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STRATIGRAPHY AND REGIONAL SIGNIFICANCE OF MISSISSIPPIAN TO JURASSIC ROCKS IN SIERRA SANTA TERESA, SONORA, MEXICO

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ABSTRACT

In Sierra Santa Teresa, about 20 km southeast of Hermosillo, Sonora, Mexico, Paleozoic strata are exposed in the upper plate, and Mesozoic rocks in the lower plate, of a post-Early-Jurassic thrust fault. Paleozoic rocks in the upper plate are divided into seven units. Units 1 through 5 are about 1,500-m thick, composed of shallow-water lime mudstone and minor wackestone, packstone, and bioclastic packstone, and range in age from Late Mississippian to Middle Pennsylvanian. Unit 6 is about 110- to 120-m thick and consists of a distinctive shallow-water packstone with abundant fusulinids and pelmatozoan detritus. Unit 7 appears to lie depositionally on unit 6 and is at least 610-m thick. It consists of relatively deep-water silty limestone, sandy limestone, limy siltstone, and limy very fine-grained sandstone, and interbedded 0.5 to 2.5-m-thick layers of conglomerate and calcarenite, commonly containing detrital fusulinids. The detrital fusulinids are late Early or Middle Permian in age and considered to indicate the approximate age of deposition of unit 7.

The lower plate rocks consist of at least 544 m of Upper Triassic and Lower Jurassic strata overlain by about 600 m of Mesozoic andesitic rocks. Upper Triassic and the Lower Jurassic strata consist of a variety of rock types including argillite, siltstone, quartzitic siltstone, limy siltstone, sandstone, limy sandstone, quartzite, conglomerate, conglomeratic sandstone, sandy calcarenite, sandy limestone, calcarenite, lime mudstone, wackestone, bioclastic packstone, boundstone, and recrystallized limestone. Corals and sponges in limestone in the lower part of the section indicate a Late Triassic age, and ammonoids in the more silty upper part of the section are considered to be Early Jurassic in age.

The relatively deep-water depositional environment of the Lower or Middle Permian siliciclastic strata of unit 7 marks a distinct change from the underlying shallow-water depositional environment of the Mississippian to Lower Permian strata of units 1 to 6. Tectonically this change can be interpreted either as (1) the development of a foreland basin in response to a subduction system to the south; or (2) development of a basin during fragmentation of the continental margin by strike-slip and transtensional faulting in an unstable continental borderland.

Upper Triassic rocks in Sierra Santa Teresa have been interpreted either as (1) an allochthonous terrane unrelated to largely nonmarine strata of the Upper Triassic and Lower Jurassic Barranca Group to the east in east-central Sonora; or (2) a facies of Upper Triassic rocks intermediate between the largely nonmarine Barranca Group to the east and marine strata of the Antimonio Formation to the northwest in northern Sonora.

Keywords: Stratigraphy, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Sierra Santa Teresa, Sonora, Mexico.

RESUMEN

En la Sierra de Santa Teresa localizada a 20 km al SE de Hermosillo, Sonora, afloran estratos paleozoicos (placa superior) que tectónicamente yacen sobre rocas mesozoicas (placa inferior), a lo largo de una falla de cabalgadura post jurásica temprana. Las rocas paleozoicas de la placa superior se dividen en siete unidades. Las unidades 1 a la 5 tienen un espesor de aproximadamente 1,500 m y están compuestas por lodolitas calcáreas, *wackestone*, *packstone* y *packstone* bioclástica que indican ambientes de aguas marinas someras; la edad de estas unidades varía del Misisípico Tardío al Pensilvánico Medio. La unidad 6 varía en espesor de 110 a 120 m y consiste en un *packstone* con abundantes fusulínidos y fragmentos de briozoarios. La unidad 7 yace sobre la unidad 6 en aparente contacto sedimentario y es de al menos 610 m de espesor. Consiste en caliza arenosa y limolítica, limolita calcárea, arenisca calcárea de grano muy fino e intercalaciones de conglomerado y calcarenita en capas de 0.5 a 2.5 m de espesor con detritos de fusulínidos.

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Las rocas de la placa tectónica inferior consisten en al menos 544 m de estratos del Triásico Superior al Jurásico Inferior, sobre los que yacen aproximadamente 600 m de rocas andesíticas mesozoicas. Los estratos del Triásico Superior y del Jurásico Inferior consisten en argilita, limolita, limolita cuarcítica y calcárea, arenisca, cuarcita, conglomerado, conglomerado arenoso, caliza arenosa, calcarenita, lodolita calcárea, *wackestone*, *packstone* bioclástico y *boundstone*. En la parte inferior de la sección, se tiene capas de calizas con corales y esponjas que indican una edad triásica tardía, mientras que en la parte más superior de la sección se tiene amonitas que indican una edad jurásica temprana.

El cambio brusco observado entre los ambientes de depósito de la unidad 7, de edad pérmica temprana a media, e interpretada como formada en aguas relativamente profundas, y los de aguas someras representados por las unidades 1 al 6 de edad misisípica a pérmica temprana, sugieren la presencia de un evento tectónico que puede interpretarse como debido al (1) desarrollo de una cuenca de tipo *foreland* formada en respuesta a un sistema de subducción dirigido hacia el sur; o bien, (2) al desarrollo de una cuenca formada por fallamiento transtensional durante la fragmentación del margen continental.

Las rocas del Triásico Superior en la Sierra de Santa Teresa han sido interpretadas como (1) parte de un terreno alóctono, no relacionado con los estratos del Grupo Barranca del Triásico Tardío y Jurásico Temprano del centro y centro-oriente de Sonora; o (2) a una facies intermedia entre los estratos no marinos del Grupo Barranca y los marinos de la Formación Antimonio, estos últimos localizados en el noroeste de Sonora. Los fusulínidos detríticos son de edad pérmica temprana o media y ésta se considera como la edad aproximada de depósito de la unidad 7.

Palabras clave: Estratigrafía, Misisípico, Pensilvánico, Pérmico, Triásico, Jurásico, Sierra Santa Teresa, Sonora, México.

INTRODUCTION

The Sierra Santa Teresa contains one of the most complete Mississippian to Lower Permian shallow-water carbonate-shelf successions in central Sonora. Depositionally above these shallow-water rocks are Permian deep-water calcareous siliciclastic rocks. All these Paleozoic rocks comprise a thrust plate that overlies marine and nonmarine carbonate and detrital Upper Triassic and Lower Jurassic strata and Mesozoic andesitic rocks.

Sierra Santa Teresa is centered about 20 km southeast of Hermosillo (Figure 1). It is a relatively small range (8 by 5 km), yet topographically rugged (Figure 2). It has a relief of about 500 m. Access is either from the north by way of unimproved ranch roads that extend south from the paved Hermosillo-Mazatán highway east of Hermosillo, or from the west by way of work roads of the Cementos del Yaqui, or unimproved ranch roads, that extend east from Sonora highway 16 (Figure 1). The Cementos del Yaqui is a large modern cement plant that derives limestone and other ingredients for cement mix from outcrops on the western part of the Sierra Santa Teresa. All of the land in the range is private and access is possible only by permission from ranch owners or the Cementos del Yaqui. All the roads into the area have locked gates.

The range has very dense vegetation, and traverses of the area and observation of the rocks are difficult. Exposures are incomplete in several parts of the succession. In addition, metamorphism has destroyed some of the original textures of the rocks and made identification of fossil material difficult. The conodont alteration index (Epstein *et al.*, 1977) is 4 to 7 in Sierra Santa Teresa (Appendix) indicating metamorphic temperatures of 190° to over 400° C.

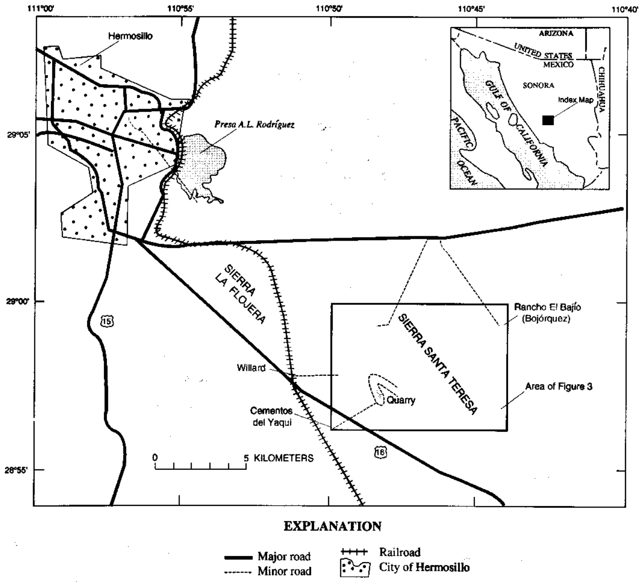


Figure 1. Index map showing location of Sierra Santa Teresa.

The range was briefly mentioned by Flores (1930) in his reconnaissance study of Sonora. He noted that the main part of the range was composed of limestone flanked by clastic rocks on the west. He apparently considered the limestone and clastic rocks to be Jurassic or younger in age. King (1939) noted fusulinids at Sierra La Flojera, 12 km north-northwest of Sierra Santa Teresa, and on a lithologic basis, King (*op. cit.*) tentatively assigned the rocks in Sierra Santa Teresa to the Permian. In the mid-1970's, Sierra Santa Teresa was studied by Françoise Peiffer-Rangin, who recognized the thick succession of Pennsylvanian and Permian rocks there, and noted a variety of fossil material that includes brachiopods, corals, pelmatozoans, ostracods, bryozoans, foraminifers, fusulinids, sponge spicules, and algae. The final results of her study, however, were not published. Rodríguez-Castañeda (1981) studied an area east of Hermosillo that included hills directly north of

Figure 2. Oblique aerial photograph of Sierra Santa Teresa.

Sierra Santa Teresa. He recognized fusulinids in Sierra La Flojera, but the rocks he considered to be Mesozoic and Triassic in age in the hills directly north of Sierra Santa Teresa are here considered to correlate with Permian unit 7 described in this paper. A study of fusulinids from relatively small outcrops in the westernmost part of the map area was made by Pérez-Ramos (1992). Some preliminary results of our studies in Sierra Santa Teresa were summarized previously (Stewart and Amaya-Martínez, 1993).

The present study consisted of geologic mapping and stratigraphic studies by John H. Stewart and Ricardo Amaya-Martínez. Paleontological studies of conodonts were by Robert G. Stamm and Bruce R. Wardlaw, of Triassic corals and sponges by George D. Stanley, Jr., and of fusulinids by Calvin H. Stevens.

STRUCTURAL SETTING

The main part of Sierra Santa Teresa is composed of Mississippian to Lower Permian strata that dip moderately to steeply west and are offset by major east-side-down north-south trending normal faults (Plate 1). This succession lies in thrust contact above a succession of overturned east-dipping Upper Triassic and Lower Jurassic strata and Mesozoic andesitic rocks. The thrust fault has an irregular east-west trace, related to downdropping of the thrust on several north-south trending normal faults. The attitude of the thrust fault was not measured, but the mapped trace suggests that it is fairly low angle. The normal faults in the range appear to be mainly high angle and east dipping.

The thrust fault in Sierra Santa Teresa that places middle and upper Paleozoic rocks over Mesozoic rocks may continue into Sierra La Flojera, 12 km to the north-northwest. There, Permian rocks may be thrust over closely juxtaposed Triassic rocks, although young alluvium covers the actual contact between the two successions.

STRATIGRAPHY OF UPPER PLATE STRATA

Mississippian to Lower Permian upper-plate rocks in Sierra Santa Teresa are divided into seven map units (Plate 1, Figure 3), referred to informally here as units 1 to 7. Unit 1 is middle or late Chesterian (Late Mississippian) to late Morrowan or Atokan (Early or Middle Pennsylvanian), unit 2 is lower Morrowan or early Atokan (Early or Middle Pennsylvanian) in age, unit 3 is Morrowan or Atokan (Early or Middle Pennsylvanian), units 4 and 5 are Atokan and Desmoinesian (Middle Pennsylvanian), unit 6 is Leonardian (Early Permian), and unit 7 is Leonardian (Early Permian) or Guadalupian (Middle Permian) (see Appendix for faunal lists and age interpretations). The lower six units are largely shallow-water carbonate rocks with a measured thickness of 1,646 m, whereas unit 7 is composed of deeper water fine-grained calcareous siliciclastic rock and interbedded calcarenite with an estimated incomplete thickness of about 610 m.

