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Structural geology and tectonic evolution of the Santa Rosa area, SW Mexico State, Mexico

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RESUMEN

Una secuencia tripartita de rocas volcánicas y sedimentarias metamorfizadas se ve expuesta entre Tejupilco y Zacazonapan, en el SW del Estado de México. La porción basal, de edad desconocida, y de grado metamórfico hasta la facies de anfibolita, incluye el gneis de Tizapa y su cobertura de esquistos y filitas. Cabalgando sobre estas rocas se encuentra un paquete tectónicamente imbricado que consiste de rocas jurásicas de la Formación Acuitlapán y calizas con estratos de sulfuros masivos de Pb-Zn (por ejemplo Santa Rosa) pertenecientes a la Formación Amatepec del Cretácico Temprano. Estas dos unidades han sido plegadas dos veces, son localmente miloníticas, y han sido metamorfizadas a facies de esquistos verdes. La estratificación transpuesta es paralela a una foliacion S_1 cuya inclinación es de 20°-30° al SW y que contiene una lineación por extensión buzante 10°-20° hacia el WSW. S_1 ha sido plegada alrededor de un eje buzante 20° al W, con desarrollo local de una foliación espaciada resultado de solución por presión, S_2. Los polos de S_2 describen una guirnalda de círculo mayor a raíz de una dispersión en forma de abanicos alrededor de charnelas de pliegues y de una tercera deformación penetrativa sólo en escala regional. Sobreyaciendo este paquete imbricado se encuentra la Formación Xochipala, del Cretácico Tardío, formada por rocas volcánicas de composición intermedia que cambian gradualmente hacia la cima a tobas, luego a grauvacas y calizas. Estas rocas han sido plegadas una vez alrededor del mismo eje buzante al W que el paquete subyacente y la única evidencia de metamorfismo es un incipiente desarrollo de hojuelas de mica blanca o clorita con incipiente orientación preferencial ligeramente oblicua a S_2 del paquete subyacente.

Fueron estudiadas las texturas cristalográficas de ejes c de calcitas en calizas Acuitlapán, Amatepec, y Xochipala. Las rocas de la Formación Amatepec muestran fuertes orientaciones preferenciales y una simetría monoclínica que indica desplazamiento del bloque de techo hacia el NE, compatible con el transporte tectónico indicado por porfidoclastos en porciones miloníticas de las grauvacas. El mecanismo de deformación interna es maclado mecánico e, con una componente de desliz en r.

Estas diferencias en la evolución estructural de los tres paquetes, en esta y otras localidades en la región, sugieren una secuencia compleja de construcción de arco con desarrollo y colapso repetido de cuencas tras-arco para esta porción de México durante el Mesozoico.

PALABRAS CLAVE: Geología estructural, tectónica, rocas metamórficas, Mesozoico, área de Santa Rosa, Estado de México.

ABSTRACT

A three part sequence of metamorphosed volcanic and sedimentary rocks is exposed between Tejupilco and Zacazonapan, in the SW of the State of Mexico. The lowermost portion, of uncertain age and up to amphibolite facies metamorphic grade, includes the Tizapa gneiss and overlying schists and phyllites. Overlying these rocks in thrust contact is a tectonically imbricated rock package consisting of graywackes of the Jurassic Acuitlapán Formation and limestones with enclosed stratabound Pb-Zn ores (e.g. Santa Rosa) of the Early Cretaceous Amatepec Formation. These two units have been folded twice, are locally mylonitic, and have undergone greenschist facies metamorphism. Transposed bedding is parallel to an S_1 foliation which dips predominantly 20°-30° SW and contains a stretching lineation plunging 10°-20° WSW. S_1 has been subsequently folded about an axis plunging 20° W, with local development of a pressure-solution spaced cleavage S_2. Poles to S_2 describe a partial great circle girdle as a result of fanning around fold hinges and a third deformation penetrative only on a regional scale. Above this imbricated package are rocks of the Late Cretaceous Xochipala Formation with volcanics of intermediate composition at the base grading upward through tuffs to graywackes and limestones. These rocks have been folded once about the same W plunging axis as the underlying package and the only evidence of metamorphism is slight growth of muscovite or chlorite flakes with a weak preferred orientation slightly oblique to S_2 of the underlying package.

Calcite c-axis fabrics of rocks from the Acuitlapán, Amatepec, and Xochipala limestones have been studied. The Amatepec rocks show strong crystallographic preferred orientation and a monoclinic symmetry which indicates a top-to-NE sense of shear, compatible with that suggested by asymmetric porphyroclasts in mylonitic portions of the graywackes; the deformation mechanism responsible for the calcite fabric development is e-twinning, with r-slip. The Xochipala rocks exhibit no such crystallographic preferred orientation.

These differences in the structural evolution of the three packages, at this and other localities in the region, suggest a complex sequence of arc construction with repeted back-arc development and collapse for this portion of Mexico during the Mesozoic.

KEY WORDS: Structural geology, tectonics, metamorphic rocks, Mesozoic, Santa Rosa area, Mexico State.

INTRODUCTION

The Tierra Caliente metamorphic complex is exposed northwest of Tejupilco and south of Zacazonapan, in the State of Mexico (Figure 1). For mining companies this sequence of metamorphosed volcanic and sedimentary rocks is a primary target of exploration for volcanogenic massive sulfides and hosts several prospects as well as operating

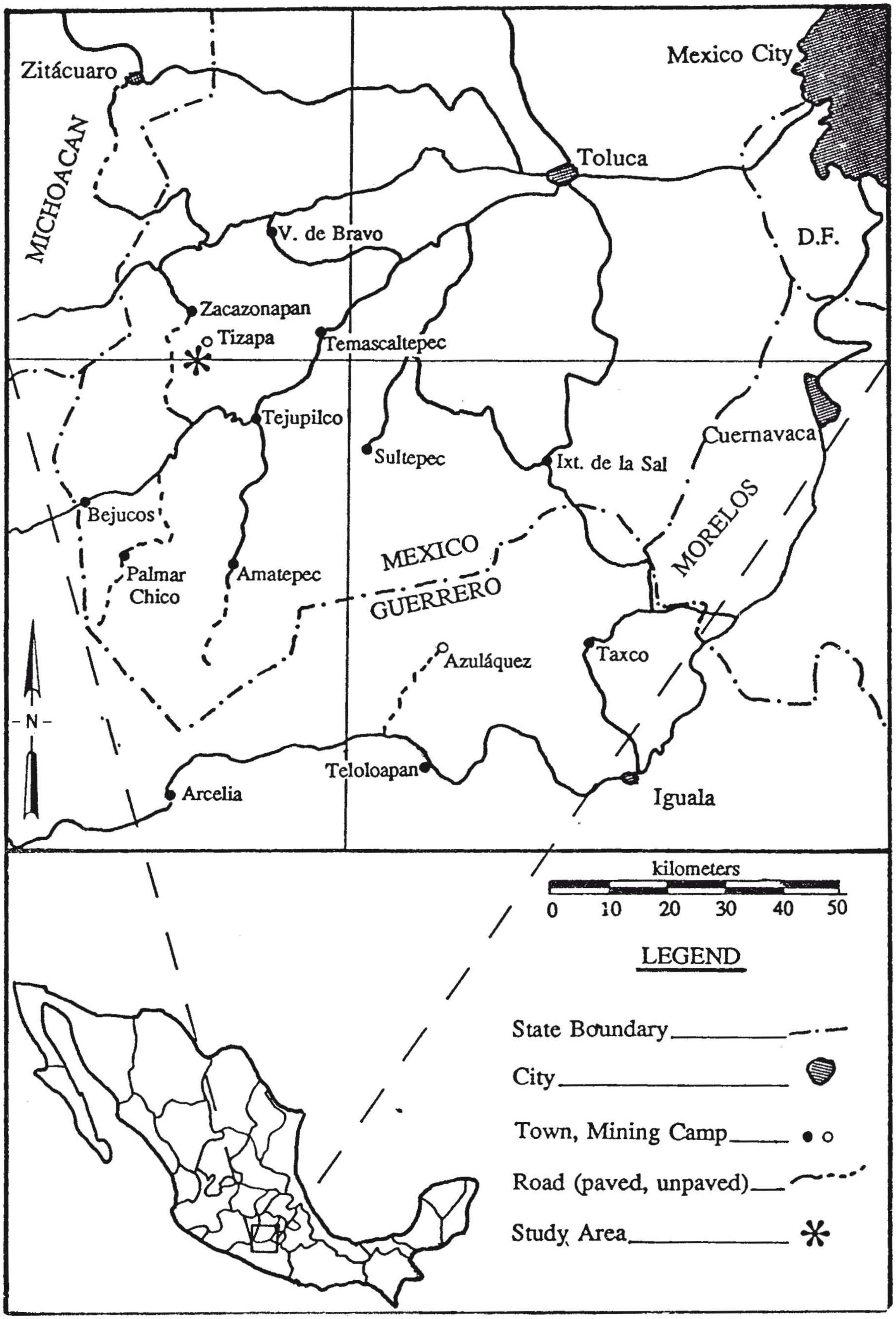

Fig. 1. Location map.

mines. In 1988 Ing. Gómez de la Rosa of the Fresnillo mining company suggested the Santa Rosa area as a possible site for a structural geology project. The purpose at the outset of the study was to better understand the three dimensional geometry of the lithologic units and the enclosed ore body, as well as to shed some light on the broader regional geology, based on the kinematics of the structures encountered.

