Revista Mexicana de Ciencias Geológicas, volumen 11, número 2,
1994, p. 147-156
Universidad Nacional Autónoma de México, Instituto de Geología,
México, D.F.

STRUCTURAL EVOLUTION OF THE SIERRA DE JUÁREZ MYLONITIC COMPLEX, STATE OF OAXACA, MEXICO

Susana Alicia Alaniz-Álvarez,[1]
Ángel Francisco Nieto-Samaniego[1] *and*
Fernando Ortega-Gutiérrez[2]

ABSTRACT

The western side of Sierra de Juárez, State of Oaxaca, Mexico, is characterized by a N-S trending structural complex more than 130 km long and 10 to 15 km wide, constituting a mylonitic belt that is the largest in Mexico. In the southern part of this belt, the mylonite protolith is formed by: (1) gneiss, granulite, anorthosite, and marble from the basement of the Zapoteco terrane (Oaxacan Complex); (2) leucocratic granitic rocks consisting in the mylonitized granite near San Pablo and San Pedro Etla, which is correlated with the Permian "Etla Granite", and the granite close to San Felipe del Agua, near the city of Oaxaca, which is considered syntectonic; (3) ultramafic basement units of the Cuicateco terrane, such as hornblendite and gabbro; (4) basic volcanic or subvolcanic rocks; and (5) sedimentary rocks of unknown origin. The mylonitization took place under metamorphic conditions in the boundary greenschist/amphibolite facies with temperatures near 500°C.

The stratigraphic relationships and a 180 ± 4 Ma muscovite K-Ar age indicate a major event of mylonitization with a Late Permian-Middle Jurassic age. The kinematic indicators and the structural detail suggest that the juxtaposition of both terranes be by thrusting of the Oaxacan Complex over the Cuicateco terrane basement to the east; later, this shear zone was reactivated many times until late Cenozoic time.

Key words: Tectonics, mylonite, Sierra de Juárez, Oaxaca, Mexico.

RESUMEN

El frente occidental de la sierra de Juárez, Estado de Oaxaca, está caracterizado por un complejo estructural de más de 130 km de longitud por 10 a 15 km de anchura, de alineación N-S, que constituye el cinturón milonítico más grande de México. La parte meridional de este cinturón está compuesta por rocas miloníticas cuyos protolitos son: (1) gneis, granulita, anortosita y mármol, pertenecientes al basamento del terreno Zapoteco (Complejo Oaxaqueño); (2) rocas graníticas leucocráticas que consisten en los cuerpos de granito milonitizado que están localizados en San Pedro y San Pablo Etla, que se correlaciona con el "Granito Etla" de edad pérmica, y el granito de San Felipe del Agua en la ciudad de Oaxaca, que se considera sintectónico; (3) gabro y hornblendita del basamento del terreno Cuicateco; (4) rocas básicas volcánicas o subvolcánicas; y (5) rocas sedimentarias de origen desconocido.

Las relaciones estratigráficas y una edad K-Ar de 180 ± 4 Ma de una muscovita indican un evento mayor de milonitización entre el Pérmico Tardío y el Jurásico Medio. El estudio de las estructuras y los indicadores cinemáticos observados sugieren que la yuxtaposición de los terrenos ocurrió por cabalgamiento hacia el oriente del Complejo Oaxaqueño sobre el terreno Cuicateco; posteriormente, esta zona de cizalla fue reactivada varias veces hasta el Cenozoico tardío. La milonitización se formó en condiciones metamórficas en el límite entre las facies de esquisto verde y anfibolita a temperaturas cercanas a 500°C.

Palabras clave: Tectónica, milonita, Sierra de Juárez, Oaxaca, México.

INTRODUCTION

The basement geology of southern Mexico is characterized by multiple tectonostratigraphic provinces known today as terranes (Coney *et al.*, 1980). The six terranes (Plate 1) distinguished in southern Mexico (Campa-Uranga and Coney, 1983; Ortega-Gutiérrez *et al.*, 1990) comprise basement rocks whose ages span from Precambrian—Zapoteco terrane—to Cretaceous—Chatino terrane—and whose overlapping formations include sedimentary, volcanic and plutonic rocks of Ordovician to late Cenozoic age.

Although the geology and evolution of some of these terranes is well known—*i. e.*, Mixteco terrane—the nature of their boundaries (Ortega-Gutiérrez, 1980) was unknown until recently (Robinson *et al.*, 1990; Ratschbacher *et al.*, 1991; Alaniz-Álvarez *et al.*, 1991). One of the most spectacular boundaries among terranes in southern Mexico is exposed in central Oaxaca, separating Precambrian gneisses of the Zapoteco terrane from younger igneous and sedimentary rocks of the Cuicateco terrane (Ortega-Gutiérrez *et al.*, 1990). The present morphotectonic expression of this boundary is the north-south trending Oaxaca Fault, showing normal displacements as young as late Cenozoic (Centeno-García, 1988).

The tectonic significance of this boundary rests on the following considerations: (1) it constitutes the largest mylonite complex in Mexico and probably one of the largest in the North American Cordillera; (2) it is the limit between two terranes, in one of which Grenvillian gneisses crop out and, in the other, thin transitional or oceanic lithosphere of Paleozoic and Mesozoic ages; (3) its possible Middle Jurassic age is anomalous in the framework of southern Cordilleran orogenic evolution; and (4) it is the present site of Cenozoic tectonic rejuvenation.

---

[1] *Estación Regional del Centro, Instituto de Geología, Universidad Nacional Autónoma de México, Apartado Postal 376, 36000 Guanajuato, Gto., México*
[2] *Instituto de Geología, Universidad Nacional Autónoma de México, Ciudad Universitaria, Delegación Coyoacán, 04510 D.F., México*

The kinematics, age, protolith, tectonic significance, and indeed, the geological nature of this fundamental structural belt of southern Mexico, have been virtually unknown. This research, based on detailed field work, and structural and petrologic studies of a sector 15 km long between the city of Oaxaca and Telixtlahuaca (Plate 1), where the mylonites are exposed in the western Sierra de Juárez, adds new elements to the understanding of the tectonic evolution of this critical part of southernmost North America.

REGIONAL GEOLOGIC SETTING

The mylonitic belt separates the Zapoteco and Cuicateco terranes, which have a different basement and, in parts, a different cover. The main geologic characteristics of both terranes are as follows.

ZAPOTECO TERRANE

The oldest and lowest unit of the Zapoteco terrane is the Oaxacan Complex (p€ in Plate 1), consisting of meta-anorthosite, quartzofeldspathic orthogneiss, paragneiss, marble, and charnockite (Ortega-Gutiérrez, 1984). Granulite-facies metamorphism occurred at 710 ± 50°C and at 7 kb (Mora *et al.*, 1986), and between 1,100 and 1,000 Ma BP (Anderson and Silver, 1971; Ortega-Gutiérrez *et al.*, 1977; Patchett and Ruiz, 1987). Fold axes and lineation in the Oaxaca Complex consistently trend north-northwest and plunge 5 to 30°.

The Oaxacan Complex is unconformably covered by shale, sandstone, limestone and siltstone of the Tiñú Formation (Pzim in Plate 1), with early Tremadocian trilobites (Pantoja-Alor and Robison, 1967). Overlying Paleozoic strata include marine shale and sandstone of the Santiago and Ixtaltepec Formations, both of Carboniferous age (Pantoja-Alor, 1970), and a heterogeneous mixture of conglomerate, sandstone and siltstone of the Yododeñe Formation of Permian age (Pzsmc in Plate 1). The Oaxacan Complex in the type locality, in Telixtlahuaca area, is intruded by a granitoid named here Etla Granite (Pzsi in Plate 1) 272 ± 8 Ma old (Ruiz-Castellanos, 1979) and further north is covered by continental deltaic sedimentary rocks of the Matzitzi Formation containing *Glossopteris* sp. of Permian age (Weber *et al.*, 1987).

