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The origin of a terrane: U/Pb zircon geochronology and tectonic evolution of the Xolapa complex (southern Mexico)

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Abstract. Terrane analysis has established differences in lithology, style of deformation, metamorphism, and radiometric ages among several basement complexes in southern Mexico. In this paper, we identify similarities in the geologic history of the adjacent Acatlán, Oaxaca, and Xolapa complexes through a U/Pb zircon study on crustal sources and timing of magmatic, metamorphic, and tectonic activity in the Xolapa complex. Our regional tectonic scenario is based on both new chronologic and previously established structural data. Inherited zircon in the Xolapa complex indicates the presence of a Proterozoic (1.0-1.3 Ga) crustal component with an age range that overlaps Grenville crystallization dates (1.0-1.2 Ga) from the Oaxaca basement, and an inherited Grenville crustal component (1.0-1.1 Ga) identified in zircons from the Acatlán complex. The Proterozoic component in the Xolapa complex indicates either that it received sediments from a continental region of Grenvillean age, for example the Oaxaca basement, which is the closest exposed Grenville crust in southern Mexico, or that the Xolapa complex has a Grenville basement. In the latter case, the Xolapa complex has been modified by widespread high-grade metamorphism and large-scale migmatization. Metamorphism and migmatization occurred from 66 to 46 Ma and locally continued into Oligocene time. Magmatism in the Xolapa complex terminated with crustal growth by plutonism, which is characterized by a systematic pattern of eastward-younging crystallization ages, from 35 Ma in the west (west of Acapulco) to 27 Ma in the east (east of Puerto Angel). Metamorphism and migmatization in the Xolapa crust may have originated from a contemporaneous change in several parameters of convergence between the Farallon and North American plates (e.g., rate and direction of subduction) and the early evolution of the Caribbean. This plate reorganization triggered sinistral transtension distributed across the southern Mexican continental margin and the eastward translation of the Chortis block. The eastward younging of the Xolapa plutons also is consistent with the motion of the Chortis block during eastward displacement of the Caribbean plate. This induced a shift of the magmatic arc from its Cretaceous to early Tertiary position along the Xolapa and Chortis blocks to its present mid-Mexican position. We conclude that a single tectonic framework accounts for the Mesozoic and Cenozoic geologic history of the southern Mexican terranes.

INTRODUCTION

The tectonic evolution of continental crust in southern Mexico has been controversial since publication of the first models describing the assemblage of Pangea. Reconstructions based on paleomagnetic data show South America overlapping parts of southern Mexico from early Mesozoic to middle Jurassic time, coincident with the opening of the Gulf of Mexico [e.g., Pindell and Barrett, 1990]. Differences in lithology, style of deformation, and radiometric ages indicate dissimilar origins through time for the southern Mexican crustal complexes and diverse spatial origins both relative to each other and relative to cratonic North America [e.g., Campa and Coney, 1983; Yañez et al., 1991].

Models for the tectonic history of the southern Mexican continental margin include either sinistral or dextral strike-slip tectonics along the northwest trending continental margin of southern North America from late Mesozoic time onward. The ambiguity arises from the uncertain position relative to the North American continental margin of the now subducted spreading ridge that separated the Farallon and Kula plates [Engebretson et al., 1985]. If dextral displacement occurred, it may have been a consequence of dextrally oblique subduction along western North America, particularly during Late Cretaceous to early Tertiary time, which implies a similar tectonic history for the Mexican and the North American Cordillera [e.g., Karig et al., 1978; Engebretson et al., 1985]. In contrast, sinistral displacement is consistent with the eastward movement of the Chortis and Nicaragua blocks during development of the Caribbean (Figure 1) [e.g., Malfait and Dinkelman, 1972; Wadge and Burke, 1983]. In these models the Chortis block was adjacent to the present continental margin of southern Mexico.

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Fig. 1. Tectonic-stratigraphic terranes in southern Mexico modified after Coney and Campa [1987] and sample locations. Inset shows present-day tectonic features of the Caribbean region.

Coney and Campa [1987] suggested that most of the southern Mexican basement comprises several suspect terranes with unknown paleogeography relative to cratonic North America. They delineated the Guerrero, Xolapa, Juarez, Oaxaca, and Mixteca terranes (Figure 1). The Xolapa and Guerrero terranes accreted to the continental margin of Mexico between Late Cretaceous and early Tertiary [e.g., Campa and Coney, 1983; Campa, 1984] or between Middle Jurassic and early Tertiary time [Moran-Zenteno et al., 1986].

Paleomagnetic data indicate similar Middle Cretaceous to Recent paleolatitudes for the Xolapa, Mixteca, and Guerrero terranes, a correspondence of paleopoles for Early Cretaceous sedimentary rocks in the Mixteca terrane with paleopoles for the North American craton, and block rotations along hypothetical northwest striking sinistral strike-slip faults [e.g., Böhnel et al., 1989; Urrutia-Fucugauchi et al., 1987]. Structural data from the Xolapa complex, from the deformation zones along its northern margin and from the northern adjoining terranes (the Xolapa hinterland), indicate differential uplift of the Xolapa complex with respect to its hinterland, subhorizontal north-south extension, and sinistral strike-slip faulting along west-northwest striking shear and fault zones during Late Cretaceous and Tertiary time [Robinson et al., 1990; Ratschbacher et al., 1991; Riller et al., 1992]. We have argued that deformation resulted from interaction between a strike-slip regime established during formation of the Caribbean and an extensional collapse of the Xolapa complex consequent to a change in the plate boundary conditions off southern Mexico [Ratschbacher et al., 1991; Riller et al., 1992]; the subduction direction changed from orthogonal to oblique and progressively younger Farallon lithosphere was subducted [Engebretson et al., 1985].

In this paper, we report a U/Pb zircon study that examines crustal development in southern Mexico. We establish the age range of magmatic and metamorphic activity in the Xolapa complex, and we evaluate whether the radiometric ages support an interpretation of the complex as a late Mesozoic to early Tertiary magmatic arc [Ortega-Gutiérrez, 1981]. We show that reworked Proterozoic crust exists in the Xolapa complex, and we correlate the history of the Xolapa complex with the magmatic and metamorphic history of the adjacent Oaxaca and Mixteca terranes. Finally, we test the existing tectonic model by establishing the time of deformation in the Xolapa complex and relate this to displacement associated with formation of Central America and the Caribbean. A key to understanding the origin of "terranes" in southern Mexico is to identify the history that is common to them.

GEOLOGIC SETTING

The Xolapa complex is 70-100 km wide, extends 600 km along the Pacific coast, and borders the Guerrero, Mixteca, Oaxaca, and Juarez terranes (Figure 1). The Guerrero terrane consists of Jurassic (?) to Early Cretaceous volcanic-sedimentary sequences [Centeno-García et al., 1993] and Late Cretaceous to early Tertiary plutons [Schaaf, 1990]. It may represent an island arc built on an oceanic sequence that received sediments from a continental source [Centeno-García et al., 1993]. The Acatlán complex comprises the multiply deformed basement of the Mixteca terrane. Early

Carboniferous, Triassic, and Jurassic continental sedimentary sequences and Late Cretaceous shallow-water carbonates and turbiditic rocks cover this complex [Ortega-Gutiérrez, 1981; Moran-Zenteno, 1984]. The Oaxaca belt is the oldest known exposed basement in southern Mexico and includes granulite- and amphibolite-grade rocks of Grenville age [Ortega--Gutiérrez, 1981]. Its sedimentary cover consists of Late Ordovician marine deposits and Carboniferous to Permian clastic rocks [Pantoja-Alor and Robinson, 1967] overlain by Aptian and Albian red beds and limestone. The Juarez terrane is poorly known. It has a pre-Mesozoic crystalline basement [Carfantan, 1981] and a deformed, late Mesozoic volcanic and sedimentary sequence [Campa, 1984].

The Xolapa complex is one of the most extensive but least known complexes in southern Mexico. It consists of high-grade metamorphic (wollastonite, cummingtonite, cordierite-sillimanite-andalusite) to migmatitic orthogneiss and paragneiss and a suite of generally undeformed plutons that crop out parallel to the coast [Ortega-Gutiérrez, 1981]. Undeformed and unmetamorphosed sedimentary assemblages, which cover the adjacent terranes, are not found overlying the complex delineated as Xolapa terrane. On the basis of large-scale migmatization of middle and lower crust, and widespread granodioritic, tonalitic, and granitic plutonism, Ortega - Gutiérrez [1981] interpreted the complex as a magmatic arc built through a continuous evolutionary process of magma emplacement and migmatization of crust. The $^{87}Sr/^{86}Sr$ values from granitic rocks between 0.704 and 0.707 support this interpretation [Moran-Zenteno, 1992].

The available age determinations for the Guerrero, Oaxaca, Mixteca, and Xolapa complexes come from Pb-α, U/Pb, Rb/Sr, K/Ar, Sm/Nd dates, and Nd model ages (Figure 2). We do not consider Pb-α dates here because of inherent problems in their interpretation. The assessment of the existing isotopic data and their geologic interpretation, particularly for the Xolapa complex, is restricted because of their incomplete documentation in abstract form.

U/Pb zircon, Rb/Sr whole rock and biotite, and K/Ar biotite dates are available for the Xolapa complex. An orthogneiss north of Acapulco yielded a concordant U/Pb zircon date of 165±3 Ma [Guerrero-Garciá, 1975]. Two U/Pb zircon dates from the Puerto Angel area (Figure 1) [Robinson et al., 1990] indicate an inherited Proterozoic crustal component (1.5±? Ga; a question mark indicates that no errors were reported), a Late Cretaceous metamorphism (78±35 Ma) for a paragneiss, and an early Tertiary intrusion (40±? Ma, concordant age) for a synkinematically foliated tonalite. Rb/Sr whole rock analyses suggest a Jurassic protolith age for two gneisses (195±44 Ma [Guerrero-Garciá, 1975] and 144±7 Ma [Moran-Zenteno, 1992]), and Early Cretaceous (128±7 Ma [Moran-Zenteno, 1992]) and early Tertiary (43±7 Ma [Guerrero-Garciá, 1975]) ages for two plutons. Bellon et al. [1982] reported a K/Ar whole rock age of 35.5±1.7 Ma from dioritic rocks drilled close to the Middle

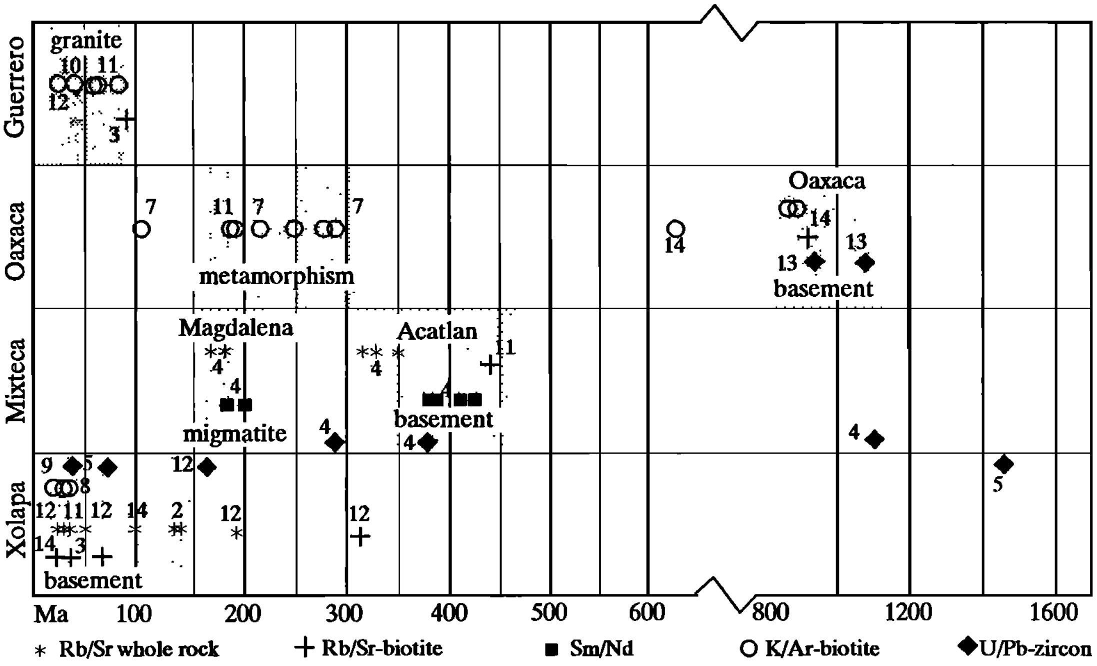

Fig. 2. Available isotopic ages from basement complexes in southern Mexico. References are 1, Moran-Zenteno [1992]; 2, Schaaf [1990]; 3, Yañez et al. [1991 and references therein]; 4, Robinson et al. [1990]; 5, Grajales-Nishimura, [1988]; 6, DeCserna et al. [1962]; 7, Bellon et al. [1982]; 8, Pantoja-Alor, [1982]; 9, Damon et al., [1981]; 10, Guerrero-Garciá [1975]; 11, Anderson et al. [1971]; and 12, Fries and Ricón-Orta [1965]. The oldest Nd model ages cluster around 1.4 Ga in the Xolapa, Oaxaca, and Acatlán complexes [Ruíz et al., 1988; Yañez et al., 1991; Moran-Zenteno, 1992].