UNIT 1

Unit 1 is the oldest exposed Paleozoic unit in Sierra Santa Teresa. The total thickness (base not exposed) is 579 m in measured section 6 in the central eastern part of the range (Plate 1, Figure 3). The unit is mostly laminated to thin-bedded limestone that includes wackestone, packstone, bioclastic packstone, and mudstone. It is characterized by relatively common pelmatozoan debris and other bioclastic material, sparse oolitic packstone, sparse low-angle cross strata, limestone containing quartz silt, and brown-weathering silicified limestone (possibly in part siliceous siltstone). Four samples analyzed for conodonts from section 6 indicate a middle or late Chesterian (Late Mississippian) age for at least the lower half of the unit and a late Morrowan or Atokan (Early or Middle Pennsylvanian) age for at least the topmost part of the unit (Figure 4; Appendix). The bryozoan *Archimedes* is present 101 m above the exposed base of the unit and also indicates a Mississippian age for the lower part of the unit.

The upper 101 m of unit 1 were also measured in section 5 in the northeastern part of the range (Plate 1, Figure 3), where much of the rock is lime mudstone locally containing laminae, beds, stringers, and nodules of chert. Unidentified brachiopods and corals are present in some beds. Conodonts identified from a sample about 24 m below the top of unit 1 indicate a middle or late Morrowan (Early Pennsylvanian) age.

From a distance, unit 1 forms a well-bedded unit with numerous small ledge-forming layers.

UNIT 2

Unit 2 is 262-m thick (Plate 1, Figure 3) and is a relatively nonresistant unit that lies between the well-bedded and ledgy unit 1 and the cliff-forming unit 3.

The lower half of unit 2 is covered. The upper half consists of limestone that includes lime mudstone and minor amounts of wackestone. The limestone is recrystallized in parts of the unit. Chert is present locally as laminae, very thin beds, and lenses. Unidentified brachiopods, corals, and pelmatozoan debris are present in a few beds. Conodonts indicating a possi-

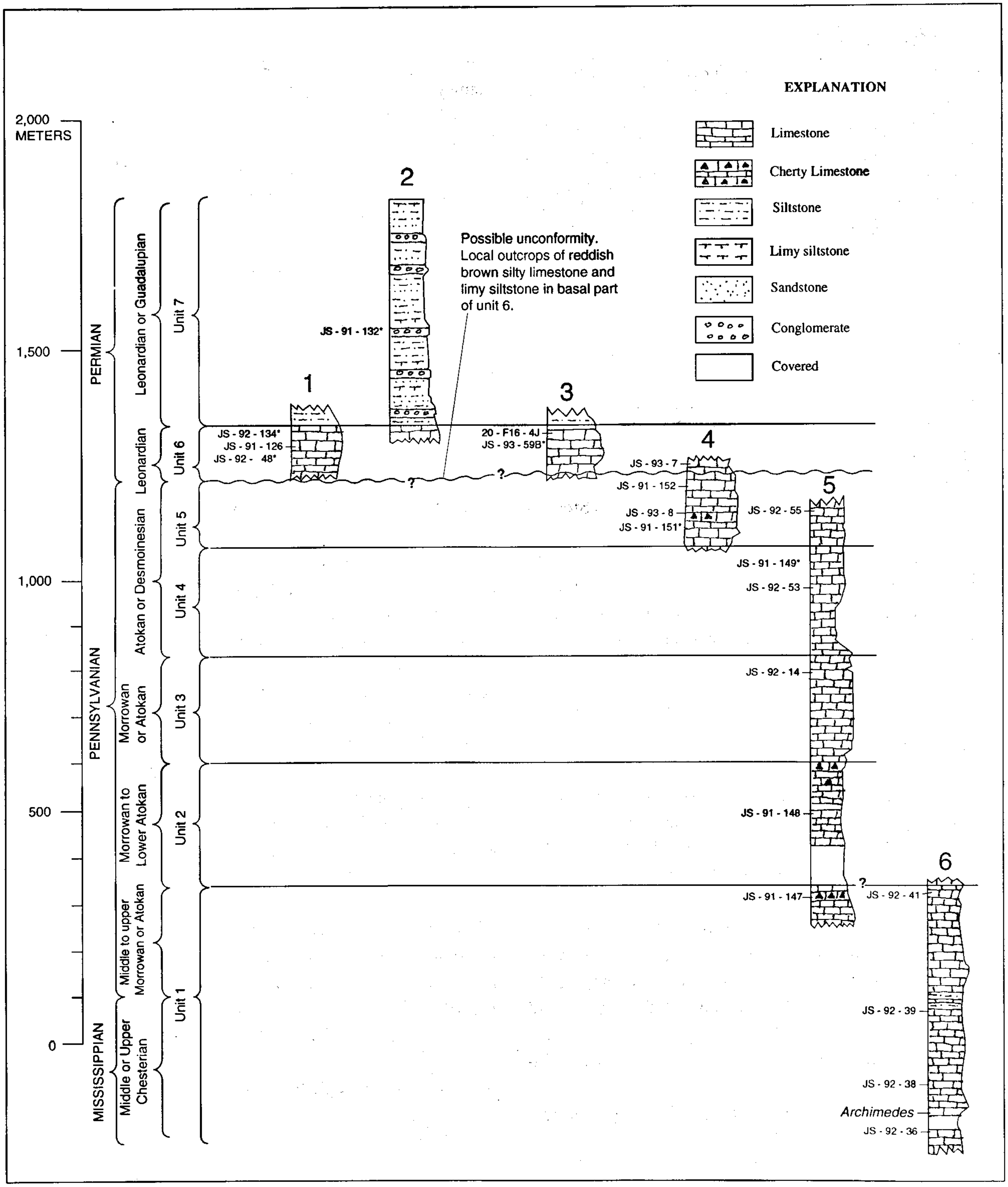
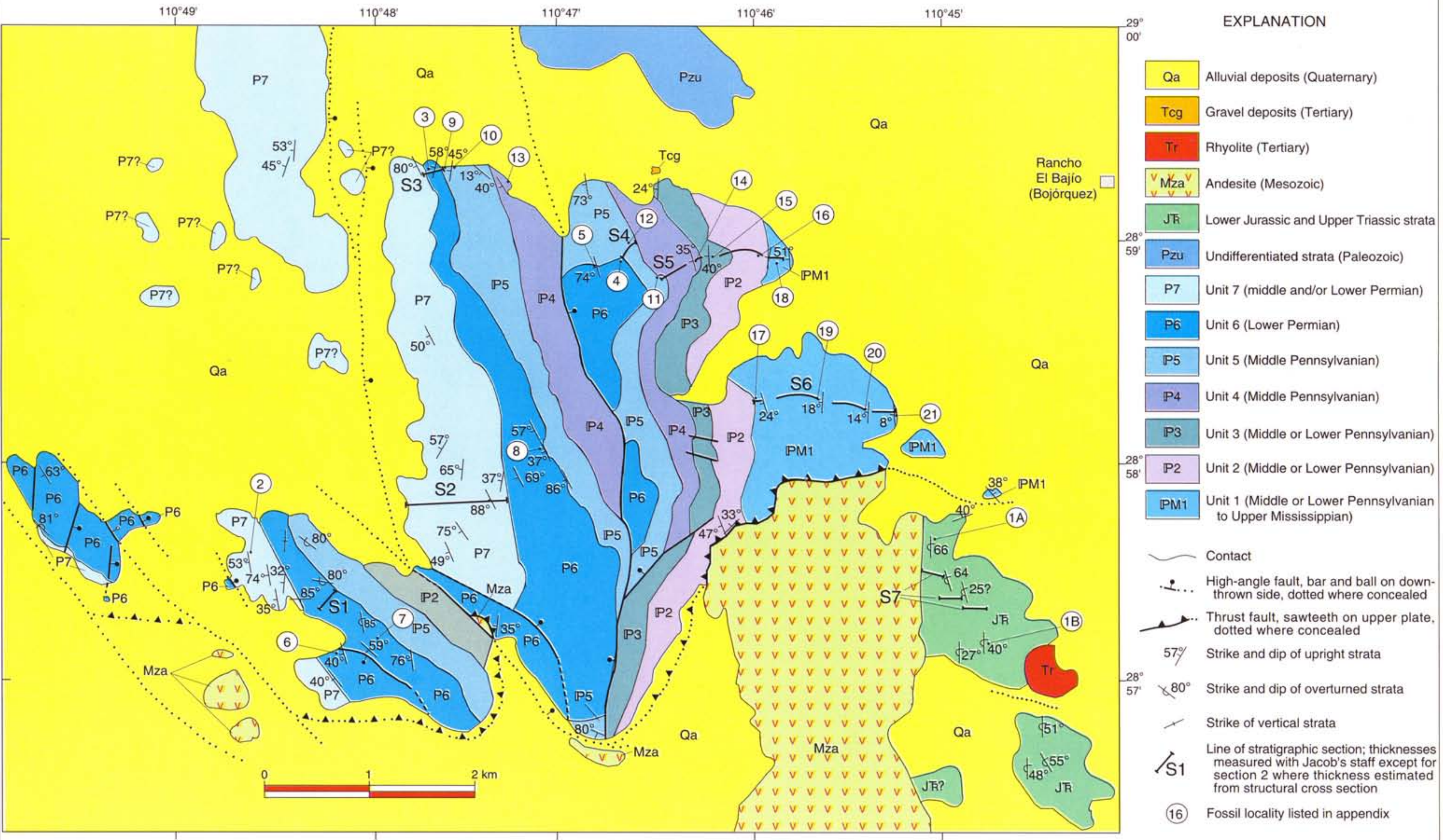


Figure 3. Correlation of Mississippian, Pennsylvanian, and Permian strata in Sierra Santa Teresa. Fossil localities are shown by sample number (see Appendix). Asterisk indicates that sample is not along line of section and position in section is estimated.

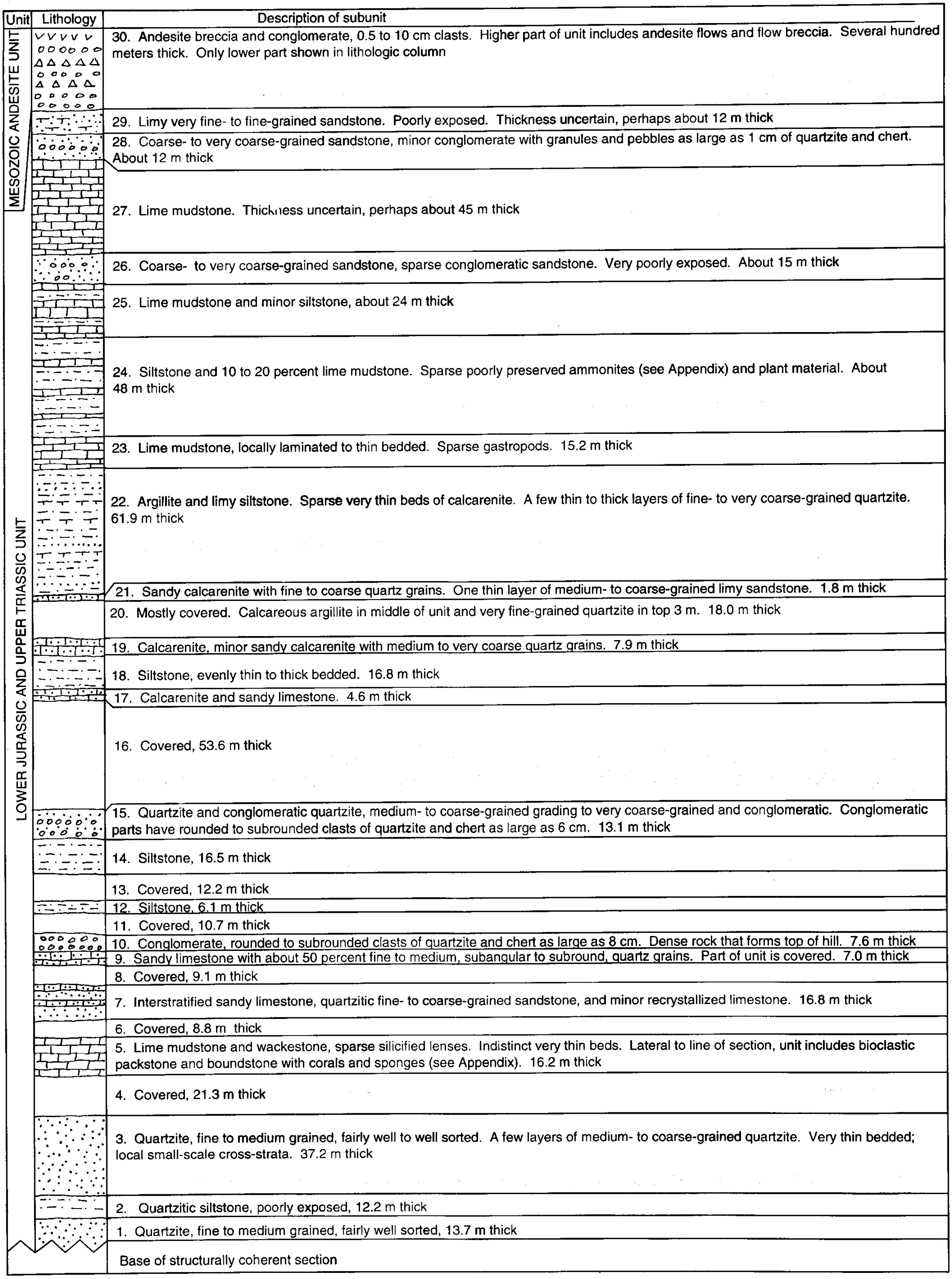
ble age range of early Morrowan to early Atokan (Early to Middle Pennsylvanian) were identified from a sample about 176 m above the base of unit 2. Because of the age indicated by conodonts near the top of unit 1, however, unit 2 is probably not older than late Morrowan.

