pb zircon ages of rocks from the Esperanza suite. (A) Cumulative plot of a metasedimentary quartzite. (B) Weighted mean age of an augen orthogneiss. (C) Concordia diagram of augen orthogneiss showing the upper and lower intercepts; circles represent only the inherited ages. (D) Weighted mean age of mylonitic leucogranite.

Sample RAC-192 is a garnet-phengite quartzite collected from Barranca Honda Creek northeast of the town of Santa Cruz Organal. Detrital zircon ages from this sample range from 1672 ± 9 to 723 ± 37 Ma. With the exception of four grains, all zircons have U/Th ratios <9, indicating derivation from magmatic rocks (Rubatto, 2002). Three major populations characterize the cumulative age pattern, one in the range 800–653 Ma (peak at ca. 719 Ma), a second in the range 1046–850 Ma (peaks at ca. 977 and ca. 917 Ma), and a third in the range 1262–1091 Ma (peaks at ca. 1244 and ca. 1130 Ma). A few grains indicate a range of 1672–1320 Ma. The youngest reliable zircon cluster at ca. 719 Ma represents the maximum depositional age for the metasedimentary succession in the Esperanza suite. Because of measures in provenance studies that were performed in the zircon cores and the relatively large laser spot, the thin zircon overgrowths originated by the eclogitic metamorphism could not be dated in this sample.

Sample RAC-190 is rutile-garnet-biotite augen gneiss, which intruded the metasedimentary succession at Santa Cruz Organal. This sample yielded $^{206}Pb/^{238}U$ ages from 1387 ± 38 to 421 ± 8 Ma with a major age cluster formed by 23 grains, which yielded a weighted mean age of 440 ± 15 Ma (mean square of weighted deviates [MSWD] = 13). This result was interpreted as an igneous crystallization age based on U/Th ratios <6.5, a mean of 3.6 (Rubatto, 2002). This age is identical to the 440 ± 14 Ma and 442 ± 5 Ma reported for these gneisses in other regions by Ortega-Gutiérrez et al. (1999) and Talavera-Mendoza et al. (2005), respectively. Thirty-nine inherited zircons yielded Mesoproterozoic to Paleozoic (1397 ± 38 to 515 ± 7 Ma) ages and define a line of Pb loss between the igneous crystallization age and a Grenvillian (ca. 1233 ± 38 Ma) component.

Sample RAC-195 is from a foliated muscovite leucogranite dike collected from Barranca Honda Creek northeast of Santa Cruz Organal. This sample yielded $^{206}Pb/^{238}U$ ages from 1140 ± 31 to 366 ± 6 Ma, with a major age cluster formed by 12 grains that yielded a weighted mean age of 372 ± 8 Ma, which is considered a crystallization age. This age coincides with the age of La Noria Granite (371 ± 34 Ma; U/Pb) (Yañez et al., 1991). Nine inherited zircons yielded Mesoproterozoic to Paleozoic (1140 ± 31 to 514 ± 23 Ma) ages and broadly define a line of Pb loss between the igneous crystallization age and a late Mesoproterozoic component.

$^{40}Ar/^{39}Ar$ Geochronology

Eight new $^{40}Ar/^{39}Ar$ ages from seven samples were obtained in this work. Three ages arose from the Xayacatlán suite, one from the Ixcamilpa suite, and four from the Esperanza suite. A summary of $^{40}Ar/^{39}Ar$ ages is given in Table 2, and the entire data set is available in the GSA Data Repository (see footnote 1).

Sample ACA-125 is a barroisite-omphacite-garnet eclogite collected from the Xayacatlán suite at Piaxtla (Fig. 1). Three-step heating experiments were performed on a phengite monograin using the argon ion laser extraction system. The argon isotopes were analyzed with the VG5400 mass spectrometer. During the first and third experiment for two fractions, the mass 40 signal was saturated and could not be measured; therefore, no age information is available for these fractions. The second experiment yielded an integrated age of 337 ± 2 Ma. The plateau age of 335 ± 2 Ma (Fig. 8A) is defined by three fractions, representing 63.5% of the ^{39}Ar released. An indistinguishable isochron age of 336 ± 6 Ma ($^{40}Ar/^{36}Ar_i$ = 403 ± 184; MSWD = 5.3 for n = 12) was calculated for the combined fractions of the three experiments performed.

TABLE 2. SUMMARY OF $^{40}Ar/^{39}Ar$ DATA

Unit	Rock	Sample	Mineral	Age in Ma*
Xayacatlán suite	Eclogite	ACA-125	Phengite	336 ± 6
	Mica schist	ACA 57	Phengite	336 ± 4
Esperanza suite	Leucogranite	RAC-101	Phengite	335 ± 2
	Mica schist	RAC-138	Phengite	345 ± 2
	Eclogite	RAC-201	Amphibole	430 ± 10
			Phengite	374 ± 4
	Pegmatite	RAC-188	Phengite	346 ± 4
Ixcamilpa suite	Blueschist	IX-13	Phengite	323 ± 12

Note: Decay constants recommended by Steiger and Jäger (1977) were used in all the ^{40}Ar-^{39}Ar data reductions.