America trench southeast of Acapulco. Rb/Sr biotite dates of gneisses and granitoids, with one exception (322±66 Ma, Guerrero-Garciá, 1975]), range between early Eocene and early Miocene ages (48 to 18.5 Ma [Fries and Rincón-Orta, 1965; DeCserna et al., 1962; Schaaf, 1990; Moran-Zenteno, 1992]). Orthogneiss and pluton K/Ar biotite dates range from 37 to 25 Ma [DeCserna et al., 1962; Grajales-Nishimura, 1988]. Nd model ages of the metasedimentary rocks vary from 1.3 to 1.6 Ga [Herrmann et al., 1991; Moran-Zenteno, 1992; Nelson et al., 1992].

Rb/Sr whole rock and biotite dates from the Guerrero terrane cover a similar time range as those in the Xolapa complex [DeCserna et al., 1962; Grajales-Nishimura, 1988]. Basement rocks of the Oaxaca terrane yield Grenville ages of 1080 to 876 Ma (K/Ar biotite, Rb/Sr biotite, U/Pb zircon, Sm/Nd garnet [Anderson and Silver, 1971; Ortega-Gutiérrez, 1981; Patchett and Ruíz, 1987; Robinson et al., 1989b]). A Grenville component (U/Pb zircon, Nd model ages) was detected in the Acatlán complex [Yañez et al., 1991]. In addition, evidence exists for late Paleozoic to early Mesozoic metamorphism in the Oaxaca complex (K/Ar mineral ages [Grajales-Nishimura, 1988]) and for Devonian and Early Carboniferous plutonism and metamorphism and Early Jurassic migmatization and dike intrusion in the Acatlán complex (Sm/Nd whole rock and mineral, U/Pb zircon, Rb/Sr whole rock and mineral ages (Yañez et al., 1991]).

This summary of radiometric data (Figure 2) documents considerable heterogeneity in ages of plutonism and metamorphism among the crustal blocks in southern Mexico, thus supporting the terrane interpretation. In the following discussion, we use petrogenetic analysis and U/Pb zircon geochronology to compare the geologic history of the Xolapa complex with that of adjoining terranes.

ANALYTICAL METHODS

Guided by mapping of key areas and a structural study [Ratschbacher et al., 1991; Riller et al., 1992; also manuscript in preparation 1993], we collected samples from metamorphic, metaigneous, migmatitic, and plutonic rocks. Zircon separates were obtained from 20 to 40 kg samples of unweathered rock by standard crushing, pulverizing, density, and magnetic separation techniques. From 19 samples we analyzed multiple zircon fractions and from two samples a single fraction. Discrimination into fractions is based on magnetic susceptibility, grain size, a petrogenetic classification based on zircon morphology [Pupin, 1983], and internal zircon morphology revealed by a cathodoluminescence aperture attached to a SEM [Vavra, 1990]. All fractions were air abraded [Krogh, 1982]. Mineral dissolution and chemical purification of Pb and U followed the method of Parrish et al. [1987]. Pb and U were loaded together onto outgassed zone-refined Re filaments using the phosphoric acid and silica gel method. Samples were analyzed at the University of Washington on a seven-collector mass spectrometer equipped with a Daly detector and a photomultiplier. Most of the U/Pb analyses were run in static mode with the ^{204}Pb signal measured by a Daly detector. U was analyzed as UO_2 in static mode or less commonly in dynamic mode using the Daly detector. Initial Pb compositions were estimated from Pb isotope analyses of HF-leached feldspars (Table 1) or from the Pb evolution model of Stacey and Kramers [1975]. Data reduction utilized the methods and algorithms of Ludwig [1989, 1990]. Table 2 presents the results of our analyses.

TABLE 1. Isotopic Compositions of Feldspars

Sample	^{206}Pb/ ^{204}Pb	^{207}Pb/ ^{204}Pb	^{208}Pb/ ^{204}Pb
Mu8	18.791	15.619	38.590
Mu13	18.758	15.583	38.408
Mu16	18.758	15.583	38.408
Mx14	18.226	15.579	38.297
Mx15	19.100	15.590	38.400
Mx8	18.840	15.590	38.490
Mu17	18.671	15.555	38.255
Mu14	18.766	15.582	38.826
Mx10	18.699	15.567	38.281
Mx12	18.710	15.557	38.308
Mu9	18.767	15.609	38.437

Plagioclase feldspars were leached for 2 min in a 5% HF solution. Dissolution by stepwise leaching indicated that the isotopic composition of the leachate did not change after the first leaching. Pb was separated by HBr-HCl ion-exchange chemistry and was loaded onto outgassed, zone-refined Re filaments using H_3PO_4-silica gel method. Pb was analyzed in static mode at 1300°C, using faraday collectors for all four isotopes. Values are corrected for mass fractionation of 0.12 ± 0.04%/a.m.u., and precisions are better than 0.1% (2σ).

RESULTS

Samples from the Xolapa complex comprise two groups: crystal-plastically deformed metamorphic rocks (migmatites and gneisses) and undeformed plutons. The purely morphologic zircon classification of Pupin [1983] reflects this grouping (Figure 3). In addition, cathodoluminescence analysis revealed inherited cores in almost all zircon fractions of the metamorphic and metaigneous rocks (with the exception of Mu10, Figures 4a and 4b). In contrast, only rarely did this technique detect cores in the zircons from the plutons (Figures 4c and 4d). Optical microscopy failed to identify cores in either group. Morphology of different samples from the same group varies only slightly. A description of rock association and type, zircon characteristics, and zircon fractions used for analysis and an interpretation of individual dates are presented in the Appendix. Figures 5 through 7 illustrate the distribution of zircon isotopic compositions in concordia diagrams. The distribution of U/Pb zircon ages and the range of magmatic and metamorphic events in the Xolapa complex are summarized in Figures 8 and 9.

Migmatites and Gneisses

Zircon from migmatites and gneisses typically yielded discordant dates, and fractions from several rocks define nonlinear discordia suggesting heterogeneous populations of

TABLE 2. Zircon Isotopic Compositions and Apparent Ages †‡

			Concentrations, ppm		Isotopic Compositions				Ages, Ma	
Sample	Size, μm	Weight, mg	U	Pb*	^{206}Pb/^{204}Pb	^{206}Pb/^{207}Pb	^{206}Pb/^{208}Pb	^{206}Pb*/^{238}U	^{207}Pb*/^{235}Pb	^{207}Pb*/^{206}Pb*
						Xolapa Complex				
Mu8, migmatite of Pochutla-Puerto Angel (96°29'09"W, 15°42'00"N)										
F20f	40-75	0.71	838.33	11.808	971.704	12.2621	8.39435	87.4	120.5	835.5(3.8)
F30g	40-75	0.90	554.17	7.4967	1419.93	13.6111	9.71809	86.4	113.5	726.5(5.9)
F80g	75-125	2.19	327.25	5.7953	911.133	13.2179	10.1001	112.1	155.3	878.3(2.9)
F60f	75-125	0.91	787.35	12.384	585.888	11.3843	6.89095	93.2	121.5	723.5(4.4)
E80g	75-125	2.51	744.64	11.483	4490.74	14.4260	11.2788	99.1	134.4	813.8(1.5)
Mu10, migmatite of Puerto Escondido (97°05'46"W, 15°50'45"N)										
E80	75-125	2.72	517.97	54.096	12621.9	13.6273	7.23048	615.5	703.6	995.8(.93)
F90	75-125	1.33	548.52	51.982	10702.3	13.6099	7.31225	561.8	655.5	992.8(.99)
E30	40-75	0.85	504.13	45.539	7233.46	13.2966	7.80581	539.6	642.5	1023.6(1.1)
Mu12, gneiss of Cruz Grande (99°07'53"W, 16°48'00"N)										
F20	40-75	0.61	1491.3	12.057	1029.91	15.9156	6.36031	49.8	51.6	132.9(8.1)
EF60	75-125	0.85	1333.9	13.678	1536.09	15.7286	8.02349	64.6	73.8	381.8(5.7)
F30	40-75	0.58	1822.4	15.508	1100.38	15.7857	6.50094	53.2	56.8	209.9(14)
Mu13-Mx3, gneiss of La Palma (99°29'42"W, 17°04'54"N)										
A15	125-165	1.14	857.21	12.092	856.051	13.8069	8.71585	87.3	100.9	435.4(2.8)
F36	125-165	0.75	1042.5	14.435	1569.79	15.3421	9.01184	88.0	102.6	456.4(4.6)
F20	40-75	0.32	919.99	10.288	579.743	13.2301	7.03465	70.1	74.9	230.7(19)
Mu16-Mx6, migmatite, south of Tierra Colorada (99°35'19"W, 17°10'53"N)										
E1	125-165	1.10	1025.4	13.564	1106.73	14.7548	9.89522	83.5	95.3	401.6(2.7)
F67	125-165	0.94	914.22	12.528	435.109	11.5142	6.68677	79.8	89.3	351.5(3.8)
F20	75-125	1.36	1418.9	18.215	1610.62	16.2300	10.1995	81.8	90.1	314.7(2.3)
F20	40-75	1.12	1403.0	15.947	1520.80	16.6514	10.7918	73.0	77.6	220.7(2.6)
Mx14, migmatite, San Gabriel Mixtepec (97°05'36"W, 16°06'16"N)										
A0	125-165	11.4	482.14	10.760	4025.60	18.5965	8.01804	140	143.6	204.6(2)
A9	125-165	6.30	197.11	5.5268	4269.61	16.9012	9.35866	178.5	198.8	446.6(5.8)
A0b	75-125	5.96	212.26	5.2895	332.408	10.7038	4.32361	132.7	134.8	172.0(9.7)
F60a	125-165	4.01	197.48	4.5391	2825.49	18.0273	7.53176	144.7	148.7	213.2(12)
F60b	125-165	2.38	207.25	4.6951	798.366	14.6805	5.98889	136.8	139.8	191.8(24)
F1	75-125	3.23	200.21	4.6128	713.519	14.3177	5.75492	136.4	138.2	169.1(17)
Mx15, gneiss, San Juan Lachao (97°08'24"W, 16°10'54"N)										
E15	125-165	1.59	951.44	15.541	1128.60	13.9994	9.33598	101.9	123.2	557.4(4.2)
F15a	125-165	1.51	936.78	12.231	879.679	14.3031	9.04029	81.1	90.6	349.6(5.7)
F15b	40-75	0.91	928.58	14.280	1592.54	15.1706	11.1369	98.8	116.2	488.7(7.1)

