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Stratigraphy and paleontology of Lower Permian rocks north of Cananea, northern Sonora, Mexico

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Abstract

Lower Permian carbonate and overlying red bed clastic rocks are present in a 2 km^2 stratigraphic window in the vicinity of Rancho La Cueva, Santa Cruz sheet (scale 1:50,000), northern Sonora, Mexico. This exposure lies unconformably beneath predominantly intermediate Upper Cretaceous volcanics yielding $^{40}Ar/^{39}Ar$ ages of 73.4 ± 0.18 and 71.1 ± 0.35 Ma. The lower part of the Permian succession consists of light- to medium-gray colored limestones of the Colina Limestone, with a minimum thickness of 235 m. Sedimentary features suggest shallow water, slightly restricted depositional environments. Although lacking observable fossils for the most part, two intervals of richly fossiliferous, silicified shell beds are present near the base and top of the Colina Limestone. The lower fauna consist mostly of gastropods and bivalves. The presence of a new microdomatid gastropod species, *Glyptospira sonorensis* n. sp., close to *Glytospira arelela* Plas, suggests a late Wolfcampian age for this horizon. The upper fauna are predominantly molluscan dominated (gastropods and bivalves), but some brachiopods (productids and the rhynchonellid genus *Pontisia*) are also present. Gastropod genera include *Bellerophon*, *Warthia*, *Euomphalus* (represented by the species, *Euomphalus kaibabensis* Chronic), *Baylea*, *Worthenia*, *Naticopsis*, *Goniasma*, *Kinishbia*, *Cibecuia*, and *Glyptospira*. The gastropods suggest a Leonardian (late Early Permian) age for this horizon, and many of the species have previously been recorded from the Supai Group and Kaibab Formation of northern and central Arizona.

The Colina Limestone is conformably overlain by 11.2 m of light-gray lime mudstone and dolostone, assigned here to the Epitaph Dolomite, which in turn is succeeded by 58.8 m of red-colored sandstone and gray lime mudstone, assigned here to the Scherrer Formation. This Lower Permian succession is significant because it further strengthens the stratigraphic ties of southeastern Arizona rocks with those of northern Sonora and confirms the presence of North American cratonal stratigraphy in the northern part of the state of Sonora, Mexico. Published by Elsevier Science Ltd.

Keywords: Lower Permian; Stratigraphy; Gastropods; Brachiopods; Sonora (Mexico)

1. Introduction

Exposures of the North American craton and its Paleozoic sedimentary cover are present in an area that extends southeastward from the Colorado Plateau in northern Arizona to the Sonoran basin and range province of northern Sonora, Mexico. In southeastern Arizona, the Paleozoic sedimentary cover is approximately 2 km thick and has been described near Tombstone by Gilluly et al. (1954) and in the Whetstone Mountains by Wrucke and Armstrong (1987) (Fig. 1). In northeastern Sonora, incomplete exposures of the Paleozoic sedimentary section have been studied in the Sierra del Tule near the United States–Mexican border by González-León (1986), in the Sierra Los Ajos east of Cananea (Aponte-Barrera, 1974), and at other sites farther east and outside the area of Fig. 1 (Stewart and Poole, 2002). In Sonora, the Proterozoic and Paleozoic sections are not exposed west of the Sierra de Los Ajos, probably because of covering Mesozoic and Cenozoic volcanic and sedimentary strata. This interpretation is supported by a small exposure of altered unfossiliferous carbonate rocks and quartzite and Proterozoic granitic rocks near Cananea (Mulchay and Velasco, 1954; Anderson and Silver, 1977) (Fig. 1). Proterozoic and Paleozoic rocks are also exposed in the Caborca area, approximately 150 km southwest of Cananea (Cooper and Arellano, 1946; Cooper et al., 1952, 1953; Easton et al., 1958; Brunner, 1975; Stewart et al., 1984; McMenamin, 1987). The Caborca section, however, constitutes part of the miogeocline of