*Ages reported are isochron ages with errors at 2σ level.

Sample ACA-57 is a chloritoid-garnet-phengite mica schist intercalated with garnet-amphibolites collected from the Xayacatlán suite at Mimilulco (Fig. 1). Single grains of the coarse-grained phengite were analyzed by laser one-step fusion and laser step-heating with the VG5400 mass spectrometer; additionally a bulk-sample was step-heated and analyzed with the MS-10 mass spectrometer. There is good agreement between the results obtained, which indicate that the sample is slightly inhomogeneous. The one-step experiments yielded a weighted mean age of 333 ± 2 Ma, whereas the integrated age of the bulk-sample analysis is 340 ± 2 Ma (Fig. 8B). Most of the data cluster in the vicinity of the *x*-intercept on the correlation diagram. The age calculated from the *x*-intercept is 336 ± 4 Ma ($^{40}Ar/^{36}Ar_i$ = 320 ± 41 Ma; MSWD = 16 for n = 12).

Sample RAC-101 is a garnet-phengite metaleucogranite with a crystallization age of 461 ± 9 Ma (U/Pb; Talavera-Mendoza et al., 2005), which intruded garnet amphibolites and mica schists from the Xayacatlán suite at Mimilulco (Fig. 1). Four step-heating analyses were performed on a phengite concentrate; two experiments were conducted on single grains and two on bulk samples. The results obtained are in excellent agreement, all yielding flat age spectra (Fig. 8C). On two fractions the mass 40 signal was saturated and could not be measured. The integrated ages calculated are indistinguishable from the isochron age of 335 ± 2 Ma ($^{40}Ar/^{36}Ar_i$ = 309 ± 13 Ma; MSWD = 2.6 for n = 29) calculated for the combined fractions of the four experiments.

Sample RAC-138 is a garnet-biotite-phengite pelitic schist from the Esperanza suite. This rock is a large xenolith within augen gneisses (sample RAC-190). Three laser step-heating experiments were performed on RAC-138 phengite single grains, plus a fourth step-heating experiment on a bulk sample with the MS-10 mass spectrometer. These display flat age spectra with a small argon loss for the low-temperature fractions (Fig. 8D). They yielded an isochron age of 345 ± 2 Ma ($^{40}Ar/^{36}Ar_i$ = 325 ± 53 Ma; MSWD = 7.3 for n = 25) calculated with most of the fractions of the four experiments performed.

Sample RAC-188 is an undeformed granitic pegmatite intruded into augen gneiss of the Esperanza suite. Four step-heating experiments were conducted on the RAC-188 phengite sample. Three were laser fusions on single grains, and one was a bulk-sample analysis. The age spectra obtained are remarkably similar; only two integrated ages are reported, because in two experiments the mass 40 signal was saturated for some fractions, and thus no age for these could be obtained. The remaining fractions, however, yielded consistent results. The integrated age of 348 ± 4 Ma, calculated for the single grain experiment, is indistinguishable from the integrated age of 347 ± 6 Ma, calculated for the bulk-sample-analysis run (Fig. 8G). The combined fractions of the four experiments yielded an isochron age of 346 ± 4 Ma ($^{40}Ar/^{36}Ar_i$ = 283 ± 5 Ma; MSWD = 2.1 for n = 35).

Sample RAC-201 is a coarse-grained omphacite-garnet-Mg-taramite eclogite collected from the Esperanza suite in Barranca Honda Creek near Santa Cruz Organal. Two minerals were analyzed from this sample: Mg-taramite and phengite, both minerals step-heated as single grains and as bulk sample. The amphibole yielded a complex age spectra, displaying moderate to severe argon loss for the low-temperature fractions (Fig. 8F). For the bulk-sample experiment, ~64% of the ^{39}Ar was released on two fractions with a weighted mean 445 ± 6 Ma age. The remaining part of the age spectra yielded older ages, indicating the possibility of inherited argon; thus the best age estimate for this sample should be taken from the correlation diagram, which gave an isochron age of 430 ± 10 Ma ($^{40}Ar/^{36}Ar_i$ = 332 ± 20 Ma; MSWD = 28 for n = 8). Two laser step-heating experiments were also performed on amphibole. One yielded a plateau age of 419 ± 4 Ma; another yielded two plateaus of 418 ± 4 Ma and 315 ± 4 Ma (Fig. 8F). The two step-heating experiments performed on the RAC 201 phengite yielded statistically indistinguishable results within the integrated (374 ± 4 Ma and 373 ± 4 Ma) (Fig. 8E) and isochron (374 ± 4 Ma; $^{40}Ar/^{36}Ar_i$ = 295 ± 12 Ma; MSWD = 3.6 for n = 17) ages calculated. The phengite of this sample occurs as >1 cm crystals in secondary lenses.