TABLE 2. (continued)

Sample	Size, µm	Weight, mg	Concentrations, ppm		Isotopic Compositions			Ages, Ma		
			U	Pb*	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$	$^{206}\mathrm{Pb}/^{207}\mathrm{Pb}$	$^{206}\mathrm{Pb}/^{208}\mathrm{Pb}$	$^{206}\mathrm{Pb}^*/^{238}\mathrm{U}$	$^{207}\mathrm{Pb}^*/^{235}\mathrm{Pb}$	$^{207}\mathrm{Pb}^*/^{206}\mathrm{Pb}^*$
Mx8, migmatite of River Papagayo (99°30'00"W, 16°47'45"N)										
E20	125-165	2.52	752.39	13.634	6429.87	19.3113	9.68876	116.8	119.6	175.4(4.6)
E0	75-125	2.47	836.18	14.904	3075.00	18.1162	9.04740	113.6	115.9	163.9(4.6)
F20a	75-125	1.20	578.91	10.596	1357.12	16.3080	7.97232	114.5	119.7	225.3(10)
F20b	125-165	1.21	668.31	12.370	1543.14	17.0101	8.23424	116.2	118.6	166.8(8.1)
Mx11, gneiss, Ometepec (98°30'16"W, 16°39'16"N)										
A0	125-165	4.55	396.44	6.6648	1445.09	16.8441	8.09976	105.8	108.2	163.22(12)
A5	125-165	7.29	339.44	6.2914	362.961	11.1811	5.11193	102.4	104.6	154.4(9.2)
A0a	75-125	5.97	484.47	7.1433	1803.11	17.5043	8.44725	93.5	95.7	152.1(9.7)
A0c	75-125	3.92	479.60	7.3789	1567.17	17.2104	8.30111	97.4	99.1	140.4(13)
ML39, mylonitic gneiss, north of Pochutla (96°29'47"W, 15°51'48"N)										
EF30	75-125	2.62	434.90	27.086	9006.24	14.9626	15.0965	399.7	461.9	784.6(1.1)
EF3	40-75	1.24	488.37	25.174	5842.27	15.3799	12.8538	330.6	380.4	695.9(7.2)
Mu17, granodiorite, southeast of Atoyac (100°21'34"W, 17°07'63"N)										
F20	40-75	0.64	779.01	5.1766	260.293	9.67873	3.32865	34.6	35.2	75.2(25)
F30g	75-125	1.29	656.78	3.9609	589.750	13.9506	4.97532	35.0	35.3	52.0(16)
Mu14, Tierra Colorada granodiorite (99°30'04"W, 17°07'54"N)										
F20	40-75	2.30	467.28	2.6965	566.052	13.5379	5.54642	34.2	35.2	104.4(9.4)
F20	75-125	1.55	479.64	2.6855	719.934	14.9408	6.13452	34.3	34.4	39.8(14)
F30	75-125	1.61	385.28	2.1214	640.490	14.3251	5.71443	34.1	34.3	51.0(19)
Mx10, tonalite of San Marcos (99°14'34"W, 16°44'43"N)										
A0	125-165	1.11	427.58	2.2944	559.605	13.4331	5.25599	30.8	32.0	118.8(4.6)
E0	75-125	4.47	498.76	2.5823	573.094	13.8291	5.66910	30.6	30.7	40.7(7)
E0	75-125	4.54	460.73	2.3738	621.485	14.2649	5.75501	30.7	30.6	29.1(7.4)
F0	75-125	4.56	497.57	2.4752	975.581	16.1331	6.77663	30.7	31.0	51.7(6.1)
F12	40-75	5.08	548.31	3.0154	602.236	14.1073	5.54353	32.2	32.2	30.5(5)
Mu11, granodiorite of Cruz Grande (99°07'53"W, 16°48'00"N)										
F14	40-75	0.43	545.92	3.6184	143.952	6.76541	2.52685	31.7	31.6	29.2(65)
Mu20, granodiorite, north of Pinotepa Nacional (98°03'21"W, 16°40'53"N)										
F30	40-75	0.88	607.75	3.4049	293.274	10.33458	3.61921	30.1	30.4	52.3(25)
Mx12, tonalite of Pinotepa Nacional (97°45'07"W, 16°09'48"N)										
E20	125-165	4.37	315.66	1.5540	442.758	12.5216	3.71342	27.2	27.4	43.9(14)
E0	75-125	3.25	361.21	1.7415	420.633	12.37256	3.47486	26.4	26.1	2.1(19)
F50	125-165	4.65	311.28	1.4705	517.953	13.27692	3.90653	26.4	26.8	57.1(14)
F0	75-125	3.93	362.07	1.6116	840.496	15.58459	4.08258	25.8	25.9	40.5(12)

TABLE 2. (continued)

			Concentrations, ppm		Isotopic Compositions				Ages, Ma	
Sample	Size, μm	Weight, mg	U	Pb*	^{206}Pb/^{204}Pb	^{206}Pb/^{207}Pb	^{206}Pb/^{208}Pb	^{206}Pb*/^{238}U	^{207}Pb*/^{235}Pb	^{207}Pb*/^{206}Pb*
Mu9, granodiorite, northwest of Pochutla (96°38'07"W, 15°51'00"N)										
F20	40-75	1.31	614.74	3.4540	255.400	9.63915	2.54024	26.6	26.6	23.2(17)
F25	75-125	1.69	509.87	2.4666	447.217	12.50257	4.25195	27.2	27.7	71.5(14)
F30	75-125	1.58	459.90	2.2633	363.441	11.51052	3.97353	26.9	27.0	36.6(16)
ML52, granite of Huatulco, (96°14'17"W, 15°45'16"N)										
F20	40-75	0.81	1121.8	5.8245	629.506	14.13706	4.43300	30.1	30.7	75.6(12)
F20	125-165	1.68	1323.0	6.7872	683.076	14.73807	4.07659	28.8	28.7	18.6(7.3)
F20	40-75	1.06	1315.9	6.5358	641.536	14.20991	4.53164	28.6	29.2	78.4(15)
Mu18, granite, south of Putla de Guerrero (97°56'48"W, 16°53'12"N)										
F20	40-75	1.05	390.32	2.2724	192.732	7.9063	3.26743	29.7	32.6	251.2(35)
F30	40-75	0.93	349.57	2.4187	362.782	10.9928	4.79112	42.3	46.3	259.5(41)
						Oaxaca Complex				
Mx25, gneiss, west of San Sebastian de Coatlan (96°43'08"W, 16°19'32"N)										
F12	75-125	0.99	227.64	38.170	5805.15	13.39732	7.54133	966.4	975.0	994.5(1.4)
F100	40-75	0.87	220.91	36.700	8863.64	13.56645	7.59914	960.7	970.3	992.2(1.4)
MM50, granite, Candelaria Loxicha [96°30'00"W, 15°52'39"N)										
F30	75-125	2.32	65.809	10.086	7073.96	13.64695	13.6058	935.6	945.5	968.6(1.7)
F50	125-165	3.12	59.674	9.1217	4106.55	13.3956	12.9772	928.9	940.1	966.4(2.1)
F40	40-75	0.92	64.115	9.7899	3428.84	13.27366	12.7228	930.7	941.6	967.3(3.4)

[*] Radiogenic Pb.

[†] All fractions were nonmagnetic at 1.8 amps, -1° tilt, 12°slope on Frantz magnetic separator or magnetic at 1.6 amps, 1° tilt, 12° slope. Values in microns indicate size range of analyzed zircons. Zircon fractions were air abraded for 1 to 40 hours. Other analytical procedures are decribed in the text and Table 1.

[‡] Corrected for mass fractionation and blank; see Table 1. Uncertainty in the calculated ages is stated at the 2σ level.

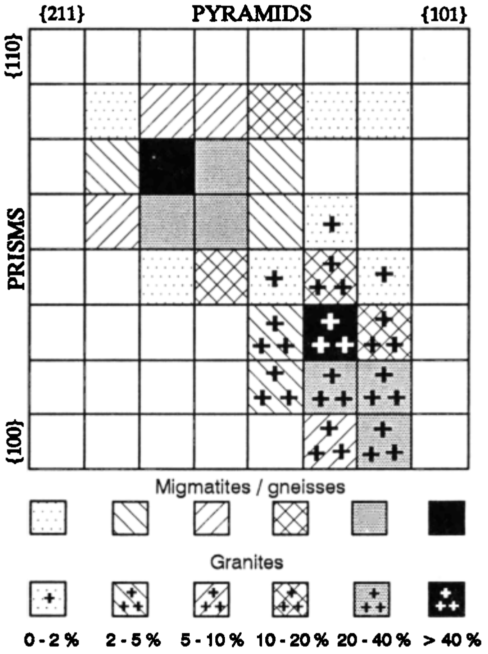

Fig. 3. Petrogenetic rock classification based on zircon morphology [Pupin, 1983]. Zircons from the Xolapa complex group in two populations: zircons from gneisses and migmatites have large steep {211} and small flat {101} pyramids with {110} or {110>>100} prisms; zircons from undeformed plutons have flat {101} or {101>>211} pyramids and {100} or {100>>110} prisms. Percentages indicate fraction of population with indicated typology.

inherited zircon. In spite of these complications, we infer that a major latest Cretaceous to mid-Tertiary thermal event (66 to 46 Ma, seven of 10 samples) affected most rocks in the Xolapa complex (Figures 5 and 8). Data obtained from Mu10, a migmatite, and Mx11, a gneiss, do not have an unambiguous age interpretation. The youngest age (25±11 Ma) on migmatization (Mu10, Puerto Escondido, southeastern Xolapa complex) indicates that high-grade metamorphism locally reached the Oligocene. Robinson et al. [1990] reported zircon analyses from a paragneiss from the Puerto Angel area that define concordia intercepts at 1.5±? Ga and 78±35 Ma; our sample from this area (Mu8) yielded intercepts at 1268±15 Ma and 48±1 Ma. They also describe a synkinematic tonalite from this region with a concordant U/Pb age of 40±? Ma.

One sample (ML39) defines an age of 180±9 Ma (Figure 5j). Similar Rb/Sr and Sm/Nd whole rock and mineral ages were reported from the Acatlán complex (San Miguel intrusions, 175±3 and 172±1 Ma and Magdalena migmatites, 204±4 and 163±2 [Yañez et al., 1991]. The 131.8±2.2 Ma age obtained from a migmatite north of Puerto Escondido (Mx14) is problematic because no evidence exists for similar U/Pb ages elsewhere in the Xolapa or adjoining terranes; however, granites and gneisses from the Xolapa complex do have similar Rb/Sr whole rock ages (144±7, 138±12, and 128±7 Ma [Moran-Zenteno, 1992]).

Zircons with or without cores from both migmatites and gneisses yielded upper intercept dates between 1.0 and 1.3 Ga (Figures 5 and 8). These ages correspond to Nd model ages from the Xolapa crust [Herrmann et al., 1991; Moran-Zenteno, 1992; Nelson et al., 1992]. We interpret these dates as crystallization ages of the migmatite and gneiss protoliths. Cathodoluminescence analysis demonstrates that the fractions comprise zircons of three different types: (1) well-rounded grains without overgrowths in one sample (Mu8), (2) rounded cores with overgrowths in most samples, and (3) no evidence of inherited cores in the zircons of two samples (Mu10 and ML39).

To further compare the geology of the Xolapa with the adjacent Oaxaca complex, we augmented the data base for the Oaxaca by dating two samples from its southern margin (Figures 6b and 6c and 8). They yielded crystallization ages (upper intercept) of 1006±17 (Mx25) and 982±36 Ma (MM50).