The project consisted of geologic mapping on a scale of 1:15,000 in an area bounded to the north and northeast by the Temascaltepec river, on the east and west by the 100°13'W and 100°15'W meridians, respectively, and on the south by the 18°59'N parallel (Figure 2). The field area is very rugged with a topographic relief of 700 m, resulting from deeply incised rivers with convex skyward valley slopes. The highest summits in the area are at an elevation of 1700 m above sea level. The climate is strongly seasonal with wet summers and dry winters; it is hot year round, hence the name of the region, Tierra Caliente (Hot Land), is deserved. Vegetation during the rainy season is lush and dense, while in the dry season it consists of dry scrub and trees.

REGIONAL GEOLOGY AND PREVIOUS RESEARCH

The metamorphic rocks exposed in the area belong to the Tierra Caliente metamorphic complex (Ortega-Gutiérrez, 1981), a sequence of eugeosynclinal sediments and volcanics of uncertain but probably Mesozoic age which have been subjected to several deformational and metamorphic events. Campa and Coney (1984) have included these rocks within the composite Guerrero tectonostratigraphic terrane.

The oldest rocks in the Tejupilco region are exposed at the core of a NNW-trending regional anticlinorium, the Tejupilco Rise (de Cserna, 1983). The rocks are poly-deformed, metamorphosed igneous and sedimentary rocks of the Taxco Schist, and their age is not well constrained. De Cserna *et al.* (1974) have reported a Pb-α age of 1100 Ma for authigenic zircons in a sericite schist, while Campa *et al.* (1974) suggest a Jurassic-Cretaceous age on the basis of fossil evidence. As noted by Neher (1983) it is quite possible that there is a profound unconformity within this sequence.

Draped over the Tejupilco Rise are clastic and carbonate rocks of the Late Jurassic Acuitlapán Formation (de Cserna and Fries, 1981), covered by thinly bedded carbonates and shales of the Early Cretaceous Amatepec Formation (de Cserna, 1983). These sediments are in turn overlain by intermediate volcanics, clastics and carbonates of the Xochipala Formation, and the Late Cretaceous marine clastic and volcanic Arcelia rocks (de Cserna, 1983). The basal contact of this entire pile with the Taxco Schists has been interpreted by de Cserna and Fries (1981) and de Cserna (1983) as an unconformity on the basis of a basal conglomerate which is seen locally. On the other hand, de Cserna (1983) has also suggested that the contact serves as a detachment (décollement) surface to accommodate the "room problem" arising from the folding that these rocks have been subjected to.

Lying unconformably on this package of sediments and volcanics is the Early Tertiary Balsas Formation (Fries, 1960; de Cserna, 1983), consisting of conglomerates, graywackes, coarse sandstones, volcanics, and volcaniclastics which form a typical continental red-bed sequence. The Balsas rocks appear to lie on the erosional surface formed when the underlying rocks were uplifted and exposed, and scattered outcrops of Balsas lying directly on Taxco Schist have been documented (de Cserna, 1983). The Balsas red-beds have been tilted and now dip moderately west-southwest.

Capping all older rocks and forming mesas and sierras with hundreds of meters of topographic relief are felsic tuffaceous rocks known collectively as the Tilzapotla Rhyolite (Fries, 1960; de Cserna, 1983). These rocks are potentially important from an economic viewpoint since they locally host Ag-Au veins (de Cserna, 1983; Tolson, 1983). The age of these ignimbrite sheets is Eocene-Oligocene (Linares and Urrutia-Fucugauchi, 1981).

At the top of the regional stratigraphic column are andesitic basalt flows of the southernmost reaches of the E-W trending Mexican Neo-Volcanic Belt. At the northern boundary of the field area the flows give rise to spectacular vertical cliffs bounding broad plateaux such as the Mesa de Tenayac. The rocks are porphyritic olivine basalts whose age is Late Miocene to Early Pliocene (de Cserna, 1983).

There are several intrusive igneous rocks in the area mostly of granitic to granodioritic composition, forming small stocks and commonly associated with Ag-Au mineralization (Charoy and González-Partida, 1981). Several of these rocks have been dated, yielding ages ranging from late Cretaceous (González-Partida, 1981) to mid Tertiary (de Cserna, 1983). The paleomagnetic database for the region is still sparse but growing rapidly. Regional syntheses by Pal and Urrutia-Fucugauchi (1977), Urrutia-Fucugauchi (1984), and Urrutia-Fucugauchi *et al.* (1987) have concluded that there is no direct evidence of major latitudinal motion of crustal blocks but there is indeed evidence of counter-clockwise block rotations about vertical axes which they explain by sinistral strike-slip motion along major E-W trending transcurrent faults. Such faults have yet to be clearly identified in the field. Urrutia-Fucugauchi and Valencio (1986) examined the magnetic properties of metavolcanic rocks overlying the Taxco Schist near Ixtapan de la Sal and reported that the strongest magnetic signature they record may have been acquired during the mid-Cretaceous deformation phase. The paleomagnetic pole obtained from these rocks diverges slightly from poles in rocks further to the east (Urrutia-Fucugauchi, 1979, 1984) which may imply relative tectonic motion between the blocks. In summary, the paleomagnetic data are as yet inconclusive, but tend to support horizontal displacements, be they of a rotational or translational nature.

Several graduate level theses have provided detailed geological maps of areas in and around the Santa Rosa prospect. Colorado-Liévano (1979), studied the mineral