Sample IX-13 is a glaucophane blueschist intercalated with mica schists and metacherts from the Ixcamilpa suite near the town of Ixcamilpa. This phengite is a fine-grained sample with the lowest K concentration of the phengites analyzed in this project. Only two single-grain analyses were performed, and the rest of the experiments were conducted as one-step multigrain laser fusions. An age of 322 ± 4 Ma was obtained from the weighted mean of the seven one-step experiments (Fig. 8H). This age is indistinguishable from the isochron age of 323 ± 12 Ma ($^{40}Ar/^{36}Ar_i$ = 287 ± 96 Ma; MSWD = 0.3 for n = 5) calculated for all experiments except for analyses 4 and 5, which yielded the youngest ages: 307 ± 7 and 295 ± 10 Ma, respectively.

DISCUSSION

P-T-t Paths and Tectonic Setting of Metamorphism

Prior to this study, most authors interpreted HP metamorphism in the Acatlán Complex as having resulted from a single event of Late Ordovician–Early Silurian (Ortega-Gutiérrez et al., 1999), Devonian (Yañez et al., 1991), or Carboniferous (Murphy et al., 2006; Nance et al., 2006) age. Our data indicate a more complex tectonothermal evolution for the Acatlán Complex and reveal the existence of three distinctive HP events of different age and physical conditions, which affected different lithologies.

Protoliths of the Xayacatlán suite formed in an oceanic setting (Meza-Figueroa et al., 2003) during Late Cambrian–Early Ordovician time (Talavera-Mendoza et al., 2005) and underwent eclogite facies metamorphism at 609–491 °C and 13–12 kb. These conditions were similar to those reported by Meza-Figueroa et al. (2003) and are comparable to those recorded in low-temperature eclogites and associated amphibolites (Coleman et al., 1965; Schliestedt, 1990; Massonne and Kopp, 2005). HP phases were partly reequilibrated during exhumation at conditions ranging from 600 °C and ~9.6 kb to 500 °C and ~6.7 kb in the epidote-amphibolite and greenschist facies, respectively. The age of the HP event and the exhumation have