The coverture is also composed of Upper Jurassic-Lower Cretaceous rocks which include continental and marine clastic rocks, and platform limestone (Jcms and Km in Plate 1). The Paleogene consists of red beds, the Neogene of volcanic rocks (Tc in Plate 1) and the upper Cenozoic of continental sediments (Csc in Plate 1) (Ferrusquía-Villafranca, 1976).

CUICATECO TERRANE

The Cuicateco terrane (Ortega-Gutiérrez *et al.*, 1990; Sedlock *et al.*, 1993) is composite and made of Paleozoic, Jurassic and Cretaceous deformed rocks, which originated in an arc or ocean environment (Delgado-Argote, 1988; Carfantan, 1983, 1986). It overrode the Maya terrane at its eastern edge, and underlies the Zapoteco terrane along the Sierra de Juárez mylonitic complex (SJMC).

The Cuicateco terrane has been divided into three broad structural units dipping gently to the west (Ortega-Gutiérrez *et al.*, 1990). The lower and easternmost structural unit is composed of a thick package of mica schist cut by basic dikes and sills, green rock (metatuff), serpentinite lenses, and gabbro (Pzmet in Plate 1); isotopic data suggest a minimum late Paleozoic age for this unit (Carfantan, 1986, p. 361).

The intermediate structural unit is also voluminous; in this area, it consists of deformed sedimentary rocks, only weakly metamorphosed, and is composed of sandstone, black slate and limestone (Mvsm in Plate 1). It contains microfossils of Berriasian-Valanginian age (Carfantan, 1981), and the ammonite *Olcostephanus* sp. of Valanginian age (Ortega-Gutiérrez and González-Arreola, 1985). A K-Ar age of 82.5 Ma obtained from a phyllite (Carfantan, 1983) could indicate incipient metamorphism at the beginning of the Late Cretaceous.

The mylonitic belt (Mmil in Plate 1) was considered the third and highest structural unit and constitutes the suture zone between the Cuicateco and Zapoteco terranes (Ortega-Gutiérrez *et al.*, 1990). It has an observed thickness of at least 8 km.

LITHOLOGY

The samples described were obtained along roads crossing the mountain front and at San Felipe del Agua, in the city of Oaxaca (Figure 1) within the SJMC.

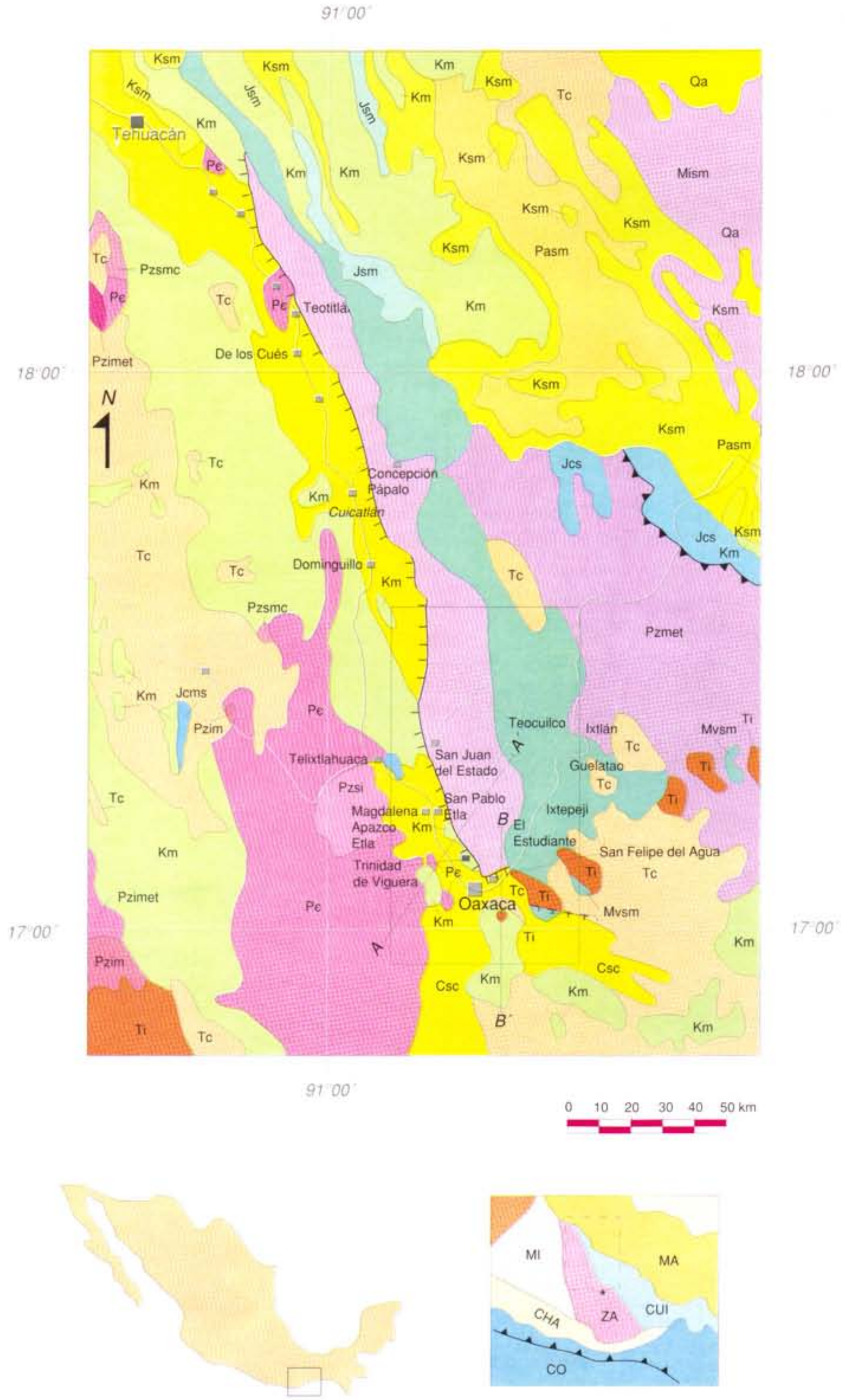
The mylonitic foliation has an anastomosed structure surrounding ellipsoidal bodies of rock much less deformed. The diversity of these mylonites includes a variable and complex strain, as well as several chemical protolith groups. These rocks contain ultramafic, mafic, quartzofeldspathic, calcareous and pelitic units.

Field identified protoliths of the mylonites include: pelitic gneiss with abundant biotite and orthogneiss with blue quartz exposed on the road from Cuicatlán to Concepción Pápalo. Marble is present between the city of Oaxaca and San Pablo and San Pedro Etla which, together with relict textures of meta-anorthosite and mafic orthogneiss, might indicate that they originally belonged to the Oaxacan Complex.

From the preliminary petrology based on over 100 thin-section petrographic studies and some chemical analyses of major elements, four principal groups were determined as follows: Group 1, ultramafic rocks; Group 2, mafic rocks; Group 3, quartzofeldspathic rocks; and Group 4, calcareous-pelitic rocks.