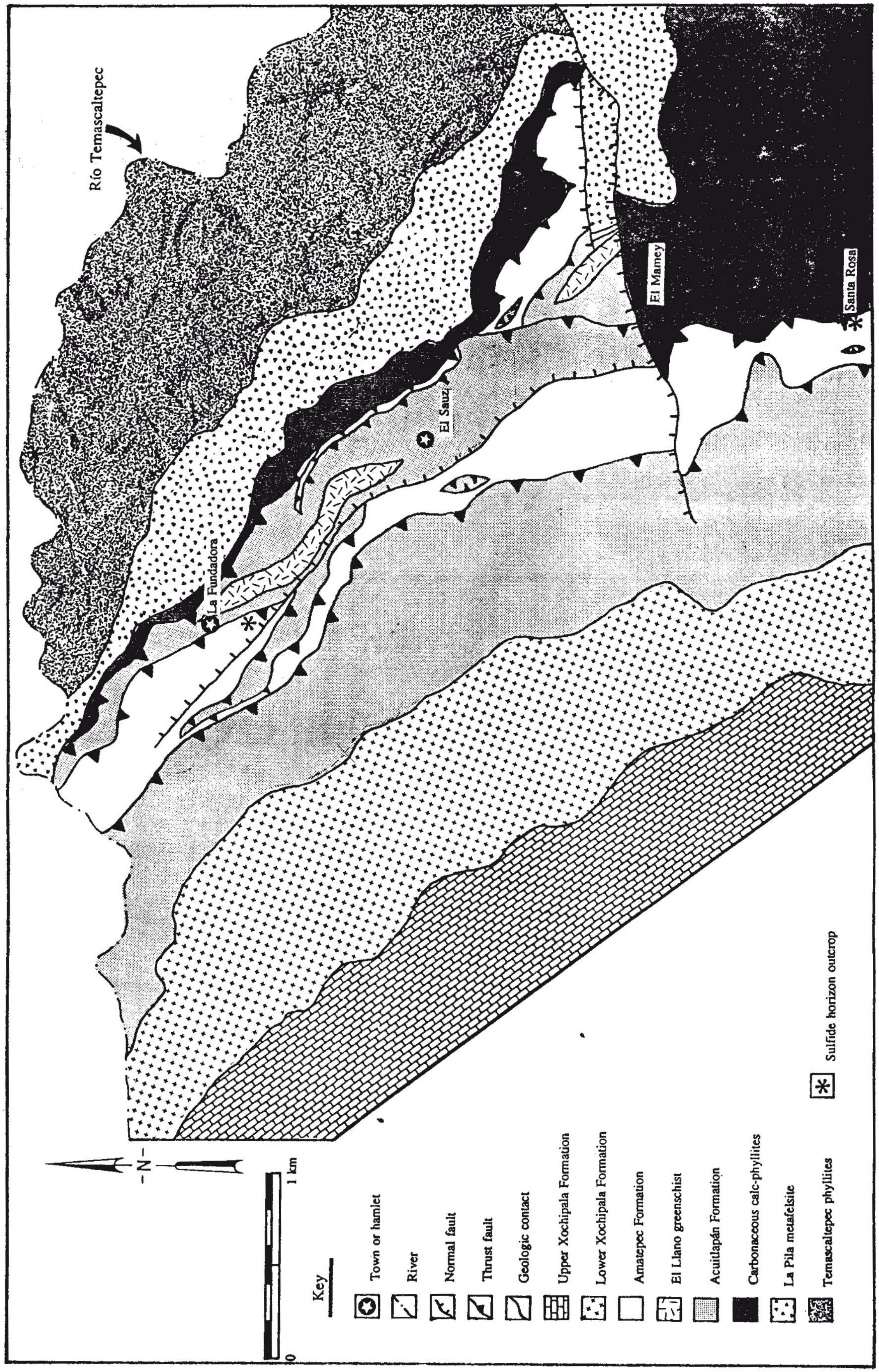

Fig. 2. Geologic map.

paragenesis of the Santa Rosa massive sulfides on the western flank of the Tejupilco Rise, and concluded on the basis of mineral zoning that the sediments and enclosed sulfides were overturned by nappe emplacement. Parga-Pérez (1981) did detailed petrology and ore paragenesis in the vicinity of the Tizapa mine, north of Santa Rosa, and was the first to describe petrographically the mylonitic gneiss exposed through a small erosional window in a river valley. This gneiss, perhaps the base of the entire Tierra Caliente metamorphic complex, is covered unconformably (?) by quartzo-feldspathic schists which grade upward to black slates and phyllites interbedded with quartz-sericite schists and massive Cu-Pb-Zn-Ag sulfides.

Elías-Herrera (1981) mapped in detail and studied the petrology of the Taxco Schists to the east of Santa Rosa, formally documenting amphibolite facies metamorphism in these rocks for the first time. He also mapped several thrust faults in the area but their sense of motion is not well constrained.

LOCAL STRATIGRAPHY

The local stratigraphic sequence can be divided into three groups on the basis of structural and metamorphic history. The bottom group is comprised of the Taxco Schists, the middle group is a tectonically imbricated package consisting of Acuitlapán and Amatepec sediments with enclosed sulfide ores, and the top group consists of the Lower and Upper members of the Xochipala Formation. This stratigraphic sequence is exposed on the western flank of the Tejupilco Rise, where the Santa Rosa prospect is located. Detailed descriptions of the stratigraphic units follow and a stratigraphic column is shown in Figure 3.

Pre-Jurassic Basement

The stratigraphically lowest rocks in the field area are well foliated, deeply weathered, coarse grained quartz-biotite schists. In the field they appear brown and very friable as a result of the weathering they have endured. These rocks are exposed at the core of a NE verging anticline on the steep sides of the Temascaltepec river valley (Figure 2). The primary foliation defined by biotite flakes is folded and a crenulation cleavage is well developed. Some of the biotite grains appear pseudomorphic after hornblende or possibly actinolite. The weathering the rocks have endured renders detailed petrography difficult.

The quartz-biotite schists are followed stratigraphically by a thin (15-20 m) horizon of green to brown chlorite schists, also deeply weathered, and then by slates and phyllites known informally as the Temascaltepec phyllites (Elías-Herrera, 1981). Some of the chlorite grains in the schists give the impression of being pseudomorphic after garnet, but again the degree of weathering precludes a categorical statement of fact. The slates are black, thinly bedded, and locally interbedded with thin (10 cm) horizons of massive pyrite with minor chalcopyrite, sphalerite and galena. Surface oxidation haloes surrounding these horizons are remarkably colorful and are a singular guide to the presence of the sulfides. The phyllites are greenish to yellowish in color with a characteristic sheen owing to the content of fine-grained muscovite. The rocks are well foliated, parallel to bedding, and the foliation is folded into chevrons with a spaced axial planar cleavage.

Covering these rocks, in thrust contact, is the La Pila meta-felsite unit, described by Elías-Herrera (1981). This is a sugar-white, fine-grained, quartz-muscovite, mylonitic schist which occurs as tabular nappes forming hogbacks dipping SW. A great deal of effort on the part of mining geologists has been expended looking for alteration patterns in this unit, in the hopes of finding massive sulfides related to it; to date these efforts have been in vain, partly as a result of the intense deformation the rock has undergone.

The slates and phyllites are in turn overlain by a very distinctive unit of carbonaceous and calcareous slates of a greenish-black color, easily identified in the field by its coloration, very fine foliation and effervescence with HCl. The foliation of these rocks is offset by a spaced, pressure solution cleavage.

This lithologically diverse package has been mapped by de Cserna (1983) as the Taxco Schist.

Acuitlapán Formation

The Acuitlapán Formation consists of meter-thick interbeds of metamorphosed carbonates, arenites, and lutites. I use the name metagraywacke to refer to it because there are graded bed intervals and the coarser-grained portions contain lith-fragments of dacitic rocks. These rocks are well bedded, well foliated, rather friable, and they weather to a buff or tan color. The calcareous portions are medium gray in color and are more resistant to weathering than the other lithologies. When the grain size of these rocks is coarsest (~3 mm), they exhibit a spotted appearance by virtue of the presence of weathered plagioclase crystals. Where lith-fragments are present they account for between 5-10 % of the rock.

Another characteristic of this rock is the almost ubiquitous presence of exsolved quartz in rounded (marble sized) or elongate (10 cm along foliation planes) clots. This quartz is typically very clean and devoid of pyrite and other sulfides.

Within the metagraywacke succession is a porphyroblastic, chloritic schist referred to by Elías-Herrera (1981) as the El Llano greenschist. However, the field relations at Santa Rosa warrant inclusion of this unit within the Acuitlapán Formation. When fresh, this rock is light gray to cream colored, with a distinctive spotted appearance produced by porphyroblasts of chlorite after hornblende.