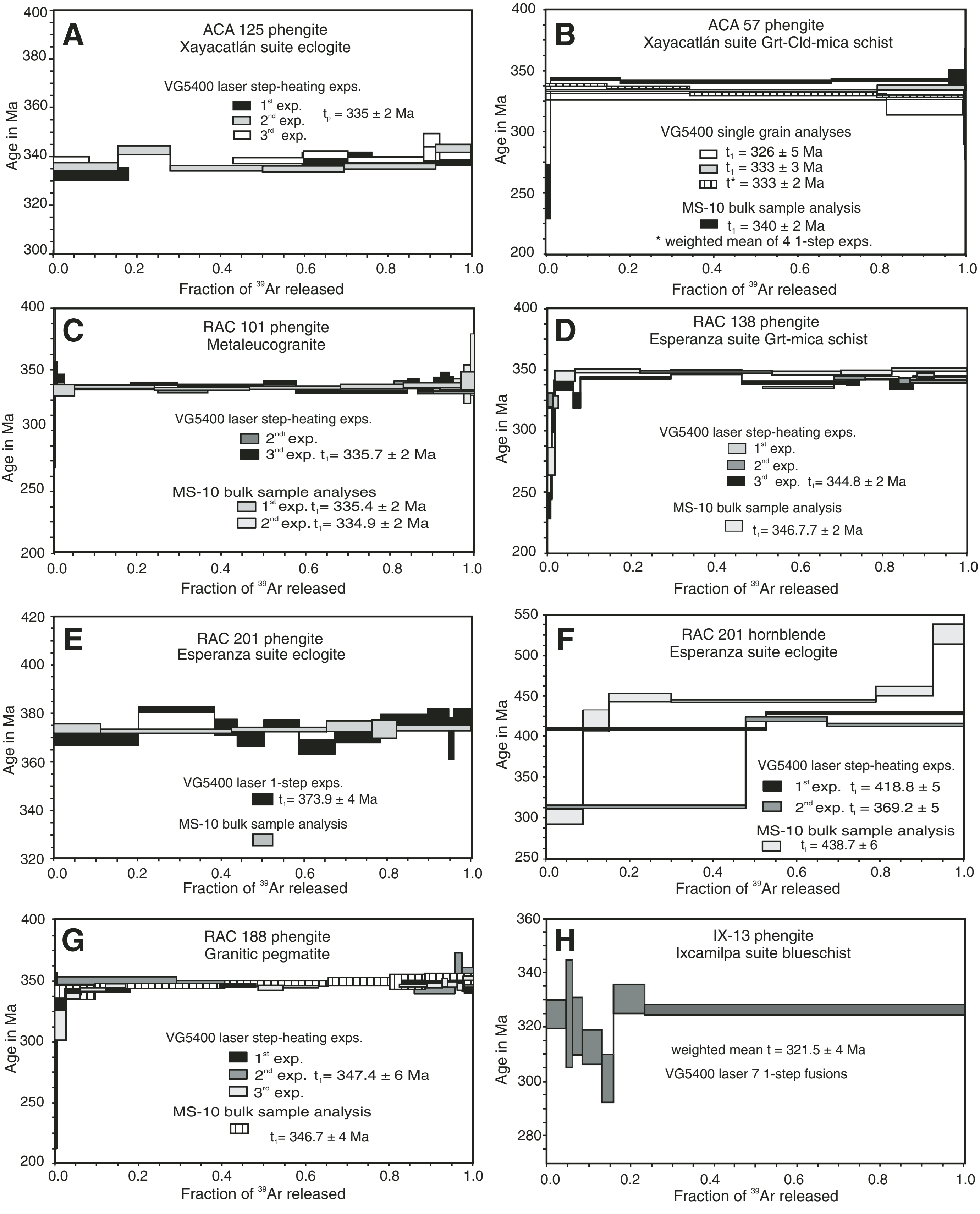

Figure 8. $^{39}Ar/^{40}Ar$ spectra from different suites of the Acatlán Complex. T—temperature; t—time. See description in text.

been bracketed between ca. 490 and ca. 477 Ma (Talavera-Mendoza et al., 2005), based on the U-Pb ages of detrital zircons and post-metamorphic leucogranites.

Subsequent metamorphic events caused reequilibration under epidote-amphibolite (T = 525–500 °C and P = ~9.5 kb) and greenschist (T = 470 °C and P = ~5–7 kb) facies conditions, which also affected leucogranites postdating the former episode. Devonian (416 ± 12 Ma, 386 ± 22 Ma; Grt-WR Sm-Nd) ages from Xayacatlán eclogites, reported by Yañez et al. (1991), likely date that epidote-amphibolite event instead of the eclogite event as originally considered. Mississippian (332 ± 4 to 318 ± 4 Ma, Ms-WR) Rb-Sr ages from eclogites (Yañez et al., 1991) and our $^{40}Ar/^{39}Ar$ ages (336 ± 2, 333 ± 2, and 335 ± 1 Ma, phengite) from an eclogite, a mica schist, and a leucogranite, respectively, record cooling through the phengite closure temperature of ~350 ± 50 °C (Geyh and Schleicher, 1990).

Data from the Xayacatlán rocks define a complex pressure-temperature-time (P-T-t) path composed of two segments (Fig. 9B). The prograde path until it reached eclogite facies and subsequent uplift followed a clockwise trajectory intermediate between those observed in Franciscan-type HP suites (e.g., Ernst, 1977, 1988) and those resulting from continent-continent collisions like those of the Alps (e.g., Tropper et al., 1999; Cartwright and Barnicoat, 2002; Putis et al., 2002). Paths similar to that of the Xayacatlán suite have been obtained from New Caledonia and Western Liguria (Fig. 9A; Ernst, 1977; Ghent et al., 1987), which are interpreted as having formed in an arc-continent collision setting. The second segment of the P-T path indicates that the Xayacatlán rocks were reburied at depths of ~30 km to reach epidote-amphibolite facies conditions during Devonian time, implying significant crustal thickening that was likely related to major thrusting. Finally, the suite was uplifted and reequilibrated at greenschist facies conditions during the Mississippian.

Mafic protoliths of the Ixcamilpa suite show oceanic geochemical affinities (De la Cruz-Vargas, 2004). In this suite, HP metamorphism reached blueschist and then epidote-amphibolite facies conditions at temperatures ranging from 200 to 580 °C and pressures between 6.5 and 9.0 kb. Blueschists underwent variable degrees of retrogression in the greenschist facies. Pelitic-psammitic schists intercalated with blueschists contain abundant ca. 477 Ma detrital zircons, indicating a maximum Middle Ordovician depositional age for the suite (Talavera-Mendoza et al., 2005). That depositional age precludes any genetic relationship with the Late Cambrian–Early Ordovician Xayacatlán suite. The Mississippian (323 ± 6 Ma) $^{40}Ar/^{39}Ar$ age obtained in phengite from blueschists probably reflects a regional tectonothermal event that affected all suites of the Acatlán Complex rather than the age of blueschist metamorphism. Thus, with the available information, the age of blueschist metamorphism in the Ixcamilpa suite cannot be better constrained than Late Ordovician–Mississippian. The absence of Silurian–Devonian detrital zircons in Ixcamilpa rocks and the existence of a major magmatic event of Early Silurian age, which may be genetically associated with a subduction process, suggest that both blueschist metamorphism and exhumation may have occurred during Late Ordovician–Early Silurian time (ca. 458–420 Ma). Data obtained from Ixcamilpa rocks define a P-T path (Fig. 9C) that resembles trajectories reported for the Sanbagawa belt (Fig. 9A; Ernst, 1988), and it is similar to the P-T path of epidote-blueschists from New Brunswick in the Appalachians (van Staal et al., 1990).

