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This paper is dedicated to the memory of Dr. Richard L. Armstrong of the University of British Columbia, Canada, who generously provided Rb-Sr and K-Ar dates for south-central Mexico.

TECTONIC IMPLICATIONS OF A MYLONITIC GRANITE IN THE LOWER STRUCTURAL LEVELS OF THE TIERRA CALIENTE COMPLEX (GUERRERO TERRANE), SOUTHERN MEXICO

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ABSTRACT

Two sequences of pre-Tertiary volcano-sedimentary rocks with island arc affinities have been differentiated in the Zacazonapan area, State of Mexico. These rocks are part of the Tierra Caliente complex or the tectonostratigraphic Guerrero terrane.

The lower sequence, grouped as pre-Cretaceous metamorphic rocks, is essentially made up of about 1,500 m of carbonaceous phyllite interbedded with greenschist (chlorite-actinolite-epidote schist) and metarhyolite lenticular bodies. This package is characterized by penetrative foliation associated with recumbent tight to isoclinal folding under greenschist facies conditions.

The upper sequence consists of argillaceous limestone, black slate and graywacke, and andesitic pillow lavas with tuffaceous and siliceous sediments. This package shows different degrees of deformation. The pillow-lavas are non-flattened or slightly flattened with an incipient development of fracture cleavage. The limestone and clastic sediments display asymmetric folding with associated crenulation cleavage, and they are characterized by non-penetrative, very low grade metamorphism. This sequence is correlated with the Cretaceous Amatepec and Xochipala formations.

The relationship between pre-Cretaceous metamorphic rocks and the Cretaceous rocks is a thrust, at least in the Zacazonapan area, although it is probable that a low-angle unconformity had acted as a sliding surface during the deformation of the Cretaceous cover (Laramide Orogeny).

At the bottom of the pre-Cretaceous metamorphic sequence, a mylonitic granite with continental crust affinity is exposed. The granite is apparently a pre-Jurassic sialic basement in the region; it is affected by a heterogeneous mylonitic deformation, changing gradually upward from massive granite into augengneiss granite, and then into blastomylonitic quartz-muscovite schist, in response to the intensity of the shear strain. The deformation of the pluton, represented by mylonitization about 400 m thick, occurred at about 500°C and 4 kb, that is, under epidote-amphibolite facies conditions. The mylonitization represents an important mesozonal shear zone indicating northeastward-directed movements, and implying an allochthonous relationship with the overlying pre-Cretaceous metamorphic rocks.

The overriding movements of the pre-Cretaceous metamorphic rocks on the apparent pre-Jurassic basal granite may be related to a décollement at mid-crustal levels, involving a thick-skinned structure. It may correspond to the first compressional tectonic event in the region (Middle or Late Jurassic Nevadan Orogeny?), probably related to the accretion of a Mesozoic submarine arc, or back-arc basin, to an old continental margin. The ductile thrusting zone, represented by shear strain in the basal granite, may be, therefore, the true accretionary boundary of the Guerrero terrane at its eastern border, and not the reverse fault that juxtaposed it against the Morelos-Guerrero platform as previously suggested.

Key words: accretionary tectonics, Tierra Caliente complex, Guerrero terrane, mylonitic rocks, metamorphic rocks, State of Mexico, Mexico.

RESUMEN

En el área de Zacazonapan, Estado de México, dos secuencias volcanosedimentarias preterciarias, con afinidad de arco de islas, han sido diferenciadas. Ambos paquetes de roca son parte del complejo Tierra Caliente o del terreno Guerrero.

La secuencia inferior, designada en este artículo como rocas metamórficas precretácicas, está constituida principalmente por unos 1,500 m de filita carbonosa intercalada con esquisto verde y cuerpos lenticulares de metarriolita. El paquete está caracterizado por una foliación penetrante

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asociada a un plegamiento recumbente cerrado e isoclinal y a un metamorfismo regional de facies de esquisto verde.

La secuencia superior consiste en caliza arcillosa con intercalaciones de pizarra y grauvaca, y espesores importantes de lava con estructura almohadillada, que, a su vez, contienen intercalaciones de sedimentos tobáceo y silíceo. El paquete presenta grados diferentes de deformación. Las lavas almohadilladas en algunos lugares no están deformadas, mientras que en otros están aplastadas con un crucero de fractura asociado. La caliza y los sedimentos intercalados manifiestan un plegamiento asimétrico con desarrollo de crucero plisado. La secuencia superior, la cual es correlacionable con las formaciones cretácicas Amatepec y Xochipala, está caracterizada en su conjunto por un metamorfismo regional de muy bajo grado no penetrante.

La secuencia superior cretácica, en el área de Zacazonapan, sobreyace a las rocas metamórficas precretácicas por medio de una cabalgadura, aunque es probable que una discordancia angular preexistente haya actuado como una superficie de deslizamiento durante la deformación de la cubierta cretácica (Orogenia Laramide).

Un granito milonitizado, con afinidad de corteza continental, está expuesto en la parte más inferior de la secuencia metamórfica precretácica. El granito es, aparentemente, un basamento siálico prejurásico en la región; está afectado por una deformación milonítica heterogénea, la cual se traduce en cambios graduales, hacia su parte superior, de granito masivo a granito augengnéisico y, después, a esquisto blastomilonítico de cuarzo-muscovita dependiendo de la intensidad de la deformación por cizallamiento. La deformación del plutón, representada por cerca de 400 m de milonitización, se desarrolló alrededor de los 500°C y 4 kb, es decir, bajo condiciones de facies de epidota-anfibolita e implica una zona de cizallamiento importante en niveles corticales medios, la cual indica movimientos hacia el noreste y sugiere la aloctonía de las rocas metamórficas precretácicas sobreyacentes.

Los movimientos de cabalgamiento de las rocas metamórficas precretácicas sobre el granito basal aparentemente prejurásico pueden estar relacionados con un *décollement* en niveles corticales medios con involucramiento del basamento. Estos movimientos pueden corresponder al primer evento tectónico compresivo en la región (¿Orogenia Nevadiana del Jurásico Medio o Tardío?), relacionados probablemente con la acreción de un arco de islas o una cuenca trasarco mesozoicos a un borde continental antiguo. La zona de cizallamiento dúctil, representada por los grados diferentes de milonitización en el granito basal, puede ser, por consiguiente, el límite de acreción verdadero del terreno Guerrero en su borde oriental.

Palabras clave: tectónica de acreción, complejo Tierra Caliente, terreno Guerrero, rocas miloníticas, rocas metamórficas, Estado de México, México.

INTRODUCTION

The scarcity of paleontologic and isotopic data, and of adequate geologic mapping in the metamorphic terrane exposed in the Tierra Caliente region of southwestern Mexico, has caused chronostratigraphic, structural, and nomenclatural controversies which are still not resolved. Several authors assigned a Late Jurassic-Early Cretaceous age to all metamorphic volcano-sedimentary rocks in this region, on the basis of scarce biostratigraphic data (Campa *et al.*, 1974; Campa and Ramírez, 1979). On the other hand, the same rocks have been differentiated by de Cserna (1978, 1982) as metamorphic basement rocks, represented by Taxco Schist, with a tentative late Paleozoic age; Taxco Viejo Greenstone, with a probable Late Triassic-Early Jurassic age; and rocks of the Mesozoic marine sedimentary cover, whose ages range from Late Jurassic to Late Cretaceous. Pending better knowledge of their true geological relationships, Ortega (1981) used the informal name of Tierra Caliente complex in order to assemble all volcano-sedimentary rocks characterized by low-grade metamorphism and intense deformation in the region. The Tierra Caliente complex is part of the vast composite Guerrero terrane of Late Jurassic to Early Cretaceous age that lacks pre-Jurassic basement according to the definition of Campa and Coney (1983).

In the Zacazonapan area, State of Mexico (Figure 1), however, an apparent pre-Jurassic plutonic basement has been found (Elías-Herrera, 1981, 1987, 1989; Parga-Pérez, 1981), whose petrographic characteristics have been mentioned. Nonetheless, important petrographic reconsiderations, some new geochemical features and the tectonic relationship of this basement with the overlying metamorphic volcano-sedimentary rocks are analyzed and discussed here. We hope that this analysis contributes to a better understanding of this apparent plutonic basement, and, in general, to bring more elements into consideration to clarify and/or to focus on some stratigraphic and structural problems of the vast composite Guerrero terrane at its eastern margin. For discussion and implications, we include some important geologic data from Taxco el Viejo area, State of Guerrero (Figure 1), where the eastermost outcrops of the metamorphic Guerrero terrane are found.