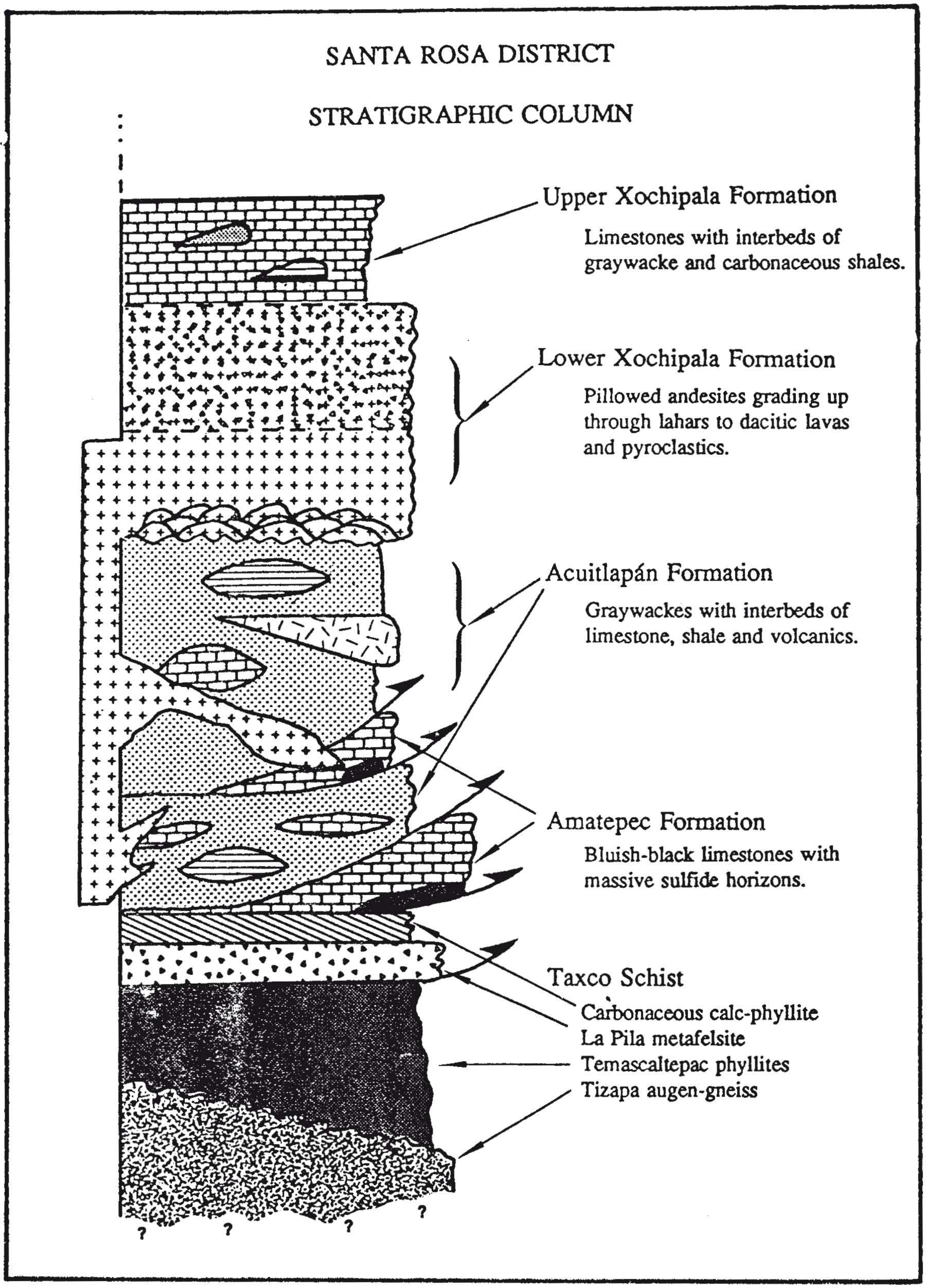

Fig. 3. Stratigraphic column.

Locally, this unit is mylonitized. The mineralogy and texture of this rock suggest that the protolith may have been a dacitic pyroclastic or porphyritic rock, and again despite some effort I was unable to find any alteration or feeder zones, nor indeed any associated sulfides.

AMATEPEC FORMATION

The Amatepec Formation consists of dark, bluish-gray to black limestones with centimeter-thick bands of white calcite and quartz which serve to enhance the ductile deformational features that this rock exhibits. Locally, thin beds of black silicic and slaty rocks are intercalated, which suggests that the probable protolith for this rock was a micritic limestone, with thin beds of chert and shale. The white bands within this unit consist of 70-80 % doubly twinned calcite with quartz and minor plagioclase. The grain size is greater in these portions (1-2 mm), than in the gray metamicritic portions (0.25-0.5 mm) and the foliation is not as well defined. The calcite of the finer grained gray rock typically shows one direction of twinning and commonly contains 1-2 mm diameter porphyroclasts with sigmoidally curved twin lamellae. Much of the unit is extremely mylonitized.

This unit hosts the massive sulfides which have made the area the target of exploration on the part of the Fresnillo mining company. The sulfides are pre-metamorphic, conformable, finely laminated to thickly bedded, and they always appear to outcrop on the hanging wall and in close proximity to the thrusts in the area (see Figure 2). The sulfides are associated with the more shaly and carbonaceous beds within the Amatepec Formation. The mineralogy of the ore is pyrite, sphalerite, galena, ± chalcopyrite, and minor magnetite as the opaque phases, with quartz and ± calcite as translucent minerals. Silver occurs in solid solution in the galena and gold is disseminated. The ore is very pyritic but grades up to 7.6 g/ton Au and 650 g/ton Ag have been reported (Fresnillo proprietary data, 1988).

XOCHIPALA FORMATION

Unconformably overlying the imbricate thrust package lies the Xochipala Formation. At the base it consists of pillowed andesitic to dacitic lavas, which grade upward into lahars. These rocks are light grayish green when fresh but weather easily to brown and yellowish brown. The pillows are about 50 cm long and the lahars have clasts between 5 and 10 cm long. Microscopically, the rocks are fine grained and rather altered which gives them a dirty appearance in thin section. The clasts in the lahars are matrix supported and the matrix consists of deeply weathered, fine grained clays and iron oxides.

Further up in the section, the lahars give way to finer pyroclastic material in the form of tuffs. Their mineralogy is essentially the same as their underlying brethren, but they acquire a spotted appearance in hand sample as a result of plagioclase phenocrysts within the chloritic matrix. In the upper reaches of the pyroclastic sequence, the tuffs become finely interbedded with black, carbonaceous mudstones, which in turn yield to graywackes and carbonates further up-section. The transition from dominantly igneous to dominantly sedimentary lithologies marks the boundary between the Lower and Upper Members of the Xochipala Formation as defined by de Cserna (1983).

The Xochipala rocks exhibit only incipient metamorphism as evidenced by the growth of chlorite and muscovite flakes with a weak preferred orientation.

IGNEOUS INTRUSIVE ROCKS

Both the Acuitlapán and Amatepec Formations have been intruded by dikes and sills of andesitic to dacitic compositions, which in fresh outcrop have a typical greenish coloration resulting from their high chlorite content. Contact metamorphism is minimal and restricted to induration of the sediments with minor silicification; skarns are not developed, even in the Amatepec carbonates. Although there is no direct evidence, other than their similar petrographic character, it seems fair to relate these igneous bodies to the Xochipala volcanics.

The Taxco Schist, in the northeast of the field area is intruded by a small granodiorite stock which outcrops in a roughly circular area about 100 m in diameter. This intrusive is probably related to the Early Tertiary felsic magmatism described by de Cserna (1983).

To summarize, the stratigraphic sequence may be divided into three groups: a lower group with variable lithology and up to amphibolite facies metamorphism; a greenschist facies massive sulfide ore-bearing middle group with tectonically interleaved rock units, intruded by intermediate composition dikes and sills; and an upper group of sub-aqueous intermediate volcanics, and volcaniclastics, covered by clastic rocks.

STRUCTURAL GEOLOGY

The structural geology of the Santa Rosa area is extremely complex. At least two, and possibly three, deformation stages are evident in the oldest rocks and there are unconformities, thrust faults and normal faults which further complicate the geometric relations among rock units. This portion of the paper will attempt to describe the methodology followed in the structural analysis, describe the morphology and geometry of the structural elements encountered, and finally draw attention to the salient structural relationships in the area.

Methods

The methodology used to study the structural geology in this area conforms in general to that described by Turner and Weiss (1963), in conjunction with more modern tools, notably extensive use of the computer to capture and manipulate data relating to crystallographic and grain shape fabrics.

On a mesoscopic scale the structural elements measured include foliations, stretching lineations, fold axes, and axial planes of two different deformation stages. Most of these elements are represented on the map in Figure 4 and on computer-generated equal area nets.