In the Esperanza suite, eclogitic metamorphism was imposed on sediments, granites, and mafic dikes. The augen gneiss protolith has an Early Silurian age (442–440 Ma) and orogenic signatures (Ramírez-Espinosa, 2001). On the other hand, field and geochemical evidence suggests that protoliths of the eclogites were mafic dikes emplaced in granites and metasediments (Vega-Granillo, 2006) in a continental rift environment (Murphy et al., 2006). Eclogitic metamorphism reached peak conditions at temperatures of 830–730 °C and pressures of 16.8–15.3 kb. The amphibole $^{40}Ar/^{39}Ar$ age from the eclogite indicates that metamorphism initiated ca. 430 ± 5 Ma. This age is concordant, within uncertainty, with a 418 ± 18 Ma U-Pb monazite age obtained by Ortega-Gutiérrez et al. (1999) from augen gneisses thought to have recorded the age of peak eclogitic metamorphism. Retrogression took place in temperatures between 690 and 640 °C and pressures between 14.3 and 10.0 kb in the amphibolite facies field. Phengite from eclogite yielded a younger 374 ± 4 Ma $^{40}Ar/^{39}Ar$ age, which reflects cooling through ~350 ± 50 °C. This age is consistent with the 372 ± 8 Ma U-Pb zircon age of a leucogranite interpreted to have resulted from decompression melting during exhumation. U-Pb ages of ca. 360–345 Ma obtained from zircon rims of migmatized amphibolites (Elías-Herrera et al., 2004) are interpreted here as the age of the migmatization event in amphibolite facies conditions instead of the age of the eclogitic metamorphism as suggested by Murphy et al. (2006).

Thermobarometric and radiometric data from the Esperanza suite define a sinuous P-T-t path (Fig. 9D). The earliest stages of prograde metamorphism were not preserved owing to equilibration under HT eclogite conditions. Afterward, uplift caused partial reequilibration of the eclogitized rocks in amphibolite facies with associated migmatization and leucogranite intrusion. The P-T path of the Esperanza suite is comparable to trajectories reported for HT eclogites included within gneisses similar to those in Norway, the Alps, Cabo Ortegal, and the Carolina terrane (Fig. 9A). In these regions, eclogitization is inferred as having resulted from the collision of continental blocks or microblocks (e.g., Ernst, 1977; Cuthbert and Carswell, 1990; Putis et al., 2002; Puelles et al., 2005; Shervais et al., 2003).

Tectonic Evolution

Following the Precambrian events, four major successive stages of convergence and collision occurred during the Paleozoic, as recorded in the Acatlán Complex. At least three of these stages generated HP assemblages of contrasting metamorphic conditions and tectonic settings. Rocks of the Xayacatlán suite were metamorphosed by the subduction of an oceanic basin to depths of ~40 km to reach low-temperature eclogite facies during the Early Ordovician. The collision of a volcanic arc with the exhumed subduction complex may have produced reequilibration at epidote-amphibolite and greenschist facies conditions. After exhumation of the Xayacatlán suite, sedimentary protoliths of the Ixcamilpa suite were deposited in a marginal basin during Middle to Late Ordovician time, as indicated by geochemistry and detrital zircon geochronology (De la Cruz-Vargas, 2004; Talavera-Mendoza et al., 2005). Ixcamilpa rocks were subducted to depths of ~25–30 km to reach epidote-blueschist facies conditions and then were exhumed relatively quickly to avoid extensive retrogression. Even though the age of blueschist facies metamorphism is poorly constrained, geochronological and geological evidence suggests that most of the metamorphism probably occurred during Late Ordovician–Early Silurian time (ca. 458–443 Ma).

During the Early Silurian (440 ± 14 to 442 ± 5 Ma), granitic bodies of batholitic dimensions intruded a sedimentary succession of Neoproterozoic–Ordovician age containing detrital zircons derived mainly from late Mesoproterozoic crustal rocks (Murphy et al., 2006; this work). Mafic dikes in an extensional environment intruded both lithologies. All these rocks composing the Esperanza suite were subsequently subducted at depths of ~60 km to reach HT eclogite facies conditions at ca. 430–418 Ma. Subduction must have occurred under continental crust to explain the peak metamorphic conditions. Fast uplift of the Esperanza