GROUP 1. ULTRAMAFIC ROCKS (HORNBLENDITE)

The rocks of this unit consist almost completely of amphiboles; so, they were classified as hornblendites. The best



EXPLANATION

Quaternary	Qa	Quaternary alluvium
Cenozoic undif	Csc	Continental-deposit strata
Paleocene	Pasm	Marine strata
Tertiary undif	Tc	Continental volcanic and sedimentary
	Ti	Plutons
Cretaceous	Ksm	Marine strata
	Km	Marine strata
Jurassic	Jsm	Marine strata
	Jcs	Marine strata
	Jcms	Continental strata
Mesozoic undif	Mvsm	Volcanic and sedimentary
	Mmil	Mylonitic rocks
Paleozoic	Pzsmc	Marine and continental strata
	Pzmet	Metamorphic rocks
	Pzsi	Plutons
	Pzim	Marine strata
	Pzimet	Metamorphic rocks
Precambrian	Pє	Metamorphic rocks

SYMBOLS

Contact

▼▼▼ Overthrust

┬┬┬ Normal fault

Computer color separation was made by José de Jesús Vega-Carrillo

GEOLOGIC MAP OF SOUTHERN MEXICO

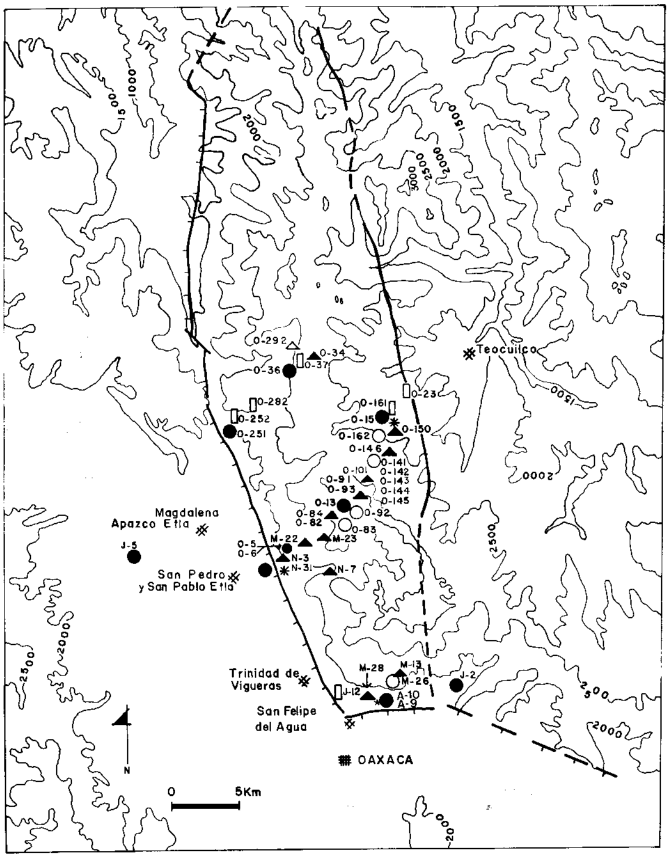


Figure 1.- Topographic map of the study area showing the sample localities. Open circles, ultramafic rocks (Group 1); solid triangles, amphibolite (Group 2); solid circles, granitic rocks (Group 3); rectangles, pelitic rocks (Group 4); asterisks show the location of samples with isotopic analysis.

outcrops are on the road midway between the San Pedro Etla and Teocuilco de Morelos Pérez towns, and in the stream bed that runs down from Cerro La Peña to San Felipe del Agua near the city of Oaxaca (Figure 1).

The rocks are homogeneously dark green, equigranular, with heterogeneous mylonitic deformation, the grain size varying with the intensity of deformation, from one or two centimeters in weakly foliated rocks to tenths of a millimeter in strongly foliated rocks. The outcrops are small and with irregular forms. Table 1 presents, in progressive order of deformation, the principal petrographic characteristics of eight representative samples; this order was established petrographically considering the degree of recrystallization, the size of the grain, and the microstructures.

There are samples with minimum deformation that are unfoliated, have reddish-brown hornblende and exhibit grain size up to many centimeters. Deformation at grain edges, is revealed by zonation of crystals, suturing, and the presence of subgrains.

Increase in the intensity of deformation caused recrystallization in the interior of the grains generating shear bands, core-and-mantle structure, recrystallized grains, reduction of grain size, and reorientation of the crystals.

Samples O-92, O-144, and O-145 (Table 1 and Figure 1) show shear bands. In sample O-83 there are a few relict grains; in general, grains are of the same size—0.05 mm long—and they are oriented in the same direction; frequently they present triple junctions at 120°. According to Simpson and De Paor (1991), this kind of texture evolves in high-temperature and slow-speed deformation systems. There are differences between samples O-83 and O-92, both of which are completely recrystallized; the grains in the first are of the same size, whereas in the second, the difference between the matrix and the porphyroclast size is very large.

Amphiboles—reddish-brown or green hornblende and tremolite/actinolite—constitute more than 85% of the total volume of the rock. Minor minerals are epidote/clinozoisite, chlorite, hematite and titanium-rich phases, such as rutile, sphene and ilmenite.

Despite the degree of deformation, the stable metamorphic associations are:

1. Green hornblende + clinozoisite / epidote + chlorite
2. Actinolite / tremolite + chlorite

Samples O-141, O-142, O-143, O-144 and O-145, in this order, were collected in a single outcrop less than 30 m long (Figure 1), in which the intensity of the strain drastically varies within a few meters and in an irregular way.

The protolith inferred for the samples of Group 1—ultramafic rocks—is an intrusive igneous hornblendite based on the following data:

1. The igneous character of the rock is determined by the red color of the cores of amphiboles, typical of high temperature hornblendes, and there is no evidence of retrogression as to suppose that it comes from a high-grade metamorphic rock.
2. Grain size may be up to many centimeters long, occasionally preserving an intersertal igneous texture.
3. Chemical composition and their mineralogical characteristics correspond to igneous hornblendites (Bogatikov *et al.*, 1981).

Although no hornblendites had been previously reported from the Cuicateco rocks, the hornblendites could be associated with gabbros of their basement.

GROUP 2. AMPHIBOLITE

Group 2 consists of amphibole + plagioclase rocks—amphibolite—such as those cropping out northeast of Magdalena Apazco Etla, along the road San Pedro Etla to Teocuilco and also at San Felipe del Agua (Figure 1). These rocks are dark green with white spots or bands forming tabular zones, a few millimeters thick, that can be continuous or not, folded or microfolded, and sheared or not. They present a phaneritic, protomylonitic, or ultramylonitic texture in complex field relationships with the rocks of this unit and other mylonites.

The rocks of this group can be classified chemically as basalt, trachybasalt and andesitic basalt, according to Le Bas's classification (Le Bas *et al.*, 1986); mineralogically as amphi-

Table 1.- Petrographic characteristics of Group 1 (ultramafic rocks).

Sample	**O-162**	**O-141**	**O-145**	**O-143**	**O-142**	**O-144**	**O-83**	**O-92**
Elevation [m.a.s.l.]	2,900	2,740	2,750	2,740	2,740	2,745	2,760	2,800
Mineralogy [%]								
Green hornblende	74	86	68	3.5	2.5	1.5		3
Reddish-brown hornblende	7.5		11.5					1
Actinolite-tremolite		1.5		93.5	86.5	88	92	89
Epidote group	3	1	7.5					
Biotite					0.5		2	
Chlorite	5	6.5	10			1	3.5	5
Quartz								1.5
Ilmenite	6	4			6	7		
Hematite	2.5	0.5		2	4	2.5	1	0.5
Rutile	1			1			0.5	
Sphene	1	0.5	3		0.5		1	
Microstructures								
Porphiroclast size [mm]	3	1-3	0.5-3	0.5	1-1.5	1	0.2-0.5	0.3-1
Matrix size [mm]				0.1	0.2-0.5	0.2-0.5		0.05-0.1
s / c bands					1	1		
Pressure shadows								
Sutured grains	3	3	3	3	3	3	1	
Subgrains	1	1		3	3	3		
Shear bands	1	1	1	1	3	3	1	
Recrystallized new grains				2	3	3	3	3
Core-and-mantle structure				2	3	3		3
Undulatory extinction	1	1		2	3	3	3	3
Zoned crystals	1				2	2		2
Foliation					1	1	3	3
Principal component = 3; minor component = 2; trace component = 1								

bolite, and texturally according to Spry's classification (Spry, 1974), as proto-, ortho-, ultra- and blastomylonite. In this paper, samples O-84, O-93 and N-31 are named protomylonite; samples M-22, N-3, N-7, O-34, M-13 and O-101, mylonitic amphibolite; and samples M-28 and O-146, blastomylonitic amphibolite (Table 2). The progressive mylonitization is noticed in the corresponding decrease of grain size and in the percentage of porphyroclasts and matrix (Table 2).