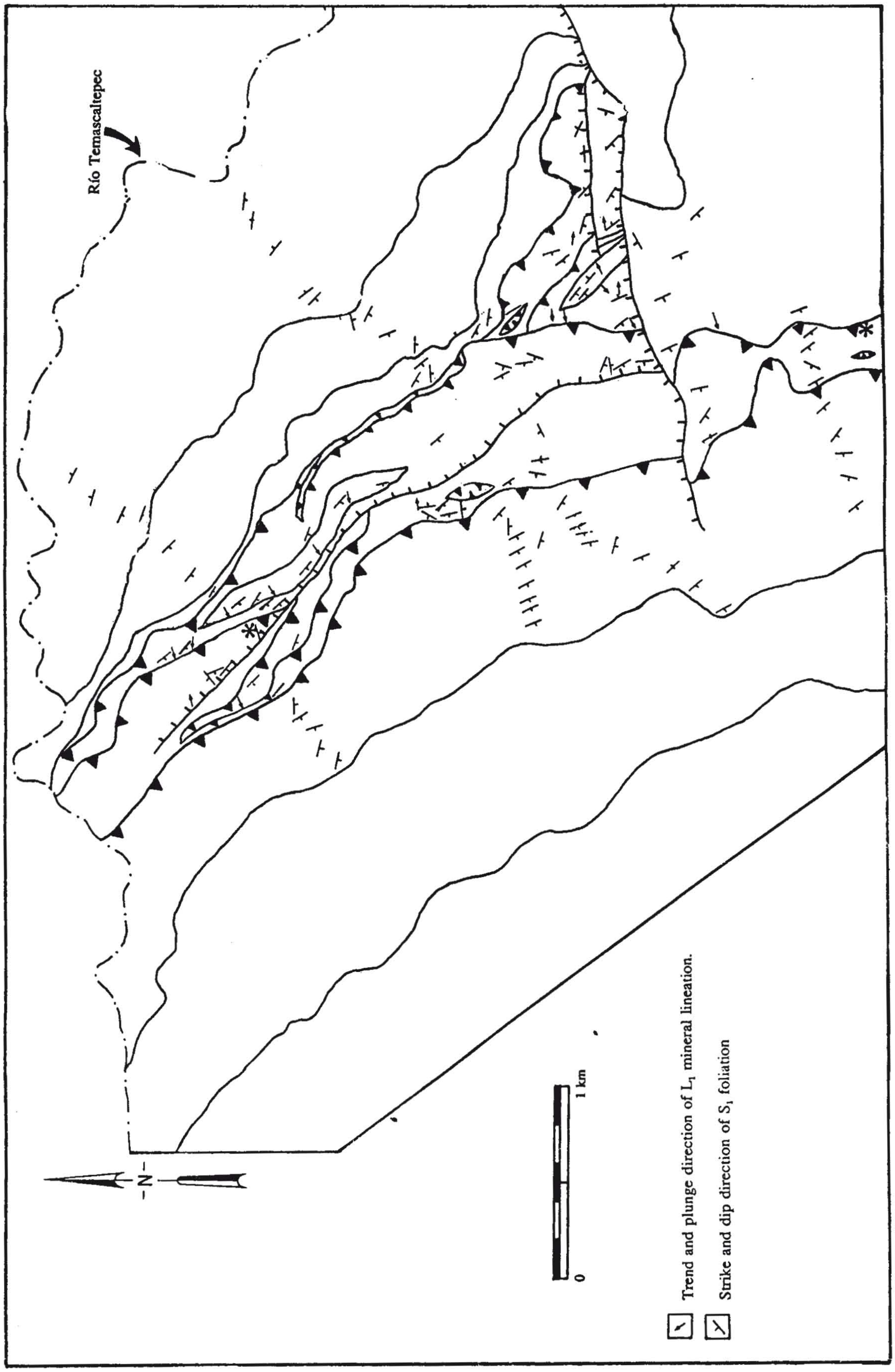

Fig. 4. Map with D_1 deformation feature orientations.

Microscopically, two analyses were carried out: in the first, calcite c-axis orientations were measured and plotted on equal area nets, following the standard techniques described by Turner and Weiss (1963) and Wenk (1985). In the second, grain boundaries from photomicrographs were digitized and fed into a computer where a program, written specifically for this project, graphically and quantitatively renders the shape fabric of the grains. The technique used follows generally, but not specifically, the mathematical manipulations proposed by Panozzo (1983, 1984, 1986) and Schmid et al. (1987). The algorithm and mathematics of the computer program are elaborated below, in the section pertaining to the shape fabrics.

First generation structures

Meter to centimeter scale folds are ubiquitous in the field area and the majority of noteworthy mesoscopic structural elements studied are related to them.

The most pervasive structural feature of the Santa Rosa metamorphic rocks is their foliation (S_1) which, as a result of bedding transposition during folding, is parallel to sedimentary layering (S_0). The foliation is defined by the preferred orientation of micaceous minerals in the more silicic lithologies and by the oblate grain shape of calcite in the calcareous units. S_1 is penetrative on macroscopic to microscopic scales and is axial planar to tight folds developed during the F_1 folding event in the area. Thinning of the limbs and thickening of the hinges suggest a flow mechanism for this deformation.

The orientation of S_1 varies considerably but in general has a northwesterly strike with a slight to moderate dip to the southwest. Equal area net plots of poles to S_1 (Figure 5a), show a marked concentration of planes dipping SW, but a partial girdle is discernible.

First generation fold axis (B_1) orientations were also measured. As the equal area nets (Figure 5b) indicate, B_1 defines a great circle girdle dipping SW, with a marked horizontal point maximum trending NW-SE.

Also associated with the first deformation (D_1) is the development of thrust faults which locally invert the Acuitlapán-Amatepec sequence and put younger Amatepec rocks in contact with older Taxco Schist rocks. Elías-Herrera (1981) has reported that thrusting within the Taxco Schist rocks is responsible for inverting the La Pila-carbonaceous schist sequence less than a kilometer to the east. The thrusting led to the development of mylonites in the La Pila, Acuitlapán, and Amatepec rocks and these are discussed in the microfabric section below. Stretching lineations associated with these mylonites are difficult to find and measure in great quantities in the field, but those that were recorded are shown in Figure 5c.

Second generation structures

Structural features developed in the metamorphic rocks during the first folding event were subsequently refolded and overprinted by a second deformation event D_2. Accompanying D_2 was the development of S_2, a spaced cleavage in the Acuitlapán graywackes, penetrative on macroscopic and mesoscopic scales. S_2 is axial planar to the F_2 folds and occurs as either a pressure solution cleavage or a crenulation cleavage. The F_2 folds are typically straight-limbed with either rounded or sharp hinges. Poles to S_2 are plotted in Figure 6a.

In the Xochipala rocks, which post-date the first deformation, D_2 has resulted in the development of chevron folds within the tuffaceous and sedimentary strata of the sequence but a penetrative planar fabric is notably tenuous or absent. In these rocks, the orientations of bedding and second generation fold axes were measured and plotted, as shown in Figure 6b, 6c.

Post-second generation structures

The contacts between rock units in Santa Rosa are offset by subvertical normal faults which are evident in the field by the development of steep scarps, and coarse breccias. These faults trend N-S and E-W and have considerable, but as yet not quantified, displacements on the order of tens of meters.

Microstructure

Oriented samples collected in the field were cut in thin section, studied petrographically and subsequently mounted on a universal stage to determine the degree of crystallographic preferred orientation of the calcite in the rocks.

The crystallographic fabrics of the Santa Rosa rocks are shown in Figure 7. The Amatepec Formation carbonates exhibit the strongest crystallographic preferred orientations of the lithologies studied, while the Acuitlapán and Xochipala rocks show roughly uniform fabrics. Furthermore the fabric in the limestones is oblique to the foliation, imparting to it an asymmetry suggestive of simple shear. This is interpreted below.

The grain surface fabric analysis was carried out, not so much as a means of calculating the strain in these rocks, but rather in order to characterize the shape fabric of the grains. These analyses were only performed on Amatepec and Acuitlapán carbonates. As mentioned previously, the technique has been described in detail by Panozzo (1983, 1984, 1986) and implemented by Schmid *et al.* (1987). Briefly, it consists of approximating the grain boundaries by a series of connected, short line segments, and then studying the orientation distribution of the segments. This was done using a computer, with input from an image digitizer. The orientation of the line segments is examined in two ways:

In the first case, a rose diagram of the orientation distribution function is drawn (Figure 7). These rose diagrams differ somewhat from traditional rose diagrams, used to