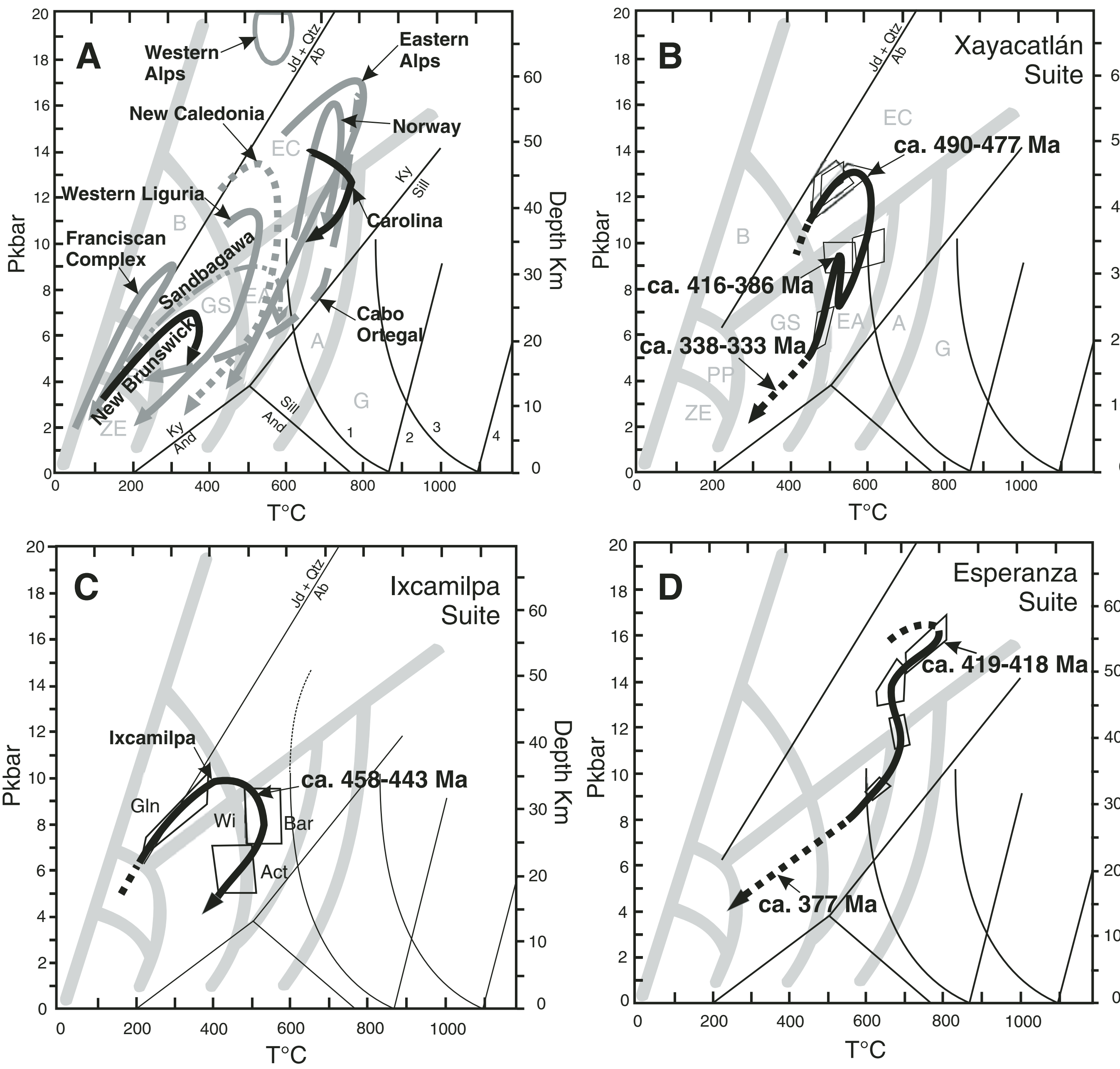

Figure 9. (A) Diagram showing pressure-temperature (P-T) paths from referred subduction and collision complexes (New Brunswick: van Staal et al., 1990; Franciscan, Sanbagawa, New Caledonia, Western Liguria: Ernst, 1988; Western Alps: Tropper et al., 1999; Eastern Alps: Putis et al., 2002; Cabo Ortegal: Puelles et al., 2005; Carolina: Shervais et al., 2003). (B) Pressure-temperature-time (P-T-t) path for the Xayacatlán suite. (C) P-T-t path for the Ixcamilpa suite; age range refers only to the peak metamorphism event. (D) P-T-t path for the Esperanza suite. ZE—zeolite facies; PP—prehnite-pumpellyite facies; B—blueschist facies; EC—eclogite facies; GS—greenschist facies; EA—epidote-amphibolite facies; A—amphibolite facies; G—granulite facies; Gln—glaucophane; Wi—winchite; Bar—barroisite; Act—actinolite. Facies fields from Spear (1995).

suite may have occurred by Late Devonian time through thrusting of the Esperanza suite over the Xayacatlán–El Rodeo suites. Devonian (416–386 Ma) metamorphic ages determined in the Xayacatlán suite (Yañez et al., 1991) may date the epidote-amphibolite facies metamorphism caused by the tectonic loading of the Esperanza suite. Isothermal decompression caused migmatization in metapelites from the Esperanza suite, and coeval emplacement of 372 ± 8 Ma leucogranites (this work). A $^{40}Ar/^{39}Ar$ phengite age indicates that the eclogites passed through the phengite closure temperature (~350 ± 50 °C) at 374 ± 2 Ma. During the Devonian, sediments of the Cosoltepec suite were deposited in a passive margin along the northwestern margin of South America, as suggested by detrital zircon geochronology (Talavera-Mendoza et al., 2005). Based on paleogeographic constraints, the amalgamation of the Cosoltepec suite with the HP suites is inferred to have occurred during the Carboniferous. The Mississippian $^{40}Ar/^{39}Ar$ phengite ages recorded in the Xayacatlán eclogites (336 ± 6 Ma), the Ixcamilpa blueschists (323 ± 6 Ma), the Esperanza pegmatite (345 ± 1 Ma), and a Middle Ordovician leucogranite (335 ± 2 Ma) indicate a regional tectonothermal event that may have been related to the cooling of these suites when they were thrust over the Cosoltepec suite. The emplacement of the Totoltepec stock, dated at 287 ± 2 Ma (Yañez et al., 1991), may have been related to the final stages of collision of Laurentia and Gondwana.