Unmylonitized amphibolite presents porphyritic texture, with phenocrysts of amphibole, and a matrix of epidote, chlorite, iron oxides, and plagioclase forming needles. The core of all amphiboles is reddish brown and in some cases zoned; the plagioclase has sutured edges, in some cases, with subgrain development. The stable metamorphic association is hornblende + chlorite + epidote + plagioclase.

Protomylonite samples have recrystallized equidimensional plagioclase with hornblende as subhedral crystals and sutured borders. The matrix is composed of small plagioclase grains, epidote and chlorite. The stable metamorphic association is green hornblende + epidote + chlorite + plagioclase, even though sample O-84 shows green biotite in veins. Calcite is present as a secondary mineral.

The mylonitic amphibolite, as can be seen from petrographic data in Table 2, has typical shear textures such as σ grains, s/c surfaces, broken and displaced crystals, and pressure shadows. Deformation at grain margins plays a secondary role. A macroscopic and microscopic foliation is also observed with some mineral segregation. The stable metamorphic associations are hornblende + oligoclase + epidote/clinozoisite + chlorite, and hornblende + oligoclase + epidote/clinozoisite + biotite.

In samples M-28 and O-146 all grains are recrystallized and have the same size (50 μm). All amphiboles are preferentially oriented and plagioclase, as well as amphibole, have well-defined borders with triple junctions at 120°. The stable metamorphic associations are hornblende + oligoclase + epidote/clinozoisite + biotite, and hornblende + oligoclase + sphene.

The Sm/Nd isotopic analysis of three mylonitic amphibolites is presented in Table 3. Sample N-1 was collected on the road from Cuicatlán to Concepción Pápalo adjacent to the Oaxaca Fault zone, in an outcrop of presumed mylonitized Oaxacan Complex. Location of the other samples is given in Figure 1.

Table 2.- Petrographic characteristics of Group 2 (amphibolite).

Sample	O-91	O-82	M-23	N-31	O-84	O-93	M-22	N-3	N-7	O-34	M-13	O-101	M-28	O-146
Rock type	And		Pmy	Pmy	Pmy	Pmy	My	My	My	My	My	My	Umy	Umy
Elevation [m.a.s.l.]	2,800	2,760	2,300	1,850	2,760	2,800	2,300	1,850	2,000	2,600	1,900	2,800	1,740	2,740
Mineralogy [%]														
Green hornblende	2		6	56	38	32.5	53.5	58.5	73.5	40	46.5	62	65	74.5
Reddish-brown hornblende	35	16.5	20	1										
Actinolite-tremolite		2	2.5			3								
Feldspar	24	18.5	35	4.5	24	39	21	25	24.5	36	15.5	32	21.5	15.5
Epidote	15	32	5	25	17		18.5	13		23				
Clinozoisite		6.5		7					1		35	6	2 + *2	
Chlorite	22	18.5	23	0.5	6	16	2	0.5						
Mica (muscovite, biotite or chlorite)					12	5		2.5					6.5	*3.5
Ilmenite					3	1.5	0.2						1	
Hematite	1						1		0.5					*3
Sphene	1	6	7.5	3		2.5	2			1	2.5			3.5
Apatite			1	0.5		0.5	1.5	0.5	0.5					
Quartz				*1.5			0.3							
Calcite				*1							0.5		*1	
Microstructures														
Porphyroclast size [mm]	1-0.5	0.5	1	1.5	1- 0.5	1	1.2	0.6	0.5	0.7	0.4	0.4		
Matrix grain size [mm]	0.1	0.1	0.1	0.02-0.05	0.05	0.05	0.1-0.3	0.1	0.05	0.1	0.05	0.1	0.1	0.05
Porphyroclasts / matrix [%]				80 / 20	40 / 60	35 / 65	60 / 40	60 / 40	30 / 70	30 / 70	20 / 80	20 / 80	100	98 / 2
s / c surfaces							2	3	3	2			3	1
Broken and displaced crystals									1	2				1
Pressure shadows						1	1	1		1		3		1
Mineral segregation									2	3		3	3	3
Sutured grains	1	1	1	3	1	1		1				1	1	
Subgrains		1	1	3	3	1	1	1		1			1	
Shear bands				3			1							
Recrystallized new grains				3	3	1	1	3	3	3			3	3
Core-and-mantle structure														
Undulatory extinction		1		3	3	2	2	1		2			1	
Zoned crystals				1				3						
Foliation							3	3	3	3		3	3	3
Principal component = 3; minor component = 2; trace component = 1														

* secondary component; And, andesite; Pmy, protomylonite; My, mylonite; Umy, ultramylonite.

The Sm-Nd model age (1.3 Ga) and the negative ε_{Nd} values determined in samples N-1 and N-3 are similar to the Sm-Nd data obtained by Patchett and Ruiz (1987) in gneisses from the Oaxacan Complex. The values $\varepsilon_{Nd} = +2.89$ and the $T_{DM} = 0.82$ of sample O-150 relate it to the Cuicateco terrane basement of oceanic affinity and whose age has been reported as Paleozoic (Carfantan, 1986; Murillo *et al.*,1992).

This group is genetically associated with both the Zapoteco and the Cuicateco terranes. The amphibolites in the western front of the mylonite belt are correlated with the Precambrian granulite-facies rocks of the Oaxacan Complex by its proximity with the gneisses of the last one, the exsolution lamellae present in the feldspars, and the isotopic data. On the other hand, the protolith of the amphibolites nearby Teocuilco, was probably an igneous volcanic or subvolcanic sequence of basic composition (basalt, trachybasalt and/or andesite), of the calc-alkaline series from the Cuicateco terrane basement. This assumption is based on: (1) the least deformed amphibolites have relict igneous textures such as phenocrysts of high-temperature hornblende, long prismatic plagioclase, and pyroxene pseudomorphs; (2) the relict intrusive structure; and (3) the oceanic affinity inferred from the isotopic data.

Table 3.- Sm / Nd isotopic analyses of three mylonitic amphibolite samples.

Sample	Sm [ppm]	Nd [ppm]	^{143}Nd/^{144}Nd	^{147}Sm/^{144}Nd	ε_{Nd}	T_{DM} [Ga]
N-1	5.7	34.0	0.512060	0.100975	-11.28	1.3
N-3	5.9	36.3	0.512054	0.099738	-11.39	1.3
O-150	1.2	4.7	0.512786	0.161508	+2.89	0.82

$(^{143}Nd / ^{144}Nd)_{DM} = 0.513114$
$(^{147}Sm / ^{144}Nd)_{DM} = 0.222$
$\lambda^{147}Sm = 6.54 \times 10^{-12}\ a^{-1}$

GROUP 3. GRANITIC ROCKS

Group 3 rocks are quartzofeldspathic, holocrystalline and light white-cream in color. These rocks predominate in the San Felipe del Agua region, in the western contact zone from San Pedro Etla to the city of Oaxaca, and in some isolated zones across the mylonitic belt. Location of studied samples is shown in Figure 1, excepting the sample O-522, which was taken on the road of Cuicatlán to Concepción Pápalo. Table 4 presents the petrographic characteristics of some mylonites of this group, a post-Cretaceous granite near El Estudiante (J-2) and one sample from the Permian Etla Granite (J-5).

In the San Pedro and San Pablo Etla area, granitic rocks transitionally pass to a fine-grained, deformed white rock, with thin bands of white mica parallel to foliation. Many samples contain two micas, besides garnet (O-5 and O-6; Table 4). Muscovite is both present as a pretectonic minor mineral and a syntectonic phase grown after the feldspars, first as sericite and later as muscovite. Biotite is observed as a pretectonic mineral.