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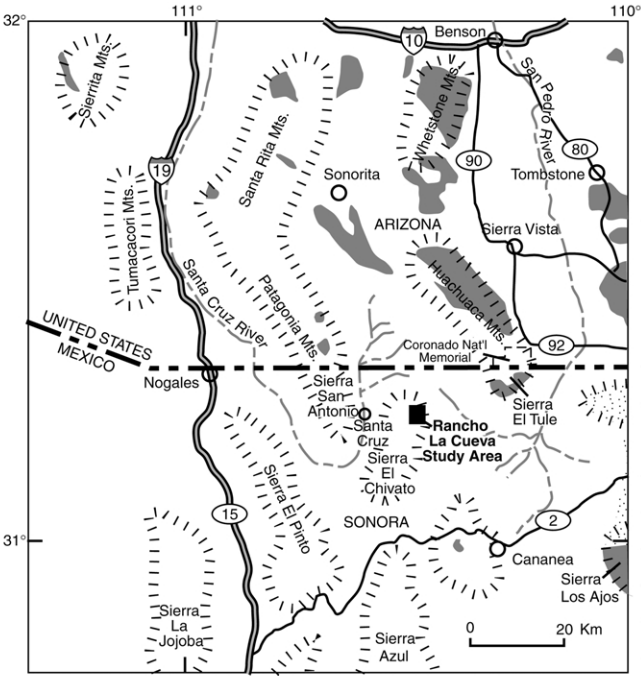

Fig. 1. Index map for southeastern Arizona and northern Sonora in the vicinity of the La Cueva study area. Shaded areas indicate locations of exposures of Proterozoic and Paleozoic rocks (Reynolds, 1988; Fernandez-Aguirre and Almazán-Vázquez, 1991).

western North America and may have been displaced southeastward to its present site along the Mojave–Sonora megashear in the Jurassic (Silver and Anderson, 1974; Anderson and Silver, 1979; Anderson and Schmidt, 1983; Stewart et al., 1997; González-León et al., 1997).

The purpose of this paper is to document and describe carbonate rocks exposed in a small stratigraphic window beneath Cretaceous and Tertiary volcanic rocks near Rancho La Cueva, 30 km north–northwest of Cananea (Fig. 1). We report on Early Permian megafossils present in the carbonate rocks and suggest a correlation of the carbonate rocks to Lower Permian units in the Paleozoic sedimentary section in southeastern Arizona. This correlation substantiates the interpretation that the carbonate and associated rocks in the Cananea area are representative of the North American craton and its sedimentary cover, as well as that these rocks extend westward an unknown distance beneath covering Cretaceous and Cenozoic units in northern Sonora. Although an incomplete section, the Rancho La Cueva locality is the westernmost known exposure of the Paleozoic sedimentary cover of the North American craton south of the international border.

2. Geologic setting

The North American craton, which consists of Proterozoic metamorphic and granitic rocks, and its 1–3 km thick sedimentary cover of Paleozoic clastic and carbonate rocks is widely exposed in southeastern Arizona and northeastern Sonora. The Proterozoic rocks consist of metasedimentary and metavolcanic rocks deposited at about 1.7 Ga and intruded by granitic rocks at about 1.6 Ga (Conway and Silver, 1989). The Proterozoic crystalline rocks are overlain by Cambrian sandstone (Bolsa Quartzite) and Cambrian and Ordovician carbonate rocks (Abrigo Limestone, El Paso Limestone). Following a period of erosion that removed much of the Ordovician and Cambrian sedimentary section, widespread deposition of carbonate rocks occurred in the Late Devonian (Martin Formation) and Mississippian (Escabrosa Limestone). After renewed erosion in the Late Mississippian, a thick succession of dominantly carbonate and lesser clastic strata was deposited during the Pennsylvanian and Permian (Naco Group, including Horquilla Limestone, Earp Formation, Colina Limestone, Epitaph Formation, Scherrer Formation, and Concha Limestone). The Naco Group was deposited in shelfal regions marginal to the southeast-trending Pedregrosa basin of northwestern Chihuahua (Blakey and Knepp, 1989).

The craton and sedimentary cover sequence was affected by various tectonic events emanating from both the east and west in the middle Mesozoic. Volcanic deposits and related intrusive units resulting from subduction along the Pacific margin of North America were emplaced in the Middle Jurassic (Tosdal et al., 1989). To the east, the extensional faulting related to the opening of the Gulf of Mexico led to development of the northeast-trending Chihuahua trough and deposition of the Bisbee Group in the Late Jurassic and Early Cretaceous (Bilodeau, 1978; Dickinson et al., 1989). Laramide-type, continentward-directed, basement-involved thrusting in the Late Cretaceous and Tertiary, apparently related to subduction along the western margin of North America, led to the formation of large basement arches (Oldow et al., 1989) and accompanying depositional basins, including the Cabullona near the eastern margin of Fig. 1 (González-León and Lawton, 1995). Subduction-related tectonism along the Pacific margin of North America also resulted in renewed volcanism and plutonism in the Late Cretaceous and Tertiary. These episodes of deformation, sedimentation, and magmatism caused structural disruption of the craton and covering Paleozoic strata and burial beneath younger deposits, particularly in north central Sonora. Locally large-scale extension in the middle Tertiary and basin and range extensional faulting in the late Cenozoic caused erosion of the sedimentary and volcanic section and produced north-trending tilted fault blocks that have locally exhumed the stratigraphy in the region.