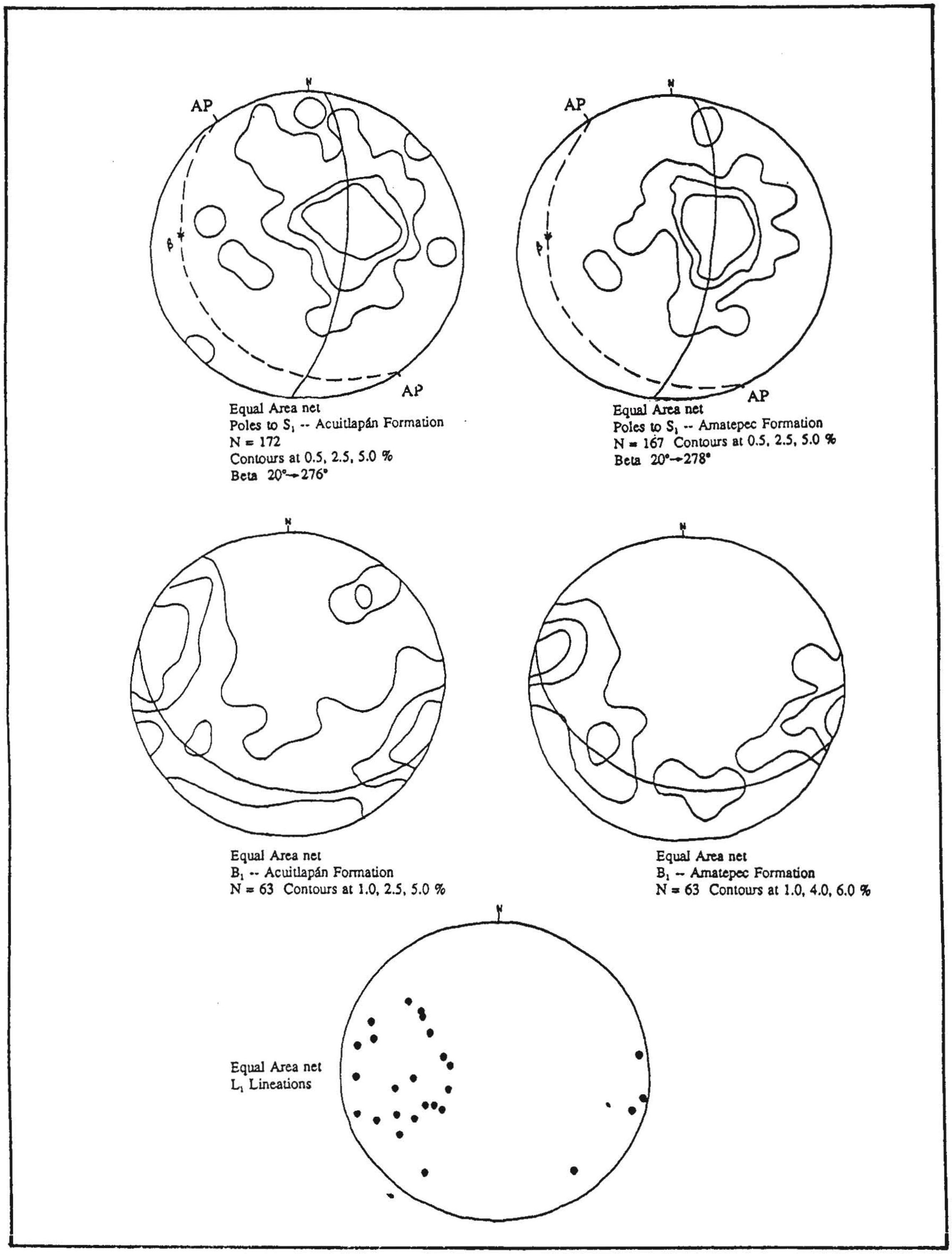

Fig. 5. Equal area nets of D_1 deformation features.

show the direction of current flow, for instance. In traditional rose diagrams, one orientation observation adds an increment to the rose petal; in this analysis, the amount added to the petal is proportional to the length of the line segment with that orientation. In this respect, the analysis diverges from that discussed by Schmid *et al.* (1987), who use a mathematical splining technique to smooth the grain outline, and then approximate the grain by line segments of equal length, which enables them to construct a traditional rose diagram.

The second manipulation of the grain boundary outline lines is the length of projection technique (Panozzo, 1986).

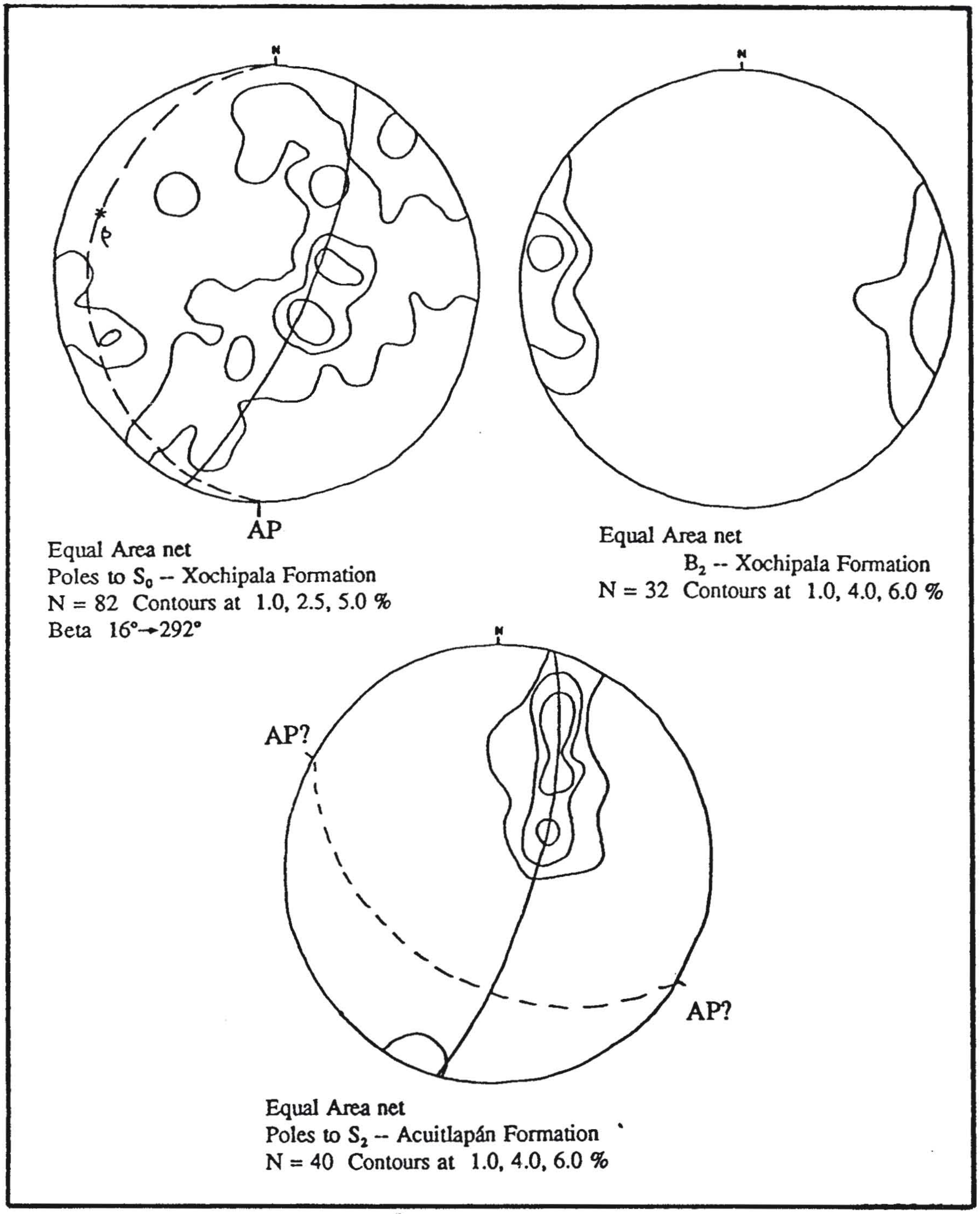

Fig. 6. Equal area nets of D_2 deformation features.

The algorithm for this consists of taking all the line segments in their initial orientation and projecting them individually onto a reference line of arbitrary orientation. The length of each projection is a function of the length of the segment and the angle (α) that it makes with the reference line. The projected lengths of all the segments are added together, which produces a sum, $P = \Sigma\, p_i$. If all the line segments are then rotated counter-clockwise by some increment α, and the line segments are again projected onto the reference line, we obtain another value for P. By repeating this process until the line segments have been rotated 180°, a function $P(\alpha)$ is generated, which represents the sum of projections of the line segments as a function of their orientation. $P(\alpha)$normalized to the total sum, can be used to characterize the degree of preferred orientation of lines, in this case, the grain boundaries (Panozzo, 1986).