Some of these granite mylonites are probably related to numerous granitic bodies that intruded the Oaxacan Complex west of the mylonitic belt; the largest of these plutons, the Etla Granite (Pzsi in Plate 1; J-5 in Table 4), has abundant K-feldspar, few or no ferromagnesian minerals, and some garnet; it was dated at 272 ± 8 Ma (Early Permian) with an initial $^{87}Sr/^{88}Sr$ of 0.7047 (Ruiz-Castellanos, 1979). The Etla Granite and the granitic mylonite near San Pedro and San Pablo have similar mineralogy.

Near San Felipe del Agua there is the biggest granite body within the mylonite belt. It has inclusions of basic and granitic mylonites, and is penetratively deformed with development of white mica in the foliation planes. There are many granitic dikes in this zone; in some of them, the foliation is intensively folded and is older than the dikes, with lesser deformation, related to the main granite body. All the dikes had a more rigid behavior during the last mylonitic deformation than the intruded rocks.

Table 4.- Petrographic characteristics of Group 3 (granitic rocks).

Sample	J5 Pzsi	J2 Ti	O-5	O-6	SFG1	SFG A10	SFD A9
Rock type	Mnz	Gr	My	Umy	My	My	Umy
Mineralogy [%]							
Plagioclase	41.5	32					
K-feldspar	45	25					
Quartz	7.5	37	11	20	24.5	30	26
Feldspar in matrix			63.5	67	28.5	25	54
Feldspar as porphyroclast			20		46	44.5	6.5
Myrmekite			1.5				
Chlorite				5.3			
Muscovite	2.5	6	2	1.5	1	0.5	
Biotite			1.5				0.5
Garnet	0.5		0.5	0.2			
Epidote	3			1			
Hematite				4			1.5
Apatite							
Microstructures							
Grain size (mm)	1-2	1					
Porphyroclast size [mm]			0.3		2-3	2-3	0.3
Matrix size [mm]			0.1	0.1	0.1-0.5	0.3	0.05
Foliation (S_n)			S_1, S_2	S_1, S_2	S_1	S_1	S_1, S_2

Pzsi, Permian intrusive Etla Granite; Ti, Post-Cretaceous intrusive; SFG, San Felipe granite; SFD, San Felipe dike; Mnz, monzonite; Gr, granite; My, mylonite; Umy, ultramylonite.

The San Felipe granite (SFG1, and SFGA10 in Table 4) contains plagioclase with deformation twinning and, in some cases, K-feldspar developed myrmekite on its margins parallel to the foliation; perthite/antiperthite exsolution lamellae is common. In general, the grain edges are sutured, though some samples have grains with straight edges forming triple points at 120°. Some plagioclase develops a core-and-mantle structure. These characteristics denote the plastic behavior of the feldspars, which, according to Simpson and De Paor (1991), occurs only at temperatures above 500°C. A 180 ± 4 Ma K-Ar age was obtained for one syntectonic muscovite from one dike in the proximity of the San Felipe Granite.

GROUP 4. CALCAREOUS-PELITIC ROCKS

This group includes metasedimentary mylonites. At San Juan del Estado several meters of phyllite are exposed. On the road from San Juan del Estado to Cerro Siempre Viva calc-silicates are exposed showing porphyroclasts of apatite and a matrix composed of quartz, calcite, zoisite, epidote and hornblende. On the eastern limits of the belt, near Teocuilco de Morelos Pérez, a crenulated schist with abundant biotite was located; this mylonitic schist is nearby a thick package of basic mylonites of Groups 1 and 2.

METAMORPHISM

During mylonitization, the rocks were subject to metamorphic conditions in the greenschist-amphibolite facies limit

(500 ± 50°C; Essene, 1990). This was determined from the following observations:

1. The samples of Groups 1 and 2 show the associations: hornblende + chlorite + epidote/clinozoisite + plagioclase, or actinolite-tremolite + green biotite + epidote + plagioclase.
2. Albite and oligoclase are coexisting in apparent textural equilibrium, as well as hornblende and actinolite.
3. The plastic deformation of the twin feldspar indicates temperatures about 500°C (Simpson and De Paor, 1991).

The thermal event that accompanied the mylonitization also affected unmylonitized amphibolite dikes, whose primary phases recrystallized to match metamorphic assemblages contemporaneously with the ductil deformation.

STRUCTURE

The SJMC is bounded by two faults. The western one, known as the Oaxaca Fault, with a north-south average direction, is a normal fault, with the downthrown block to the west, and a minimum vertical displacement of 1,700 m in the Dominguillo-Teotitlán area (Centeno-García, 1988). At the city of Oaxaca it is orthogonally cut off by another fault trending N85°W that limits the belt to the south. In the Trinidad de Vigueras area, the Cenozoic Oaxaca Fault bounds the mylonitic belt along a N15°W, 35°W trending plane. The mylonite is exposed in the uplifted block, and gneisses from the Oaxacan Complex and a Cretaceous sedimentary sequence in the downthrown block (Plate 2). The sedimentary sequence is formed by interbedded sand, shale and breccia. The breccia contains mainly mylonite, limestone and gneiss clasts.

In the eastern margin of the SJMC, mylonitic rocks underlie marine sediments of Valanginian age (Carfantan, 1986; Ortega-Gutiérrez and González-Arreola, 1985) belonging to the Cuicateco terrane. Near El Estudiante, clasts of mylonite occur in a breccia interbedded with the Valanginian sedimentary sequence.

The mylonitic belt is limited to the south by the normal Donají Fault (Nieto-Samaniego *et al.*, in press), which separates it from Oaxacan Complex gneisses underlying a sedimentary sequence consisting of thin-bedded siltstone, sandstone and shale, probably belonging to the Valanginian sedimentary sequence mentioned above. The fault contact plane measured near San Felipe del Agua trends N60°W and dips 25°SW (Plate 2).

The most important mesostructural characteristic of the tectonized belt is the mylonitic foliation seen throughout the belt. Its direction changes gradually, from parallel to the limiting faults, to perpendicular to them in the core of the belt (Plate 3). Inclination of the foliation is variable; on the belt margins, it is predominantly to the west with angles between 20 and 70°, whereas in the core, it is apparently at random.

Lineation measurements were made on axes of mesofolds and mineral lineations. Throughout the mylonitic belt, fold axes are parallel to the direction of foliation; whereas mineral lineation has a consistently general north-south orientation and an almost horizontal inclination (Plate 3).

Near San Felipe del Agua, there are structures indicative of different phases of mylonitic deformation. Some of these structures reflect contrasting mechanical behavior of the competent mylonitized granite dikes and the host mylonite that is more ductile.

The granite dikes are foliated and cracked, showing a ductile strain overprinted by a brittle strain. Bookshelf sliding (Ramsay and Huber, 1987) produced by brittle strain is parallel to the N-S regional trend of mineral lineation and indicates senses of movement both top to the north and top to the south (Plate 3). In addition, s/c surfaces (Simpson and Schmid, 1983) developed in a chlorite-rich mylonite show the same senses of movement. These kinematic indicators show a relative movement in which the upper plate moved over the lower plate along north-south direction during a brittle-ductile transition deformation.

On the other hand, microscopic shear bands measured in the foliated granite do not show a single sense of movement, and the σ structures are deformed. These structures precede the bookshelf sliding structure mentioned above, and therefore they were overprinted by at least two phases of deformation.

At least two events of ductile and another of brittle-ductile deformation in the Sierra de Juárez mylonitic complex were documented. The first event was proposed by Ortega-Gutiérrez and coworkers (1990) as a major thrust in which the Zapoteco terrane was juxtaposed over the Cuicateco terrane. The observed structures that record the thrust are: (1) the contact between the mylonite and the host rocks dips 30° to the west; (2) the oldest rocks (Precambrian Oaxacan Complex) are in the upper plate; and (3) the mylonite foliation dips 25-60° to the west at the western edge of the structutral belt.

Some structures record a second event of ductile deformation, such as interference patterns, chaotic foliation in the core of the mylonite belt and ambiguous σ structures. It is suggested that the foliation and σ structures have been formed during the thrust, and then they have changed their direction and have suffered deformation in a later oblique movement.