GEOLOGY OF THE ZACAZONAPAN AREA

A mylonitic granite, the principal topic of this paper, is exposed in this area, and it represents the bottom of the metamorphic rocks. Over this, two sequences of pre-Tertiary volcano-sedimentary rocks with submarine arc affinities were differentiated. The lower sequence, and surely the oldest, corresponds to the "basement metamorphic rocks" or Taxco Schist of de Cserna (1982) who assigned a late Paleozoic age to it. This sequence is overriding the mylonitic granite. The upper sequence represents an apparent Cretaceous cover that is unconformably overlying the basement metamorphic rocks (de Cserna, 1982).

In the present study, the metamorphic rocks of the lower sequence are grouped as pre-Cretaceous metamorphic rocks (Figure 2) until better and satisfactory geochronologic data are obtained. The package is made up of around 1,500 m of carbonaceous phyllite interlayered with greenschist (chlorite-actinolite-epidote schist), whose protoliths are lahars and submarine pyroclastic flows, amphibolitic metabasites (mapped as actinolite schist), and lenticular metarhyolite bodies with a probable premetamorphic nature of submarine rhyolitic hyalotuff. All these rocks have a penetrative ductile deformation, that is, an intense development of penetrative foliation associated with recumbent tight to isoclinal folding under greenschist facies conditions. Although a complex tectonothermic evolution with local mineral

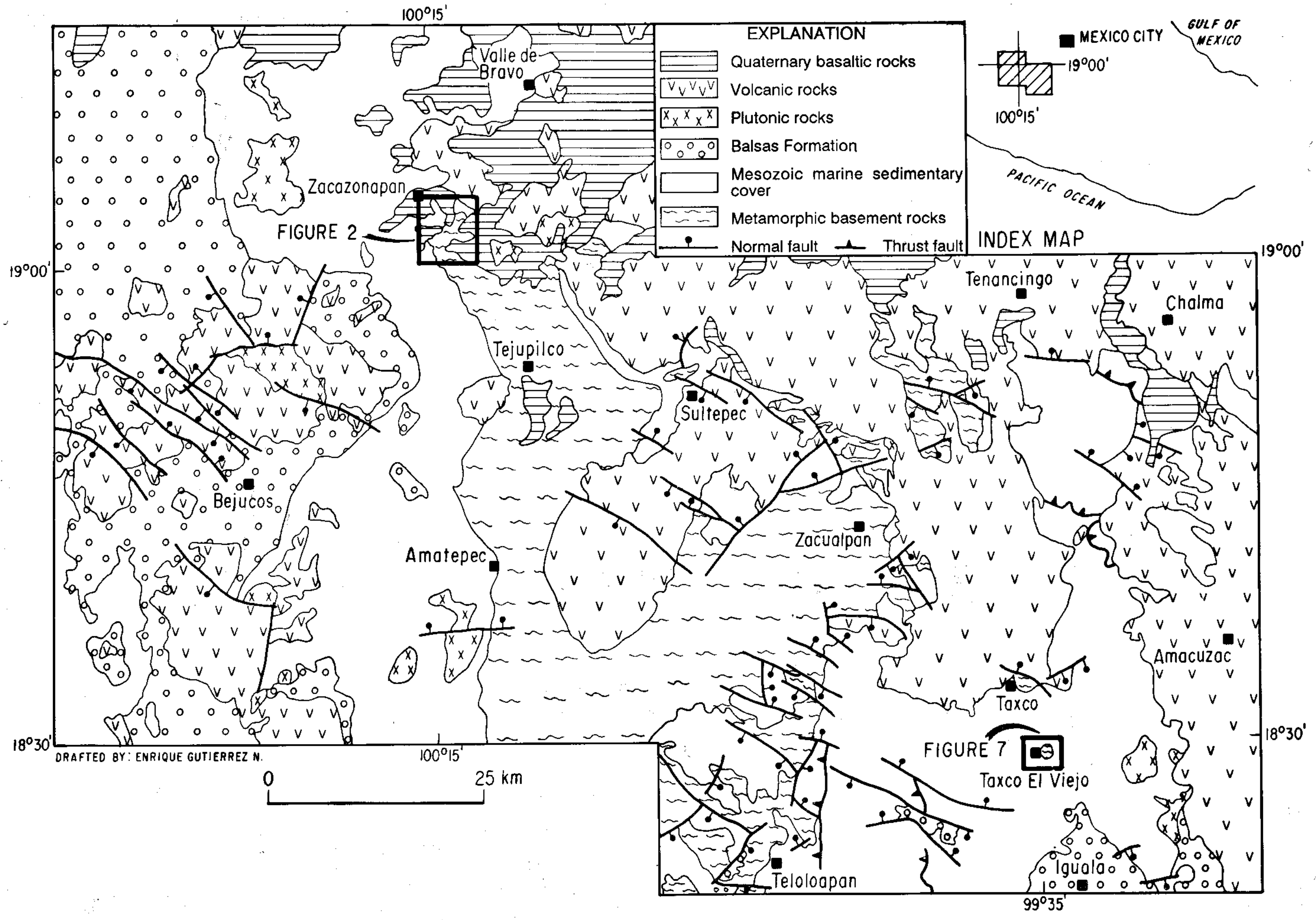

Figure 1.- Simplified map showing geologic setting of the Zacazonapan and Taxco el Viejo areas. The geology from parallel 19 towards the south is after de Cserna (1982, 1983) and de Cserna and Fries (1981). The remaining area is after DEGEGETENAL (1983).

assemblages of the lower part of the amphibolite facies has been reported (Elías-Herrera, 1981, 1989; Parga-Pérez, 1981), the occurrence of almandine within pelitic rocks in the lower part of the sequence indicates that, at least, upper greenschist facies conditions were reached in the Zacazonapan area.

Several deformational events have been proposed for the metamorphic rocks of the region (Campa *et al.*, 1974; Campa, 1978; Elías-Herrera, 1981, 1989; Parga-Pérez, 1981, de Cserna and Fries, 1981; de Cserna, 1982), however, the geometry and kinematics of the different phases of deformation have not been clearly established. In the southeastern adjoining San Lucas del Maíz area, it is considered that the recumbent tight to isoclinal folding with penetrative axial-plane foliation corresponds to the first phase of deformation; the folding of the foliation into close angular asymmetric folds, with incipient development of a non-penetrative second foliation, to a second phase; and an apparent anticlinal structure with NW-SE axial trace, defined essentially by the behavior of the penetrative foliation, to the third phase of deformation (Elías-Herrera, 1989).

In terms of economic geology, one of the most important syngenetic massive sulfide deposits in the region occurs within the pre-Cretaceous metamorphic rocks of the Zacazonapan area. In Figure 2, the underground extension of the Tizapa massive sulfide deposit is delineated, which, at present, is open toward the northwest according to drill-hole data. Toward the south, the ore deposit is limited by a normal fault. For details about the Tizapa ore deposit, the reader is referred to Parga-Pérez and Rodríguez-Salinas (1983).

The Cretaceous upper sequence consists of argillaceous limestone with interbedded black slate and graywacke, and important thicknesses of andesitic pillow lava with interbedded tuffaceous and siliceous sediments. Fossils have not been found in these rocks, however, they are correlated with the Cretaceous Amatepec and Xochipala formations (de Cserna *et al.*, 1978; de Cserna, 1982).