Our study area is located at Cerro La Cueva and Cerros Colorados, approximately 10 km east of the village of Santa Cruz and 9 km south of the international border (Fig. 1). Access to the study area is from the east, from near El Chale, through private ranchlands along a seldom-traveled dirt road that terminates at a small collection of abandoned buildings that together compose Rancho La Cueva. The study area lies in a region of tree- and brush-covered hills and ridges that extends northward from the Sierra El

Chivato. Although most rocks exposed in the area consist of Cretaceous and Tertiary volcanic and sedimentary rocks, geologic mapping by the US Geological Survey (USGS) and Cyprus–Amax de Mexico (1995–1996) reveals the presence of a 2 km^2 region near Rancho La Cueva that is underlain by carbonate rocks that were believed to host significant copper mineralization. Field studies of the carbonate rocks were conducted by the USGS during May 1995, September 1996, and March–April 1997 in an effort to delineate the stratigraphy, age, and geologic setting of these previously unknown rocks. Results of this work were presented in the form of an abstract (Blodgett et al., 1998).

3. Geology of Rancho La Cueva area

Our geologic map of the Rancho La Cueva area shows that the carbonate rocks are exposed in a northwest-trending stratigraphic window through Cretaceous and Tertiary volcanic rocks (Fig. 2). The carbonate rocks consistently dip northeastward and are divided into three stratigraphic units: a thick unit of thick-bedded light-gray limestone, an overlying thin unit of pink-weathering dolomite, and a capping unit of red-weathering siltstone and sandstone. We correlate these units with Lower Permian units in southeastern Arizona: the Colina Limestone, Epitaph Dolomite, and Scherrer Formation, respectively, of the Naco Group. The carbonate rocks are unconformably overlain by volcaniclastic rocks of Late Cretaceous age along the northeastern margin of the stratigraphic window but faulted against the volcaniclastic rocks along the western and southern margins. Tertiary ash-flow tuff is present at Cerro La Cueva in the extreme northwestern part of the map area, but these rocks do not directly adjoin the Paleozoic rocks in the stratigraphic window.

Along the northeastern margin of the stratigraphic window, where the contact between the Permian and Cretaceous units is depositional, bedding attitudes in the volcaniclastic rocks have similar strike and dip patterns to those in the underlying carbonate rocks. This relationship indicates that the carbonate and volcanic units are nearly concordant and the unconformity is not angular (Fig. 3). Nonetheless, a distinctive tuff unit in the volcaniclastic rocks (Fig. 2) appears to truncate laterally against the carbonate rocks, which suggests that the volcaniclastic rocks onlap on the carbonate units and the unconformity is of buttress type. The faults that bound the western and southern margins of the window are poorly exposed but appear to be steeply dipping normal faults that drop the Cretaceous and Tertiary volcanic section down against the carbonate rocks. The stratigraphic separation across the north–northeast-trending fault along the western margin of the window appears to be the greater of the two faults because Tertiary ash-flow exists above the volcaniclastic rocks to the west but not to the east. The details of the interaction of the Tertiary volcaniclastic rocks and normal faults were not evaluated in this study, however, and the less likely interpretation that the ash-flow tuff unit is younger than the normal faults, and thus could lie unconformably across all older structures and units, remains possible.

Although largely a northeastward-dipping homoclinal sequence, the carbonate succession in the La Cueva stratigraphic window displays an anticline–syncline pair approximately 0.4 km east of Rancho La Cueva (Figs. 2 and 4). The fold pair is northwest trending and close spaced, with an amplitude of about 20 m. The folds are moderately asymmetric with apparent southwest-directed contractional structural transport. Because the folds cannot be traced for more than 200 m, it is uncertain whether the Cretaceous volcaniclastic strata are involved in the deformation. The close spacing of the folds suggests that the structures are rooted in a thrust fault at shallow depth, possibly at or near the base of the Colina. The amount of shortening represented by the folds is small, but the presence of the folds suggests that the Permian rocks were subjected to an episode of contractional deformation.