A posterior event was recorded in asymmetric mesostructures, such as bookshelf sliding, s/c surfaces, and the mineral lineation. The measure of these structures in the San Felipe area shows a top to the north and top to the south movement that implies a displacement on the shear zone during a ductile-brittle deformation. Since the main mylonitic foliation in this area is inclined to the south (Plate 3), the asymmetric top to the south structures could be formed in an early movement of the normal type Donají Fault posterior to the mylonitic belt formation.

DISCUSSION

The plate reconstruction of southern Mexico region has been one of the least agreed upon aspects of the reconstruction of Pangea. The present study, although preliminary, allows to add some constraints to this reconstruction, specially between the Permian and the Middle Jurassic, interval in which it is inferred that the SJMC was formed.

The SJMC has been regarded as a shear zone by many authors. Ortega-Gutiérrez and coworkers (1990) and Sedlock and coworkers (1993) inferred that the Cuicateco terrane was overthrust by the Zapoteco terrane before Early Cretaceous based on their southwest-dipping structure and stratigraphic relationships. Padilla y Sánchez (1986) considered this belt as the southern part of the Tamaulipas-Oaxaca Fault and he interpreted it as a dextral fault "along which the Yucatán block drifted apart south-southeastwardly from North America during the Late Jurassic"; he named the Tamaulipas-Oaxaca fault after the lineament that coincides with the boundaries of early Mesozoic landmasses in eastern Mexico. Pindell (1985) proposed the Tamaulipas-Golden Lane-Chiapas fault zone to be a linear trend defined in the eastern side of Tamaulipas and offshore Veracruz, and extending to the south into Chiapas; he suggested that this fault be a right-lateral transform zone between Yucatán and eastern Mexico, which allowed migration of Yucatán away from the Texas-Lousiana margin; evidences that support the existence of this fault are the perpendicular relations between the magnetic anomaly trends and this linear trend (Shepherd *et al.*, 1982 *in* Pindell, 1985), and the salt distribution in the Gulf of Mexico (Bufler *et al.*, 1979, *in* Pindell, 1985); Pindell pointed out that Callovian or Oxfordian red beds and anhydrites were deposited contemporaneously with the intracontinental extension.

The present study documents the thrust and its reactivation between the Early Permian and the Middle Jurassic. The Juchatengo island-arc rocks in southern Oaxaca (Grajales-Nishimura, 1988) and the abundant upper Paleozoic granitic bodies in Puebla and Oaxaca states (Grajales-Nishimura *et al.*, 1991), along a N-S trend parallel to the mylonite belt, are indicative of an east-dipping subduction zone active during the upper Paleozoic along the western Mexican continental margin. The geographic position, time and vergence of the thrust mylonite belt could be related to the subduction regime mentioned above.

The structures formed during the reactivation of this shear zone are hidden, but our data strongly favor that they were formed about Early Jurassic time in a movement oblique to the thrust direction. If Pindell's (*op. cit.*) tectonic reconstruction is correct, then the shear zone will have right-laterally moved at this time during the southward displacement of the Yucatán block as the Gulf of Mexico opened.

CONCLUSIONS

The geologic and petrologic studies of the southern Sierra de Juárez mylonitic complex, allow to differentiate five principal units from four lithological groups that make up the mylonitic belt. Each one of these lithological groups shows different degrees of deformation and allows an inference of the nature of its protolith based on the least deformed rocks. Their characteristics and protolith are:

The first unit includes pelitic gneiss, marble, meta-anorthosite and mafic orthogneiss of the Oaxacan Complex, which were ductily deformed on the western margin of the mylonitic belt.

The second unit consists of leucocratic granitic rocks (Group 3), with muscovite within mylonitic foliation planes. The mylonitized granite near San Pablo and San Pedro Etla is correlated with the Permian Etla Granite. The mylonitized granite close to San Felipe del Agua is considered syntectonic by structural relationships (Plate 2).

The third unit corresponds to ultramafic rocks (Group 1) constituted of more than 90% in volume of amphibole and is classified as hornblendite. These rocks do not belong to the Oaxacan Complex because they preserve primary magmatic textures, but they can be correlated with gabbroic rocks of the Cuicateco terrane.

The fourth unit is made up of volcanic or subvolcanic rocks of basic composition (Group 2) and calc-alkalic affinity. These rocks probably belong to the Cuicateco terrane basement.

The fifth unit represents sedimentary rocks of diverse origin and lithologies (Group 4). Near San Juan del Estado, there are mylonitized phyllites. The last lithology consists of a mylonitized biotite schist located near Teocuilco de Morelos Pérez. Until now, the nature of these pelitic rocks is unknown.

The mylonitic deformation was formed under metamorphic conditions in the limit of the greenschist and amphibolite facies, which corresponds to a temperature of 500 ± 50°C. The metamorphic associations belonging to this facies are present in every rock in this belt. Microtextural evidence indicates that muscovite was formed under the effects of the deformation.

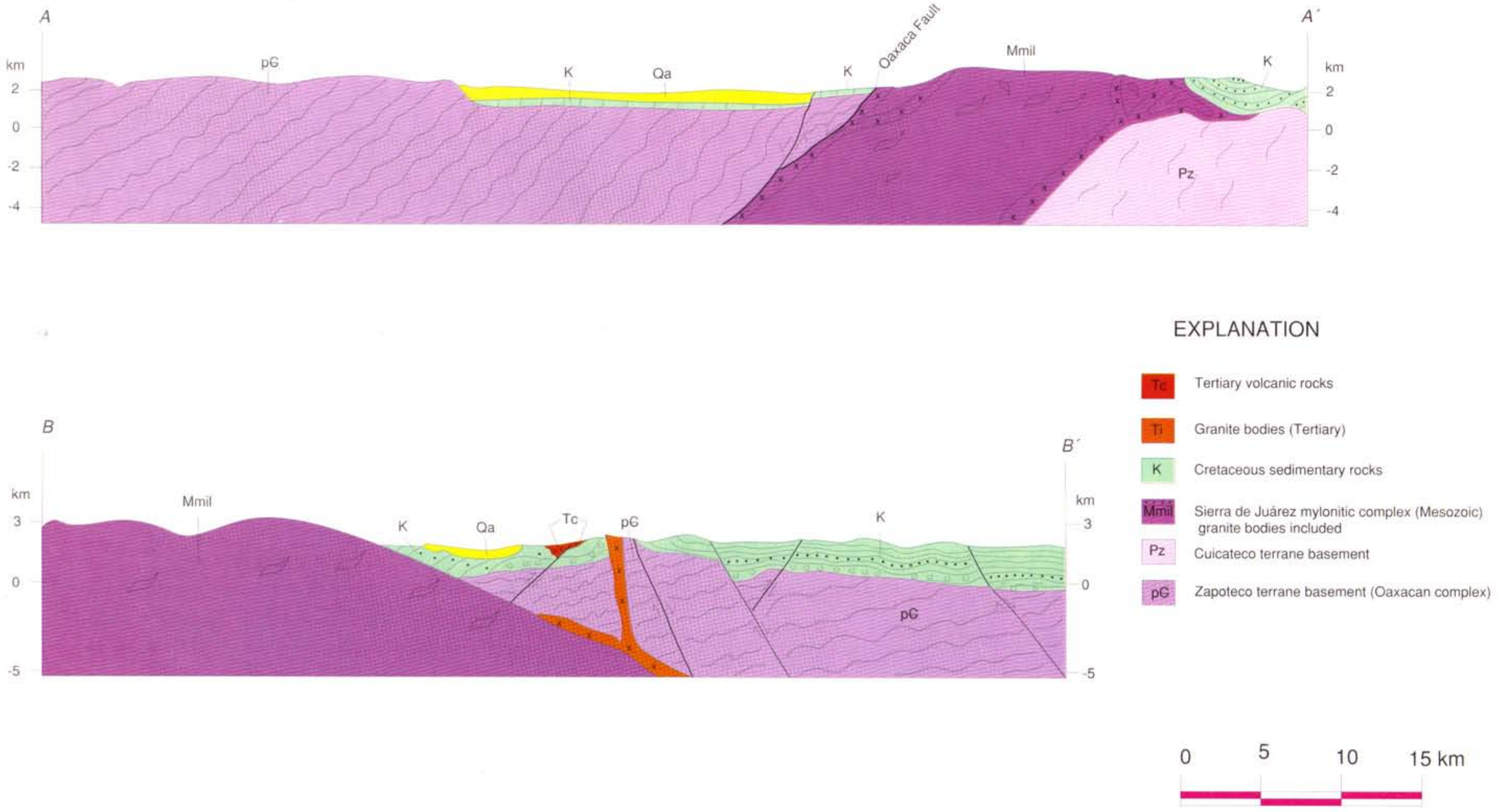
The structural features and the kinematic indicators show that the mylonitic belt was formed by thrust to the east and later reactivated with a probably lateral displacement.