The Cretaceous cover shows different degrees of deformation. The pillow lavas are non to slightly flattened, with incipient development of fracture cleavage. In all the observed exposures, the primary structures in the lavas indicate a normal stratigraphic position for the sequence. Near the contact with calcareous sediments, the pillow lavas are strongly flattened and marked by a single conspicuous foliation. In fact, the contact between pillow lavas and argillaceous limestone is characterized by alternating local tectonic wedges of foliated volcanic material and calcareous sediments. The calcareous and clastic sediments display folding with associated crenulation cleavage, in which compositional differentiation is absent or minimally developed. Small-scale thrust faults are common in the sequence, and transposition of bedding sometimes can be seen. The degree of deformation of the cover increases toward the contact with the pre-Cretaceous

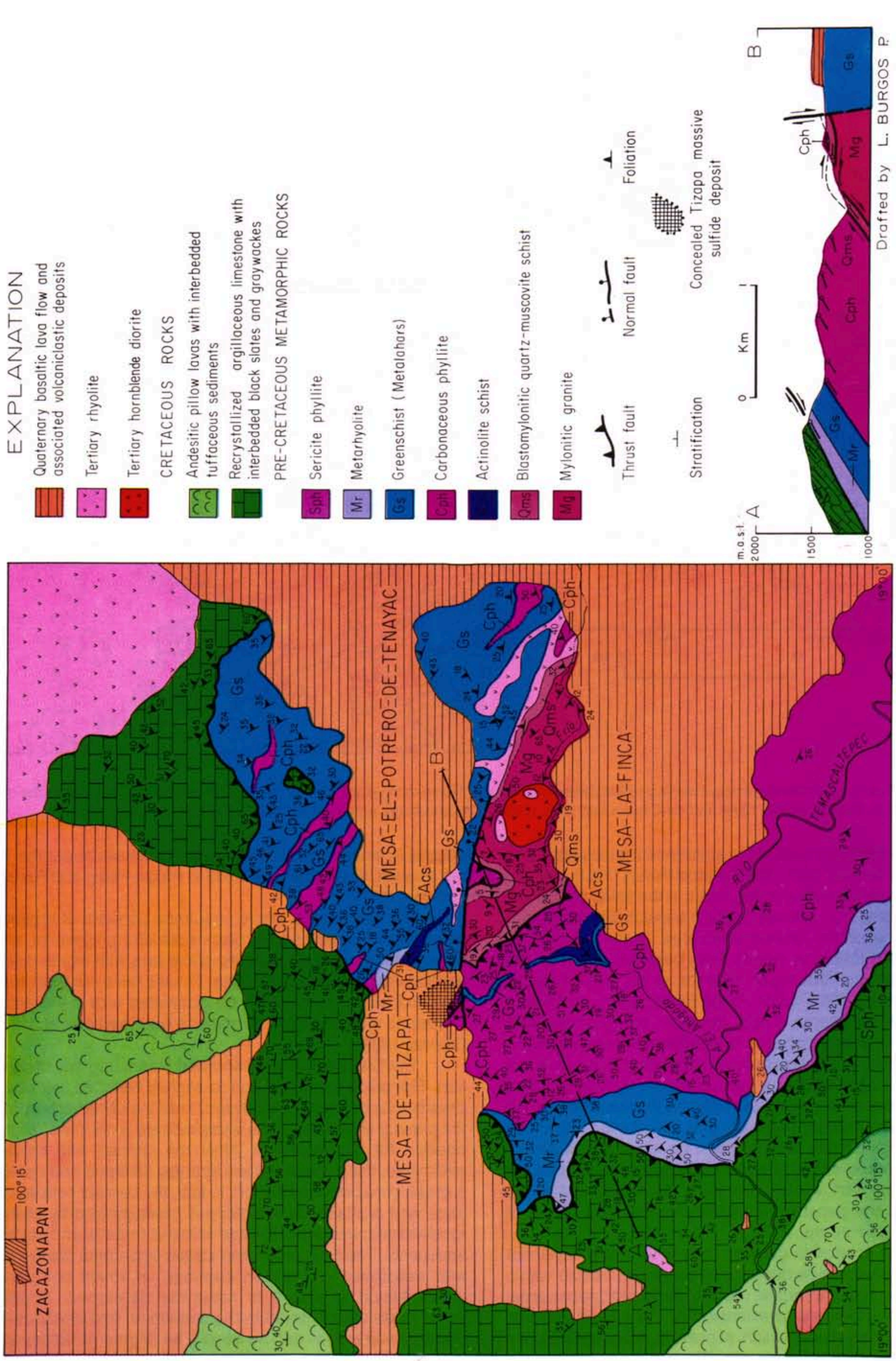

Figure 2.- Geologic map of the Zacazonapan area with a cross section.

metamorphic rocks. In these parts, the limestone shows an intense development of penetrative foliation with rootless intrafolial recumbent isoclinal folds, and it is completely recrystallized. The foliation in the limestone is almost parallel to the main foliation of the underlying metamorphic rocks; furthermore, in the southwestern part of the area, the recrystallized argillaceous limestone seems to grade downward into sericitic phyllite. These features suggest a single, continuous, deformed package of volcano-sedimentary rocks, as it has been considered by some authors (Campa *et al.*, 1974; Campa, 1978; Campa and Ramírez, 1979). Nevertheless, in the central part of the area, the distribution of the foliated and recrystallized Cretaceous limestone is really discordant with the structural trend of the pre-Cretaceous metamorphic rocks (Figure 2). The distribution of the limestone conforms the periclinal structure of the basement fold or Tejupilco uplift adduced by de Cserna (1978, 1982).

The unconformable relationship between basement and cover (de Cserna, 1978; de Cserna and Fries, 1981; de Cserna, 1982) has justly been a point of debate. Although this relationship is being studied by the first author in the Tejupilco region, the work is not completed at this time. The gradual increase of deformation in the Cretaceous cover toward the contact with pre-Cretaceous metamorphic rocks, and the truncation of the metamorphic trend by the limestone suggest, at first analysis, an important thrust surface and not necessarily an angular unconformity, at least in the Zacazonapan area (Figure 2). However, it is probable that the unconformity proposed by de Cserna (1982) acted as a sliding surface during the deformation of the cover, facilitating the overriding movement, whose magnitude of displacement is unknown.

MYLONITIC GRANITE

According to stratigraphic and structural data, the mylonitic granite represents the lowest exposed level of the metamorphic terrane of the Tierra Caliente region (Figure 3). The Tizapa area is the only locality where the mylonitic granite has been found, and its distribution, unfortunately, is very local. The mylonitic granite is bound by a normal fault, which served as channelway for the emplacement of small Tertiary rhyolitic bodies (Figure 2). The granite is also intruded by an undeformed small Tertiary stock of hornblende diorite. Dr. R. L. Armstrong, of the University of British Columbia, Canada, in 1982 collected several samples of augengneiss granite for Rb-Sr geochronometry, and his preliminary results indicate a 258-240 Ma (Late Permian-Early Triassic) age for the rock (written communication, 1983).

PETROGRAPHY

The granite is a leucocratic medium-coarse grained rock with heterogeneous deformation. According to the intensity of deformation, it gradually changes upward from massive granite into augengneiss granite and then into blastomylonitic quartz-muscovite schist toward the overlying metavolcano-sedimentary rocks (Figure 3). At the central part of its outcropping area, near the hornblende diorite stock, it is massive and slightly fractured, and consists of 45% microperthitic and granophyric orthoclase, 30% quartz, 15% plagioclase (An_{10-14}), 9% biotite, and 1% other minerals (averaged values of several samples).

In thin section, the slight deformation is evidenced by protoclastic texture, where quartz shows undulating extinction and partial recrystallization to fine-grained aggregates with lobate grain boundaries, biotite is slightly curved and kinked, and K-feldspar shows only internal dislocation, as indicated by different optical orientations in the same crystal. In this case of minimum deformation, muscovite is very scarce (<1%), and it is replacing biotite. Muscovite also forms from plagioclase as sericite.

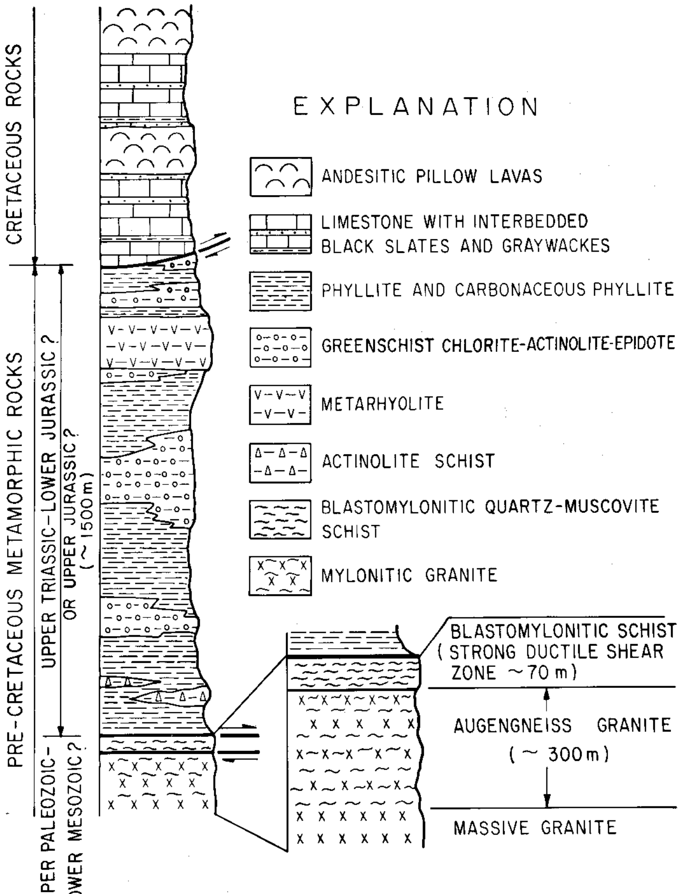

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Figure 3.- Schematic tectono-stratigraphic column for the pre-Tertiary rocks of the Zacazonapan-Tejupilco area. At the bottom of the sequence a mylonitic granite of unknown age is exposed. The granite gradually changes upward into augengneiss granite and then into blastomylonitic quartz-muscovite schist in response to the intensity of the shear strain.