In addition to the folding, the carbonate rocks display the effects of thermal alteration along the southwestern margin of the window. The alteration has resulted in decalcification of the carbonate rocks, destruction of most sedimentary structures, and development of many veins of silica locally, with evidence of Cu mineralization including azurite and malachite. Along the southwest edge of the limestone body, a northwest-trending, irregular zone of propylitic alteration is bordered by argillically altered rock in the northwest part of the area. The southeastern limb of the alteration contains propylitic alteration bordered on the north by a large zone of marbleized rock. Lenses of garnet–pyroxene–magnetite and pyroxene–actinolite skarn are present near the contact of these alteration types, as are sericite–quartz veins and minor copper oxides. A large portion of the northeastern margin of the body is unaltered.

Alteration suggests the proximal influence of a hypabyssal intrusion similar to the granodiorite and minor quartz monzonite (63.0 ± 0.8 Ma) that occur locally but are not exposed in the study area (Gray et al., 2002). The alteration may have accompanied or postdated normal faulting because it locally affects volcaniclastic rocks on the downthrown side of the normal fault that bounds the southwestern margin of the stratigraphic window. The alteration diminishes in intensity over a distance of 100–200 m to the northeast, away from the fault and into the carbonate rocks, which suggests that the alteration was generated by a local thermal anomaly, perhaps an unseen intrusive body at depth, as portrayed schematically in the cross-section in Fig. 2.

3.1. Measured section

A measured section through the Lower Permian strata exposed in the stratigraphic window at Rancho La Cueva is shown in Fig. 5. The section is 305 m thick and includes