UNIT 3

Unit 3 is 230-m thick (Figure 3) and forms the lowest of three major cliff-forming units in Sierra Santa Teresa. Unit 3 consists of limestone that includes lime mudstone and minor



GEOLOGIC MAP OF SIERRA SANTA TERESA, SONORA, MEXICO



Unit	Description of subunit
MESOZOIC ANDESITE UNIT	30. Andesite breccia and conglomerate, 0.5 to 10 cm clasts. Higher part of unit includes andesite flows and flow breccia. Several hundred meters thick. Only lower part shown in lithologic column
	29. Limy very fine- to fine-grained sandstone. Poorly exposed. Thickness uncertain, perhaps about 12 m thick
	28. Coarse- to very coarse-grained sandstone, minor conglomerate with granules and pebbles as large as 1 cm of quartzite and chert. About 12 m thick
LOWER JURASSIC AND UPPER TRIASSIC UNIT	27. Lime mudstone. Thickness uncertain, perhaps about 45 m thick
	26. Coarse- to very coarse-grained sandstone, sparse conglomeratic sandstone. Very poorly exposed. About 15 m thick
	25. Lime mudstone and minor siltstone, about 24 m thick
	24. Siltstone and 10 to 20 percent lime mudstone. Sparse poorly preserved ammonites (see Appendix) and plant material. About 48 m thick
	23. Lime mudstone, locally laminated to thin bedded. Sparse gastropods. 15.2 m thick
	22. Argillite and limy siltstone. Sparse very thin beds of calcarenite. A few thin to thick layers of fine- to very coarse-grained quartzite. 61.9 m thick
	21. Sandy calcarenite with fine to coarse quartz grains. One thin layer of medium- to coarse-grained limy sandstone. 1.8 m thick
	20. Mostly covered. Calcareous argillite in middle of unit and very fine-grained quartzite in top 3 m. 18.0 m thick
	19. Calcarenite, minor sandy calcarenite with medium to very coarse quartz grains. 7.9 m thick
	18. Siltstone, evenly thin to thick bedded. 16.8 m thick
	17. Calcarenite and sandy limestone. 4.6 m thick
	16. Covered, 53.6 m thick
	15. Quartzite and conglomeratic quartzite, medium- to coarse-grained grading to very coarse-grained and conglomeratic. Conglomeratic parts have rounded to subrounded clasts of quartzite and chert as large as 6 cm. 13.1 m thick
	14. Siltstone, 16.5 m thick
	13. Covered, 12.2 m thick
	12. Siltstone, 6.1 m thick
	11. Covered, 10.7 m thick
	10. Conglomerate, rounded to subrounded clasts of quartzite and chert as large as 8 cm. Dense rock that forms top of hill. 7.6 m thick
	9. Sandy limestone with about 50 percent fine to medium, subangular to subround, quartz grains. Part of unit is covered. 7.0 m thick
	8. Covered, 9.1 m thick
	7. Interstratified sandy limestone, quartzitic fine- to coarse-grained sandstone, and minor recrystallized limestone. 16.8 m thick
	6. Covered, 8.8 m thick
	5. Lime mudstone and wackestone, sparse silicified lenses. Indistinct very thin beds. Lateral to line of section, unit includes bioclastic packstone and boundstone with corals and sponges (see Appendix). 16.2 m thick
	4. Covered, 21.3 m thick
	3. Quartzite, fine to medium grained, fairly well to well sorted. A few layers of medium- to coarse-grained quartzite. Very thin bedded; local small-scale cross-strata. 37.2 m thick
	2. Quartzitic siltstone, poorly exposed, 12.2 m thick
	1. Quartzite, fine to medium grained, fairly well sorted, 13.7 m thick
	Base of structurally coherent section

Figure 4. Column showing Upper Triassic and Lower Jurassic strata and part of overlying Mesozoic andesite unit.

amounts of wackestone and recrystallized limestone. Sparse chert is present locally, and a few beds of silty limestone are present in the upper 61 m of the unit. A few beds containing pelmatozoan debris are also present, but other fossil material is sparse. In detail, the limestone of unit 3 is laminated to thin bedded, but on a larger scale major cliff-forming units increase in thickness upward in the unit. This upward thickening of units appears to be part of a cycle of deposition that started during deposition of the nonresistant strata in unit 2 and is marked by a more or less progressive increase in the thickness of major sedimentary packages and of cliff-forming units upward in the section. Units 4 and 5 appear to be similar upward thickening cycles. Conodonts from a sample collected 196 m above the base of unit 3 indicate a Morrowan or Atokan age (Early or Middle Pennsylvanian).

Unit 3 is characterized by massive bare-rock cliffs, similar in appearance to those of units 5 and 6. Such cliff-forming rocks dominate the scenery on the east side of Sierra Santa Teresa.

UNIT 4

Unit 4 is 261-m thick (Figure 3) and is a relatively nonresistant unit on top of the cliff-forming strata of unit 3. It consists of limestone that includes lime mudstone and sparse bioclastic wackestone. A layer from 102 to 104 m above the base of unit 4 contains abundant silicified shells, pelmatozoan debris, and fusulinids (JS-92-53). The fusulinids have been identified as *Fusulinella clarki* and *F. searighti*? of Atokan (Middle Pennsylvanian) age, and conodonts from the same locality indicate the same age. Unidentified colonial corals are present in a layer from 178 to 190 m above the base of unit 4 in section 5. Desmoinesian (Middle Pennsylvanian) conodonts have been identified from a sample (JS-91-149) near the base of the upper one-quarter of unit 4 in the northern part of Sierra Santa Teresa, about 2 km northwest of section 5. This Desmoinesian age, based on conodonts, is inconsistent with an Atokan age (JS-93-8), based on fusulinids, in the overlying unit 5. The authors of the present paper do not know if this inconsistency is caused by the incompatibility of age assignments based on different fossil types, or if it indicates problems with correlation of units laterally along the outcrop. Sample JS-91-149 was not collected in the same area as JS-93-8, and the relative position of these samples as indicated here possibly could be somewhat in error. In any case, the upper part of unit 4 and all of unit 5 may be very close to the same age.

UNIT 5

Unit 5 is 164-m thick in measured section 4 (Plate 1 and Figure 3). It is a resistant cliff-forming unit and consists mostly of lime mudstone that contains sparse irregular lenses, nodules, and stringers of light-gray-weathering chert. The basal 12 m are wackestone with common large pelmatozoan fragments, but wackestone is sparse in the remainder of the unit. Fusulinids (JS-93-8) of Atokan age were collected from a thin layer of wackestone within dolomitic? lime mudstone about 79 m above the base of the unit in section 4. About 1.8 km northwest of section 4, two conodont samples yielded ages. The lower sample (JS-91-151) is about 100 m below the top of unit 5, and the conodonts are of late Atokan to early Desmoinesian age. The upper sample (JS-91-152) is about 38 m below the top of unit 5, and the conodonts are of Atokan to Desmoinesian age.

UNIT 6

Unit 6 is the most resistant unit in Sierra Santa Teresa and forms the highest part of the range as well as prominent outcrops elsewhere. It is about 112-m thick in section 3 in the northern part of the range, and about 122-m thick in section 1 in the southwestern part of the range (Plate 1 and Figure 3). It is a limestone that consists mostly of bioclastic packstone characterized by 1 to 5 mm pelmatozoan bioclasts, fusulinids, and grains of limestone in a lime mud matrix. Irregular lenses, nodules, and stringers of chert are present, but sparse. The abundant bioclastic material in the limestone and the presence of large generally well preserved, fusulinids distinguish this unit in the field from any others in the range. Unit 6 at section 1 consists mostly of this type of bioclastic packstone, but unit 6 at section 3 is composed mostly of recrystallized limestone only locally containing pelmatozoan and fusulinid material. The unit at section 3 is important, however, because it preserves transitional beds between units 6 and 7. The transitional succession starts above a thick recrystallized limestone that forms the main part of unit 6. Above this limestone is a 2-m-thick layer of pale-red siltstone similar to siltstone in unit 7. This siltstone is in turn overlain by a 3.7-m-thick layer of recrystallized limestone similar to that in unit 6. The succession is capped by a thick succession of limy siltstone typical of unit 7.

In two places in the range (in an old bulldozer cut about 0.5 km northwest of section 1, and near and along a foot trail near the summit of Sierra Santa Teresa about 2 km northeast of section 1) pale-red and reddish-brown silty limestone and limy siltstone are present in the lower part of unit 6. Where observed 0.5 km northwest of section 1, the limy siltstone is evenly laminated, whereas some low-angle cross strata as well as laminated strata were observed at the locality 2 km northeast of section 1. This silty interval is believed to be widespread in the range and to form the nonresistant slope-forming lowermost part of unit 6 between the cliff-forming unit 5 below and the cliff-forming part of unit 6 above.

Unit 6 contains an abundant fusulinid fauna of early or middle Leonardian (Early Permian) age. The fusulinids include *Parafusulina spissisepta*, *Parafusulina* sp., *Schwagerina crassitectoria*, and *Schwagerina* aff. *S. guembeli*. Latest Wolfcampian conodonts were identified from a sample (20-F16-4J) from near the top of unit 6 near section 3. No Upper Pennsylvanian strata are recognized in Sierra Santa Teresa. On this basis, the contact between the Middle Pennsylvanian unit 5 and the Lower Permian unit 6 is interpreted as an unconformity.

In addition to the fusulinids reported here in unit 6, Pérez-Ramos (1992) reports six different species of *Parafusulina* in what we here call unit 6 from the small hills about 3 km east of Willard (Figure 1). These are the most westerly outcrops shown on Plate 1. Pérez-Ramos (1992) indicates that these fusulinids are Leonardian and Guadalupian (Early and Middle Permian) in age. The Guadalupian age reported by Pérez-Ramos (1992) is based on the presence of *Parafusulina empirensis* that Pérez-Ramos indicates is Guadalupian referring to the work of Sabins and Ross (1963). However, in the abstract of the article of Sabins and Ross (1993), *P. empirensis* is assigned a Leonardian age whereas in the description of the species in the main text they allow that the age could be Guadalupian. The authors of the present report assign a Leonardian age to unit 6 because (1) all of the fusulinids reported here (Appendix) are Leonardian, (2) the age of *P. empirensis* is uncertain, and (3) conodonts (Appendix) from the upper part of unit 6 are Early Permian.

UNIT 7

Unit 7 is a thick unit of deep-water calcareous siliciclastic rocks distinctly different from the shallow-water carbonate strata of units 1 to 6. Most of the unit consists of silty limestone, sandy limestone, limy siltstone, and limy sandstone composed of a mixture of lime mud and detrital quartz grains ranging in size from coarse silt to very fine sand. These strata are laminated to thin-bedded and locally contain thin ripple-laminated and possible convoluted layers. No grading was noted, but grading would be difficult to detect in such fine-grained strata. *Nereites*-facies trace fossils are abundant in road cuts leading to the main Cementos del Yaqui quarry, about 0.5 km west of section 3. Interstratified with these calcareous siliciclastic strata are 0.5- to 2.5-m-thick layers of conglomerate and calcarenite that crop out prominently, yet constitute only a few percent of the total thickness of the unit. The calcarenite is composed of a mixture of pelmatozoan, fusulinid, limestone, and chert grains, generally ranging from 1 to 4 mm in size, and locally as much as 10 mm. These calcarenite units are generally massive and contain no internal stratification. Possible grading was noted in a few beds.