The transition from weakly deformed massive granite into moderately to strongly deformed foliated granite is very gradual, and occurs over a distance of around 50 m. At macroscopic scale, increasing deformation is marked by the development of a coarse foliation and, finally, a strong anastomosing foliation, defined essentially by biotite, that wraps around quartz and up to 5 cm long feldspar grains, to form an augengneiss structure (Figure 4A, B). The deformed granite has no obvious lineation features; nevertheless, the typical C-S surfaces of shear zones in deformed granites (Berthé *et al.*, 1979; Vernon *et al.*, 1983; Choukroune and Gapais, 1983; Lister and Snoke, 1984) are well developed in some places (Figure 4A, B). The narrow shear zone with intense grain-size reduction, and with strong foliation development is common toward the upper part of the pluton.

At microscopic scale, the gneissic foliation is mainly defined by aligned muscovite, biotite and minor epidote, as well as granoblastic layers of quartz, albite and grains of microcline (Figure 4C, D). The porphyroclasts of feldspar and undulous quartz are wrapped by strong preferred orientation of micas and fine-grained quartz-albite aggregates. Fragments of feldspar are pulled apart and dispersed in quartz-feldspathic layers, some of

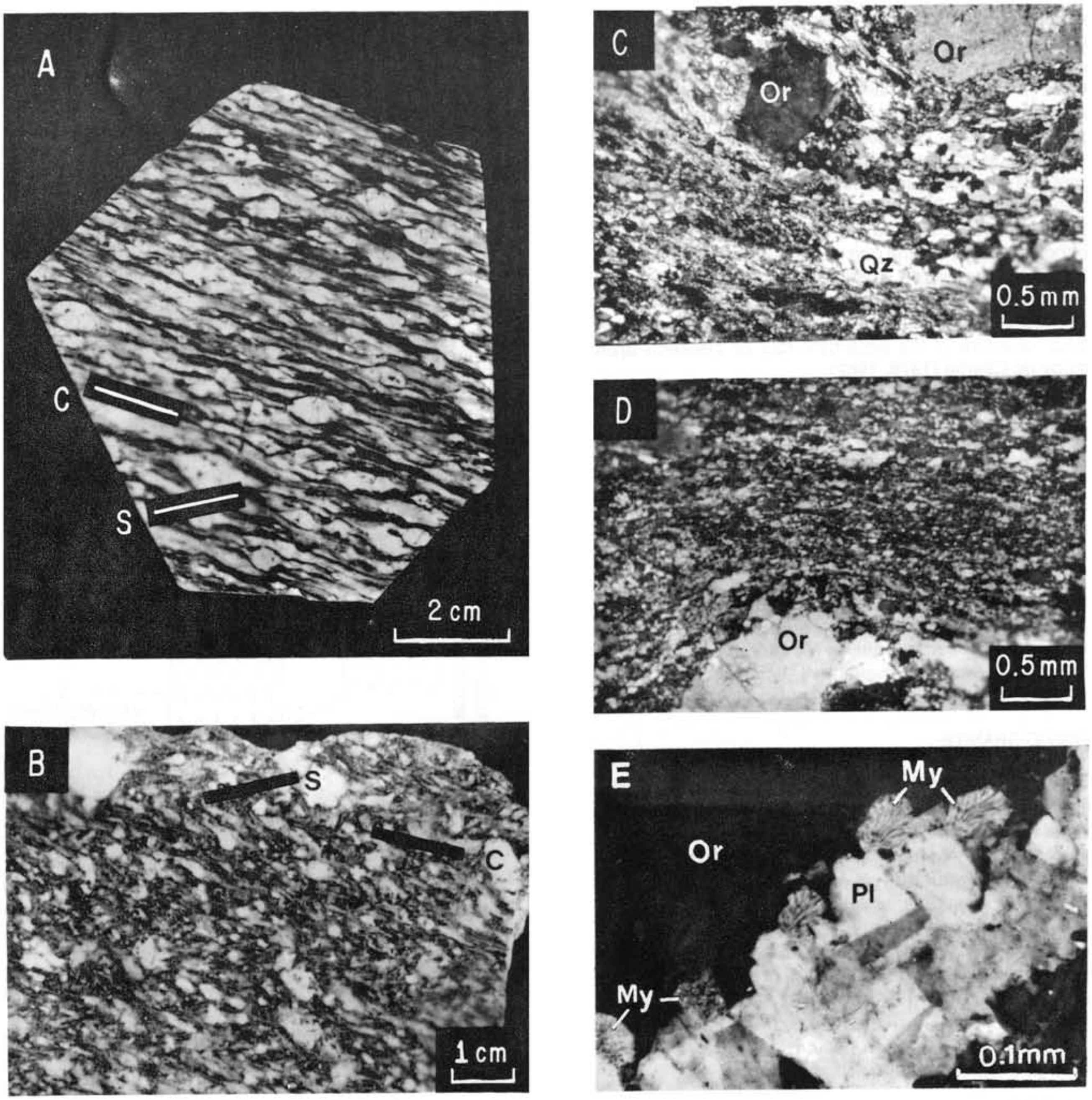

Figure 4.- Augengneiss granite. A: Polished surface of augengneiss granite (type I S-C mylonite, Lister and Snoke, 1984) showing mylonitic fabric with typical S-C surfaces, which indicate a dextral shear sense. The augen are orthoclase and quartz. B: Another polished surface of the mylonitic granite with local asymmetric folding deforming the S and C surfaces, which are compatible with dextral simple shear. This folding probably represents the most advanced stage of the deformation in relation to A. C: Internal mylonitic deformation of the granite; anastomosing foliation wraps around orthoclase porphyroclasts (Or); the foliation is essentially constituted of granoblastic quartz aggregates (Qz), rotation and recrystallization of biotite and crystallization of muscovite. D: Orthoclase porphyroclast (Or) with partial crystallization into plagioclase and quartz at its border; it is surrounded by an blastomylonitic matrix constituted of quartz, albite, muscovite and biotite. E: Detail of the border of porphyroclastic orthoclase (Or) showing patches of plagioclase (Pl) with syntectonic myrmekitic growths (My). The syntectonic myrmekitic intergrowths have been described in deformed granites at epidote-amphibolite and amphibolite facies in other mylonitic complexes (Simpson, 1985; La Tour, 1987; Simpson and Wintsch, 1989; Gapais, 1989). The photomicrographs are in cross-polarized light.

which are kinked and/or fractured. Myrmekitic growths at the borders of some porphyroclastic orthoclase are common (Figure 4E); other orthoclase grains are partially inverted to microcline toward the edges. The complete inversion of orthoclase to microcline occurs in dispersed, fine grains of K-feldspar in which the microcline, in addition to quartz and albite, forms granoblastic layers. The orthoclase-microcline inversion (variation in the degree of triclinicity) is a well-known petrographic feature in zones of shear strain (Smith, 1974; Eggleton, 1979; Eggleton and Buseck, 1980; Bell and Johnson, 1989). Fractures filled with quartz and/or epidote are common in feldspar porphyroclasts.

Muscovite is more abundant than biotite in the foliated granite. There is a direct relation between muscovite abundance and intensity of deformation in the pluton; in the slightly deformed granite the white mica is almost absent. In the moderately deformed granite, muscovite is strongly aligned and intimately intergrown with biotite which tends to decrease. Muscovite, with minor amounts of Fe-oxides and/or titanite, apparently crystallized during the deformation from the breakdown of biotite. In this case, biotite is also aligned and probably recrystallized, although there are kinked flakes that have no preferred orientation and correspond to primary biotite. The magmatic biotite is essentially nonaligned, or it is present as roughly aligned flakes several millimeter long, and some of which show postectonic chloritization. The metamorphic biotite tends to be fine-grained (≤ 1 mm) and strongly orientated parallel to the foliation.