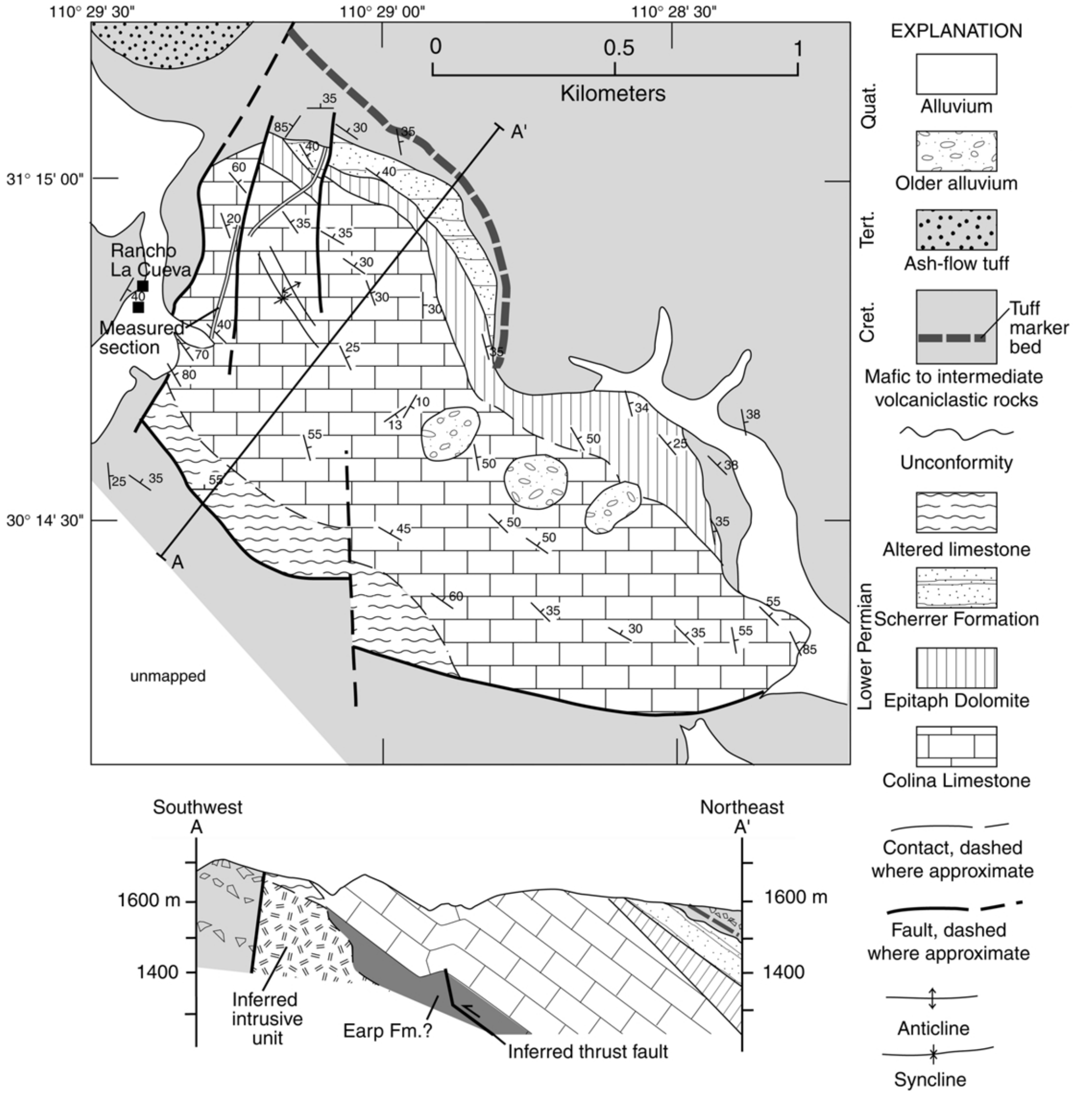

Fig. 2. Geologic map for the Rancho La Cueva area.

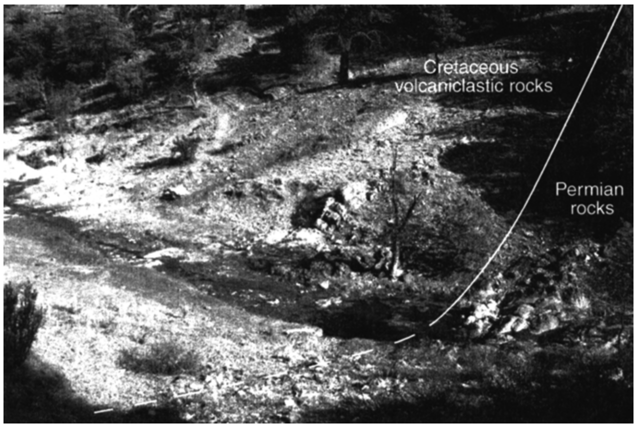

Fig. 3. Unconformable contact of Upper Cretaceous volcaniclastic rocks on underlying Lower Permian Epitaph Dolomite and Scherrer Formation.

Fig. 4. Anticline–syncline pair in the strata of the Colina Limestone about 0.4 km east of Rancho La Cueva.