The top of unit 7 is not exposed and thus the total original thickness of the unit is unknown. An estimated exposed thickness of about 610 m was calculated from structural cross-sections (shown as section 2 on Figure 3) along the western part of the range, but the exact thickness is uncertain. Faults that would seriously disrupt the stratigraphic sequence may be hidden because of the poor exposures and the lithologic homogeneity of the unit.

The nature of the contact between units 6 and 7 is critical in understanding the structural history of the range. Previous work (Stewart *et al.*, 1990) led to speculation that Lower Permian rocks lithologically correlative to unit 7 in Sierra La Flojera, 12 km west northwest of Sierra Santa Teresa, could be either depositionally above Lower Permian shallow-water carbonate rocks or in thrust contact above these carbonate rocks. In Sierra La Flojera, critical outcrops to distinguish between these two possibilities are not present. However, in Sierra Santa Teresa the relations between these two units are exposed. Throughout the range, the structural attitudes of strata in units 6 and 7 are similar, suggesting that the contact between them is not a significant angular unconformity or the location of a major thrust. Rocks of unit 7 do not appear to be more folded than those of unit 6, as would be expected if unit 7 was structurally emplaced over unit 6, nor is folding more evident near the contact in either unit. In addition, where observed in detail, the contact appears to be depositional, and at one locality it is transitional. The best exposure of the contact is in man-made cuts along the main road to the quarry of the Cementos del Yaqui. Here, the rocks dip steeply, but the general attitudes of rocks above and below the contact are similar. In this exposure, unit 7 is somewhat more contorted than unit 6, but that does not seem surprising because the fine-grained strata of unit 7 would be expected to be less structurally competent than the limestone of unit 6. The authors' interpretation is that some structural movement has occurred along or near the contact, but that the movement has been minor. Finally, the transition of rock types between units 6 and 7 at section 3, described previously, seems to confirm that these units are in normal sedimentary contact.

Fusulinids in the calcarenite beds of unit 7 are somewhat abraded suggesting that they were transported to the sites of deposition after their death and thus indicate only the approximate age of sediment deposition. Such detrital fusulinids include *Parafusulina* sp. aff. *P. boesei* from a sample (JS-91-132) in calcarenite 0.75 km west-northwest of section 1 in the southwestern part of the range. This fusulinid is early Guadalupian in age. In Sierra La Flojera, 12 km north-northwest of Sierra Santa Teresa (Stewart *et al.*, 1990), strata lithologically similar to and correlated with unit 7 contain detrital fusulinids that are broken, but free of matrix (Stewart *et al.*, 1990). These fusulinids are Wolfcampian in age and indicate that locally, at least, strata correlative to unit 7 contain detrital fusulinids older than unit 6 (Leonardian) that underlies unit 7 in Sierra Santa Teresa.

STRATIGRAPHY OF LOWER PLATE ROCKS

Two major units are recognized in the lower plate, a sedimentary unit of Late Triassic and Early Jurassic age and an andesitic unit of Mesozoic age. These rocks are exposed in a generally east-dipping overturned section a short distance south of the main part of Sierra Santa Teresa (Figure 2).

UPPER TRIASSIC AND LOWER JURASSIC UNIT

The Upper Triassic and Lower Jurassic strata in Sierra Santa Teresa are lithologically variable and at least 544-m thick (section 7, Plate 1 and Figure 4). The unit consists of argillite, siltstone, quartzitic siltstone, limy siltstone, sandstone, limy sandstone, quartzite, conglomerate, conglomeratic sandstone, and a variety of limestone types that include lime mudstone, sandy calcarenite, sandy limestone, calcarenite, lime mudstone, wackestone, bioclastic packstone, boundstone, and recrystallized limestone. At section 7 (Plate 1), the succession is steeply dipping and generally overturned to the west. Subunits 1 to 23 of scction 7 were measured in detail; but units 24 to 29 are poorly exposed, their thicknesses are estimated, and the stratigraphic succession as described may be significantly in error due to hidden structures. Sandy limestone in the Upper Triassic and Lower Jurassic strata consists of fine to coarse angular quartz sand in a limestone matrix. Other rocks are clearly calcarenites that contain scattered quartz grains or layers of concentrated quartz grains. These sandy rocks contain scour surfaces and low-angle cross strata. Thick cliff-forming quartzite, quartzitic conglomerate, and conglomerate are characteristic of the succession. These rocks consist of poorly sorted fine to very coarse quartz arenite and of conglomerate with rounded to subangular quartzite clasts and subangular to subrounded chert clasts. Some of the chert clasts contain fragments of shelly fossil material suggesting that they were originally chert replacement layers in limestone. Quartzite clasts as large as 8 cm were noted. Argillite and siltstone are present as nonresistant layers and as resistant siliceous or quartzitic layers. The middle part of the succession (Section 7, subunits 18 through 25, and perhaps as low in the section as covered unit 16) contains abundant, nonresistant argillite and siltstone and generally forms a valley. The quartzite and conglomerate layers, as well as some limestone layers, are resistant and form ledges.

Subunit 5 of section 7 (Figure 4) is characterized by coral and sponge biostromal and bioclastic limestone beds 2 to 5-m thick interbedded with fissile argillite or siltstone. The limestone forms at least two beds and is partly recrystallized. The limestone is light to dark gray and characterized by light-yellowish-gray mottled patches. This mottling is interpreted to represent dissolution of the limestone and infilling with fine insoluble clay and silt residues derived from the dissolution (most likely in the vadose environment). The individual limestone beds appear to pinch and swell and vary in thickness laterally.

The limestone of subunit 5 contains abundant sponges, lesser amounts of corals, and minor amounts of other fossil material (Appendix). Large chambered thalamid sponges are easily recognized on outcrop. They include encrusting *Cinnabaria expansa* (as large as 20 cm long), *Fania* sp., and the upright sponge *Nevadathalamia cylindrica*. A possible ichthyosaur bone fragment was also observed with the sponges, and unidentifiable mollusks (gastropods and bivalves) are also present. Corals include branching colonial taxa such as *Retiophyllia* sp., which are too strongly recrystallized for species identification, the cerioid colonial coral *Chondrocoenia waltheri* (previously illustrated from this locality by Stanley *et al.* [1994, p. 14–15, figs. 11.1 to 11.3]), and a colonial encrusting coral *Astraeomorpha sonorensis*. The corals and sponges in subunit 5 are typical of the Upper Triassic (Norian), and they appear endemic to certain sites in west-central Nevada in the Luning Assemblage (Stanley, 1979; Senowbari-Daryan and Stanley, 1992) as well as Sonora (Stanley and González-León, 1995). In Sonora, they have been reported from the Antimonio Formation stratotype at Sierra del Álamo near Caborca (Stanley *et al.*, 1994).

While not representing a reef environment, these fossils do signify warm, shallow water and biogenic (biostromal) activity in a basin which was receiving an influx of fine-grained terrigenous sediment. The large thalamid sponges were capable of living in the resulting turbid-water environment. The composition and lithologic nature of this fossiliferous interval at Sierra Santa Teresa and the obvious similarities with the stratotype of the Antimonio Formation at Sierra del Álamo, where the biostromes are present near the top of the lower member, suggest that these two Sonoran sections may correlate.

Other fossil material in the Upper Triassic and Jurassic unit consists of ammonoids in subunit 24 that are poorly preserved, but are considered to be Early Jurassic in age (David Taylor, 1997, oral communication; Appendix). These ammonoids are in an upper, siltstone-rich, part of the Lower Jurassic and Upper Triassic succession, suggesting a correlation with lithologically similar and age-equivalent strata in the lower part of the upper member of the Antimonio Formation in Sierra del Álamo (Stanley and González-León, 1995). Poorly preserved and unidentifiable plant material also is present in subunit 24, and unidentified gastropods are present in subunit 23.

MESOZOIC ANDESITE UNIT

A thick unit of andesite overlies the Upper Triassic and Lower Jurassic strata. The contact was not observed in detail and could be a fault, at least locally. The andesite consists of abundant 1-2 mm plagioclase laths in an aphanitic matrix. The andesite locally contains epidote, areas of silicification, and a greenish (propylitic?) alteration. Most of the andesite is massive; locally it is a breccia composed of angular clasts of andesite 1 to 10 cm in size set in an andesitic matrix.

The andesite is undated, but its stratigraphic position above the Upper Triassic and Lower Jurassic strata and its altered character (silicification, epidotization, propylitization) indicate a resemblance to Mesozoic volcanic rocks elsewhere in Sonora. The andesite lithologically resembles the Tarahumara Formation that overlies the Upper Triassic and Lower Jurassic Barranca Group in Sierra San Javier (Stewart and Roldán-Quintana, 1991, and references therein), 110 km east-southeast of Sierra Santa Teresa. Similar andesitic rocks crop out in other parts of east-central Sonora and are considered to be Late Cretaceous in age on the basis of U-Pb studies

(McDowell *et al.*, 1994; F.W. McDowell, oral communication, 1996). In addition, a Late Cretaceous age for the Tarahumara Formation is indicated by plant material (Ricalde-Moreno and Cevallos-Ferriz, 1993). Thus, if the correlation with the Tarahumara Formation is correct, the andesitic unit in Sierra Santa Teresa is Upper Cretaceous.

No structural attitudes were measured in the Mesozoic andesitic rocks. If these rocks are steeply dipping, similar to the Upper Triassic rocks, they may be at least 600-m thick.

REGIONAL RELATIONS OF CHESTERIAN (UPPER MISSISSIPPIAN) STRATA IN SONORA

The oldest strata exposed at Sierra Santa Teresa are middle to late Chesterian (Mississippian) limestones that are at least 298-m thick (samples JS-92-36 to JS-92-39, Figure 3), and could be thicker if part of the undated section between samples JS-92-39 and JS-92-41 is also Chesterian in age (Figure 3). Elsewhere in Sonora, strata of Chesterian age are either absent, thin, or poorly known. At Sierra Agua Verde (Figure 5, locality 5) in east-central Sonora, where detailed stratigraphic and paleontologic studies have been made (Stewart *et al.*, in press), about 44 m of Chesterian limestone are recognized on the basis of foraminifera. Conodonts from the same section indicate only a late Meramecian or Chesterian age for these same strata. Perhaps some Chesterian strata at Sierra Agua Verde are missing due to pre-Pennsylvanian erosion. Chesterian shallow-water carbonate rocks are also recognized in the Cobachi area (Figure 5, localitiy 3), but the thickness of these rocks is unknown. About 20 m of Chesterian limestone are recognized at Cañón de Santa Rosa (Holcomb, 1979; Devery, 1979) (Figure 5, locality 18). The authors of the present paper are not aware of any other areas in Sonora where strata of definite Chesterian age are recognized, although such strata could certainly be present in other sections that have not been discovered or studied in detail. In any case, the thick section of Chesterian strata at Sierra Santa Teresa seems important and may indicate that these strata were deposited in a local basin, perhaps on the outer-shelf.

REGIONAL RELATIONS OF PENNSYLVANIAN AND PERMIAN ROCKS IN SONORA

Pennsylvanian and Permian rocks crop out in an east-west belt in east-central Sonora, in widely spaced localities in northeastern Sonora, and in isolated localities at El Antimonio and El Capitán in northwestern Sonora (Figure 5). This distribution pattern is much more restricted than the distribution pattern of Neoproterozoic and Paleozoic rocks as a whole in Sonora. In part, this limited distribution may be due to inadequate geologic exploration in the region, and perhaps discoveries of significant new localities of these rocks will be found elsewhere in Sonora. However, the authors of the present paper think that discoveries of new localities, although they likely will be made, will not significantly change the overall distribution pattern of these rocks. This conclusion is based on (1) the authors' general understanding of the extent of geologic exploration in the region; (2) the absence of these rocks by erosion prior to deposition of Mesozoic rocks in large regions of northern Sonora; and (3) the extent of Cenozoic and Quaternary cover rocks. The authors think that Pennsylvanian and Permian rocks originally covered much, if not all, of Sonora and that the present outcrops are small remnants or exposures of this originally widespread deposit.