The transition from augengneiss granite to blastomylonitic quartz-muscovite schist occurs over a distance of 1-5 m, and it is characterized by remarkable grain-size reduction, strong recrystallization, and intense development of foliation and mineralogical changes with blastomylonitic banding in some places (Figure 5A). By means of these features, it was possible to map the schist which, according to the structural section A-B, has a thickness of around 70 m (Figure 2). Thin-section observations show that granoblastic quartz and muscovite are predominant and strongly aligned, biotite practically disappears, and feldspar grains decrease in size and abundance (Figure 5B, C). Some orthoclase fragments and plagioclase survived the deformation and recrystallization processes, although most of the feldspar grains were inverted to fine-grained microcline (Figure 5D). Microcline and albite grains are common in the granoblastic assemblages. In samples where feldspar is relatively abundant, muscovite is scarce; however, where the feldspar is scarce, the muscovite is abundant. Apparently, some of the feldspar also reacted to form phyllosilicate.

The mylonitic augengneiss granite was transformed into blastomylonitic quartz-muscovite schist where the ductile shear deformation was more intensive. The same situation occurs in narrow shear zones in the augengneiss granite observed near the contact with the schist on the Arroyo Frío (Figure 2).

Other petrographic features of the deformed granite are some schlieren, that are a few tens of centimeters long, and muscovite-garnet schist xenoliths. The schlieren are fine-grained and rich in biotite, and show the same internal deformation as the surrounding augengneiss pluton. Strong development of muscovite and epidote, recrystallization of biotite into fine-grained flakes, complete recrystallization of quartz, intense fragmentation of feldspars with partial recrystallization to albite and microcline, and myrmekitic intergrowths at edge of some orthoclase porphyroclasts, are grain-scale features of this deformation in the schlieren.

The muscovite-garnet schist xenoliths were recognized along the Arroyo Frío (Figure 2). They are small lenticular bodies

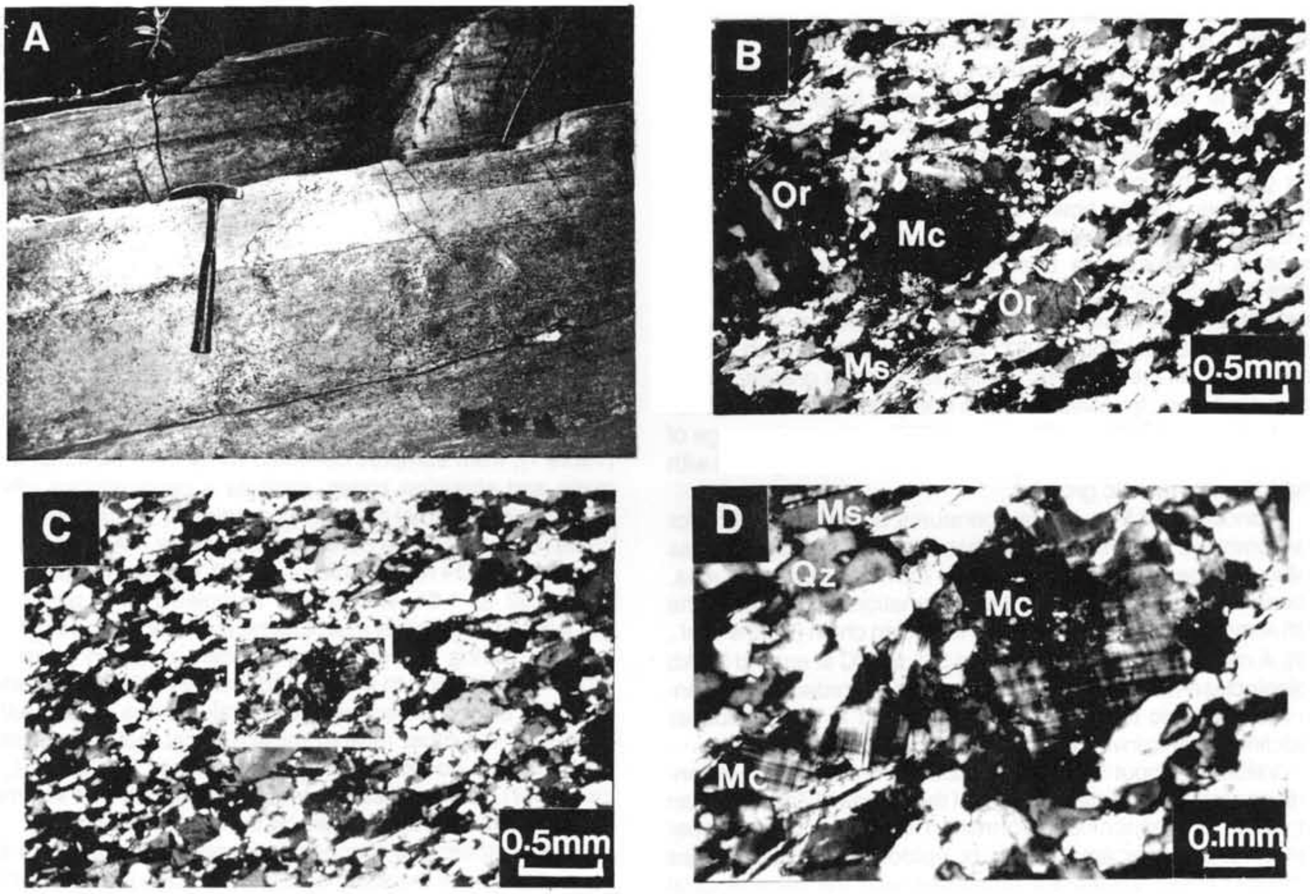

Figure 5.- Blastomylonitic quartz-muscovite schist. A: Blastomylonitic banded structure in the schist. B: Thin section of the schist showing its components: granoblastic quartz, fragments of orthoclase (Or), crystals of microcline (Mc) and aligned flakes of muscovite; biotite is absent. C: Blastomylonitic texture; the syntectonic recrystallization is almost complete in the schist, the granoblastic assemblage is constituted of quartz, muscovite, microcline and albite. D: Detail of the area inset in C showing the granoblastic aggregate with microcline (Mc), quartz and muscovite. The microcline is abundant in the blastomylonitic schist and it is formed from orthoclase. The orthoclase-microcline inversion is a petrographic feature well known in mylonitic deformation of granitic rocks (Eggleton and Buseck, 1980; Bell and Johnson, 1989). The photomicrographs are in cross-polarized light.

observed in a zone a few meters thick and 10 m long. The foliations of the schist xenoliths and of the augengneiss are clearly parallel and continuous. The mineralogy of the schist is muscovite, quartz, minor biotite and porphyroblasts of almandine-rich garnet with synkinematic internal structures. This mineralogy suggests a pelitic nature for the xenoliths. Metamorphism probably was coeval with the mylonitization of the granite. Some schist xenolith samples show hydrothermal alteration defined by chloritization, Fe-oxides after pyrite, and tourmaline, possibly related to the intrusion of the Tertiary hornblende diorite stock.

P-T ESTIMATES OF THE DEFORMATION

The metamorphism of overlying metapelite and schist xenoliths is syntectonic with the shearing of the granite, as is suggested by the foliation and contact relationships. Consequently, the occurrence of syntectonic almandine-rich garnet in adjacent metapelitic rocks and in pelitic schist xenoliths within the granite indicates that the deformation of the pluton occurred at least under upper greenschist facies conditions. Quartz-muscovite-biotite-almandine in the pelitic schist xenoliths is a characteristic assemblage of the greenschist-amphibolite transition facies (epidote-amphibole zone), amphibolite facies (Turner, 1968) or epidote-amphibolite facies (Miyashiro, 1973).

Although the temperature at which garnet first forms is not yet known, Winkler (1976) considered about 4 kb at 500°C as P-T conditions for almandine-rich garnet formation. Temperatures of 459°C and 470°C have been deduced at the garnet zone in pelitic schist in metamorphic terranes (Ferry, 1980; Lang and Rice, 1985).