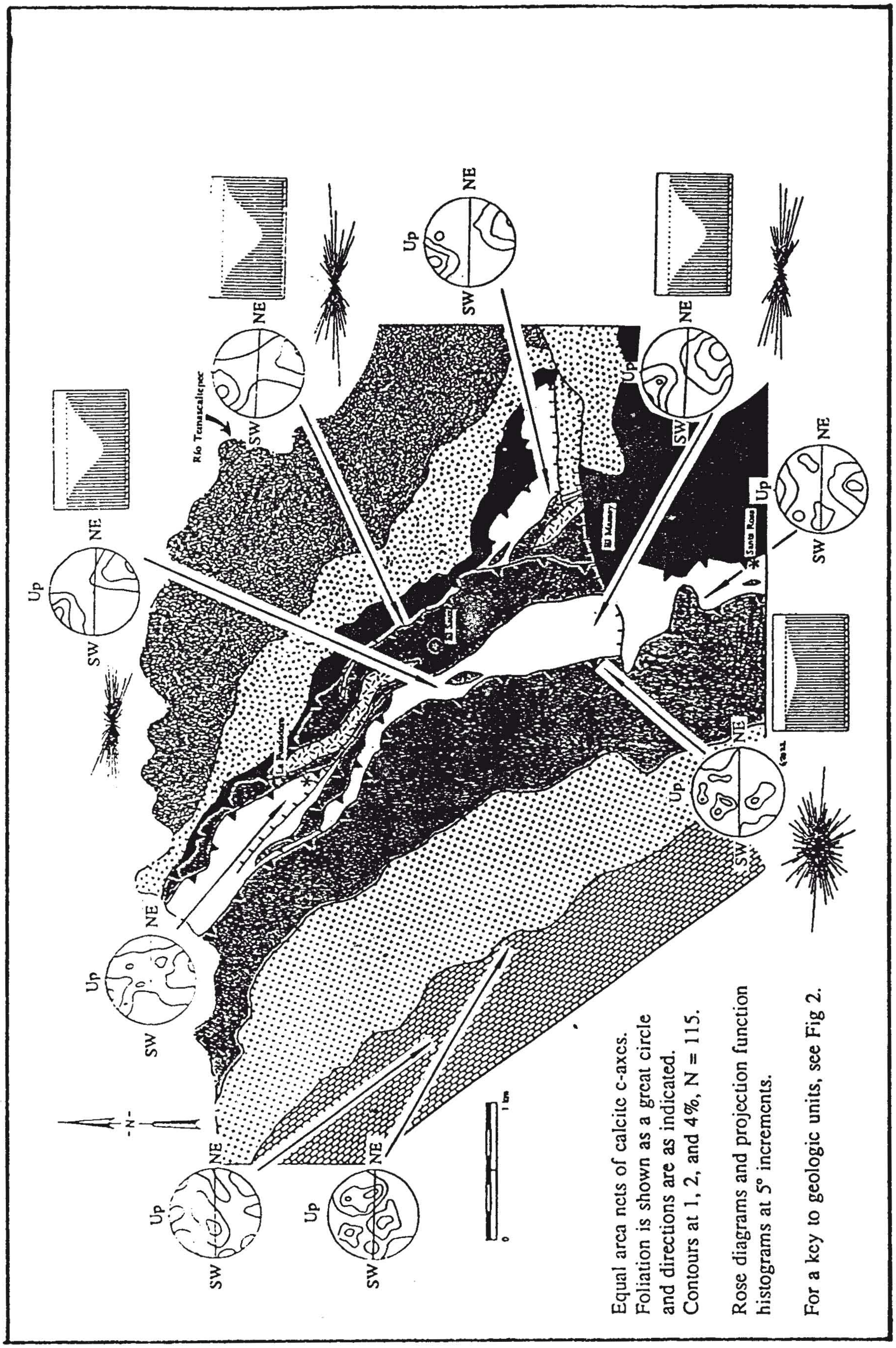

Fig. 7. Microfabric map.

Histograms of P versus α can be plotted, and those with deep troughs and high peaks, indicate strong parallelism of line segments, while flatter distributions are indicative of more random orientations. Examples of these are also shown in Figure 7.

Asymmetric σ and δ porphyroclasts with recrystallized tails were also found and the sense of shear they record noted. These were most common within the mylonitic portions of the El Llano greenschist and Acuitlapán formation but also occur within the Amatepec carbonates.

INTERPRETATION

A brief perusal of the geological map, the structural orientation data, and the photomicrographs of the rocks is sufficient to reveal the complexity of the area. This section of the paper will attempt to sift chronologically through the information in order to suggest a plausible geologic history for this portion of Mexico.

Geometrical considerations

The symmetry of first generation structures, S_1, B_1 and L_1, is monoclinic which is interpreted in part to be the result of a second deformation oblique to the first. Poles to S_1 (Figure 5a) describe partial great circle girdles on equal area nets, and the poles to these girdles plunge 10°-20° towards the west.

The B_1 fold axes also describe great circles dipping to the SW and the presence of this feature in other portions of the Tierra Caliente complex has been the subject of debate in the past. Tolson (1982) suggested that the girdle was caused by non-affine particle movement in the plane of foliation causing rotation of the fold axes toward the direction of transport; a mechanism proposed by Hansen (1971). Neher (1983), however, interpreted the girdle as the result of passive rotation of the linear structures in the direction of maximum elongation during the later stages of D_1 and the duration of D_2, arguing that fold axes do not behave kinematically as mechanical entities; a view supported by Tobisch and Fiske (1982) and Ramsay (1979). Treagus and Treagus (1981), however, have modelled kinematically active fold axis migration and conclude that the final orientation of the axis depends on several parameters, notably the rheology of the layers, the initial orientation of the fold axis with respect to the principal strain axes, and the strain history. The fact that B_1 lies in a plane despite the effects of a second deformation, lends credence to a model involving passive rotation as suggested by Neher (1983).

The equal area net plot of L_1 shows a partial small circle girdle roughly centered on an axis plunging ~20°W with a maximum concentration plunging ~10°WSW. The fact that L_1 and B_1 share the same degree of symmetry but not the same geometry is puzzling. However, the L_1 distribution is geometrically compatible with the rotation of a linear element trending NE-SW about a horizontal E-W axis, which coincides with the F_2 fold axes. This suggests that the maximum elongation of the lineated rocks was NE-SW, prior to D_2.

In light of the previous discussion regarding the mechanically active versus mechanically passive behavior of structural elements, L_1 would appear to have behaved actively during D_2 in contrast with B_1, perhaps by virtue of the different mechanical properties acquired by the rocks as they were mylonitized. Regrettably, this is still an unresolved issue in this area and surely provides a topic for future research.

Poles to S_2 in the metamorphic package describe a partial great circle girdle attributed by Neher (1983) to cleavage fanning around fold hinges, rather than to a third deformation event. While it is true that the S_2 cleavage is fanned, there is evidence of a third deformation, penetrative only on a regional scale. In Santa Rosa S_2 dips moderately to steeply to the SSW, while in Valle de Bravo it dips moderately to the NNE. Fold axes of F_2 folds in the Xochipala formation show a horizontal point maximum trending WNW. There is good agreement between the axial planes of F_2 derived from the S_1 orientations and S_2. Likewise, the poles to the S_1 girdles are sub-parallel to the B_2 orientation.

All these facts in conjunction suggest that D_1 produced tight folds with the development of a penetrative foliation. The maximum compressive stresses during this event were oriented NE-SW. The second deformation folded S_1 of the metamorphic rocks and S_o of the Xochipala rocks tightly about an E-W axis indicating that the direction of greatest shortening was oriented N-S.

Microfabrics

The calcite crystallographic preferred orientation diagrams (Figure 7) of the clastic rocks are quite different to those of the carbonate rocks. The Amatepec limestones exhibit strong c-axis fabrics while the graywackes of the Acuitlapán and Xochipala formations show no such preferred orientation. This is in accord with what is seen in the field where the limestones are much more strongly deformed than the more competent strata. It should be noted, however, that the more silicic mylonitic portions of the Acuitlapán sediments and volcanics may well have strong quartz crystallographic fabrics which were not studied. Likewise, the shape fabrics show a gradation from large elongations in the Amatepec limestones, to intermediate values in the Acuitlapán greywackes.

In keeping with the other structures in the area, the shape fabrics and crystallographic textures of the Amatepec rocks exhibit an asymmetry with respect to the foliation plane. In the case of the c-axis fabric this is a good indicator of the sense of shear (Schmid *et al.*, 1987;

Wenk *et al.*, 1987; Dietrich and Song, 1984). The direction of tectonic transport in the Santa Rosa area as determined from the fabrics is toward the northeast, in agreement with the asymmetric porphyroclasts observed in the more siliceous rocks.

The asymmetry of the shape fabric means that it cannot truly represent a strain ellipse, and hence cannot be used for calculations of strain. On the other hand, Schmid *et al.* (1987) stated that their experimental work documented such asymmetries when their samples deformed by grain boundary migration at temperatures greater than ~700° C. The appearance of the rock in thin section, however, does not warrant such a mechanism, nor does the petrological character of the rocks justify such a temperature. The deformation mechanism in these rocks is more likely to be e-twinning as evidenced by the single point maximum of the c-axis fabrics. The sigmoidal character of the twin lamellae in the calcite porphyroclasts is also suggestive of movement on other crystallographic planes, perhaps r-slip (Schmid *et al.*, 1987). Another factor possibly contributing to the asymmetry of the shape fabric may be the effects of the second episode of deformation. It is a shame, however, that the shape fabric asymmetry is not consistently of the same "handedness" as the crystallographic fabric, since this precludes its use as a kinematic indicator.

Geological considerations

The stratigraphy of the Santa Rosa area consists of three distinct piles of volcanic and sedimentary rocks of island arc affinity, separated in time by regional tectonic events, so that each successive pile has experienced one less deformation than its predecessor. This suggests the development of sedimentary basins followed by shortening, uplift, and arc construction, in turn followed by collapse of the arc with the renewed growth of another basin beginning another cycle.