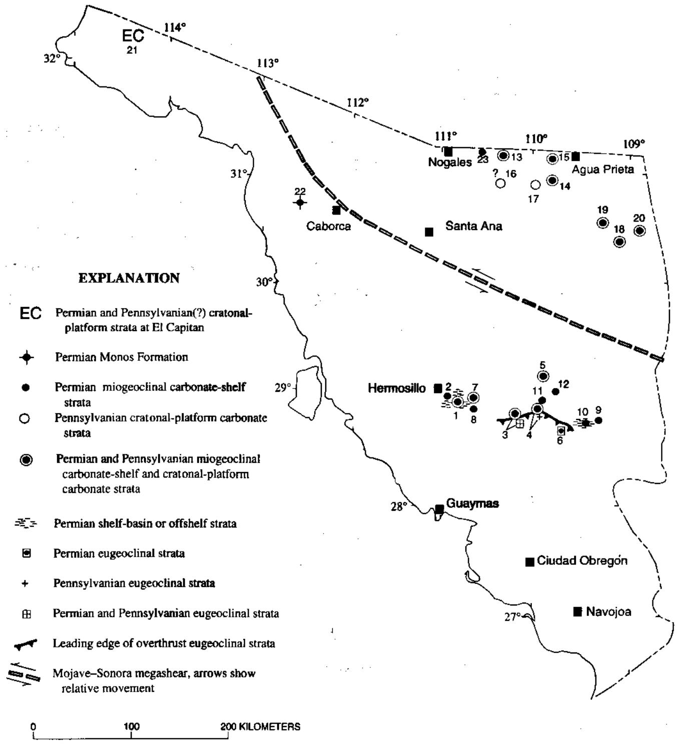


Figure 5. Distribution of Pennsylvanian and Permian rocks in Sonora. Based on information from Menicucci and collaborators (1982), Françoise Peiffer-Rangin (unpublished report), Pérez-Ramos (1992) and more specific information listed below. *1*, Sierra Santa Teresa: Pérez-Ramos (1992); this report; *2*, Sierra La Flojera: Stewart and collaborators (1990); *3*, Cerro Cobachi area: Noll (1981); Ketner and Noll (1987); *4*, Barita de Sonora area: Menicucci and collaborators (1982); F.G. Poole and R.J. Madrid *in* Stewart and collaborators (1990); *5*, Sierra Agua Verde area: Menicucci and collaborators (1982); Ochoa-Granillo and Sosa-León (1993); Stewart and collaborators (1997); *6*, Sierra El Aliso: Bartolini and collaborators (1989, 1991); *7*, Rancho Las Norias: Vega and Araux (1987); *8*, Cerro San Francisco (Cerro Valuarte of Menicucci *et al.*, 1982): King (1939); Menicucci and collaborators (1982), J.H. Stewart and R.C. Douglass (unpublished data); *9*, Sierra Santo Domingo: Pérez-Ramos (1992); *10*, Sierra El Encinal and La Zacatera area: Schmidt (1978), Hewett (1978); *11*, Sierra Martínez: Menicucci and collaborators (1982); *12*, Cerro Tinaja: Menicucci and collaborators (1982); *13*, Sierra El Tule: González-León (1986); *14*, Cerros Las Mestañas: Peiffer-Rangin (unpublished report); *15*, Sierra La Morita: Françoise Peiffer-Rangin (unpublished report); *16*, Cananea: Mulchay and Velasco (1954); *17*, Sierra Los Ajos: López-Ramos (1982); *18*, Cañón de Santa Rosa: Imlay (1939), Dunbar (1939), Devery (1979), Holcomb (1979); *19*, Cañón de Noche Triste (Pilares de Teras, Sierra de Teras): Imlay (1939), Dunbar (1939), Tovar (1959); *20*, Sierra Huchita Hueca area: Imlay (1939), Dunbar (1939); *21*, El Capitán: Leveille (1984); *22*, El Antimonio: Cooper (1953); *23*, La Cueva: Blodgett and collaborators (1998).

Pennsylvanian strata in Sierra Santa Teresa (upper part of unit 1 and units 2-5) are about 950-m thick. Other outcrops of Pennsylvanian rocks in central Sonora are in Rancho Las Norias, Cobachi, Barita de Sonora, and Sierra Agua Verde (see Figure 5 for location and references). Of these localities, only in Sierra Agua Verde are exposed Pennsylvanian strata thick and moderately well studied (Stewart *et al.*, in press). There, in an incomplete exposure, Pennsylvanian strata are at least 688-m thick and consist primarily of shallow-water limestone, mostly packstone and wackestone with minor amounts of grainstone, lime mudstone, and argillaceous lime mudstone. Packstone and wackestone containing quartz silt and fine sand are common, and sparse layers of fine- to medium-grained quartz sandstone also are present. The Pennsylvanian strata at Sierra Santa Teresa contrast with those at Sierra Agua Verde in not containing silty or sandy limestone or quartz sandstone. Pennsylvanian rocks in northeastern Sonora (see Figure 5 for locations and references) are composed largely of limestone that has been correlated with the Horquilla Formation of southeastern Arizona (González-León, 1986). The Pennsylvanian strata at Cañón de Santa Rosa, Cañón de Noche Triste, and Sierra Huchita Hueca are included by several geologists (including Holcomb [1979], and Devery [1979]) as part of the El Tigre Formation that has been correlated by Tovar (1969) with the Horquilla Formation of southeastern Arizona.

The Pennsylvanian rocks described in the preceding paragraph consist of relatively shallow-water carbonate strata. A different facies of Pennsylvanian strata, consisting of allochthonous relatively deep-water eugeoclinal strata in fault contact with Paleozoic shallow-water carbonate rocks, is present in the Cerro Cobachi area (Ketner and Noll, 1987) and the Barita de Sonora area (F.G. Poole and R.J. Madrid, *in* Stewart *et al.*, 1990). These Pennsylvanian deep-water deposits consist of interbedded chert, mudstone, siltstone, turbiditic sandstone, conglomerate, barite, limestone, and some dolomite that were emplaced as an allochthonous sheet (the Sonora allochthon), along with other Paleozoic deep-water strata (Poole *et al.*, 1995a), onto the Paleozoic carbonate shelf during the Late Permian to Middle Triassic Sonora orogeny (Poole and Madrid, 1988; Stewart *et al.*, 1990; Poole *et al.*, 1995a).

Strata of Permian age are more widely exposed in Sonora than those of Pennsylvanian age (Figure 5). In most areas, they consist of shallow-water carbonate rocks (Menicucci *et al.*, 1982; González-León, 1986; Pérez-Ramos, 1992). Permian strata in northeastern Sonora have been correlated with formations in southeastern Arizona (Tovar, 1969; González-León, 1986).

In Sierra Santa Teresa, Lower Permian shallow-water carbonate rocks (unit 6) are conformably overlain by Lower or Middle Permian deeper-water calcareous siliciclastic rocks (unit 7). The shallow-water carbonate rocks at Sierra Santa Teresa appear to be part of the widespread Permian carbonate deposits that characterize much of Sonora, but the calcareous siliciclastic rocks represent a distinctly different type of deposit. Correlative Lower and Middle Permian deep-water siliciclastic deposits have been recognized in the closeby Sierra La Flojera (Stewart *et al.*, 1990) and similar deep-water siliciclastic rocks have been mapped by Schmidt (1978) and Hewett (1978) in the Sierra El Encinal and La Zacatera area (Figure 5, locality 10). In these areas, as in the Sierra Santa Teresa, the siliciclastic rocks contain turbiditic siltstone, sandstone, and locally conglomerate, and in the Sierra La Flojera area, they contain coarse debris-flow conglomerate with clasts of limestone, siltstone, and chert as large as 25 cm (Stewart *et al.*, 1990). *Nereites* association trace fossils, which are generally considered to have formed in deeper water, are present in Sierra La Flojera, Sierra Santa Teresa, and in the Sierra El Encinal and La Zacatera area (Stewart *et al.*, 1990). In the Sierra El Encinal and La Zacatera area, the siliciclastic rocks were named the Mina México Formation by Schmidt (1978) and Hewett (1978), and considered by them to lie depositionally on dated, fusulinid-bearing Lower Permian carbonate strata. Schmidt (1978) and Hewett (1978) did not paleontologically date the Mina México Formation, but conodonts from silty limestone from the Mina México collected after their studies are Early Permian in age (Stewart *et al.*, 1990). Radelli and collaborators (1987) considered the Mina México Formation to be allochthonous and part of widespread allochthonous bodies (in part the same as the Sonora allochthon of Poole *et al.*, 1995a) in central Sonora, but they did not present any field evidence that the Mina México Formation is allochthonous with respect to the underlying shallow-water Lower Permian carbonate rocks. The authors here follow the interpretation of Schmidt (1978) and Hewett (1978) that the Mina México Formation is depositionally above Lower Permian strata, and consider it a deeper-water deposit similar to unit 7 at Sierra Santa Teresa.

Relatively deep-water Lower Permian strata are recognized in the Cerro Cobachi area (Ketner and Noll, 1987) and in Cerro El Aliso area (Bartolini *et al.*, 1989 and 1991). In these areas, paleontologically dated rocks are detrital limestone within argillite and chert successions. The authors of the present paper here consider these relatively deep-water Permian rocks to be eugeoclinal and part of the Sonora allochthon of Poole and collaborators (1995b). This interpretation is based on the association of these rocks with known middle and upper Paleozoic eugeoclinal rocks and on their general complex structural style that is similar to that of known allochthonous eugeoclinal rocks. Alternately, these Permian rocks could be related paleogeographically to basinal strata such as unit 7 at Sierra Santa Teresa and the Mina México Formation. In this interpretation, the Lower and Middle Permian detrital rocks, including unit 7, the Mina México Formation, and the possible eugeoclinal allochthonous rocks are all successions deposited in a complex structural environment, presumably, as described below, during a time when the Paleozoic margin of Sonora changed from a stable margin to a tectonically active one.

Permian rocks are also recognized in the El Antimonio area (Figure 5, locality 22) of northern Sonora (Cooper, 1953;

Dunbar, 1953; Brunner, 1979), far from other outcrops of Permian rocks in Sonora. At El Antimonio, the Permian succession, assigned to the Monos Formation, is estimated by Cooper (1953) to be about 550 to 760-m thick. It consists of two units. The lower unit is composed of siltstone, limy siltstone, very fine-grained sandstone, and 0.5- to 3-m-thick fossiliferous detrital limestone beds. The siltstone and very fine grained sandstone are locally graded and contain Bouma A, B, and C subdivisions. The detrital limestone beds contain abraded fossils and appear to be gravity-flow deposits. These possible gravity-flow deposits and the graded siltstone and sandstone suggest that they are relatively deep-water deposits. The upper unit of the Monos Formation consists of resistant fossiliferous limestone (Cooper, 1953; Brunner, 1979). One layer in the upper unit contains giant fusulinids of Guadalupian (Middle Permian) age (Dunbar, 1953). What the authors of the present paper call the upper unit of Monos Formation was considered by Brunner (1979) to be a shallow-water deposit. The exact structural relations between the lower and upper parts of the Monos Formation are poorly known, but careful mapping of faunal zones by Cooper (1953, fig. 2) clearly confirms that the lower unit is older than the upper unit. This relation suggests a shallowing upward succession of strata in the Monos Formation (deep-water deposits in the lower unit to shallow-water deposits in the upper unit), the opposite of the shallow- to deep-water upward succession in Sierra Santa Teresa.

A unique, in Sonora, succession of presumed Permian, and perhaps Pennsylvanian, strata is recognized at El Capitán (Figure 5, locality 21) in far northwestern Sonora near the international boundary (Leveille, 1984). These rocks are highly deformed and metamorphosed, but lithologic correlations with nonmetamorphic rocks to the north in the United States clearly indicate that the succession includes the Pennsylvanian and Permian Supai Group, the Permian Coconino Sandstone, and the Permian Kaibab Limestone as well as Mesozoic units. These formations are found throughout a large region of easternmost California and southern and central Arizona. They are clearly a continuation of cratonal platform rocks that characterize the interior part of North American and are distinctly different than Pennsylvanian or Permian rocks elsewhere in Sonora.