Undeformed Plutons

Oligocene granitic, granodioritic, and tonalitic plutons aligned parallel to the coast mark another event in the evolution of the Xolapa complex. Almost all plutons have a minor inherited component (e.g., Mu9, Mu14, and Mx10, Figure 7) indicated by slight reverse discordance of one or two zircon fractions from each sample. Crystallization ages of the granitoids vary systematically with location, from 35 Ma in the western to 27 Ma in the eastern part of the Xolapa complex (Figure 9a); the data describe a statistically significant trend in crystallization ages. A similar trend (Figure 9a) that is statistically less significant, reflects cooling, and is permissive of a different interpretation, is present in Rb/Sr and K/Ar biotite ages in the Xolapa complex [Guerrero-Garciá, 1975; Damon and Coney, 1983] and in the Guerrero terrane [Schaaf, 1990].

For two of our samples Rb/Sr biotite cooling ages are available for the same pluton [Schaaf, 1990]: a granodiorite (Mu17) north of Acapulco yielded a zircon date of 35 Ma and a biotite date of 28.3 Ma; the Tierra Colorada granodiorite (Mu14) yielded a zircon date of 34.3 Ma and a biotite date of 26.3 Ma. These results suggest a 7-8 m.y. period between crystallization (assumed U/Pb closure in zircon, 700°C) and cooling to 300°C (assumed Rb/Sr closure in biotite), corresponding to a (model dependent) cooling rate of 50°-60°C/m.y.

Age Limits on Deformation of the Xolapa Complex

A belt of tectonites marks the boundary between the Xolapa complex and the adjacent terranes to the north [Ratschbacher et al., 1991; Riller et al., 1992]. The 34.3 Ma crystallization age of the Tierra Colorada pluton (Mu14) places a lower bound on crystal-plastic deformation along one segment of the deformation zone; both Robinson et al. [1989a] and Riller et al. [1992] observed the pluton crosscutting the mylonites. The 62±20 Ma La Palma gneiss (Mu13), the 66 to 46 Ma gneisses in the Xolapa complex, and the Albian to Cenomanian sedimentary rocks (Morelos Formation, Mixteca terrane [Fries, 1962]), all have evidence of crystal-plastic deformation [Riller et al., 1992]. Thus mylonitization along the

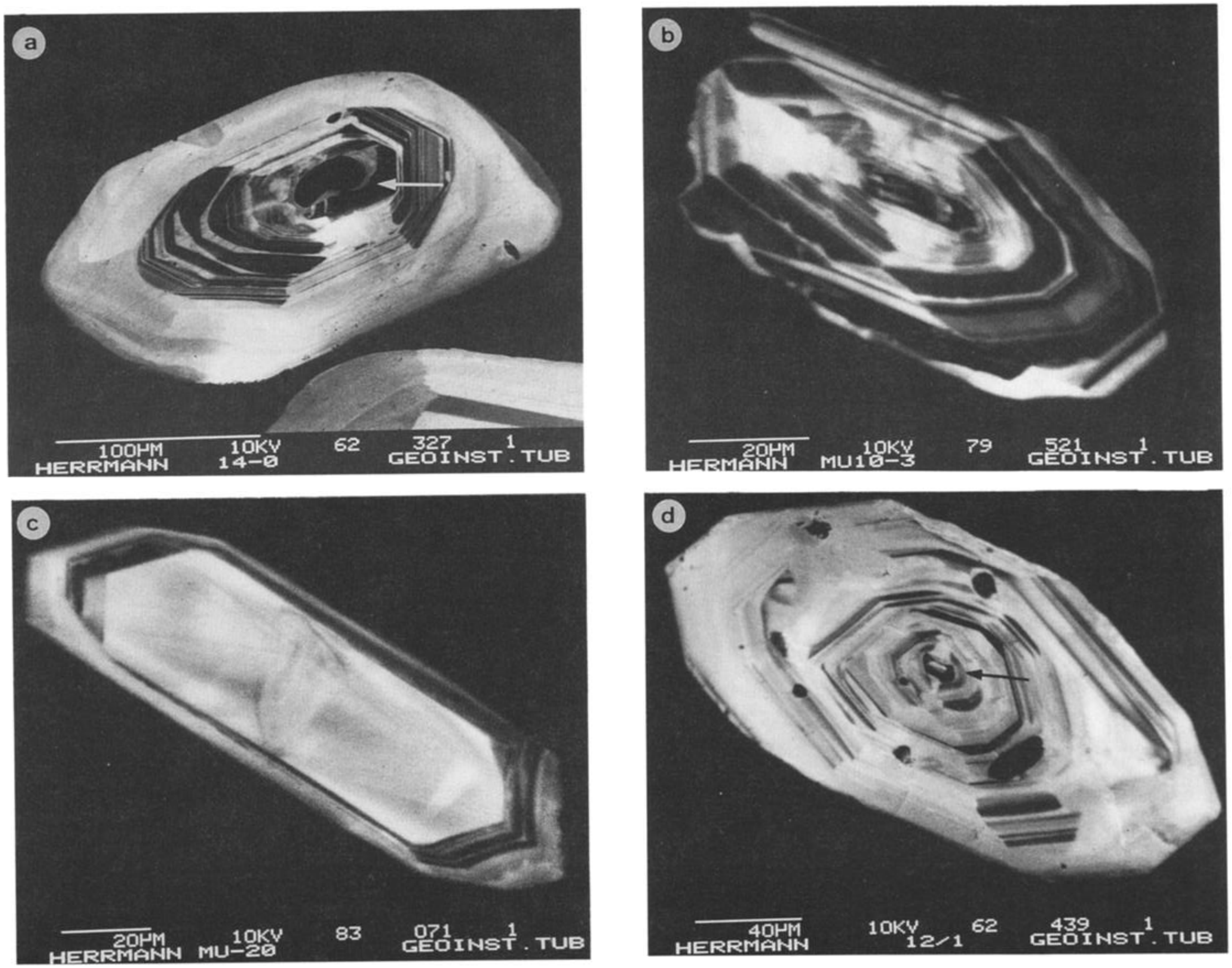

Fig. 4. Cathodoluminescence photomicrographs of zircons: (a) Mx14, migmatite, zircon with inherited core (at arrow head), (b) Mu10, migmatite, zircon without inherited core, (c) Mu20, granodiorite, zircon without core, and (d) Mx12, tonalite, zircon with small inherited core (at arrow head).

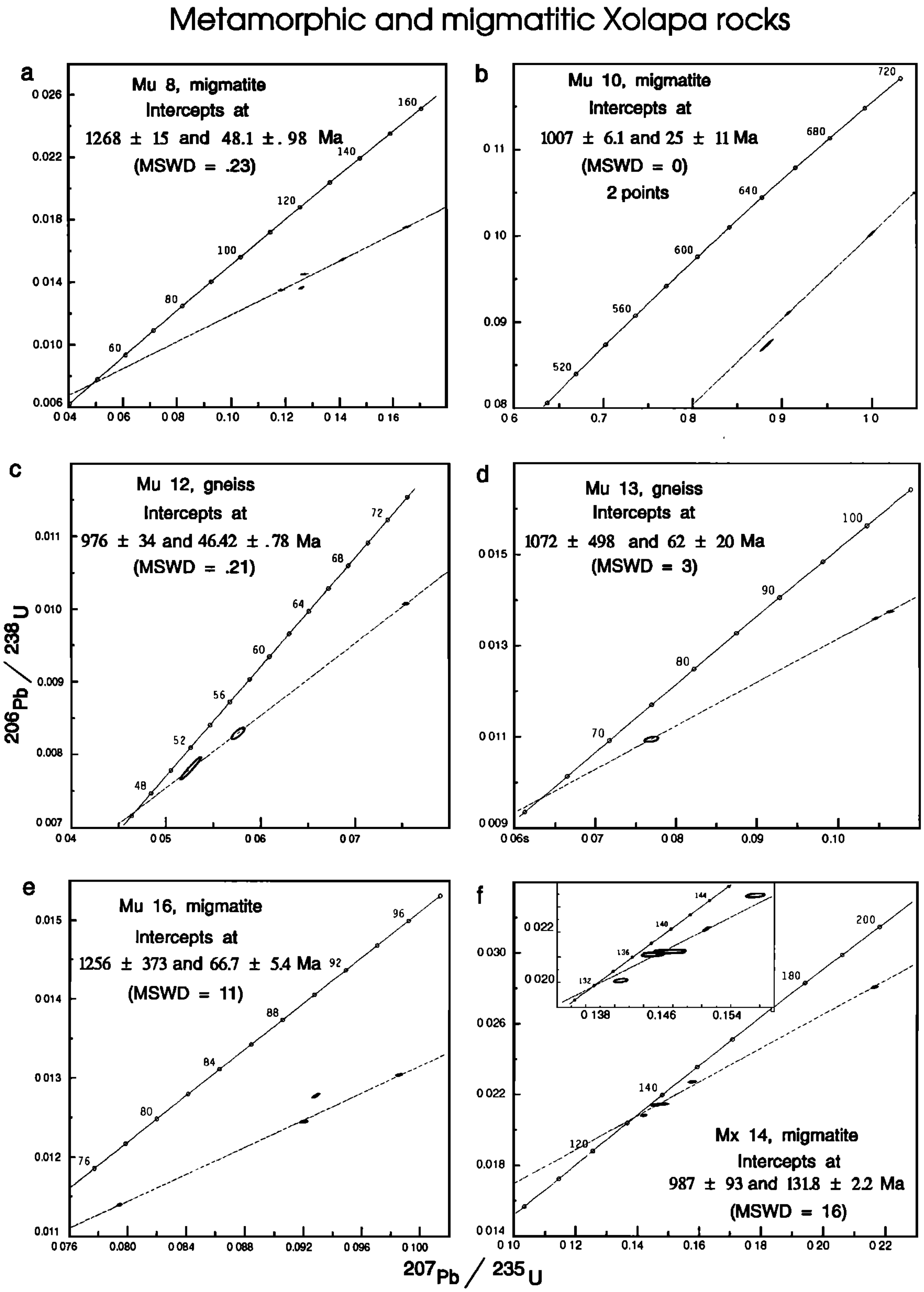

Fig. 5. Concordia diagrams illustrating isotopic composition of zircon from metamorphic and migmatitic rocks of the Xolapa complex. Locations of samples and isotopic ratios are given in Figure 1 and Table 2. See Appendix and text for interpretation.