While a detailed geological summary of surrounding areas, such as Guerrero and Michoacán, is outside the scope of this paper, it is noteworthy that there is evidence for such cycles outside the Santa Rosa area. Parga-Pérez (1981) has proposed an unconformity over the strongly mylonitized Tizapa augen gneiss (7 km N), with the deposition of a marine sedimentary succession interbedded with felsic rocks and volcanogenic massive sulfide ores. Similarly, Solís and Chiody (1986) did a detailed geological and structural analysis in Azuláquez, Guerrero (60 km SE), and found marine sediments locally interbedded with massive sulfides, and dacitic lavas and pyroclastics. The work of López-Trinidad *et al.* (1987) documenting the presence of the Palmar Chico ophiolite (25 km SSW), argues strongly in favor of back-arc basin development. The previously mentioned theses by Tolson (1982) and Neher (1983) in the Valle de Bravo area (25 km NNE) describe structural style and lithologies which also support such a hypothesis.

TECTONIC MODEL

Certain aspects of the geological evolution for this portion of Mexico are still not well constrained, notably the absolute timing of events and detailed geochemistry of the rocks. The evolutionary model presented here is very general and, to a certain degree, speculative. Nonetheless, it is offered as a working hypothesis to be verified, modified or rejected in the light of results from future studies. The model, summarized by a cartoon in Figure 8, is as follows:

During the Triassic, a sequence of marine sediments was deposited unconformably on the rocks of the "Tizapa fossil arc" whose basement is the strongly mylonitized gneiss. There ensued a period of arc growth during the Late Triassic-Early Jurassic, during which the rocks were subjected to upper greenschist/lower amphibolite burial metamorphism, thus forming the Taxco Schists. Toward the end of the Jurassic this arc rifted apart forming a basin floored by oceanic crust separating the two arc remnants. The remnant to the west corresponds to the Michoacán crustal block of Campa and Ramírez (1979) and Urrutia-Fucugauchi and Valencio (1986) or the Guerrero-Alisitos arc of Coney (1983), which was the site of arc-related processes, while the eastern remnant corresponds to the Guerrero-Morelos block upon which a stable platform sequence was deposited. Until the lower to mid-Cretaceous, the polarity of subduction was to the east, as it is today. However, when the Palmar Chico back-arc basin closed, a phase of westerly-directed subduction was initiated beneath the Michoacán block, as previously suggested by Urrutia-Fucugauchi and Valencio (1986) as well as Coney (1983). Closure of the marginal basin during the mid-Cretaceous led to regional deformation, greenschist facies metamorphism and thrusting which led to the emplacement of the ophiolite. Yet another sedimentary basin developed during the Late Cretaceous, in which the marine volcanic and sedimentary rocks of the Xochipala and Arcelia Formations were deposited. Collision with the Zihuatanejo arc (Campa and Ramírez, 1979) during the latest Cretaceous and Early Tertiary, led to deformation of these rocks with only the slightest metamorphic effects and the uplift that resulted from this collision contributed to the Balsas red-bed sediments. During Paleocene and Eocene time the area was subjected to large scale folding and granodioritic to quartz-monzonitic igneous activity locally accompanied by precious and base metal deposits of economic importance. Dominantly extensional stresses have affected the area from the Miocene to the present (Campa, 1974).

CONCLUSIONS

The extremely complex field relations, structures, and petrology of the rocks in the vicinity of Santa Rosa have been described and interpreted. The findings conclude that the stratigraphic sequence can be divided into three packages: a lower sequence of up to amphibolite facies metamorphic grade, consisting of interbedded sediments and volcanics which have been penetratively folded twice; a tectonically interleaved middle portion of graywackes, with minor volcanics, and limestones with enclosed sulfide

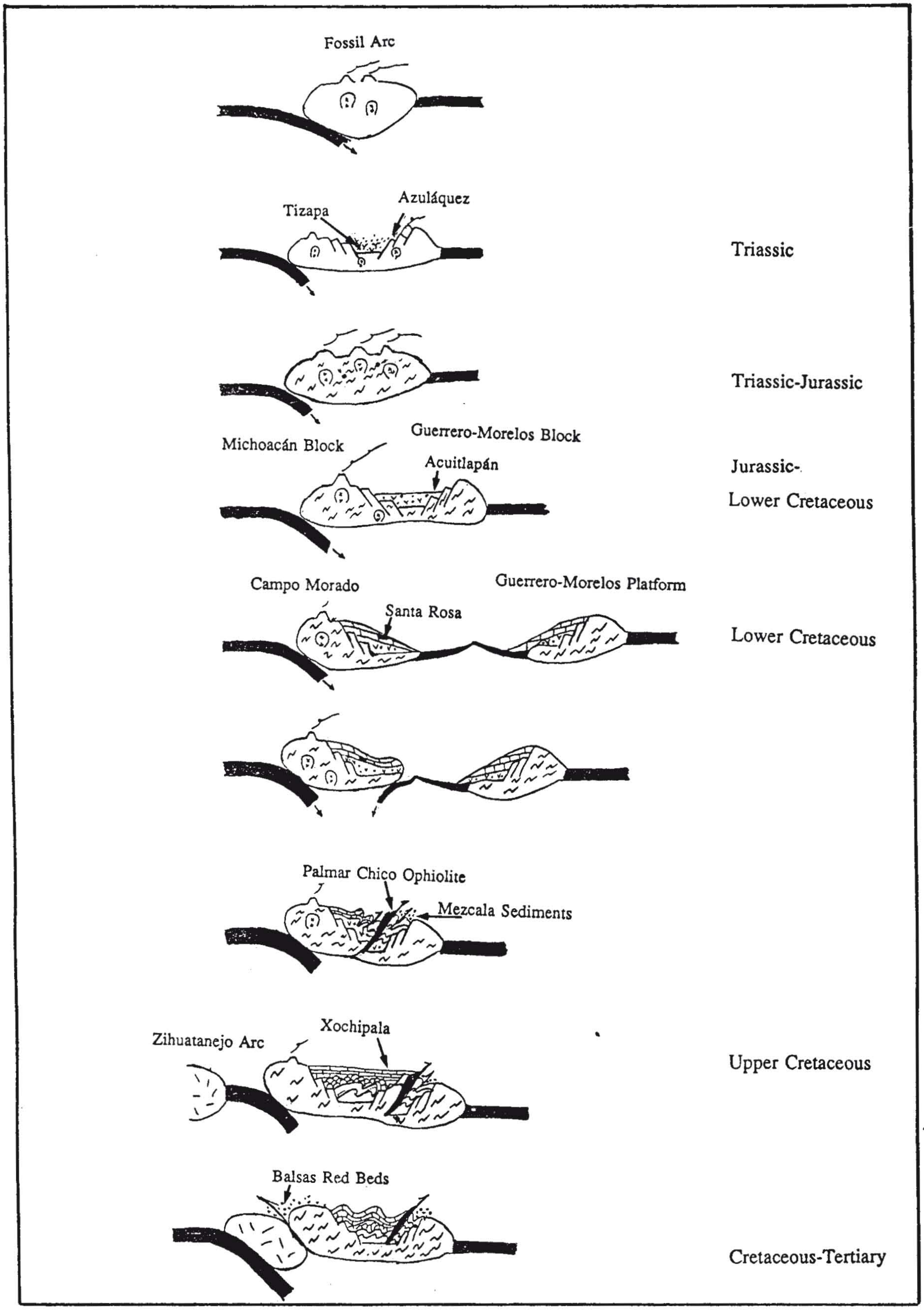

Fig. 8. Tectonic model, see text for details.

ores which has been subjected to two phases of penetrative deformation and greenschist facies metamorphism; and a top group of sub-aqueous, intermediate volcanics grading to tuffs and graywackes interbedded with dirty limestones, which has been folded only once and exhibits only incipient metamorphism.

Kinematic indicators in mylonites of the intermediate group, c-axis fabrics and asymmetric porphyroblasts, suggest a northeasterly direction of tectonic transport during thrusting, which occurred in the mid-Cretaceous and was accompanied by greenschist facies metamorphism and the development of a penetrative foliation S_1. The structures developed during the first deformation were subsequently folded about a sub-horizontal E-W trending axis and a southerly dipping axial plane; this event locally developed a penetrative cleavage S_2 but was not accompanied by significant metamorphism.

There are still many unresolved problems in the area, but a tectonic model which can be tested has been proposed. Specific questions that can be addressed to refute, alter, or support the model include:

Geochemical studies of the metavolcanic rocks in the various packages to determine whether they are related to each other or not, and to ascertain whether there are any regional trends which may be indicators of subduction polarity.

Geochronological studies to better constrain the timing of events in the area, in particular the deformations and the igneous events.

Structural analyses to gain a better insight to the large scale kinematic framework on a regional scale and its variation in time.

The geology of the Santa Rosa as presented here is just a small piece of an enormous puzzle that is the geological evolution of the southwest of Mexico. Only by putting together many such pieces will we begin to understand the complex evolution of this part of North America.

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