On the other hand, the breakdown of feldspar to quartz, muscovite, epidote and albite in augengneiss granite from the Zacazonapan area, is a characteristic feature of granite deformed under greenschist conditions (*e.g.*, Mitra, 1978, 1984; Simpson, 1985; Gapais, 1989); however, syntectonic myrmekitic intergrowths of oligoclase and quartz, also occurring in some augengneiss samples, are described in deformed granites at epidote-amphibolite facies and amphibolite facies, and it attests to important strain-enhanced diffusion processes at grain scale (Simpson, 1985; La Tour, 1987; Simpson and Wintsch, 1989; Gapais, 1989). In the mylonitic Peninsular Ranges granite, southeastern California, involved under a compressional tectonic regime, Anderson (1983) and Simpson (1985) estimated a range of 450-550°C, and 4-5 kb for the mylonitic deformation in granite with syntectonic myrmekitic growths.

Conditions of 5 kb and temperatures of less than 500°C for the assemblage albite-microcline, that occurs in the augengneiss granite, and the blastomylonitic schist from Zacazonapan area, are considered appropriate for the deformation of granites in the South Armorican Shear Zone at the Hercynian chain (Berthé *et al.*, 1979). A metamorphic temperature of 505±30°C at around 3.5 kb for plagioclase-microcline association was recorded in Buchan-type metamorphic terrane and it was related to the K-feldspar monoclinic-triclinic inversion (Ferry, 1980).

Values of about 500°C and 4 kb are consequently reasonable to accompany the deformation of the granite at Zacazonapan area; thus, the mylonitic deformation occurred under upper greenschist to lower amphibolite or epidote-amphibolite facies conditions. These values are consistent with the mineralogical assemblage in the metapelitic rocks and those of the deformed granite.

RELATIVE TECTONIC AGE

The relative tectonic age of the granite is considered pretectonic as indicated by the following data.

1. Solid-state deformation in the pluton is characterized by different degrees of mylonitic deformation toward its border. All visible evidence is consistent with solid-state deformation, and the granite shows no evidence of magmatic foliation according to the criteria discussed by Paterson and coworkers (1989).

2. Mineral assemblages defining the foliation in the granite indicate a temperature of around 500°C, which is below emplacement temperatures of plutons. The syntectonic plutons, on the other hand, tend to show evidence of transition from magmatic to high temperature (amphibolite facies) solid-state foliation (Paterson *et al.*, 1989; Vernon *et al.*, 1989).

3. Discrete and undeformed zones in the central part of the exposure area of the granite, and strong foliation in its border and in adjoining rocks suggest that the pluton behaved as a rigid body during the deformation of the country rocks. This is consistent with the characteristics of pretectonic plutons discussed by Paterson and Tobisch (1988) and Vernon and coworkers (1989), and it is also consistent with pretectonic granite in terms of observed structural patterns (*e.g.*, Gapais, 1989).

4. Contact-metamorphic minerals are absent in the surrounding pelitic rocks. The scarce almandine-rich garnet porphyroblasts in the carbonaceous phyllite near the granite are synkinematic with the regional metamorphism, which is characterized by greenschist facies. Hornfels assemblages could have been preserved after the low grade regional metamorphic event. The metamorphic aureole of a syntectonic pluton shows the highest grade (amphibolite facies) near the pluton and grades into regional metamorphic assemblages away from the granitoids (Paterson and Tobisch, 1988; Vernon *et al.*,1989). A premetamorphic plutonic intrusion affecting the pre-Cretaceous volcano-sedimentary sequence is disregarded due to the absence of contact-metamorphic minerals, and the lack of cross-cutting relations.

GEOCHEMISTRY

Although the mylonitic granite is affected by weak metasomatism and hydrothermal alteration in very local and erratic zones, which are probably related to the undeformed small hornblende diorite stock and rhyolitic bodies, it is assumed that during the mylonitization the losses and enrichments of elements were minimal. Geochemical analyses of deformed granite (Table 1), from samples collected away from the local metasomatic and alteration zones, indicate a peraluminous character similar to continental collision granitoids or continental arc granitoids (Figure 6A). The peraluminosity index —A/CNK = molecular $Al_2O_3/(CaO+Na_2O+K_2O)$— of 10 granite samples, ranges from 1.02 to 1.64, with seven samples highly peraluminous (A/CNK > 1.15). This is a geochemical characteristic of granitoids intruded during the continent-continent collision phase of an orogeny, according to Maniar and Piccoli (1989). The metapelitic xenoliths are consistent with the peraluminous nature. Although cordierite, the most reliable mineralogical indicator of strongly peraluminous composition or S-type affinity (White *et al.*, 1986; Zen, 1987), has not been found, it is probable that sedimentary material had been assimilated by the granitic magma.

Nonetheless, a syncollisional continental nature for the deformed granite at the study area is difficult to visualize, because a syntectonic emplacement is improbable, and the surrounding rocks are essentially characterized by low grade metamorphism. In regions with this kind of granite, medium to high grade metamorphism or migmatized rocks are common (*e.g.*, Le Fort,1981; Vidal *et al.*, 1982; Strong and Hanmer, 1981). On the other hand, even though the continent-continent collisional environment is, undoubtedly, the best known setting for peraluminous plutonism,

Table 1.- Analyses of mylonitic granite from Zacazonapan area.

	TC1	TC7	TC7A	TC50	TC51	TC53	TC53A	TC54	TQ1	TQ2
SiO_2 (wt%)	66.30	65.53	68.00	70.33	69.29	67.46	69.80	68.14	67.10	68.40
TiO_2	0.55	0.75	0.84	0.45	0.65	0.45	0.65	0.38	0.48	0.58
Al_2O_3	14.40	14.16	14.40	15.25	14.42	17.47	14.20	16.49	14.22	13.15
Fe_2O_3	0.75	1.49	1.56	2.64	1.62	2.83	0.95	3.04	0.90	0.60
FeO	3.85	3.98	2.44	0.87	2.74	2.21	2.32	2.02	3.52	4.50
MnO	n. d.	n. d.	0.07	0.01	0.02	0.04	0.05	0.03	0.08	0.09
MgO	2.46	3.14	1.71	1.05	1.36	0.58	1.35	0.37	2.79	2.60
CaO	2.59	1.92	1.29	1.20	1.29	0.74	1.21	0.91	2.23	1.80
Na_2O	2.95	2.60	2.86	2.20	2.85	2.60	2.90	2.00	3.05	2.05
K_2O	4.25	4.96	4.18	4.40	4.88	4.91	4.55	4.80	3.46	3.90
P_2O_5	n. a.	n. a.	0.15	0.14	0.22	0.13	0.06	0.34	1.17	1.20
LOI	1.35	1.68	1.40	1.28	1.40	1.03	0.89	1.06	0.80	1.20
Total	99.45	100.21	98.90	99.82	100.74	100.45	98.93	99.58	99.80	100.07
R_1^* (molar)	1.53	1.46	1.57	1.82	1.44	1.82	1.46	1.95	1.62	1.74
$R_2^\#$	1.02	1.08	1.25	1.45	1.16	1.60	1.20	1.64	1.10	1.22
Rb (ppm)	206	170	n. a.	203	187	210	232	194	n. a.	n. a.
Sr	214	210	n. a.	187	164	179	134	196	n. a.	n. a.
Y	17	15	n. a.	18	16	18	26	17	n. a.	n. a.
Nb	14	13	n. a.	13	12	17	21	14	n. a.	n. a.

$^*R_1 = Al_2O_3/(Na_2O+K_2O)$ $^\#R_2 = Al_2O_3/(CaO+Na_2O+K_2O)$. n. d. = not detected n. a. = not analyzed

The analyses were carried out at the Instituto de Geología, UNAM. Major elements were analyzed by wet chemistry, LOI by gravimetry, trace elements by X-ray fluorescence. The analyses were corroborated with analyses of two samples made at Bondar-Clegg Labs., in Canada.

it is not the only setting in which this kind of pluton can occur. Peraluminous granitoids have been documented in continental belts located far inland from active arcs (Miller and Bradfish, 1980), in active accretionary prisms (Hill *et al.*, 1981), in anorogenic rift systems (Martin and Bowden, 1981), and in back-arc basin environments (Lalonde, 1989).

On the Rb *vs.* Y+Nb discriminant diagram (Figure 6B), the mylonitic granite plots within the arc granite field, which comprises granites from tholeiitic oceanic arcs, calc-alkaline arcs (whether oceanic or continental), and granites intruded at active continental margins. This contrasts with the strong peraluminosity as a diagnostic feature of syncollisional granites. The diagram suggests that the granite from Zacazonapan area was generated in a volcanic arc regime, environment into which Pearce and coworkers (1984) grouped oceanic and continental settings, although mylonitic granite plots very close to boundary with collisional granite field.