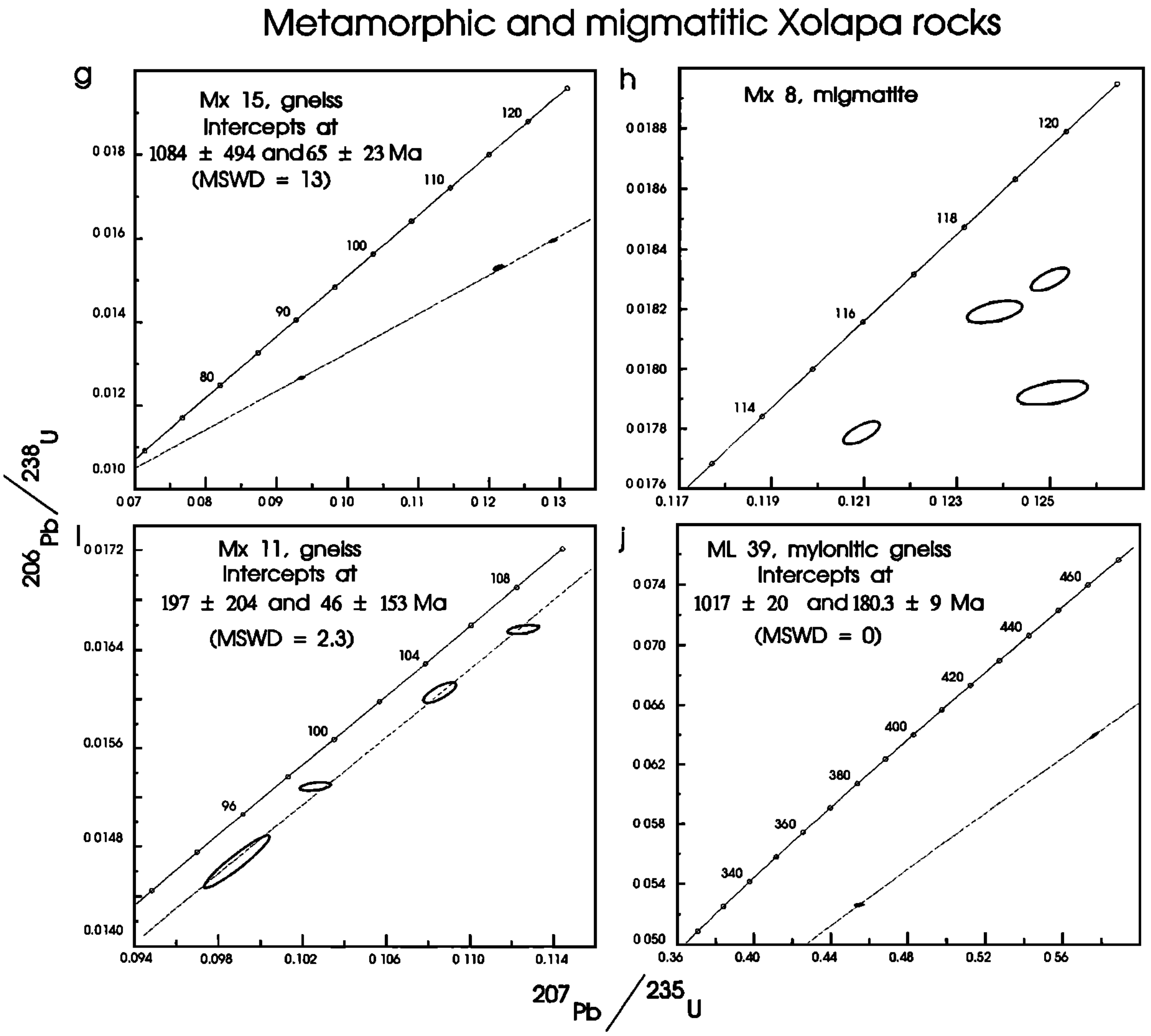

Fig. 5 (continued)

Tierra Colorada shear zone occurred during Paleocene and Eocene time. Our zircon date (34.3 Ma) on the Tierra Colorada granodiorite is in contrast to a 55±1 Ma Rb/Sr isochron, obtained from eight whole rock analyses of different plutons sampled over a distance of approximately 80 km (Acapulco, Tierra Colorada, Cruz Grande [Moran-Zenteno, 1992]). We believe the assumption that the Rb/Sr samples come from apophyses of a single cogenetic pluton is incorrect.

The 40±? Ma U/Pb zircon age, obtained for a synkinematic tonalite at Puerto Angel [Robinson et al., 1990], provides additional evidence for (middle) Eocene crystal-plastic deformation within the Xolapa complex. Late Eocene brittle-ductile transtensional faulting coincided with final cooling of the Tierra Colorada granodiorite. Oligocene to possibly Recent brittle, sinistral shearing affected undeformed plutons [Ratschbacher et al., 1991; Riller et al., 1992] and tilted Miocene volcanic rocks (Papagayo Formation [DeCserna, 1965]).

DISCUSSION

Our zircon analyses demonstrate that the Xolapa complex contains a Proterozoic crustal component and that the history of the complex includes Late Cretaceous to early Tertiary high-grade metamorphism and migmatization and Oligocene crustal growth by magmatic accretion. We use this geochronologic framework to discuss the geologic history of the Xolapa complex, and we identify similarities among the basement complexes in southern Mexico.

The study provides evidence for Grenville age rocks as a source for the old crustal component in the Xolapa complex. The homogeneity of these ages throughout the Xolapa crust (1268±15 to 976±34 Ma for five samples, and three samples with larger errors that also overlap this range; Figures 5 and 8) indicates that the source(s) had, within 200-300 m.y., similar ages, or that sources of variable ages were effectively and uniformly homogenized. We propose that the Proterozoic

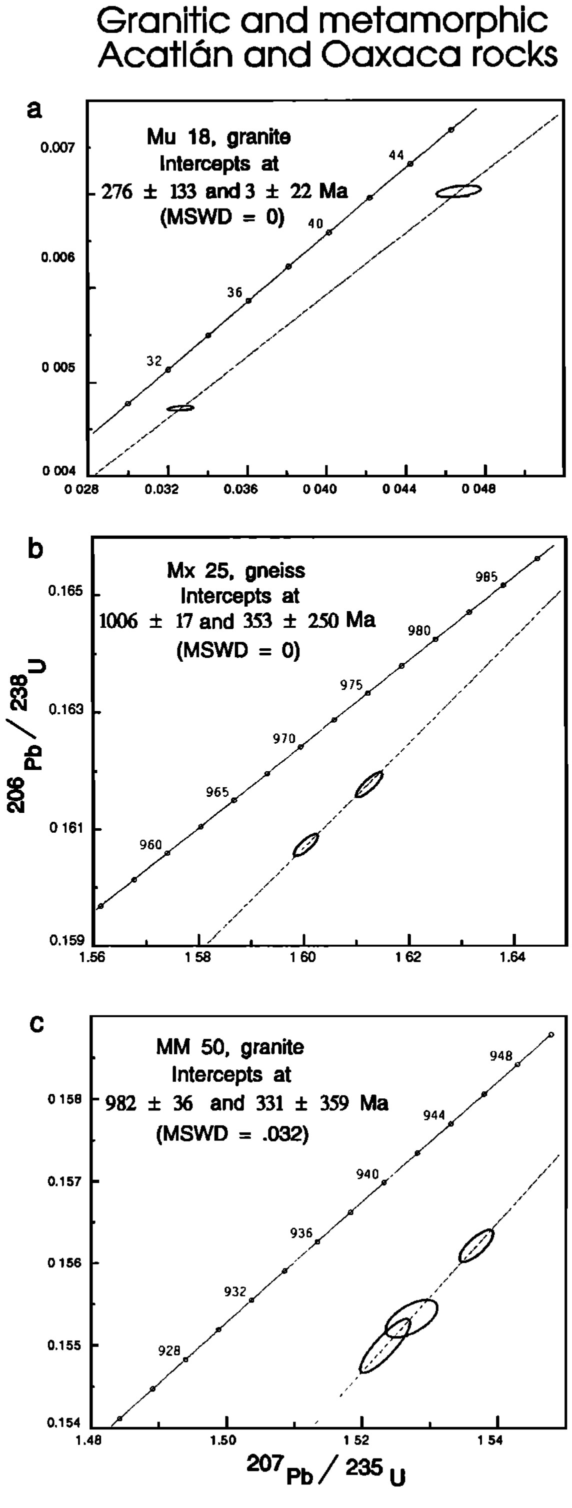

Fig. 6. Concordia diagrams illustrating isotopic composition of zircon from granitic and metamorphic rocks of the Acatlán and Oaxaca complexes. Locations of samples and isotopic ratios are given in Figure 1 and Table 2. See Appendix and text for interpretation.

crustal component either originated from sedimentary input from a Grenville age source or reflects the presence of reworked Grenville crust in the Xolapa complex. In the first case, a continental region of Grenville age shed sediments onto the Xolapa complex. A likely tectonic setting is an accretionary prism associated with a subduction zone, for example, the Triassic-Cretaceous trench-arc system of southwestern North America. The ages indicate that the Xolapa complex received sediments from a cratonic area with a spectrum of ages similar to regions that currently border the Xolapa complex; i.e., the Oaxaca and Acatlán complexes. In the second case, the Xolapa and its northeastern hinterland share the same basement; however, in contrast to the Oaxaca complex, the Xolapa complex was pervasively modified by Late Cretaceous to early Eocene metamorphism and migmatization and by late Eocene and Oligocene plutonism. Grenville age crust is found in small inliers in northern and eastern Mexico, in the Oaxaca terrane, which is the only known exposed Grenville crust in southern Mexico, and in northern South America (Santa Marta and Santander massifs of Colombia) [Patchett and Ruíz, 1987]. The Xolapa complex may have received its Proterozoic component from any of these places. An additional possible source of the Proterozoic signature is the Acatlán complex and related, but mostly covered, Paleozoic sedimentary rocks west of the Grenville crust. Yañez et al. [1991] interpreted the Acatlán complex as part of an Acadian orogenic wedge receiving its sedimentary input from Grenville complexes to the east, e.g., the Oaxaca complex. Paleozoic additions to the Acatlán crust (e.g., the Esperanza granitoids) were less extensive, and, if a source for the Xolapa complex, are not obvious in our isotopic results. However, such Paleozoic additions may explain zircon population heterogeneities that render the interpretation of some of our migmatite samples impossible (samples Mx8 and Mx11).

Parsimony calls for a model which ties the Xolapa complex to the neighboring Oaxaca and Acatlán complexes. This is supported by the following arguments. First, tectonic and paleomagnetic studies indicate an absence of large-scale lateral or convergent displacements among the terranes in southern Mexico [Ratschbacher et al., 1991; Riller et al., 1992; Böhnel et al., 1989]. Second, our results (samples Mx25 and MM50) and published data for the Oaxaca basement [e.g., Anderson and Silver, 1971; Patchett and Ruíz, 1987] demonstrate its Grenville age and indicate that the Acatlán sedimentary rocks may have originated from the Oaxaca complex [Yañez et al., 1991]. Third, morphologic studies of zircon from the Xolapa complex indicate crustal recycling. Migmatitic paragneiss with rounded zircons (Mu8) of Grenville age may either indicate silt (grain size 0.1 to 0.3 mm, quartz equivalent [Engelhardt, 1973]) derived from erosion of Oaxaca or Acatlán rocks or that zircons were rounded by corrosion during Xolapa migmatization (for discussion of this process, see Watson and Harrison [1983] and Vavra [1990]. Zircons with rounded cores and euhedral overgrowths in migmatites may again indicate either Oaxaca or Acatlán sedimentary input or migmatitic corrosion, followed by new growth during high-grade metamorphism. We interpret zircons without cores but with isotopic evidence of a Grenville age as zircons that crystallized in the Oaxaca basement and underwent severe Pb loss during Xolapa metamorphism and migmatization.