Regional Correlation

The origin and evolution of the Acatlán Complex has been related to the North America Cordillera (Campa and Coney, 1983), the Appalachian chain (Yañez et al., 1991; Ortega-Gutiérrez et al., 1999; Talavera-Mendoza et al., 2005), or northern South America (Murphy et al., 2006; Nance et al., 2006). Based on zircon U-Pb geochronology, some authors (e.g., Ortega-Gutiérrez et al., 1999; Talavera-Mendoza et al., 2005, 2006) further related the evolution of this complex to the closure of both the Iapetus and Rheic Oceans, whereas others (e.g., Murphy et al., 2006; Nance et al., 2006) considered an exclusively Rheic evolution. Although U-Pb detrital zircon signatures rule out a Cordilleran origin for the Acatlán Complex, a conclusive linkage to either Laurentia or northwestern South America Gondwana is disputable with the known data.

The geochronological and thermobarometric data presented here indicate that the Acatlán Complex records major tectonothermal events of Ordovician, Silurian, Devonian, and Carboniferous age, including three distinctive HP metamorphic episodes. They coincide in time, physical conditions, and tectonic settings with the Taconian-Penobscotian, Salinian, Acadian, and Alleghanian orogenies. To our knowledge, such a succession of tectonothermal events has not been reported for northern South America, but they have been recognized along the Appalachian-Caledonian chain. Therefore, a genetic connection and correlation of the Acatlán Complex with the Appalachian-Caledonian system seems straightforward.

Eclogitic rocks of comparable P-T conditions and ages as those of the Xayacatlán suite have been described both in the northern Appalachians (Gaspé and Baie Verte regions; Trzcienski, 1987; Jamieson, 1990) and the southern Appalachians (Western Blue Ridge; Willard and Adams, 1994; Miller et al., 2000). In the Appalachian-Caledonian chain the origin of these eclogites has been related to the collision of arcs either against the Laurentian margin (Grampian, Humberian, Taconian phases) or the Ganderian-Avalonian margin (Penobscotian phase; McKerrow et al., 2000).

On the other hand, blueschists of similar age and metamorphic conditions as the Ixcamilpa suite have been reported in New Brunswick, where they are related to the closure of an intra-Iapetus basin during the Salinian orogeny (van Staal et al., 1990; van Staal, 1994). Available detrital zircon geochronology of the Ixcamilpa suite suggests an origin within an intra-Iapetus basin (Talavera-Mendoza et al., 2005, 2006) near an Avalonian type of terrane.

The Silurian HP metamorphism of the Esperanza suite is partially coeval with Late Ordovician to Late Silurian compressive events (450–423 Ma) related to the accretion of various elements of Ganderia to Laurentia (Salinic orogeny) and with the collision of the Avalonia composite against Laurentia (Acadian orogeny, ca. 421–395 Ma; van Staal and Whalen, 2006). The Late Devonian age, inferred for the uplift of the Esperanza suite and the emplacement of leucogranites, is also coeval (395–360 Ma) with events related to the docking of the Meguma terrane, which are referred to as the Neoacadian orogeny (van Staal and Whalen, 2006). Although the northern Appalachian Acadian orogeny is difficult to trace through the central and southern Appalachians, Rast and Skehan (1993) discussed some evidences of its imprint in those regions. In the southern Appalachians, eclogites of similar metamorphic conditions to those in the Esperanza suite were reported in the Carolina terrane (Shervais and Dennis, 1999). In this terrane the eclogitic metamorphism has been related either to a 570–535 Ma event or to a Late Ordovician–Early Silurian event (Shervais et al., 2003) and predates the emplacement of ca. 414 Ma granites (Samson and Secor, 2000); Hibbard et al., 2002). The second suggested age is coincidental with that of the eclogitic event in the Esperanza suite.

We propose that the Acatlán Complex was formed as part of the Appalachian orogen and may have been located south of the Ouachita fold-and-thrust belt during Permian time (Fig. 10). In the first stages of the breakup of Pangea, the counterclockwise rotation that caused the opening of the Gulf of Mexico could have moved the Acatlán Complex to the southeast, attached to the Maya block. Final adjustments must have occurred before the Early Cretaceous, when the complex reached its present position as suggested by paleomagnetic data (Fang et al., 1989; Böhnel, 1999).

CONCLUSIONS

Thermobarometry and geochronology in the Acatlán Complex reveal that three HP metamorphic events of different P-T conditions and age occurred through the early-middle Paleozoic. The Xayacatlán suite records a complex polymetamorphic evolution involving eclogite facies metamorphism (T = 491–609 °C; P = 12–13 kb) ca. 490–477 Ma, overprinted by epidote-amphibolite and greenschist facies events (T = 500–525 °C; P = ~9.5 kb) of 416–386 Ma and ca. 336 Ma ages, respectively. The metamorphic events are coeval with the Taconian-Penobscotian, Acadian, and late Acadian events of the Appalachian-Caledonian chain. The Xayacatlán suite P-T path is consistent with subduction, followed by exhumation, during an arc-continent collision. Epidote-amphibolite overprinting metamorphism suggests crustal thickening related to the thrusting of the Esperanza suite over the Xayacatlán–El Rodeo suites.