REGIONAL RELATIONS OF UPPER TRIASSIC AND LOWER JURASSIC ROCKS IN SONORA

In Sonora, Upper Triassic and Lower Jurassic rocks crop out in a northwest-trending zone from near the southern border to near the northern border of the state (Figure 6). In southern Sonora, these strata consist of the Barranca Group that has been dated as Late Triassic on the basis of plants and an ammonoid in the Santa Clara and Sierra de San Javier area (Alencáster, 1961; Stewart and Roldán-Quintana, 1991, and references therein); as Late Triassic on the basis of plants in the Los Pilares (King, 1939, p. 1656), Onavas (King, 1939, p. 1656), and San Marcial areas (Alencáster, 1961); as Triassic or Early Jurassic on the basis of plants and bivalves in the Moradillas area (King, 1939, p. 1656-1557); and as Late Triassic on the basis of an ammonoid in the San Bernardo area (Martínez-Jiménez, 1984, p. 139). The distribution of the Barranca Group is not well known, and some rocks originally mapped as Upper Triassic in central Sonora have proven to be quartzites of Ordovician age (Stewart *et al.*, 1990; Bartolini *et al.*, 1991). On Figure 6 are shown outcrops of Upper Triassic Barranca Group where they have been dated paleontologically and where conspicuous graphite or coal layers are present in strata that lithologically resemble the Barranca Group. These graphite or coal layers are characteristic of the Barranca Group where it has been dated and are considered to be a good indication of its presence. The Barranca Group consists largely of nonmarine sandstone, conglomerate, and siltstone; marine ammonoid layers are known in Sierra de San Javier and in the San Bernardo area. The best exposures of the Barranca Group are the Santa Clara and Sierra de San Javier area where it is divided into three formations (Arrayanes, Santa Clara, and Coyotes) and is about 3,000-m thick (Stewart and Roldán-Quintana, 1991). An east-west belt of outcrops of the Barranca Group in central Sonora has been interpreted as a rift-basin deposit, but this interpretation has been challenged by Lucas and Marzolf (1994) and Lucas (1996). Lucas (1996, *op. cit.*) interprets the upper formation in the Barranca Group (Coyotes Formation) to have been deposited in an extensional basin, and thus similar to the rift-basin origin of Stewart and Roldán-Quintana (1991), but considers that the lower two formations of the Group (Arrayanes and Santa Clara) represent a distinctly different tectonostratigraphic sequence. Lucas and Marzolf (1994) and Lucas (1996) consider the unfossiliferous Arrayanes as possibly Early Triassic in age, the fossiliferous Santa Clara Formation as Late Triassic, and the unfossiliferous Coyotes Formation as Early Jurassic in age. The Early Jurassic age of the Coyotes Formation is based on the possible correlation of the Coyotes Formation with dated Upper Jurassic clastic rocks in northwestern Sonora (Lucas, 1996).

Upper Triassic and Lower Jurassic strata in west-central and northwestern Sonora northwest of outcrops of the Barranca Group (Figure 6) are assigned to the Antimonio terrane by Stanley and González-León (1995). This terrane, as defined by Stanley and González-León (*op. cit.*), includes the outcrops of Upper Triassic and Lower Jurassic rocks at Sierra Santa Teresa. The terrane is composed predominantly of marine strata and is considered to be allochthonous relative to Paleozoic miogeoclinal strata. The most complete outcrop of these strata is at Sierra del Álamo west of Caborca (Figure 6, locality 2) where over 3.4 km of mainly Upper Triassic and Lower Jurassic strata are assigned to the Antimonio Formation (González-León, 1980; Callaway and Massare, 1989; Stanley and González-León, 1995; Lucas and González-León, 1994; González-León *et al.*, 1996). The Antimonio Formation is divided into two members. The Upper Triassic lower member

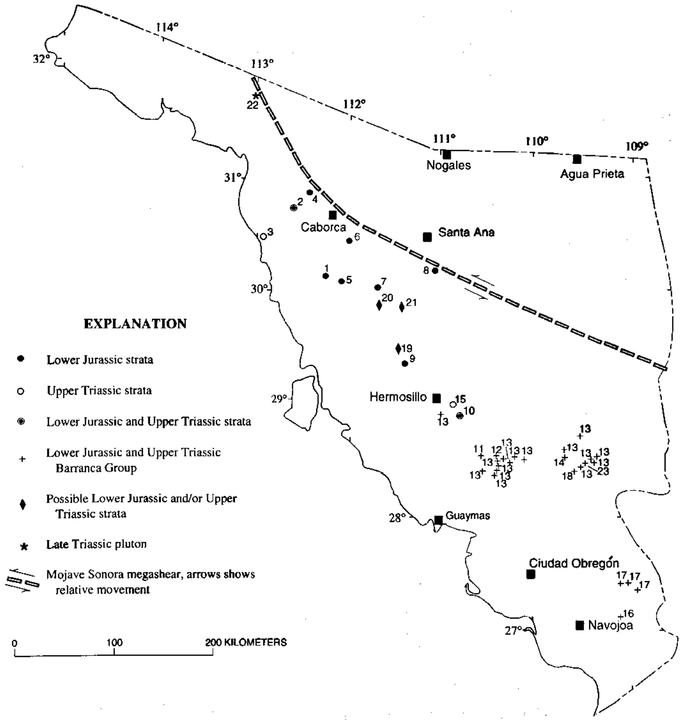


Figure 6. Distribution of Upper Triassic and Lower Jurassic rocks in Sonora. Based on information from Stanley and González-León (1995) and other information as listed below: *1*, Pozos de Serna (Calmus *et al.*, 1997); *2*, Sierra del Álamo (El Antimonio): González-León (1980), Stanley and González-León (1995) and references therein; *3*, Barra Los Tanques: Stewart and collaborators (1990), Stanley and González-León (1995); *4*, Cerro Basura: Corona (1979), with fossil identification in Stanley and González-León (1995, p. 9); *5*, Sierra La Jojoba: Radelli (1990); *6*, Cerro Chinos: Longoria and Pérez (1979); *7*, Sierra Santa Rosa: Hardy (1981); *8*, Sierra Caracahui: Flores (1929). Stanley and González-León (1995) indicate that an Early Jurassic ammonoid fauna is present at this locality citing Flores (1929). However, Flores (1929) does not indicate ammonoids at this locality, but does indicate the similarity of other types of fauna (including *Weyla*) present in Sierra Caracahui with the Early Jurassic fauna at Sierra Santa Rosa. *9*, Sierra López: Ávila-Angulo (1987, 1990); *10*, Sierra Santa Teresa: this report; *11*, Sierra de Moradillas: King (1939), Abadie (1981), Vassallo (1985); *12*, San Marcial: Alencáster (1961); *13*, Coal or graphite deposits interpreted to be in the Barranca Group of Upper Triassic age: King (1939), Consejo de Recursos Minerales (1994), Pérez-Segura (1985); *14*, Santa Clara and Sierra de San Javier: Alencáster (1961), Stewart and Roldán-Quintana (1991), Cojan and Potter (1991); *15*, Sierra La Flojera: Roldán and González-León (1985); Stewart and collaborators (1990), Lucas and González-León (1994); *16*, Álamos mining district (Piedras Verdes area): Vázquez-Pérez (1975). Age assignment of rocks based on lithologic correlation. *17*, San Bernardo area, graphite mines interpreted to be in Triassic rocks: Consejo de Recursos Minerales (1994), Pérez-Segura (1985). Ammonoid (*Acanthinites* Mojsisovics, 1893) of Norian (Late Triassic) age reported by Martínez-Jiménez (1984, p. 139); *18*, Onavas: King (1939, p. 1656); *19*, Sierra El Carnero: J.H. Stewart and R. Amaya-Martínez (unpublished studies); *20*, Rancho Curiel: J.H. Stewart and R. Amaya-Martínez (unpublished studies); *21*, Rancho Bellavista: J.H. Stewart and R. Amaya-Martínez (unpublished studies); *22*, Late Triassic pluton, 15 km southwest of Sonoyta: Stewart and collaborators (1986); Tosdal and collaborators (1990); *23*, Los Pilares: King (1939, p. 1,656).

consists of shallow- to deep-water fine-grained sandstone, siltstone, mudstone, and lenticular beds of chert-pebble conglomerate. The lowermost part of what has been mapped as the Antimonio Formation contains Permian (Guadalupian) brachiopods (Lucas *et al.*, 1997), although perhaps these Permian strata would be better assigned to the Monos Formation. Above these beds containing Permian brachiopods are strata in which Early Triassic ammonoids have recently been discovered (Lucas *et al.*, 1997). Higher in the lower member are beds containing Karnian and Norian ammonoids and bivalves, and in the upper part of the lower member are distinctive Norian biostromal carbonate beds dominated by corals, chambered sponges, and oysterlike bivalves (Stanley and González-León, 1995). The Lower Jurassic upper member of the Antimonio Formation is composed predominantly of coarse-grained siliciclastic rocks. Ammonoids and bivalves near the base of the upper member are Hettangian or early Sinemurian in age.

Norian coral-bearing carbonate beds, correlative with those in the Antimonio Formation, are present at Barra los Tanques, about 40-km southwest of Sierra del Álamo, and at Sierra Santa Teresa. The Norian beds at Sierra Santa Teresa contain corals and sponges that are identical to those at Sierra del Álamo (Stanley *et al.*, 1994; Stanley and González-León, 1995), and this relation suggested to Stanley and González-León (1995) that the overlying siliciclastic rocks in Sierra Santa Teresa may be correlative to the lower part of the upper member of the Antimonio Formation at Sierra del Álamo. Stanley and González-León (1995) used these similarities, along with other information, to suggest that the Upper Triassic and Lower Jurassic strata at Sierra Santa Teresa are part of a single allochthonous terrane (the Antimonio terrane) that includes the Antimonio Formation and other isolated outcrops in west-central and northwestern Sonora. They consider these strata to be stratigraphically and structurally distinct from the Upper Triassic strata of the Barranca Group.

An alternate interpretation is that the strata assigned to the Antimonio terrane by Stanley and González-León (1995) are essentially autochthonous relative to underlying rocks and were originally deposited directly on Paleozoic miogeoclinal or eugeoclinal rocks. In this view, the rocks of the so-called Antimonio terrane represent a widespread overlap assemblage covering rocks deformed during the Late Permian to Middle Triassic Sonora orogeny. In accordance with this concept, the Upper Triassic and Lower Jurassic strata in Sierra Santa Teresa represent an intermediate facies between the largely nonmarine Barranca Group to the east and southeast and the largely marine Antimonio Formation to the northwest. The Upper Triassic and Lower Jurassic strata in Sierra Santa Teresa do, in fact, contain coarse conglomerate, sandstone, and plant-bearing siltstone and shale that resemble strata in the Barranca Group while, on the other hand, they contain the coral- and sponge-bearing beds, mentioned above, that are faunally identical to those in the Antimonio Formation. The presence of strata similar to both the Barranca Group and the Antimonio Formation is consistent with the idea that Sierra Santa Teresa section is an intermediate facies between the Barranca Group and Antimonio Formation.

Additional support for the idea that rocks of the Antimonio terrane are autochthonous relative to underlying rocks is the possible depositional contact of these rocks with miogeoclinal strata observed in some parts of Sonora. Such possible depositional contacts are noted in the following areas (Figure 6): (1) At Pozos de Serna, Lower Jurassic strata containing Early Jurassic ammonoids, bivales, and gastropods are reported (Calmus *et al.*, 1997) to unconformably overlie Precambrian and Cambrian strata. (2) In Cerro Rajón (Stewart *et al.*, 1984), rocks apparently continuous with those reported to contain Early Jurassic ammonoids by Longoria and Pérez (1979) appear to lie depositionally on Lower Cambrian miogeoclinal strata (Stewart *et al.*, 1984). The basal beds of these presumed Lower Jurassic strata consist of a boulder conglomerate with clasts as large as 1 m of quartzite apparently derived from underlying Neoproterozoic and Lower Cambrian units. Radelli (1990), on the other hand, considers this contact to be a thrust. (3) At Sierra El Carnero, strata containing poorly preserved Jurassic? ammonoids (David Taylor, written communication, 1997) appear to rest depositionally on underlying Devonian carbonate rocks (dated on the basis of conodonts, Charles Sandberg, oral communication, 1995). The lowest beds of the Jurassic?, and possibly Upper Triassic, strata are a cobble conglomerate at Sierra El Carnero. (4) At Sierra López, 60 km southeast of Sierra El Carnero, the contact of Lower Jurassic rocks (Ávila-Angulo, 1987, 1990) and underlying Devonian strata (identified by conodonts, John Repetski, written communication, 1987) has not been observed in detail because of dense brush, but the general attitude of the Lower Jurassic rocks and underlying Devonian strata is similar. The lowest rocks of the Lower Jurassic succession are chert-pebble conglomerate with clasts as large as 8 cm. (5) At Rancho Curiel, undated, but presumably Mesozoic, cobble conglomerate appears to rest depositionally on Neoproterozoic miogeoclinal strata. (6) At Rancho Bellavista, undated, but presumably Mesozoic, granule and pebble conglomerate containing silicified tree logs, appears to rest depositionally on Neoproterozoic miogeoclinal strata. Nevertheless, present evidence does not clearly prove that Upper Triassic and Lower Jurassic strata are in depositional contact with underlying miogeoclinal strata, and more detailed work is necessary to clarify these relations.