Permian granites are the youngest pretectonic rocks with well-known ages that show mylonitic deformation. This is the reason to consider the beginning of mylonitization after the Late Permian. A syntectonic muscovite yielded a K-Ar age of 180 ± 4 Ma. During the Valanginian, the mylonite belt was exposed as shown by clasts of mylonite found within Valanginian marine sediments near the city of Oaxaca.

These data constrain the belt age from Late Permian to Late Jurassic. Exhumation of the belt began after the Jurassic, was exposed in the Valanginian, and was again uplifted in the upper Cenozoic by normal faulting.

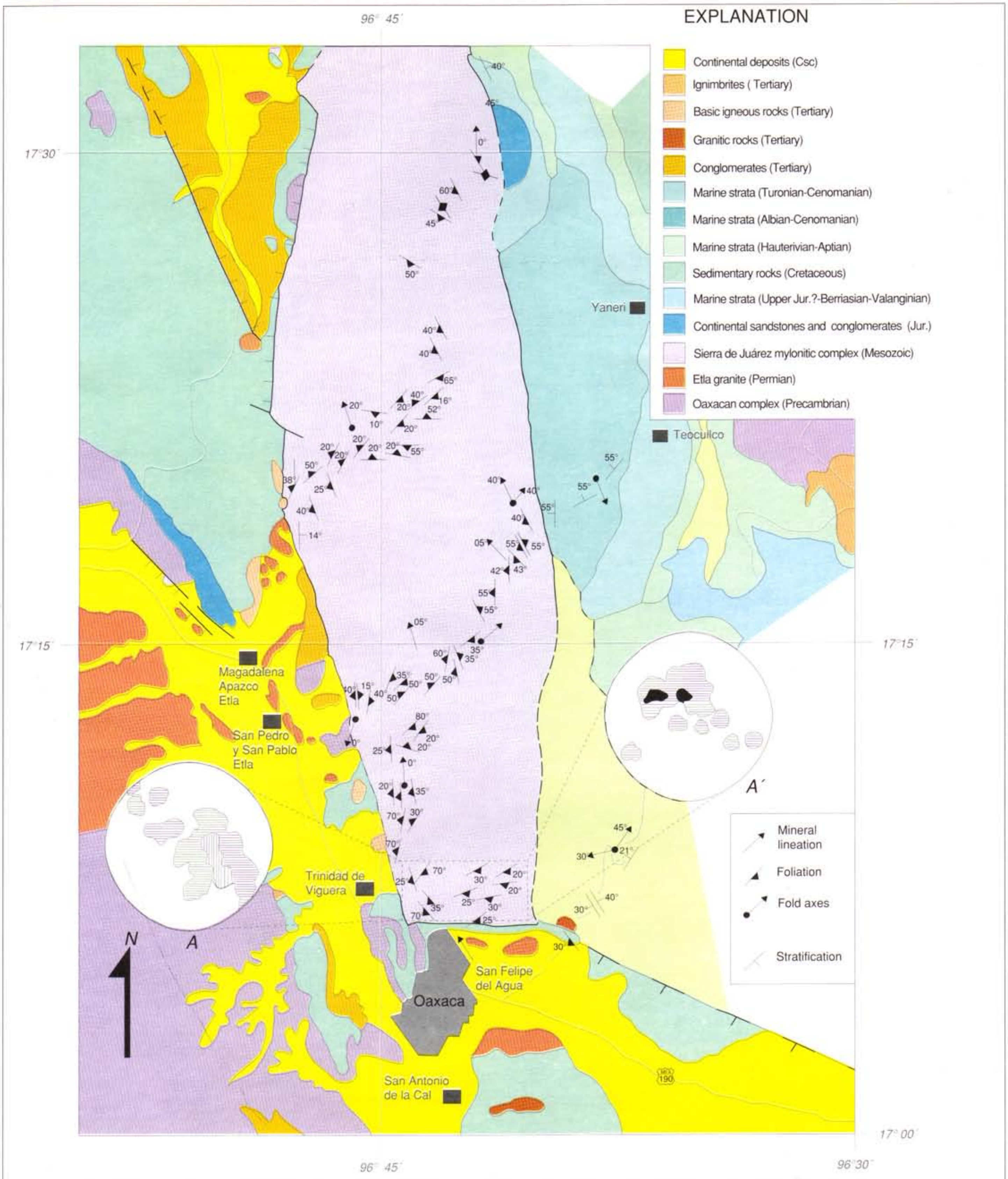
ACKNOWLEDGMENTS

The authors would like to thank Barbara Martiny, Margarita Reyes-Salas, Consuelo Macías-Romo, Crescencio Garduño-Paz and Juan Tomás Vázquez-Ramírez, all of whom



Computer color separation was made by José de Jesús Vega-Carrillo

STRUCTURAL CROSS SECTIONS



(A) Low hemisphere stereonet of the foliation in the Trinidad de Viguera-San Felipe del Agua zone and(A') in the San Felipe del Agua-Donají zone

Computer color separation was made by José de Jesús Vega-Carrillo

STRUCTURAL MAP OF THE SIERRA DE JUÁREZ AREA, OAXACA

collaborated with them on technical aspects of the work described here. We thank Dante J. Morán-Zenteno for making the Sm/Nd isotopic analysis in the University of Munich and for helpful discussions. Gerardo Aguirre made helpful comments on earlier versions of this manuscript. This paper benefitted from critical review by Peter Coney and an anonymous reviewer. This work was partially supported by PADEP, UNAM (project No. 030316), and CONACyT (project D112-903637).

BIBLIOGRAPHICAL REFERENCES

Alaniz-Álvarez, S.A.; Ortega-Gutiérrez, Fernando; Mújica-Sánchez, Hugo; and Ramírez-Hernández, Alfonso, 1991, Geología y petrología de las tectonitas del frente occidental de la sierra de Juárez, Estado de Oaxaca: Universidad Nacional Autónoma de México, Instituto de Geología; Universidad Autónoma de Hidalgo, Instituto de Investigaciones en Ciencias de la Tierra; Sociedad Mexicana de Mineralogía; y Secretaría de Educación Pública, Subsecretaría de Educación Superior e Investigación Científica, Convención sobre la evolución geológica de México, y Congreso Mexicano de Mineralogía, 1, Pachuca, Hgo., Mexico, Memoria, p. 5 (abstract).

Anderson, T.H., and Silver, L.T., 1971, Age of granulite metamorphism during the Oaxacan orogeny, Mexico: Geological Society of America Abstracts with Programs, v. 3, p. 492 (abstract).

Bogatikov, O.A. *et al.*, 1981, Klassifikatsia i nomenclatura magmaticheskix govnix porod spravochnoe posobie: Moscow, Nedra, 160 p.

Campa-Uranga, M.F., and Coney, P.J., 1983, Tectono-stratigraphic terranes and mineral resource distributions of Mexico: Canadian Journal of Earth Sciences, v. 20, p. 1040-1051.