Some characteristics of continental margin granite may reconcile the peraluminous character with the trace-element signature. Furthermore, the primary mineralogy of the granite, with biotite as the only ferromagnesian mineral, is consistent with this type of granite, whereas in island arc granitoids, hornblende is the dominant ferromagnesian, and plagioclase is more abundant than K-feldspar (Pearce *et al.*, 1984; Maniar and Piccoli, 1989). A continental margin environment is, therefore, reasonable for the emplacement of the pluton taking into account the geochemical and petrographic data. The granite as an internal part of a submarine island arc is improbable, although the local exposure of the pluton is a serious limitation and it prevents knowing possible petrographic variations or other plutonic associations.

DISCUSSION AND IMPLICATIONS

The mylonitic granite had previously been considered to be an old basement rock, and the directly overlying quartz-muscovite schist, taking into account its feldspar content, to be an arkosic unit formed by the denudation of the granitic basement (Parga-Pérez, 1981; Elías-Herrera, 1981, 1987, 1989). Those authors, therefore, assumed a premetamorphic nonconformable relationship between the local and apparent plutonic basement and the overlying pre-Cretaceous volcano-sedimentary rocks. Nonetheless, this primary relationship is simplistic and inconsistent with the mylonitic deformation of the granite and the severe deformation of the pre-Cretaceous metamorphic cover. A dynamic relationship must be considered in order to explain the strong deformation in both types of rocks.

The deformation of the pluton, represented by several hundred meters of mylonitization, including about 70 m of granite converted to blastomylonitic quartz-muscovite schist at its uppermost part, indeed implies an important mesozonal shear zone

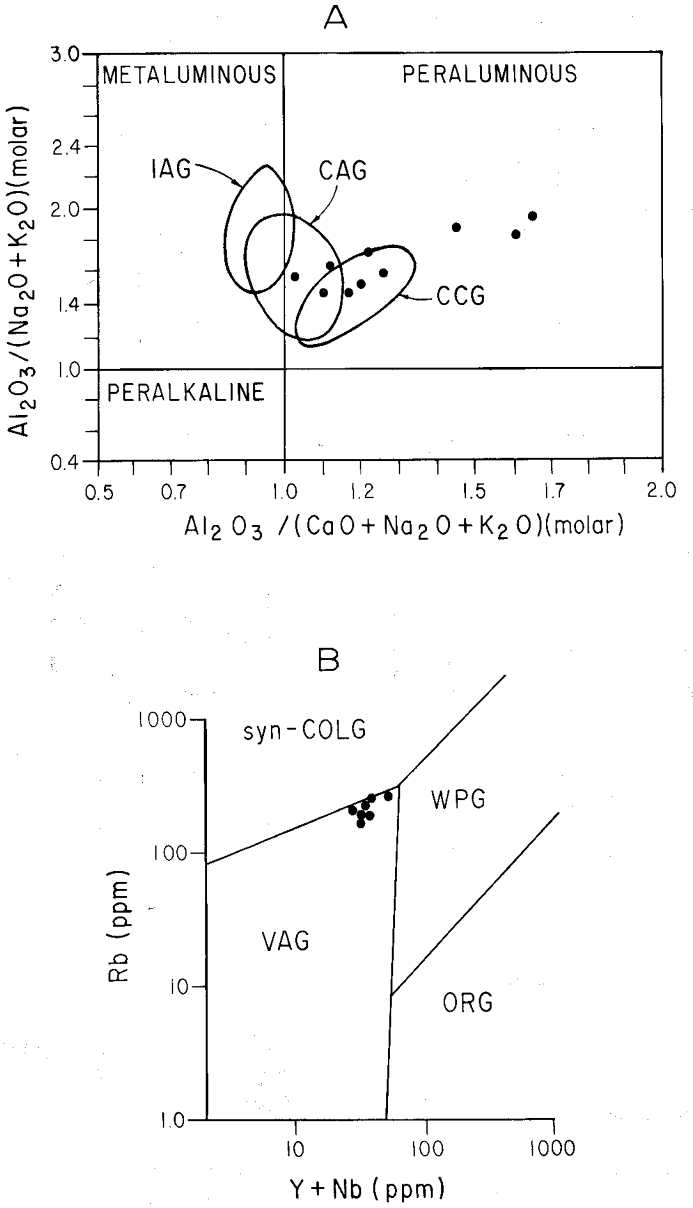

Figure 6.- A: Shand's index diagram with distinction among island arc granitoids (IAG), continental arc granitoids (CAG) and continental collision granitoids (CCG) (Maniar and Piccoli, 1989). B: Rb *vs.* (Y + Nb) discriminant diagram for syn-collision (syn-COLG), volcanic arc (VAC), within plate (WPG) and oceanic ridge granites (ORG) (Pearce *et al.*, 1984). In both diagrams the closed circles represent mylonitic granite samples from Zacazonapan area.

(Figure 3). The deformation indicates non-trivial northeastward-directed movements along the ductile thrust zone, according to the geometry of C-S surfaces in some suitable outcrops of mylonitic granite. It suggests the allochthoneity of the overlying pre-Cretaceous metamorphic rocks. Vergence of folds, small thrust faults, and regional foliation in these rocks indicate that the overriding movement occurred under a compressional tectonic regime whose principal shortening direction was SW-NE.

The tectonic contact between granite and pre-Cretaceous metamorphic rocks may be a mid-crustal level décollement, implying the existence of a pre-Jurassic crystalline basement, that is, a thick-skinned structure. The existence of a true pre-Jurassic basement on which submarine arc or back-arc basin lithofacies could have deposited, is therefore feasible and suggested by:

1. The evident pretectonic nature of the granite.

2. The peraluminous continental crustal affinity of the granite. This type of granite is unusual and incompatible as the roots at the base of the volcano-sedimentary sequence of submarine arc or back-arc basin affinity.

3. The structural position of the deformed granite. Although the age of its pre-Cretaceous metamorphic cover has not been well established, a pre-Jurassic age for the granite is probable, taking into account that it underlies metamorphic rocks, which have been considered to be upper Paleozoic basement, based on geological inferences (de Cserna, 1978, 1982; de Cserna and Fries, 1981). A pre-Jurassic age for the granite would also be reasonable if the overlying metavolcano-sedimentary rocks are of Late Jurassic-Early Cretaceous age, as indicated by dispersed paleontologic data (Campa *et al.*, 1974; Campa, 1978; Campa and Ramírez, 1979; Campa and Coney, 1983).

4. Preliminary Rb-Sr isotope data indicate a Late Permian-Early Triassic age for the granite (Dr. R. L. Armstrong, written communication, 1983).

The mylonitic deformation of the apparent sialic basement, together with the deformation and metamorphism of the pre-Cretaceous rocks, thus, may correspond to the first compressional tectonic event in the region (Middle-Late Jurassic Nevadan Orogeny?). This is probably related to the accretion of Mesozoic submarine arc or back-arc basin to an old continental margin locally represented by the granite. However, in the Taxco el Viejo area (Figure 7), pre-Cretaceous metavolcano-sedimentary rocks are overriding the Albian carbonate Morelos-Guerrero platform.

In the Tierra Caliente region, folding, foliation and low-grade metamorphism of pre-Albian rocks have previously been considered Cenomanian on the basis of some paleontologic data (Campa, 1978; Campa and Ramírez, 1979). Ortega-Gutiérrez (personal communication, 1991), from observed field relationship at Taxco el Viejo area (Figure 7), also suggested that the metamorphism of the Guerrero terrane is related to its tectonic accretion onto the Morelos-Guerrero platform. Campa (1978), and Campa and Ramírez (1979) consider, however, that the tectonic emplacement of the metamorphic rocks onto the Albian carbonate platform occurred during the Paleocene.

A serious problem for the interpretation which connects a Cenomanian deformation with regional metamorphism is to explain satisfactorily how the Albian Morelos-Guerrero platform escaped that deformation. For us, the metamorphism is clearly pre-Cretaceous. Clasts of rhyolitic metatuffs, greenschist, phyllite and quartzite, as components of a metaconglomerate at the Taxco el Viejo area (Figure 7), imply an older geologic evolution, including erosion of the metamorphic rocks before their tectonic emplacement on the Lower Cretaceous Morelos Formation by means of a thrust fault. The metamorphic rocks at Taxco el Viejo area, thus constitute the eastermost known exposure of the Guerrero terrane.