A special note is necessary about relations at Sierra del Álamo. Here the Antimonio Formation is in depositional contact on the underlying Permian Monos Formation. Stanley and González-León (1995) include the Monos Formation in their Antimonio terrane, and thus consider both the Monos Formation and the unconformably overlying Antimonio Formation as allochthonous. One alternative to this interpretation is that only the Monos Formation is allochthonous and that the Antimonio Formation is essentially an autochthonous overlap sequence. An allochthonous origin for the Monos Formation has been proposed (Stewart *et al.*, 1990) because it contains giant fusulinids (Dunbar, 1953) that characterize accreted terranes in western North America that were originally outboard of the Paleozoic continental margin (Ross and Ross, 1983; Stevens, 1995), and this interpretation is still possible if the Antimonio Formation is considered an overlap assemblage. Still another possible interpretation is that the Monos Formation is actually part of the North American Cordilleran miogeoclinal succession in Sonora, and is not part of an accreted terrane. If the Monos Formation is part of the North American Cordilleran miogeocline, then the giant fusulinids they contain would apparently also be related to North America, and not to an exotic terrane. In this regard, giant fusulinids also are present in west Texas, where they are clearly part of Paleozoic North America, and Stevens (1995) notes that one of the giant fusulinids in west Texas is similar to that in the Monos Formation and to others in the accreted terranes of western North America. Concerning giant fusulinids, an error is acknowledged here in the report of Stanley and González-León (1995). They state (p. 9) that giant fusulinids are present in Nevada, but in reality none are known to occur there.

The only other Upper Triassic rocks known in Sonora are granitoids about 15 km southwest of Sonoyta in northernmost Sonora that have a U-Pb uranium age of 225 Ma (Stewart *et al.*, 1986; Tosdal *et al.*, 1990).

TECTONICS

The rocks of Sierra Santa Teresa provide important new information on the tectonic setting of Sonora, interpretations which vary and are controversial. The authors of the present paper discuss here the major aspects of the tectonic setting of middle Paleozoic to Mesozoic rocks in Sierra Santa Teresa and in Sonora as a whole.

CORDILLERAN MIOGEOCLINE

The thick succession of shallow-water carbonate rocks of Mississippian, Pennsylvanian, and Early Permian age (units 1-6) in Sierra Santa Teresa are considered a continuation, or a structurally offset segment, of thick shallow-water carbonate rocks that characterize the continental-margin shelf deposits of the Neoproterozoic and Paleozoic Cordilleran miogeocline in the western United States. This interpretation is based on the general similarity of Neoproterozoic and Paleozoic successions in Sonora and those in the western United States (Poole and Hayes, 1971; Eells, 1972; Stewart *et al.*, 1990; Poole *et al.*, 1995b; Stewart *et al.*, in press). In detail, however, some characterisitcs of the succession at Sierra Santa Teresa (thick Chesterian carbonate rocks, absence of Pennsylvanian quartz sandstone), as noted previously, are different from comparable-age strata of the Cordilleran miogeocline in Sonora.

LOWER AND UPPER PERMIAN BASIN DEPOSITS

The Lower and Middle Permian deep-water siliciclastic strata (unit 7) in Sierra Santa Teresa represent a distinct change from underlying shallow-water carbonate strata. These siliciclastic strata are considered to lie depositionally on the underlying rocks (see discussion under unit 7), and this interpretation is critical in understanding the tectonic setting of these rocks. Assuming this interpretation is correct, the siliciclastic rocks were deposited in a basin that formed abruptly after the deposition of shallow-water Lower Permian rocks (unit 6). This abrupt change in depositional setting is here interpreted to reflect a change in the tectonic setting of Sonora. During the Neoproterozoic to Early Permian, what is present-day Sonora was along a stable continental margin and the site of thick continental-shelf deposits (Cordilleran miogeocline). The deep-water siliciclastic strata that were deposited in Early or Middle Permian time mark the onset of a tectonically active continental margin. This active margin may be the result of the initiation, or close approach, of a subduction zone that led to the Late Permian to Middle Triassic emplacement of a major allochthon of deep-water eugeoclinal rocks during the Sonora orogeny (Poole and Madrid, 1988; Stewart *et al.*, 1990; Poole *et al.*, 1995a). If the subduction zone dipped south, the weight of the approaching allochthon could have caused the continental margin to subside and form a deep depositional basin (a foreland basin) above what had originally been a shallow-water shelf. Such an interpretation has been proposed for late Paleozoic foreland basins along the southern margin of ancestral North America, when North America collided with Gondwana (Pindell, 1985; Armin, 1987; Poole and Perry, 1997). Other Permian and/or Pennsylvanian basins in the United States that lie inland from the Paleozoic continental margin (for example the Paradox Basin) are clearly not typical foreland basins, but have nevertheless been interpreted as intraplate deformation related to tectonic interaction of ancestral North America and Gondwana (Kluth and Coney, 1981; Smith and Miller, 1990).

The basins east of Sonora have been related to the tectonic interaction of ancestral North America and Gondwana (Pindell, 1985; Viele and Thomas, 1989; Poole and Perry, 1997), but the margin of Gondwana may not have extended as far west as Sonora (Pindell, 1985; Stewart, 1992), and the nature of the plate encroaching on Sonora is poorly understood. Such a plate might include poorly known, and poorly dated, metamorphosed chert-argillite-limestone successions, flysch deposits, carbonate strata, schist, and metavolcanic and metaplutonic rocks in Sinaloa that are in part at least of Mississippian to Early Permian age (Malpica-Cruz, 1972; Mullan, 1978; Gastil *et al.*, 1991; López-Ramos, 1981, p. 5), although some rocks have a Triassic protolith age (Anderson and Schmidt, 1983).

Alternately, the Lower and Middle Permian basin deposits in Sonora could be related to fragmentation of the continental margin by strike-slip and transtensional faulting in an unstable continental borderland. Such a hypothesis has been proposed to explain late Paleozoic basins in eastern California (Stone and Stevens, 1988) and in a broad zone in the southwestern United States and northern Mexico (Dickerson, 1987), although Snow (1992) has questioned the transtensional interpretation for the eastern California basins and considers them to be foreland basins formed in a compressional regime. In Sonora, no firm evidence of a Permian strike-slip regime has been presented, although Stewart (1992) and Sedlock and collaborators (1993) have speculated that a transform fault extended across northern Mexico in Permian time connecting Permian magmatic arcs in the western United States and eastern Mexico. Such a setting accounts for the absence of known Permian volcanic rocks in what is considered the transform segment of northern Mexico, in contrast to the abundance of Permian volcanic rocks in the western United States and eastern Mexico where subduction related magmatism is widespread. Further evidence of strike-slip faulting may be found in the nature of the contact between miogeoclinal and eugeoclinal strata in Sonora, which, as first proposed by Silver and Anderson (1983), may be a strike-slip fault boundary. This boundary of eugeoclinal and miogeoclinal rocks in Sonora has generally been considered to be a thrust related to the Late Permian to Middle Triassic Sonora orogeny (Poole *et al.*, 1995a; Poole and Perry, 1997), but possibly these thrust relations are the result of much younger structures that modified an originally strike-slip boundary. Such a possibility is suggested by the relatively narrow width of the present overthrust belt (Stewart *et al.*, 1990; Poole *et al.*, 1995a), a relation that would be likely if an original strike-slip boundary was modified by later, relatively minor, thrusting. Truncation of the miogeocline by strike-slip faulting in central Sonora is also possible. This idea is suggested by the possible absence of Paleozoic shelf-edge deposits in east-central Sonora, and by the poorly defined relation that eugeoclinal strata in central Sonora may have originally been juxtaposed against medial or outer shelf Ordovician strata, whereas in eastern Sonora they are juxtaposed against medial or inner-shelf Ordovician strata (Poole *et al.*, 1995a, b).

UPPER TRIASSIC CONTINENTAL MARGIN OR ALLOCHTHONOUS MARINE ROCKS

Upper Triassic marine strata at Sierra Santa Teresa and elsewhere in Sonora appear to be a continuation, or an offset segment, of marine Upper Triassic strata of the western United States. These Upper Triassic marine rocks in Sonora and the western United States exhibit great lithologic heterogeneity and include successions that consist largely of carbonate rocks, successions of largely nonvolcanic fine-grained to conglomeratic siliciclastic rocks, and successions that are volcanic rich (Stanley and González-León, 1995; Saleeby and Busby-Spera, 1993; Schweickert and Lahren, 1993; Stewart, 1997). This heterogeneity appears to reflect different depositional environments along the Upper Triassic continental margin, as well as possible tectonic juxtaposition of contrasting allochthonous terranes (Silberling *et al.*, 1987). In Sonora, the degree to which the Upper Triassic and Lower Jurassic rocks are allochthonous is an unresolved problem, as has been discussed above under regional relations of Upper Triassic and Lower Jurassic rocks.

Another unresolved problem is the scarcity of volcanic material in Upper Triassic rocks in Sonora (Stewart *et al.*, 1986). Present-day Sonora is within the position of the presumed source region for the volcaniclastic lower part of the Chinle Formation in Arizona, western New Mexico, southern Utah, and southern Nevada (Stewart *et al.*, 1986). On the other hand, Upper Triassic volcanic and plutonic rocks in southeastern California and western Nevada (Saleeby and Busby-Spera, 1993) which could be the source rocks for the Chinle sediments, are in an unlikely location. Thus, both the possible volcanic source rocks for the Chinle Formation and the essentially nonvolcanic Upper Triassic rocks in Sonora seem in the wrong place relative to the location of the volcaniclastic lower part of the Chinle Formation. A speculative resolution of this anomaly is that the southeastern California and western Nevada candidate source terrane originally lay in what is now Sonora and was later transported tectonically by large right-lateral motion into its present position. In this speculation, the essentially nonvolcanic rocks of Sonora were originally located far southeast of Sonora in a region where volcanic activity was minor and transported into their present position by the same right-lateral movement that displaced the volcanic source terrane to the northeast. Such a hypothesis may require complex tectonic movements if the Triassic rocks of Sonora rest depositionally on older rocks, as discussed above, and these older rocks have been offset left-laterally along the hypothetical Mojave-Sonora megashear described below. A reconciliation of these speculations may require first pre-Upper Triassic (presumably Permian) large-scale left-lateral movement on the Mojave Sonora megashear (see below), or similar faults, and post-Upper Triassic lesser-scale right-lateral movement on the same, or other faults, to account for the present distribution of Precambrian, Paleozoic, and Mesozoic rocks.

MOJAVE-SONORA MEGASHEAR

A major unresolved problem of Sonora geology is the concept of a major left-lateral fault (the Mojave-Sonora megashear) that has been proposed to offset rocks from eastern California to the Caborca region (Silver and Anderson, 1974; Anderson and Schmidt, 1983). The concept is based mainly on the distribution pattern of dated Precambrian crystalline basement rocks, on the similar distribution pattern of unconformably overlying Neoproterozoic and Cambrian rocks (Anderson and Silver, 1979, 1981; Anderson and Schmidt, 1983; Stewart *et al.*, 1984, 1990, in press), on the distribution pattern of the Eureka Quartzite and rocks considered correlative in Sonora (Ketner, 1986; Stewart *et al.*, 1990), and on the distribution pattern of Triassic (Stanley and González-León, 1995) and of Jurassic (Jones *et al.*, 1995) rocks. The concept of a megashear has been greatly debated (see Stewart *et al.*, 1990; and in press, for discussion of the pros and cons of the concept) and no consensus has been reached as to whether such a fault is necessary to explain the geologic patterns noted in the western United States and northwestern Mexico. In addition to questions concerning the validity of the concept, different interpretations have been made as to the amount and timing of the proposed offset. Anderson and Schmidt (1983) propose 700 to 800 km of offset based on the supposed offset of Cambrian rocks from the Death Valley area in California to the Caborca region. Ketner (1986) proposed 1,000 km of offset of the Ordovician Eureka Quartzite and rocks considered correlative in Sonora; Stanley and González-León (1995) propose as much as 1,000 km of offset of Triassic strata from western Nevada to the El Antimonio area in Sonora; and Stewart and collaborators (in press), in a discussion of several possible interpretations, suggest 600 km of offset from the San Bernardino Mountains to the Caborca region. The time of displacement has generally been considered to be Jurassic (Silver and Anderson, 1974; Anderson and Silver, 1979; Anderson and Schmidt, 1983; Jones *et al.*, 1995) although Stevens and collaborators (1992) suggested a late Paleozoic age.