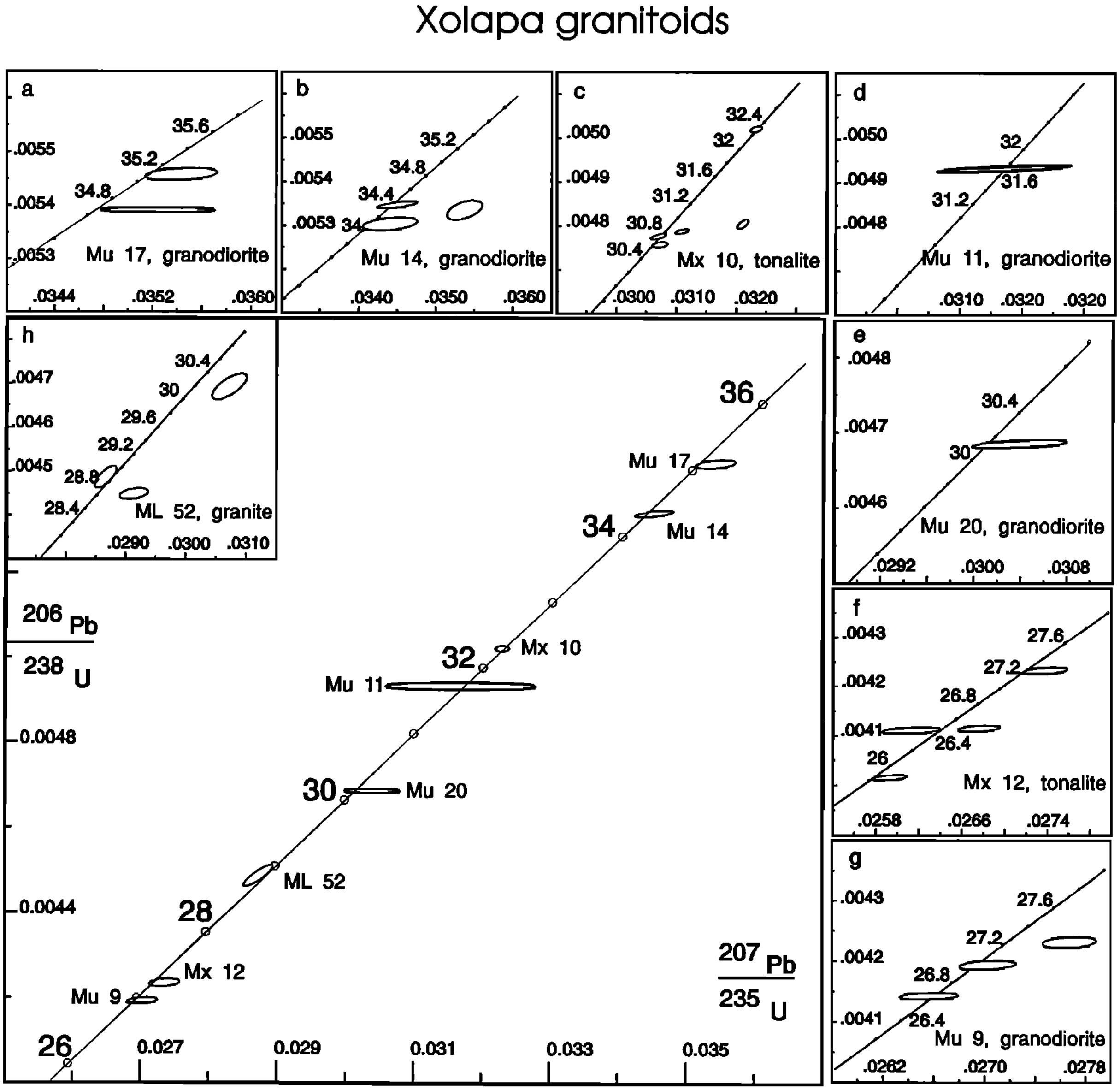

Fig. 7. Concordia diagrams illustrating isotopic composition of zircon from undeformed plutonic rocks of the Xolapa complex. Locations of samples and isotopic ratios are shown in Figure 1 and Table 2. See Appendix and text for interpretation.

Inference of a Jurassic or Cretaceous event on the basis of a Middle Jurassic zircon date (165±3 Ma) from an orthogneiss [Guerrero-Garciá, 1975], our single Early Cretaceous date (131.8±2.2 Ma, Mx14) from a migmatite, and the approximately coeval Rb/Sr dates (144±7, 138±12, 128±7 Ma [Moran-Zenteno, 1992]) from orthogneisses and granites, is speculative. The dates may reflect magmatism, migmatization, and high-grade metamorphism associated with subduction, and we suggest that during the Jurassic and Cretaceous a magmatic arc developed along the southern margin of the North American craton (compare to Ortega-Gutiérrez [1981]; Damon and Coney [1983] and Engebretson et al. [1985]).

The Xolapa complex records high-grade metamorphism and large-scale migmatization peaking at 66 to 46 Ma. The duration of this thermal activity coincides with a time (70 to 40 Ma) of fast sinistral oblique subduction of the Farallon plate beneath the southern North American continental margin [Engebretson et al., 1985] and is consistent with the interpretation of the Xolapa complex as a magmatic arc with its thermal activity peaking in early Tertiary time. Widespread crustal growth by plutonism of granodioritic, tonalitic, and granitic composition occurred between 35 and 27 Ma, with one Rb/Sr whole rock date (43±7 Ma [Guerrero-Garciá, 1975]) possibly indicating local earlier activity. This may represent the

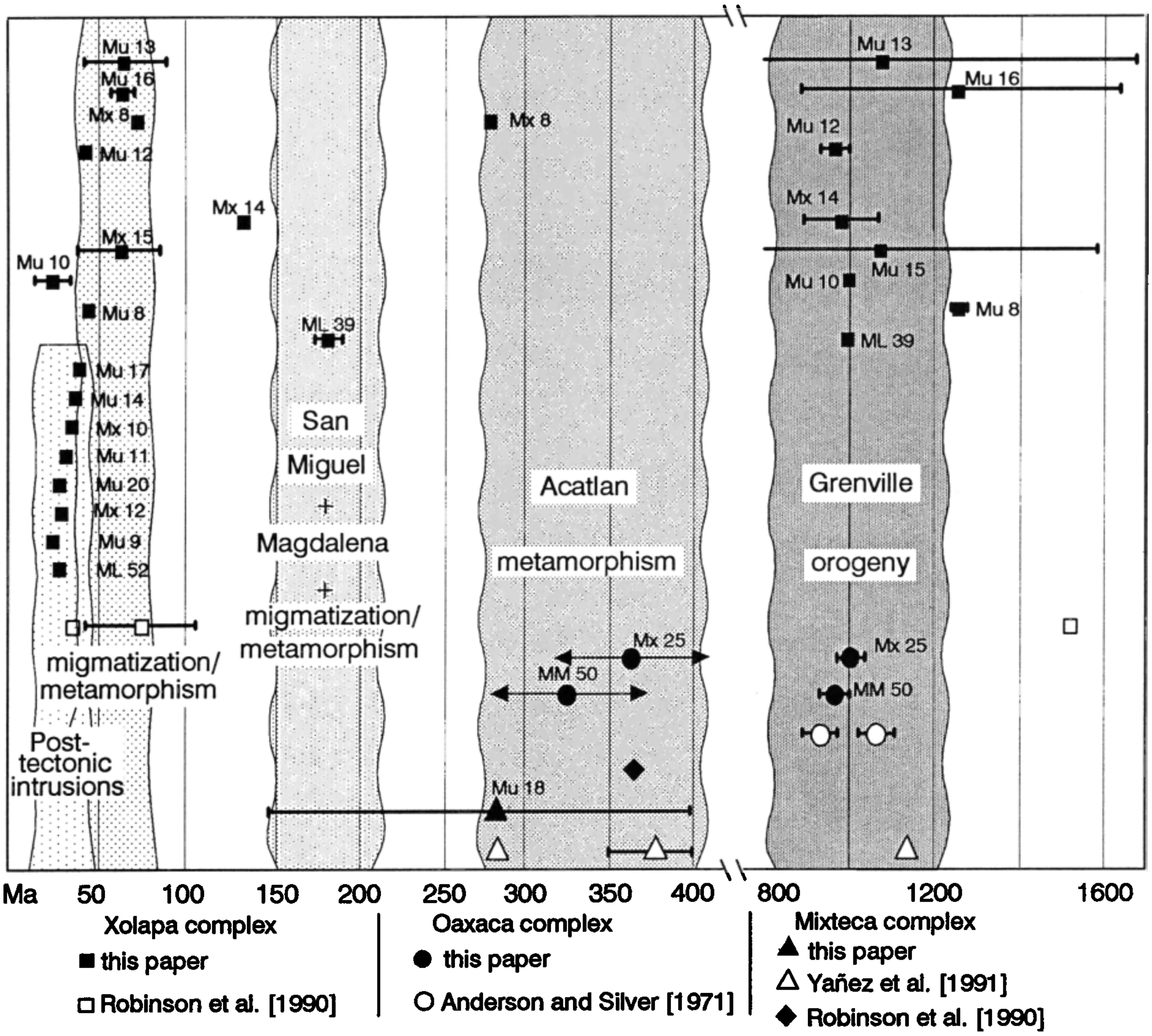

Fig. 8. U/Pb zircon ages from the Xolapa (squares), Acatlán (triangles), and Oaxaca (circles) complexes in southern Mexico. Shaded regions approximately delineate proposed range of magmatic and metamorphic events.

final stage of arc evolution within the Xolapa complex before magmatic activity shifted to its present mid-Mexican position (Mexican Volcanic Belt).

In the following we relate the isotopic evidence for the age of migmatization, metamorphism, and deformation, and the west to east younging in pluton crystallization, to a single late Mesozoic-early Tertiary tectonic setting. We propose that changes in the subduction parameters of the Farallon plate, the evolution of the Caribbean region, the deformation within and along the northern margin of the Xolapa complex, and the magmatism and metamorphism within the Xolapa complex are connected. Figure 10 summarizes the inferences about the regional plate tectonic setting and the geologic history of the Xolapa complex that we used to develop our model.

The plate tectonic framework. First, Engebretson et al. [1985] showed that the rate of Farallon-North America convergence along the southern Mexican continental margin increased and convergence was sinistral and more tangential between 70 and 40 Ma than during the Jurassic and most of the Cretaceous. Second, the Caribbean plate was established as an individual plate at about 75 Ma; this is indicated by the onset of arc magmatism along its southwestern margin (Panamá-Costa Rica arc), the reversal in subduction polarity along its northeastern margin (Greater Antilles arc), and the beginning of its northeastward migration into the gap between North and South America [Pindell and Barrett, 1990]. Third, continuous eastward motion of the Caribbean plate and the Chortis block, which probably was on the northwestern margin of the Caribbean plate and was temporarily adjacent to the Xolapa complex, is documented since the early Paleocene by intra-arc rifting in Jamaica [Mann and Burke, 1990] and is particularly well documented since the early Eocene by the