Carfantan, J.C., 1981 (1984), Evolución estructural del sureste de México—paleogeografía e historia tectónica de las zonas internas mesozoicas: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 5, p. 207-216.

——— 1983, Les ensembles géologiques du Mexique méridional—Évolution géodynamique durant le Mésozoïque et le Cénozoïque: Geofísica Internacional (Mexico), v. 22, p. 9-37.

——— 1986, Du système cordillérain nord-américain au domaine Caraïbe—Étude géologique du Mexique méridional: Chambéry, Université de Savoie, Ph.D. dissertation, 558 p. (unpublished).

Centeno-García, Elena, 1988, Evolución estructural de la falla de Oaxaca durante el Cenozoico: México, D.F., Universidad Nacional Autónoma de México, Facultad de Ciencias, M. Sc. thesis, 156 p. (unpublished).

Coney, P.J.; Jones, D.L.; and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 299, p. 329-333.

Delgado-Argote, L.A., 1988, Geología preliminar de la secuencia volcanosedimentaria y serpentinitas asociadas del Jurásico (?) del área de Cuicatlán-Concepción Pápalo, Oaxaca: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 7, p. 127-135.

Essene, E.J., 1990, The current status of thermobarometry in metamorphic rocks: University of Michigan, Mineralogical Laboratory, Contribution 453.

Ferrusquía-Villafranca, Ismael, 1976, Estudios geológico-paleontológicos en la región Mixteca; parte 1, Geología del área Tamazulapan-Teposcolula-Yanhuitlán, Mixteca Alta, Estado de Oaxaca, México: Universidad Nacional Autónoma de México, Instituto de Geología, Boletín 97, 185 p.

Grajales-Nishimura, J.M., 1988, Geology, geochronology, geochemistry, and tectonic implications of the Juchatengo green rock sequence, State of Oaxaca, southern Mexico: Tucson, The University of Arizona, M. Sc. thesis, 145 p. (unpublished).

——— 1991, La franja magmática del Paleozoico tardío en Oaxaca y sur de Puebla y sus implicaciones tectónicas: Universidad Nacional Autónoma de México, Instituto de Geología; Universidad Autónoma de Hidalgo, Instituto de Investigaciones en Ciencias de la Tierra; Sociedad Mexicana de Mineralogía y Secretaría de Educación Pública, Subsecretaría de Educación Superior e Investigación Científica, Convención sobre la evolución geológica de México, y Congreso Mexicano de Mineralogía, 1, Pachuca, Hgo., Mexico, Memoria, p. 61 (abstract).

Le Bas, M.J.; Le Maitre, R.W.; Streckeisen, A.; and Zanettin, B.A., 1986, Chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Mora, C.I.; Valley, J.W.; and Ortega-Gutiérrez, Fernando, 1986, The temperature and pressure conditions of Grenville-age granulite-facies metamorphism of the Oaxacan complex, southern Mexico: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 6, p. 222-242.

Murillo-Muñetón, G.; Torres-Vargas, R.; and Navarrete-R., O., 1992, El macizo de La Mixtequita—redefinición: Sociedad Geológica Mexicana, Convención Geológica Nacional, 11, Veracruz, Ver., Resúmenes, p. 131 (abstract).

Nieto-Samaniego, Á.F.; Alaniz-Álvarez, S.A.; and Ortega-Gutiérrez, Fernando, in press, Estructura interna de la falla de Oaxaca e influencia de las anisotropías litológicas durante su actividad cenozoica: Revista Mexicana de Ciencias Geológicas.

Ortega-Gutiérrez, Fernando, 1980, Algunas rocas miloníticas de México y su significado tectónico: Sociedad Geológica Mexicana, Convención Geológica Nacional, 5, México, D.F., Resúmenes, p. 99-100 (abstract).

——— 1984, Evidence of Precambrian evaporites in the Oaxacan granulite Complex of southern Mexico: Precambrian Research, v. 23, p. 377-393.

Ortega-Gutiérrez, Fernando; Anderson, T.H.; and Silver, L.T., 1977, Lithologies and geochronology of the Precambrian craton of southern Mexico: Geological Society of America Abstracts with Programs, v. 9, p. 1121-1122 (abstract).

Ortega-Gutiérrez, Fernando, y González-Arreola, Celestina, 1985, Una edad cretácica de las rocas sedimentarias deformadas de la sierra de Juárez, Oaxaca: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 6, p. 100-101.

Ortega-Gutiérrez, Fernando; Mitre-Salazar, L.M.; Roldán-Quintana, Jaime; Sánchez-Rubio, Gerardo; and de la Fuente, Mauricio, 1990, North American Continent-Ocean Transect Program, Transect H-3—Acapulco Trench to the Gulf of Mexico across southern Mexico: Geological Society of America, Decade of North American Geology Program, scale 1:500,000, 9 p., map and sections.

Padilla y Sánchez, R.J., 1986, Post-Paleozoic tectonics of northeast Mexico and its role in the evolution of the Gulf of Mexico: Geofísica Internacional (Mexico), v. 25, p. 157-206.

Pantoja-Alor, Jerjes, 1970, Rocas sedimentarias paleozoicas de la región septentrional de Oaxaca: México, D.F., Sociedad Geológica Mexicana, Libro-guía de la excursión México-Oaxaca, p. 67-84.

Pantoja-Alor, Jerjes, and Robison, R., 1967, Paleozoic sedimentary rocks in Oaxaca, Mexico: Science, v. 157, p. 1033-1035.

Patchett, P.J., and Ruiz, Joaquín, 1987, Nd isotopic ages of crust formation and metamorphism in the Precambrian of eastern and southern Mexico: Contributions to Mineralogy and Petrology, v. 96, p. 523-528.

Pindell, J.L., 1985, Alleghenian reconstruction and subsequent evolution of the Gulf of Mexico, Bahamas, and proto-Caribbean: Tectonics, v. 4, p. 1-39.

Ramsay, J.G., and Huber, M.I., 1987, The techniques of modern structural geology; Volume 2, Folds and fractures: London, Academic Press, 462 p.

Ratschbacher, L.; Riller, U.; Meschede, M.; Herrmann, U.; and Frisch, W., 1991, Second look at suspect terranes in southern Mexico: Geology, v. 19, p. 1233-1236.

Robinson, K.L.; Gastil, R.G.; and Girty, M.S., 1990, Eocene intra-arc transtension; the detachment of the Chortis block from southwestern Mexico: Geological Society of America Abstracts with Programs, v. 22, p. 78 (abstract).

Ruiz-Castellanos, Mario, 1979, Rubidium-strontium geochronology of the Oaxaca and Acatlán metamorphic areas of southern Mexico: The University of Texas at Dallas, Ph. D. dissertation, 178 p. (unpublished).

Sedlock, R.L.; Ortega-Gutiérrez, Fernando; and Speed, R.C., 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geological Society of America, Special Paper, v. 278, 153 p.

Simpson, Carol, and Schmid, S.M., 1983, An evaluation of criteria to deduce the sense of movement in sheared rocks: Geological Society of America Bulletin, v. 94, p. 1281-1288.

Simpson, Carol, and De Paor, Deelang, 1991, Deformation and kinematics of high strain zones: Annual Meeting of the Geological Society of America, San Diego, Short Course Notes, 116 p.

Spry, Alan, 1969, Metamorphic textures: New York, Pergamon, 350 p.

Weber, Reinhard; Centeno-García, Elena; and Magallón-Puebla, Susana, 1987, La formación Matzitzi (Estado de Puebla) tiene edad permocarbonífera: Universidad Nacional Autónoma de México, Instituto de Geología, Segundo Simposio de Geología Regional de México, Mexico, D.F., Programa y Resúmenes, p. 57-58 (abstract).

Manuscript received: May 31, 1993.
Corrected manuscript received: April 29, 1994.
Manuscript accepted: May 5, 1994.