The data presented in this report do not clearly support or refute the concept of the Mojave-Sonora megashear. This uncertainty arises from the absence of a clear knowledge of regional facies patterns of the Mississippian, Pennsylvanian, and Permian rocks in Sonora and some differences between the section at Sierra Santa Teresa and those elsewhere in Sonora. Nevertheless, the Santa Teresa succession does not correspond in detail with stratigraphic successions in eastern California from which the Sonora rocks would have been offset if the concept of the Mojave-Sonora megashear is correct. Differences in the Sierra Santa Teresa and eastern California successions are (1) Chesterian carbonate rocks are thin in eastern California (Poole and Sandberg, 1977, 1991) whereas they are thick in Sierra Santa Teresa, although elsewhere in Sonora they are also thin; (2) unconformities are present in the Pennsylvanian and Permian successions in eastern California (Stevens, 1977; Rich, 1977; Ross, 1991), but apparently nowhere in eastern California are Leonardian strata unconformably above Middle Pennsylvanian strata as they are in Sierra Santa Teresa; and (3) the time of change from shallow-water carbonates to deeper water deposits is Wolfcampian in eastern California (Stone and Stevens, 1988), whereas in Sierra Santa Teresa it is younger than Leonardian. These differences between Sonora and eastern California can either be used to argue against the concept of the Mojave-Sonora megashear or indicate moderately rapid facies changes, and, in the case of the change to deeper water deposition, diachronous events along the Cordilleran miogeocline.

Stanley and González-León (1995) have proposed that Norian (Upper Triassic) carbonate rocks in Sierra del Álamo that have a distinctive coral and sponge fauna have been offset left laterally along the Mojave-Sonora megashear from carbonate rocks in western Nevada that have a similar fauna. The sponge-coral rocks of subunit 7 in Sierra Santa Teresa are a major south-southeast extension of this fossiliferous Norian carbonate rock. Thus, if the Sierra del Álamo area has been displaced along the megashear, then Sierra Santa Teresa probably was also. However, other quite different hypotheses are possible including that of Stevens and collaborators (1992) who proposed that movement on the megashear was mainly late Paleozoic and therefore would not be a factor in understanding the distribution of Triassic rocks.

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APPENDIX: FOSSIL LOCALITIES AND IDENTIFICATIONS

All conodonts identified by R.G. Stamm and B.R. Wardlaw; all fusulinids identified by C.H. Stevens; corals and sponges identified by George D. Stanley, Jr.; and ammonoids by David G. Taylor (written communication, 1997). Localities shown on Plate 1, and sample numbers indicated in Figure 3.

JURASSIC

Loc. 1A—JS-92-1 and JS-92-2: Subunit 24 of Upper Triassic and Lower Jurassic unit (Figure 4); stratigraphic section 7. Lat. 28°57.5'N, Long. 110°45'W

Ammonoids:
- *Discamphiceras*?
- *Angulaticeras*?
- Age: Late Hettangian? (Early Jurassic?)

TRIASSIC

Loc. 1B—JS-92-5 and JS-92-5A: Subunit 5 of Upper Triassic and Lower Jurassic unit (Figure 4); stratigraphic section 7. Lat. 28°57.2'N, Long. 110°44.8'W

Conodonts:
- *"Epigondelella"* n. sp. C Orchard, 30 Pa elements. Kozur (1989) would synonymize this epigondolellid with a non-bifurcate basal surface in the new genus *Mockina*.
- Indeterminate fragments: 1M, 1 sb.
- Age: Late Triassic, middle Norian

Corals:
- *Chondrocoenia waltheri*
- *Retiophyllia* sp.
- *Astraeomorpha sonorensis*
- Age: Triassic, Norian

Sponges:
- *Fania* sp.
- *Nevadathalamia cylindrica*
- *Cinnabaria expansa*
- Age: Triassic, Norian

Unidentified mollusks (gastropods and bivalves)

?Ichthyosaur bone fragment

PERMIAN

Unit 7

Loc. 2—JS-91-132: About 250 m above base of unit 7; Lat. 28°57.44'N, Long. 110°48.58'W

Fusulinids:
- *Parafusulina* sp. aff. *P. boesei*
- Age: Permian, early Guadalupian

Unit 6

Loc. 3—20-F16-4J (31679-PC), upper part of unit 6; Lat. 28°59.32'N, Long. 110°47.69'W

Conodonts:
- *Mesogondolella bisselli* (Clark and Behnken)
- *Streptognathodus* sp.
- *Sweetognathus whitei* (Rhodes)
- *Sweetina* sp.
- Age: Early Permian
- CAI: 5.5

Loc. 4—JS-93-7: 8.5 m above base of unit 6, stratigraphic section 4; Lat. 28°59.02'N, Long. 110°46.72'W

Fusulinids:
- *Parafusulina* sp.
- Age: Early Permian (probably Leonardian)

Loc. 5—JS-92-59B: Lower or middle part of unit 6; Lat. 28°57.2'N Long 110°46.8'W

Fusulinids:

Parafusulina spissisepta

Age: Permian, Leonardian

Loc. 6—JS-91-134: Unit 6; Lat. 28°57.06'N, Long. 110°48.12'W

Fusulinids:

Parafusulina sp.

Age: Permian, early or middle Leonardian

Loc. 7—JS-91-126: Lower part of unit 6; Lat. 28°27.13'N, Long. 110°47.90'W

Fusulinids:

Parafusulina sp.

Schwagerina aff. *S. guembeli*

Age: Permian, early or middle Leonardian

Loc. 8—JS-92-48: Lower part of unit 6; Lat. 28°58.0'N, Long. 110°47.1'W

Fusulinids:

Schwagerina crassitectoria

Age: Permian, Early Leonardian

PENNSYLVANIAN

Unit 5

Loc. 9—JS-91-152 (31680-PC): 38.1 m below top of unit 5; Lat. 28°59.29'N, Long. 110°47.57'W

Conodonts:

Adetognathus lautus Gunnell

Diplognathodus coloradoensis (Murray and Chronic)

Idiognathodus sp.

Sweetina?

Age: Middle Pennsylvanian, Atokan to Desmoinesian

CAI: 6.0-7.0

Loc. 10—JS-91-151 (31681-PC): About 100 m below top of unit 5; Lat. 28°59.31'N, Long. 110°47.53'W

Conodonts:

Adetognathus lautus Gunnell

Diplognathus coloradoensis (Murray and Chronic)

Hindeodus "minutus" sp. 2? (of Wardlaw and Stamm)

Idiognathodus claviformis? Gunnell

Age: Middle Pennsylvanian, late Atokan to early Desmoinesian

CAI: 5.5

Loc. 11—JS-92-55: 85 m above base of unit 5, on slope above where stratigraphic section 5 measured; Lat. 28°58.8'N, Long. 110°46.4'W

Conodonts:

Adetognathus lautus Gunnel, 18 Pa elements

Hindeodus minutus (Ellison), 5 Pa elements

Neognathodus medadultimus Merrill, 20 Pa elements

Idiognathodus sp., 10 Pa elements

Diplognathodus coloradoensis (Murray and Chronic), 8 Pa elements

Unassigned ramiform elements: 6 Pb, 1 M, 2 Sc

Fragments: 44

Age: Middle Pennsylvanian, Atokan to early Desmoinesian

CAI: 5.0

Loc. 12—JS-93-8: About 79 m above base of unit 5, stratigraphic section 4; Lat. 28°59.02'N, Long. 110° 46.72'W

Fusulinids:

Fusulinella sp. aff. *F. accuminata*

Age: Pennsylvanian, Atokan

Unit 4

Loc. 13—JS-91-149 (31682-PC): near base of upper one-quarter of unit 4; Lat. 28°59.28'N, Long. 110°47.25'W

Conodonts:

Diplognathodus coloradoensis (Murray and Chronic)

Idiognathoides sp.

Neognathodus caudatus Lambert

Age: Pennsylvanian, Desmoinesian

CAI: 5.5

Loc. 14—JS-92-53: 102 to 104 m above base of unit 4, stratigraphic section 5; Lat. 28°58.9'N, Long. 110° 46.4'W

Fusulinids:

Fusulinella clarki

F. searighti?

Age: Pennsylvanian, Atokan

Conodonts:

Neognathodus bothrops Merrill, 8 Pa elements

Neognathodus medadultimus Merrill, 5 Pa elements

Idiognathodus sp., 12 Pa elements

Hindeodus minutus (Ellison), 20 Pa elements

Idiognathoides sinuatus?, Harris and Hollingsworth, 1 Pa element

Neogondolella clarki/dombasica?, 1 juvenile Pa element

Unassigned ramiform elements: 8 Pb, 1 M, 1 Sc.

Age: Middle Pennsylvanian, Atokan

CAI: 4.5 - 5.0

Unit 3

Loc. 15—JS-92-14: 196 m above base of unit 3, stratigraphic section 5; Lat. 28°58.2'N, Long.110°45.2'W

Conodonts:

Hindeodus minutus (Ellison), 1 Pa element

Idiognathoides sinuatus Harris and Hollingsworth, 2 Pa elements

Idiognathodus sp. indet., 2 juvenile Pa elements

Neognathodus sp. indet., 1 juvenile Pa element

Fragments: 6

Age: Early to Middle Pennsylvanian, Morrowan (but not earliest) through Atokan

Unit 2

Loc. 16—JS-91-148 (31683-PC): About 176 m above base of unit 2, stratigraphic section 5; Lat. 28°58.98'N, Long. 110°45.91'W

Conodonts:

Declinognathodus sp.

Hindeodus "minutus" sp. 1 (of Wardlaw and Stamm)

Idiognathodus sp.

Idiognathoides sinuatus Harris and Hollingsworth

Age: Early (but not earliest) Morrow to early Atokan
CAI: 4.0

PENNSYLVANIAN AND MISSISSIPPIAN
Unit 1

Loc. 17—JS-92-41: 6 m below top of unit 1; Lat. 28°58.3'N, Long. 110°45.9'W
Conodonts:
Idiognathoides marginodosa Grayson, Morphotype A, 2 Pa elements
Idiognathodus sp. indet., 2 broken Pa elements
Idiognathoides convexus (Ellison and Graves), 18 Pa elements
Unassigned ramiform elements: 4 Pb, 1 Sc
Fragments: 68
Age: Early to Middle Pennsylvanian, late Morrowan through Atokan. The occurrence of *Id. marginodosa*, known from the Atoka Formation of Oklahoma, may restrict the age to the Atokan. However, the complete range of *Id. marginodosa* is poorly defined

Loc. 18—JS-91-147 (31684-PC): About 24 m below top of unit 1, stratigraphic section 5; Lat. 28°58.92'N, Long. 110°45.80'W
Conodonts:
Adetognathus spathus (Dunn)
Declinognathodus noduliferus (Ellison and Graves)
Idiognathodus sinuosis Ellison and Graves
Idiognathoides sinuatus Harris and Hollingsworth
Age: Pennsylvanian, Middle to Late Morrowan
CAI: 6.0

Loc. 19—JS-92-39: 274 m below top of unit 1, stratigraphic section 6; Lat. 28°58.25'N, Long. 110°45.6'W
Conodonts:
Cavusgnathus unicornis Harris and Hollingsworth, 1 Pa element
Gnathodus bilineatus? (Roundy), 1 juvenile Pa element
Gnathodus girtyi simplex Dunn, 3 Pa elements
Yogelgnathus postcampbelli (Austin and Husri), 43 Pa elements
Fragments: 21
Age: Late Mississippian, middle to late Chesterian

Loc. 20—JS-92-38: 431 m below top of unit 1, stratigraphic section 6; Lat. 28°58.2'N, Long. 110°45.4'W
Conodonts:
Cavusgnathus unicornis Harris and Hollingsworth, 9 Pa elements
Gnathodus sp. indet., 1 juvenile and 1 broken Pa element
Hindeodus spiculus (Youngquist and Miller), 4 broken Pa elements
Hindeodus cf. *cristulus* (Youngquist and Miller), 5 broken Pa elements
Kladognathus sp., 12 elements
Age: Late Mississippian, latest Meramecian to late (but not latest) Chesterian

Loc. 21—JS-92-36: 572 m below top of unit 1, stratigraphic section 6; Lat. 28°58.2'N, Long.110°45.2'W
Conodonts:
Cavusgnathus unicornis Harris and Hollingsworth, 13 Pa elements
Gnathodus girtyi girtyi Hass, 20 Pa elements
Hindeodus sp. indet., 3 broken Pa elements
Kladognathus sp., 18 elements
Phacistognathus muricatus (Dunn) 2 Pa elements
Gnathodus defectus? Dunn, 3 broken Pa elements
Fragments: 102
Age: Late Mississippian, middle to late Chesterian