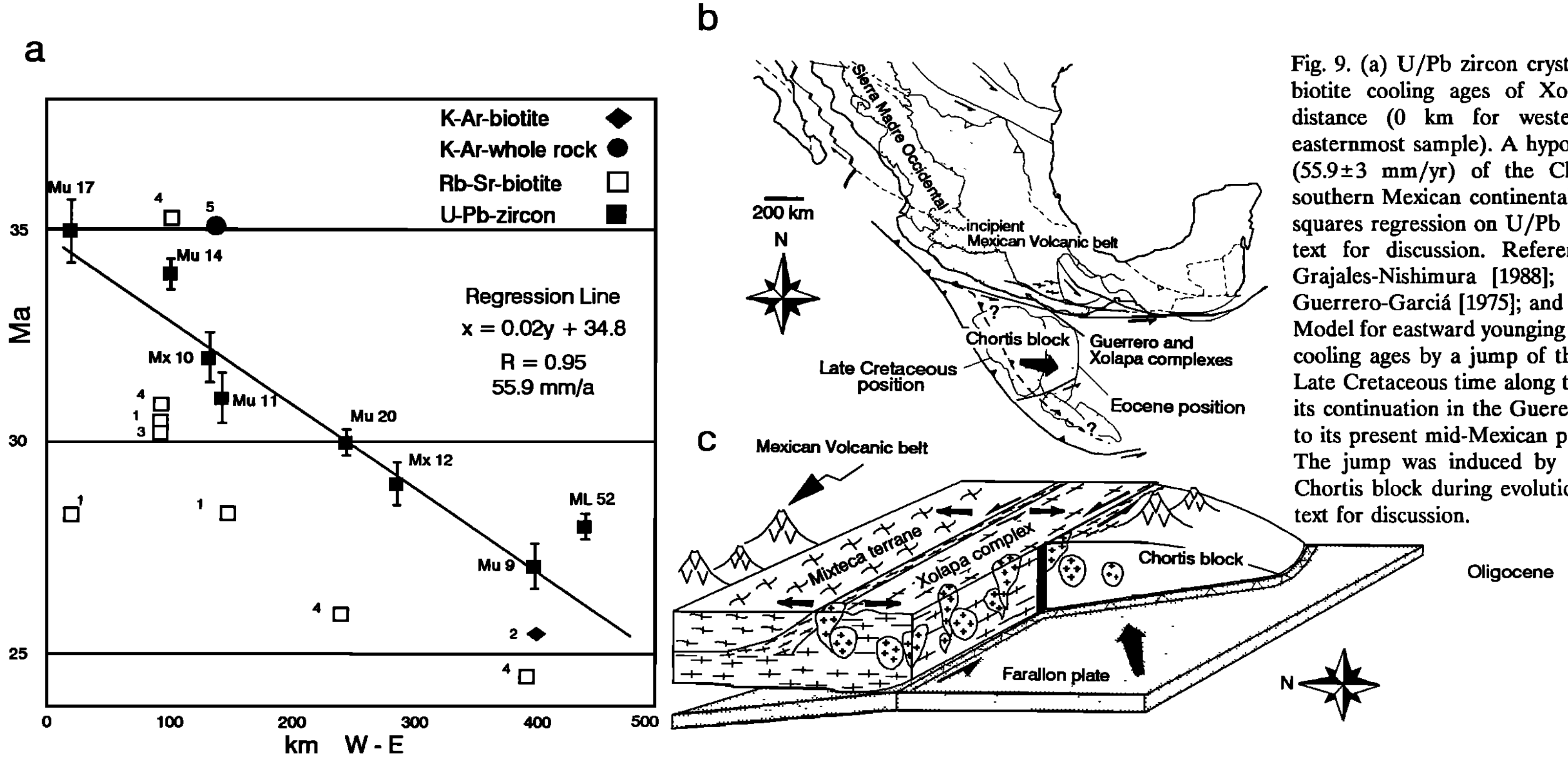

Fig. 9. (a) U/Pb zircon crystallization and Rb/Sr and K/Ar biotite cooling ages of Xolapa plutons versus latitudinal distance (0 km for westernmost sample, 500 km for easternmost sample). A hypothetical sinistral translation rate (55.9±3 mm/yr) of the Chortis block along the former southern Mexican continental margin was calculated by least squares regression on U/Pb (zircon) crystallization ages. See text for discussion. References are 1, Schaaf [1990]; 2, Grajales-Nishimura [1988]; 3, DeCserna et al. [1962]; 4, Guerrero-Garciá [1975]; and 5, Bellon et al. [1982]. (b and c) Model for eastward younging of both pluton emplacement and cooling ages by a jump of the magmatic arc, located during Late Cretaceous time along the Sierra Madre Occidental and its continuation in the Guerrero, Xolapa, and Chortis blocks, to its present mid-Mexican position (Mexican Volcanic Belt). The jump was induced by the eastward movement of the Chortis block during evolution of the Caribbean region. See text for discussion.

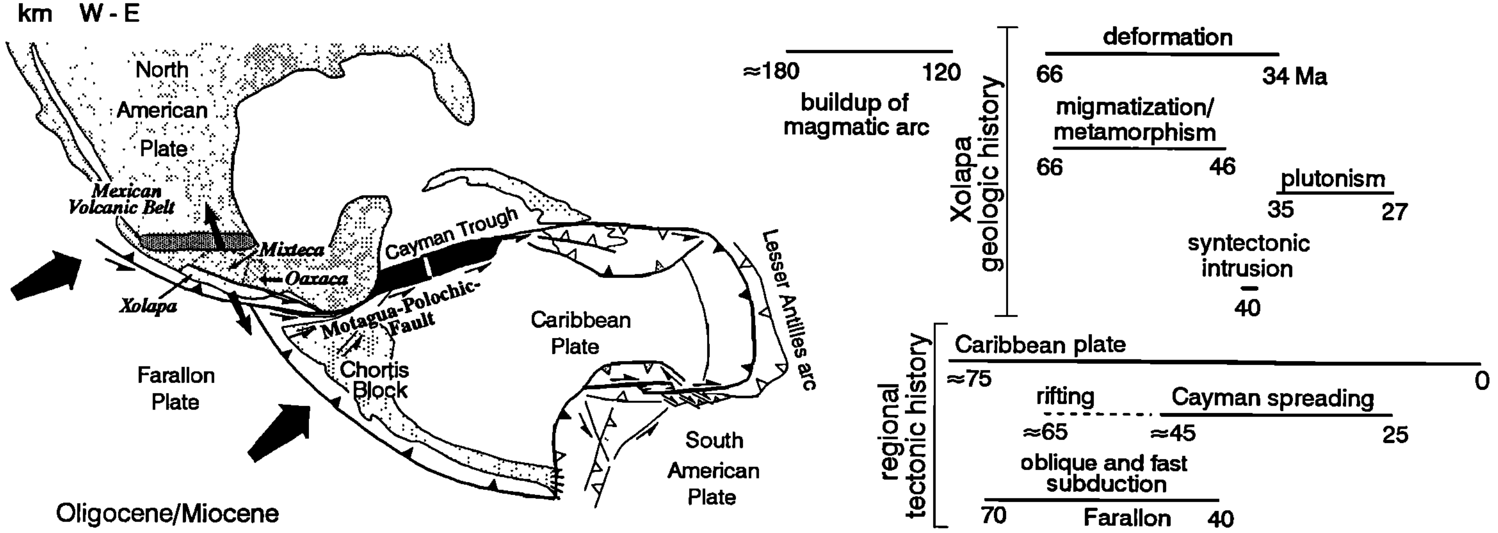

Fig. 10. Constraints on the late Mesozoic-Tertiary tectonic scenario of southern Mexico. Left: plate tectonic reconstruction of southern Mexico and the Caribbean during late Oligocene-early Miocene time after Pindell and Barrett [1990], illustrating the truncation of the former south Mexican continental margin, the eastward movement of the Chortis block along a forerunner of the Motagua-Polochic fault, and the opening of the Cayman trough. Right: Time lines of geologic history of the Xolapa complex and regional tectonic history of the Caribbean region.

opening of the Cayman trough [Malfait and Dinkelman, 1972; Pindell and Barrett, 1990; Wadge and Burke, 1983]. Ridge spreading rates in the trough were high (20-30 mm/yr) from 50-45 Ma until about 25 Ma, then decreased to 15-16 mm/yr thereafter [Rosencrantz et al., 1988].

Geologic history of the Xolapa complex. Sinistral transtensive, crystal-plastic deformation is restricted to between 66 and 35 Ma, as indicated by the 66 to 46 Ma dates of crystal-plastically deformed Xolapa migmatites, the 35-27 Ma dates of undeformed plutonites, and the 40 Ma date for a syntectonic tonalite (see results above and Robinson et al. [1990]). Deformation continued during late Eocene and Oligocene time by brittle- ductile, sinistral transtensional faulting and by postmagmatic brittle sinistral shearing, implying that the migmatites and metamorphic rocks had cooled below the threshold for crystal-plastic deformation in quartz (300°C [Voll, 1980]) by this time. The transtensional deformation inferred by structural analysis requires north-south extension in addition to sinistral wrenching, particularly during its early history [Ratschbacher et al., 1991].

We speculate that a change in plate boundary forces, induced by change in convergence rate and direction, and the coeval and probably related onset of northeast translation of the Caribbean plate initiated Late Cretaceous crustal extension in the Xolapa complex [Ratschbacher et al., 1991; Riller et al., 1992]. Subhorizontal extension effectively increases temperature in and reduces pressure for a volume of rock originating in the lower crust [e.g., Sandiford and Powell, 1986]. Extension may have caused metamorphism and migmatization in the Xolapa complex from 66 to 46 Ma. Additionally, differental uplift of the Xolapa complex with respect to its hinterland probably moved the high-grade metamorphic rocks and migmatites to a mid to upper crustal level.

Subduction, continuing to Recent, probably induced the plutonism starting at 35 Ma in the western Xolapa complex. A reduced temperature contrast between magma and crust due to crustal heating by extension (see above), and fracturing of the upper crust by transtensional faulting induced by the eastward translation of the Caribbean plate, facilitated magma rise. Intrusion into probably high crustal levels undergoing transtension may have contributed to pluton cooling (50°-60°C/m.y.). A spatial connection between fault zones and intrusives and hydrothermal activity was noted by Negendank et al. [1981], Salinas-Prieto [1984], and Ratschbacher et al. [1991].

Interpreting southern Mexican tectonics in context of the evolution of the Caribbean region also provides a mechanism for the eastward younging of both pluton emplacement and cooling ages during Oligocene time (Figures 9b and 9c) (compare with Damon and Coney [1983] for an interpretation of the cooling ages). The magmatic arc was located along the Guerrero, Xolapa, and Chortis blocks during Jurassic to earliest Tertiary time (Figure 9b) and was a continuation of the Sierra Madre Occidental and the Greater Antilles arcs. As the Chortis block moved east, the arc progressively stepped inland to its present mid-Mexican position. This shift was induced by disruption of this Jurassic-Cretaceous southern Mexican-Caribbean arc system south of the Guerrero and Xolapa complexes and north of the Chortis block by the eastward movement of the Chortis block as part of the Caribbean plate (Figure 9b) (compare this to Wadge and Burke [1983], who postulate truncation of the southern Mexican continental margin). We assume that the depth of the Farallon slab determined the locus of magmatism. During Late Cretaceous and earliest Tertiary time when the Chortis block, as the northwestern edge of the Caribbean plate, was between the Guerrero and Xolapa complexes and the trench, the dip of the Farallon slab was such that the locus of magmatism was within the Chortis and Xolapa blocks. As the Chortis block moved eastward, the trench became marginal to the Xolapa block, and the locus of magmatism (remaining at the same slab depth) shifted inward to the Mexican Volcanic Belt (Figure 9c). Thus, as the Chortis moved laterally with time, termination of magmatism in the Xolapa block migrated from west to east. This model makes several testable predictions: (1) The onset of magmatic activity in the Mexican Volcanic Belt was earlier in the west than the east. (2) Magmatic activity in the Xolapa and Chortis blocks overlapped in time. (3) The Chortis block was adjacent to the Guerrero and Xolapa complexes during Late Cretaceous time. In this case the trench-to-arc distance was such that the Xolapa complex was part of the magmatic arc trending along the west coast of mainland Mexico, comprising the Sierra Madre Occidental and the Guerrero, Xolapa, and Chortis complexes and continuing into the Greater Antilles. (4) A similar west-east trend of pluton crystallization ages exists in the Guerrero terrane, but ages are older than in the Xolapa complex.

Wadge and Burke [1983] summarized the (sparse) evidence for eastward movement of magmatism along the Mexican Volcanic Belt from late Eocene to Pliocene times, supportive of the first prediction. Within the Chortis block, plutons located along a zone parallel to the Motagua-Polochic fault zone in Guatemala and Honduras have ^{39}Ar/^{40}Ar biotite dates of 34.7 to 35 Ma and a K/Ar biotite date of 35.9 Ma (Figure 10) [e.g., Donnelly et al., 1990]; this is a preliminary indication of support for the second prediction. Testing the third prediction requires paleomagnetic and isotopic age data from the Chortis block; but several authors [e.g., Wadge and Burke, 1983] infer that the Chortis block was adjacent to the southern Mexican margin on the basis of modeling closure of the Cayman trough along its bounding faults. Initial evidence for the anticlockwise rotation of the Chortis block, required by this model, was obtained by Gose and Swartz [1977] from Honduras. Rb/Sr whole rock dates from plutonic rocks of the Guerrero complex range from approximately 70 Ma in the west to 40 Ma in the east [Schaaf, 1990]. These data support our fourth prediction and indicate that the eastward movement of the Chortis block may indeed have started during Late Cretaceous time. Interpreting the eastward trend of zircon crystallization ages of the Xolapa plutons as a hypothetical sinistral translation rate of the Chortis block gives a plate motion velocity of about 56 mm/yr (Figure 9a), which is faster than the maximum rate of 30 mm/yr for the opening of the Cayman trough [Rosencrantz et al., 1988] but slower than the average Oligocene convergence rate of the Farallon and North America plates (about 80 mm/yr) [Pindell and Barett, 1990]. Note also that the end of magmatic activity in the Xolapa complex (35-27 Ma) was approximately contemporaneous with the beginning of volcanic activity in the central Mexican

Volcanic Belt (32-27 Ma, K/Ar ages of early andesites [Mooser, 1972]). At this time the Chortis block may have been translated far enough to the east that magmatism could spread eastward from the northwest-southeast axis of the Sierra Madre Occidental belt.