The tectonic relationship between the eastern margin of the Guerrero terrane and the Cretaceous carbonate shelf in the Teloloapan-Taxco area has previously been considered to be a thrust (Campa *et al.*, 1976; Campa, 1978; Campa and Ramírez, 1979). This thrust, whose magnitude of displacement is unknown, was analyzed near Taxco el Viejo, State of Guerrero, by the present authors. At Taxco el Viejo, located 90 km SE from the Zacazonapan area (Figures 1 and 7), the exposed metamorphic rocks are strongly foliated rhyolitic metatuff which is interbedded with phyllite and greenschist (metavolcaniclastic rock). There is also a foliated metaconglomerate with clasts of the afore-mentioned metamorphic rocks near the contact with the Albian lime-

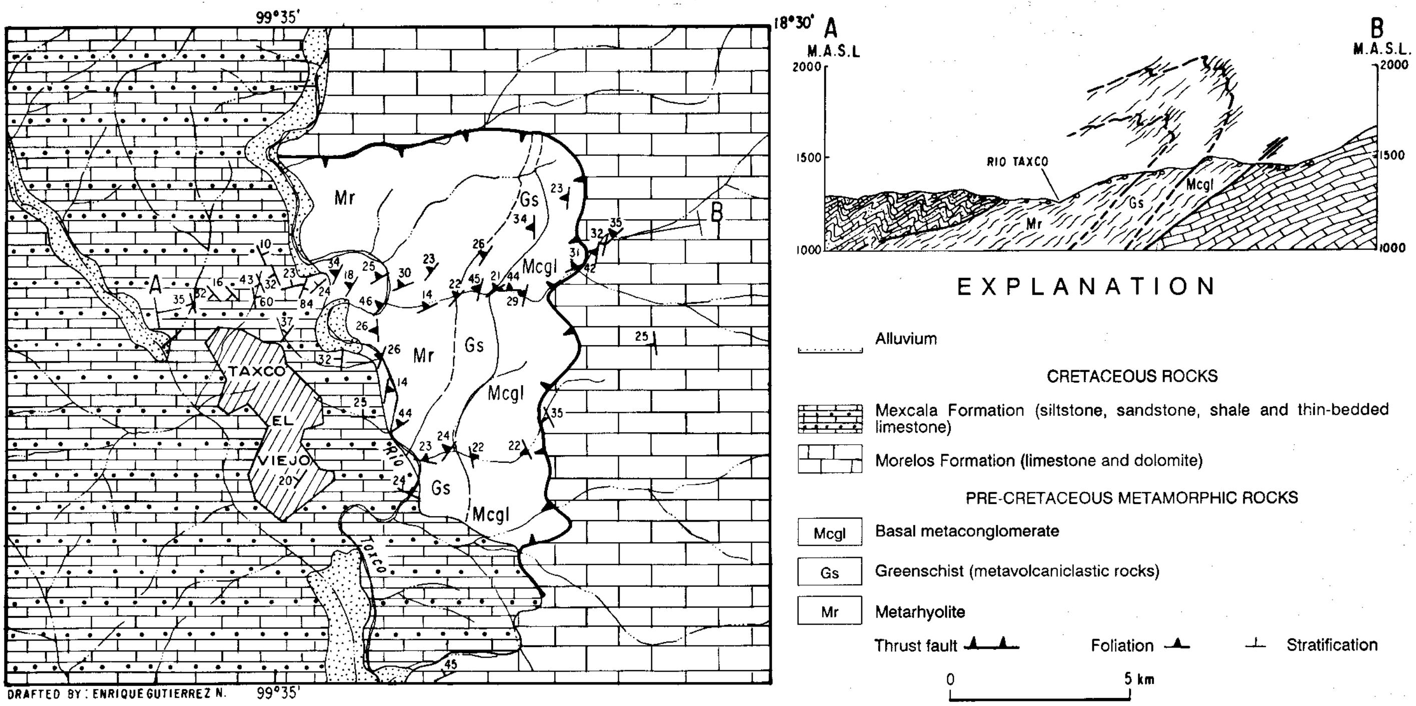

Figure 7.- Simplified geologic map and section of the Taxco el Viejo area. The section A-B shows the geometry of folding of each lithostratigraphic unit: the Mexcala Formation is characterized by close chevron folds, the Morelos Formation by gentle to open cylindrical folds. The pre-Cretaceous metamorphic rocks are strongly foliated and, according to the structural position of the basal metaconglomerate and the relationship between foliation and lithologic contact, its small exposure area probably corresponds to an inclined limb of an overturned fold, as is illustrated in the section. The folding deduced from the foliation in the metamorphic rocks is probably Jurassic. The tectonic emplacement of these rocks over the Morelos Formation may have taken place during the Laramide Orogeny.

stone of the Morelos Formation. All these metamorphic rocks, which were grouped as Taxco Schist and Taxco Viejo Greenstone by Fries (1960), are effectively overriding the Albian Morelos Limestone, which does not show important tectonic effects, although it is locally foliated near the metaconglomerate (Figure 7). The postmetamorphic overriding probably occurred under near surface conditions without significant ductile deformation. The dating of this deformation is tenuous, because of the conflicting stratigraphic, paleontologic and structural information. For example, the Upper Cretaceous Mexcala Formation rests on the metamorphic rocks at Taxco el Viejo without significant internal deformation, whereas at Taxco, this same unit on top of the metamorphic rocks is intensely deformed. The age of the top of the Morelos Formation, established paleontologically, varies from place to place from early Albian to early Cenomanian, implying a former erosion surface (Fries, 1960). Consequently, the structural relations presently observed in the Taxco el Viejo area could be explained by an imbricate structure formed during the Late Cretaceous deformation (Laramide). This in turn implies that the Laramide Orogeny was a thin-skinned tectonic event in the region, just as it was depicted in the Iguala area, a short distance to the south of the Taxco el Viejo area (de Cserna, 1983).

The metamorphism of the Guerrero terrane, therefore, and in our viewpoint, cannot be dated as Cenomanian, nor related to the overriding of the carbonate platform. The regional low-grade metamorphism is probably Jurassic. Urrutia-Fucugauchi and Linares (1981) reported 108±5 and 125±5 Ma whole-rock K-Ar dates for greenschist and altered andesite , respectively, from Ixtapan de la Sal, State of Mexico; they correlated this data with the metamorphic event previously considered by Campa and coworkers (1974) and Campa (1978) as Early Cretaceous. However, the K-Ar dating of metamorphic rocks from Ixtapan de la Sal may indicate an uplift and not the age of metamorphism since K-Ar dates of orogenic belts form a metamorphic veil that postdates the occurrence of the principal tectonic and metamorphic events (Armstrong, 1966; Faure, 1986, p. 84).

On the other hand, the metamorphic rocks cropping out at Taxco el Viejo and surrounding areas, may be correlated with the upper part of the pre-Cretaceous metamorphic sequence extensively exposed in the Tejupilco region. The rhyolitic metatuff at Taxco el Viejo is very similar to the metarhyolite mapped in the upper part of the metamorphic sequence in the Zacazonapan area (Figure 2), and in San Lucas del Maíz, near Tejupilco (Elías-Herrera, 1981, 1989). Metafelsite within the middle and lower parts of the pre-Cretaceous sequence in the Tejupilco region has not been found. Local metaconglomeratic units overlying volcaniclastic greenschist at the uppermost part of the pre-Cretaceous metamorphic sequence have also been recognized in some places to the NW of Tejupilco.

Under these circumstances, it is probable that different parts of the Guerrero terrane at its eastern margin were involved in important thrusting at different times, and under different conditions during its Mesozoic evolution. The oldest thrust (Middle-Late Jurassic?) and the most important, judging by tectonic effects, is the thick-skinned structure involving the shearing and ductile deformation of the apparent basal granite at mid-crustal levels (epidote-amphibolite facies conditions). It may correspond to the true accretionary boundary of the Guerrero terrane related to its tectonic incorporation into a continental framework. The thrust faulting at the Teloloapan-Taxco area, considered by some authors as the accretionary boundary (Campa and Coney, 1983), may instead be a post-accretion thin-skinned structure.

Listric contraction faults affecting different structural levels might be connected with the basal detachment, although this tectonic relationship must be proved. In this sense, the local exposure of the basal granite is a serious problem.

If the basal granite at Zacazonapan area is not a component of an autochthonous continental margin, and the accretion of the Guerrero terrane at its eastern border includes its apparent basement, the relationship between basal granite and pre-Cretaceous metamorphic rocks could be part of a tectonic evolution prior to the accretion to the continental North America. In this context, it is difficult to offer sound explanations about the accretionary boundary of the huge Guerrero terrane in agreement with the tectonostratigraphic character of this terrane.

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