The Ixcamilpa suite underwent epidote-blueschist facies metamorphism at temperatures between 200 and 390 °C and pressures between 6.5 and 9.0 kb probably during the Late Ordovician. This first stage was followed by an increase in temperature from 390 to 580 °C and a decrease in pressure from 9.0 to 6.0 kb, related to the exhumation of the suite, probably in Silurian time.

The Esperanza suite records a Silurian (430 ± 5 Ma to 418 ± 18 Ma) eclogitic metamorphism (T = 730–830 °C; P = 15–17 kb). Thermobarometric and geochronologic data suggest a rapid uplift of this suite, which is related to migmatization and emplacement of leucogranite dikes of 372 ± 8 Ma. In large phengite crystals from eclogite, the $^{39}Ar/^{40}Ar$ system was closed at 374 ± 2 Ma. A retrogressive P-T path passed through the amphibolite, epidote-amphibolite, and greenschist facies fields. The Esperanza

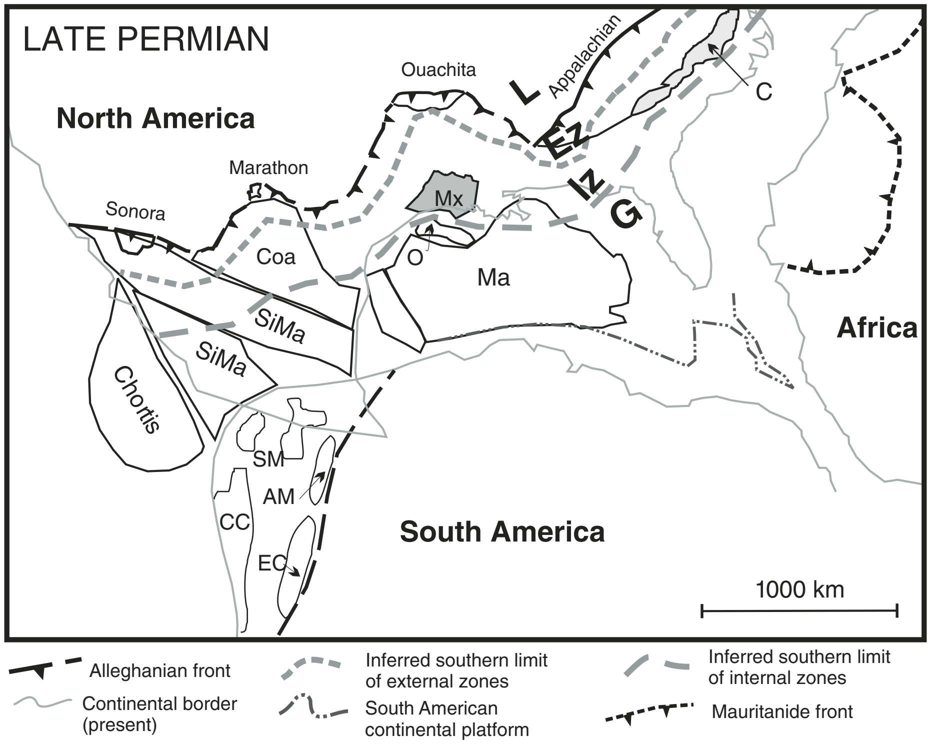

Figure 10. Hypothetical reconstruction of the Alleghanian Appalachian orogen and its extension to northern Mexico, showing a probable location for the Acatlán Complex (in gray). L—Laurentia; Ez—external zones of folds and thrusts without metamorphism; Iz—internal zones including Paleozoic HP suites of varied affinity; G—Gondwanaland. Terranes: CC—Central Cordillera; EC—Eastern Cordillera; AM—Andes of Mérida; SM—Santa Martha block; Coa—Coahuila; O—Oaxaca; Mx—Mixteco; Ma—Maya; SiMa—Sierra Madre; C—Carolina (light gray).

suite P-T path is consistent with metamorphism by collision and sinking of a continental microblock under a continental crust, followed by a relatively fast uplift.

Our $^{40}Ar/^{39}Ar$ geochronology reveals the existence of a generalized tectonothermal event between 346 and 323 Ma, which may have originated by cooling when the HP suites were thrust over the Gondwana-bordering Cosoltepec suite, closing the Rheic Ocean.

According to this work, the geotectonic evolution of the Acatlán Complex records a more complex history than was previously proposed (Yañez et al., 1991; Ortega-Gutiérrez et al., 1999; Murphy et al., 2006). Its tectonic events are significantly similar to those along the Appalachian-Caledonian chain, which are related to the closure of the Iapetus and Rheic Oceans.

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