CONCLUSIONS

Our U/Pb zircon study combined with regional structural analyses by us and others support the following history for basement complexes in southern Mexico.

1. The Xolapa complex contains a Proterozoic crustal component and underwent Late Cretaceous through early Tertiary high-grade metamorphism and migmatization (66-46 Ma) and Oligocene (35-27 Ma) crustal growth by magmatic accretion.
2. The Proterozoic crustal component of the Xolapa complex either originated from sedimentary input from a Grenville source or indicates the presence of reworked Grenville crust. In the first case, the isotopic ages indicate that the Xolapa complex was receiving sediments from a cratonic area with an age composition similar to areas that currently border the Xolapa complex; i.e., the Oaxaca and Acatlán complexes. In the second case, the Xolapa and its northeastern hinterland share the same basement; however, metamorphism and migmatization pervasively modified this basement in the Xolapa complex.
3. Jurassic and Cretaceous (165-128 Ma) U/Pb zircon and Rb/Sr whole rock dates may reflect construction of a magmatic arc along the Xolapa complex by subduction along the southern margin of the North American craton. Thermal activity culminated during early Tertiary time (66-46 Ma).
4. Crustal growth by plutonism (35-27 Ma) following migmatization probably represents final arc evolution along the Xolapa complex, before magmatic activity shifted to its present mid-Mexican position.
5. Subhorizontal crustal extension in what is today the southern Mexican continental margin caused by plate boundary rearrangements at the onset of the evolution of the Caribbean may explain the increased thermal input causing migmatization and high-grade metamorphism in the Xolapa complex.
6. A move of the magmatic arc from its position along the Xolapa and Chortis blocks to its present mid-Mexican position, caused by eastward drift of the Chortis block during the formation of the Caribbean, is consistent with eastward decreasing ages of both pluton emplacement and cooling.
7. Our geochronometric and petrogenetic analyses combined with previously established structural data show that a single regional tectonic framework can account for the Mesozoic and Cenozoic geologic history of these complexes.

APPENDIX: ROCK TYPE AND ASSOCIATION, ZIRCON FRACTIONS AND CHARACTERISTICS, AND AGE INTERPRETATION

Xolapa Complex: Migmatites and Metamorphic Rocks

Mu8: Migmatite south of Pochutla. From the leucosome one fraction from the 40 to 75 μm and two from the 75 to 125 μm size range, all comprising clear, rounded to subeuhedral grains, define a chord with an upper intercept at 1268±15 Ma and a lower intercept at 48.1±0.98 Ma (Table 2 and Figure 5a). The 1.27 Ga date represents the crystallization age of the protolith and the 48 Ma date the time of Tertiary migmatization. The proximity of all populations to the lower intercept implies almost total lead loss during metamorphism. Zircons from the melanosome do not define a line with an interpretable age, but points plot close to the chord defined by the leucosome.

Mu10: Migmatite from Puerto Escondido. Two of three air-abraded, least magnetic zircon fractions of euhedral grains constitute a regression line with intercepts at 1007±6.1 and 25±11 Ma (Table 2 and Figure 5b). Using all fractions, the lower intercept is at -133 Ma. We did not use the smallest size fraction for calculation. No inherited cores were observed. The 25 Ma date may represent Oligocene high-temperature metamorphism, but the complicated zircon systematics render its interpretation questionable.

Mu12: Migmatitic gneiss from Cruz Grande. All three fractions of clear to pink, euhedral zircons define a regression line with an upper intercept at 976±34 and a lower intercept at 46.4±0.78 Ma (Table 2 and Figure 5c). The two fractions close to the lower intercept are the smallest fractions (40 to 70 μm) but differ in magnetic susceptibility. The most discordant point comprises the least magnetic zircons and comes from the 125 to 150 μm fraction. The euhedral habit suggests crystallization during migmatization. The strong discordance indicates an old component in some crystals, although cores were not observed.

Mu13-Mx3: La Palma gneiss east of Tierra Colorada. Cathodoluminescence analyses revealed inherited cores in most of the pink, euhedral, elongated zircons of all populations. Intercepts at 1072±498 and 62±20 Ma were calculated (Table 2 and Figure 5d). The cores are rounded, indicating detrital origin or corrosion in Zr- undersaturated magma. We infer a 1.1 Ga crystallization age for the gneiss protolith.

Mu16-Mx6: Migmatite south of Tierra Colorada (10 km southwest of Mu13). Cathodoluminescence revealed rounded cores. An upper intercept at 1256±373 and a lower intercept at 66.7±5.4 Ma were calculated (Table 2 and Figure 5e, three fractions). A fourth fraction plots off the discordia, probably due to inclusions and impurities observed in this particular population.

Mx14: Migmatite north of Puerto Escondido. Six fractions define a regression line with intercepts at 987±93 and 131.8±2.2 Ma (Table 2 and Figure 5f). The least magnetic and longest abraded fraction yielded the most discordant age indicating that the upper intercept represents the apparent age of the cores revealed by cathodoluminescence analyses. The 131 Ma age is the oldest migmatization event detected in the Xolapa complex.

Mx15: Migmatitic gneiss south of the Oaxaca-Xolapa boundary, San Juan Lachao. Three fractions (40 to75 μm and 75 to 125 μm size range, clear grains) define intercepts at 1084±494 and 65±23 Ma (Table 2 and Figure 5g). Cores were observed in all populations.

Mx8: Migmatite at the Papagayo river. Zircons from the leucosome show little isotopic variability and do not define a single chord; therefore we were not able to infer a statistically reliable age (Table 2 and Figure 5h). The mostly clear, euhedral zircons revealed cores in all fractions. The melanosome did not yield enough zircons for analysis.

Mx11: Gneiss from Cruz Grande. Four fractions of pink, elongated, mostly clear grains define a straight line (Mean Square of Weighted Deviates = 2.3) on the concordia diagram, but their discordance and near parallelism to the concordia curve yields very poorly constrained intercepts (197±204 and 46±153 Ma) (Table 2 and Figure 5i). Cathodoluminescence detected cores in all studied zircons. The value of these dates is unclear.

ML39: Mylonitic gneiss north of Pochutla. This mylonite, separating the Xolapa and the Oaxaca complexes, is structurally analogous to the mylonites along the northern margin of the Xolapa complex at Tierra Colorada and Juchatengo [Ratschbacher et al., 1991]. A small yield of elongate and clear zircons without cores was recovered. Two fractions define intercepts at 1017±20 and 180.3±9 Ma (Table 2 and Figure 5j). Isotopic compositions reflect either significant Pb loss in a 1 Ga granite during mylonitization at 180 Ma or (so far unrecognized) metamorphism at 180 Ma and later mylonitization. We prefer the second interpretation, because we dated mylonites with similar kinematics to a Late Cretaceous-early Tertiary age in the Tierra Colorada area.

Xolapa Terrane: Undeformed Plutons

Mu17: Granodiorite north of Acapulco. Abundant, clear, euhedral, and elongate zircons yielded a 35 Ma crystallization age (Table 2 and Figure 7a). The fractions represent sizes of 40 to 75 μm and 75 to 125 μm and the least and second least magnetic populations. There is little evidence for Pb loss or an inherited component.

Mu14: Tierra Colorada granodiorite. The 34 Ma date (Table 2 and Figure 7b) of this pluton, which intruded the mylonite zone along the northern margin of the Xolapa complex, gives a minimum age for crystal-plastic deformation [Riller et al., 1992]. Euhedral, clear, and nonmagnetic grains were analyzed. The fractions contain an inherited component, but the clustering does not permit a best fit line calculation. A Rb-Sr biotite date reflects cooling at 26.3 Ma [Schaaf, 1990].

Mx10: Tonalite east of San Marcos. Although cores were not detected (optically and by cathodoluminescence), the clear to pink, elongate zircons may contain an inherited component. Four of five populations, which represent the least magnetic, plot on or near concordia at 31 Ma (Table 2 and Figure 7c). The dispersion of dates is systematic with respect to grain size: the coarsest give the oldest and the finest fractions the youngest dates. The fraction farthest off the concordia is most strongly magnetic. Minor Pb loss apparently has affected the fine fraction, so our best estimate for the crystallization age is 32 Ma.

Mu11: Granodiorite north of Cruz Grande. One fraction of least magnetic, clear, and euhedral zircons in needle form yielded a concordant date of 32 Ma (Table 2 and Figure 7d). The dates of Mx10 and Mu11 are concordant, indicating that the samples (15 km apart) come from coeval plutons or from apophyses of the same pluton.

Mu20: Granodiorite north of Pinotepa Nacional. Single fraction of clear, light pink to yellow, and elongate zircons give a 30 Ma crystallization age (Table 2 and Figure 7e).

Mx12: Tonalite east of Pinotepa Nacional. Four fractions of euhedral, elongate, clear or light pink, small or coarse zircons give a 28 Ma crystallization age (Table 2 and Figure 7f). The slight dispersion along concordia probably reflects minor Pb loss.

Mu9: Granodiorite northwest of Pochutla. A slightly discordant 75 to 125 μm and two 40 to 75 μm concordant fractions indicate a crystallization age of 27 Ma (Table 2 and Figure 7g). Zircons differ in magnetic susceptibility and are euhedral and light pink. The discordance is probably caused by Pb inheritance in cores of the coarse fractions (not detected by microscopy or cathodoluminescence). The discordant fraction yields a $^{207}Pb/^{206}Pb$ age of 71±14 Ma.

ML52: Granite east of Pochutla. The fractions contain mostly clear to yellow, euhedral to subeuhedral zircons and differ in size and time of abrasion. Inheritance of an old component, probably small cores or cloudy inclusions in the 125 to 150 μm fraction, is indicated. We suggest a crystallization age of 29 Ma (Table 2 and Figure 7h).

Mu18: Granite north of Pinotepa Nacional. This sample was taken south of the proposed Xolapa-Mixteca terrane boundary, though reconnaissance work to date has not revealed mylonites generally characteristic of this boundary. Assignment of this granite to either the Xolapa or the Acatlán complex is possible. The discordant nature of the zircons (upper intercept at 276±133 Ma) makes interpretation of an age questionable although the Permian age is similar to the 286±2 Ma age from the Totoltepec stock in the Acatlán complex and to ages of granites in the Oaxaca complex [Yañez et al., 1991].

Oaxaca Terrane

Mx25: Gneiss from west of Miahuatlan; MM50: granite north of Pochutla. Three fractions from each sample were analyzed and within error limits give similar ages. Zircons are well rounded and dark pink. Upper intercepts for Mx25 and MM50 are 1006±17 and 982±36 Ma, respectively (Table 2 and Figures 6b and 6c). Similar dates were reported from the Oaxaca basement by Anderson and Silver [1971] and Robinson et al. [1990]. The lower intercepts at 353±250 and 331±359 Ma within unacceptable large uncertainties are similar to 371±34 Ma (U/Pb zircon age) of the Esperanza pluton in the adjacent Mixteca terrane [Yañez et al., 1991], which represents a major mid-Devonian magmatic event.

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