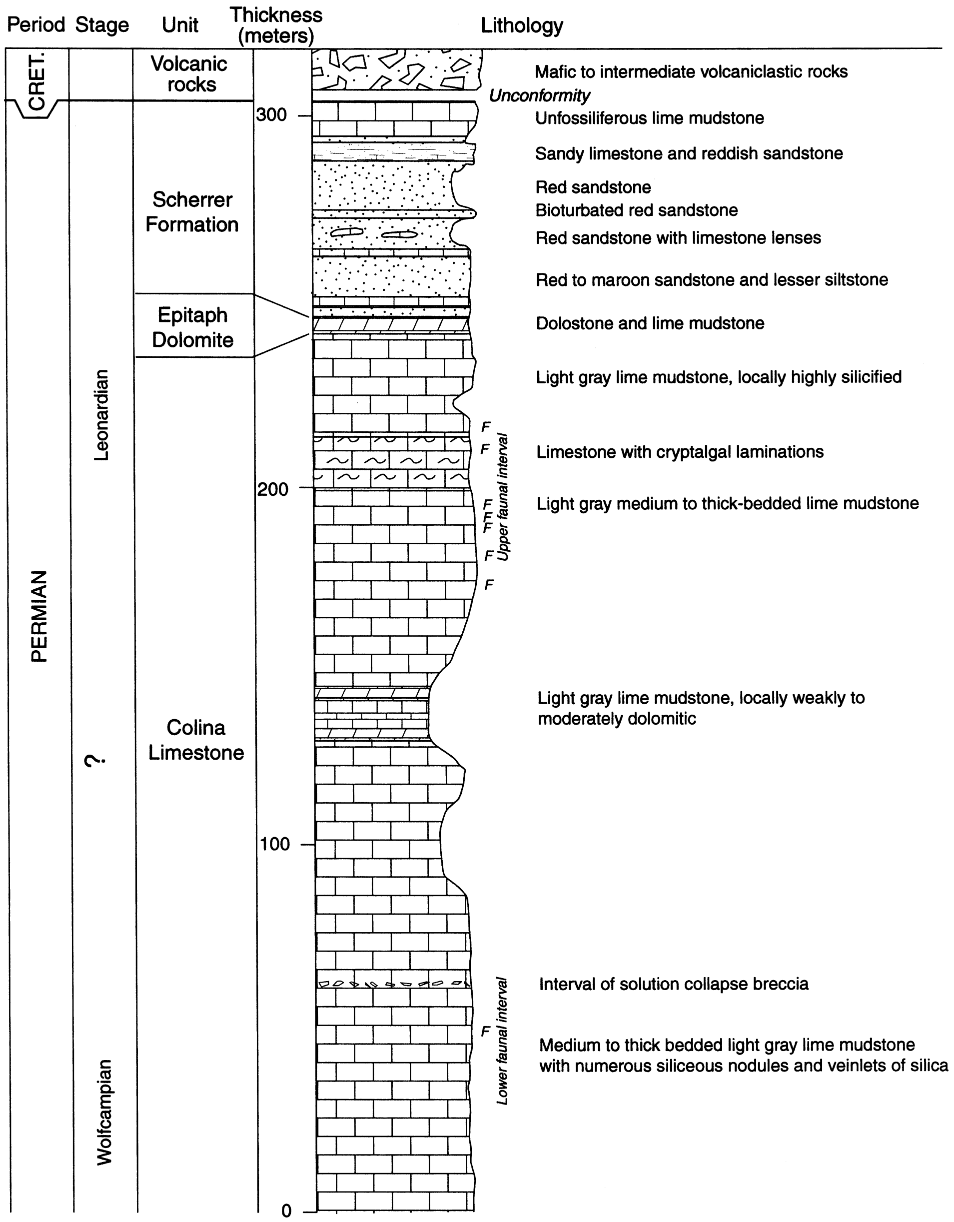

Fig. 5. Measured section through the Lower Permian strata exposed in the stratigraphic window at Rancho La Cueva.

nearly the entire thickness of carbonate and associated clastic strata in the stratigraphic window. The base of the section lies at the creek bottom approximately 200 m southeast of Rancho La Cueva, extends over the ridge to the northeast, and terminates at the base of the volcaniclastic strata.

On the basis of the paleontologic and lithologic criteria described next, we divide the stratigraphic section into three units that we assign, from base to top, to the Lower Permian Colina Limestone, Lower Permian Epitaph Dolomite, and Lower Permian Scherrer Formation. The lithologic description of these units is provided. We also provide a description of the Cretaceous volcaniclastic strata that immediately overlie the Permian rocks.

3.2. Colina limestone

The lower part of the measured Permian succession consists of light- to medium-gray colored limestones of the Colina Limestone with minimum thicknesses of 235 m. The lowermost portion of the Colina Limestone, exposed south of the measured section, is represented by highly folded and recrystallized limestones. No attempt was made to measure these lowermost beds because of their degree of recrystallization and complicated structural character. The lower part (0–58 m above the base) of the measured section of the Colina Limestone consists of medium- to thick-bedded lime mudstone that contains one moderately fossiliferous, silicified megafaunal horizon at 39.6–45.6 m above the base of the section. The character of this mollusc-dominated fauna (mainly gastropods and bivalves) indicates a very shallow water, inner carbonate platform depositional environment for the lower part of the unit. A prominent solution collapse breccia is present 58–64 m above the base of the section (Fig. 6(C)). This interval is perhaps the result of an interval of non-deposition and solution collapse brought on by subareal erosion. The interval between 64 and 161 m above the base of the measured section is, for the most part, poorly exposed. The lower three-quarters of this interval are highly silicified and contain many siliceous nodules and veinlets of silica. The interval, however, appears to be better preserved along the course of the small stream east of the measured section, where it is characterized by limestones with abundant cryptalgal laminations (Fig. 6(B)) and bird's-eye texture (Fig. 6(A)). No megafossils were recognized from this interval. The absence of marine fauna, as well as the abundance of cryptalgal lamination and bird's-eye structure in the limestones, indicates an intertidal to supratidal environment for much of the interval.

The upper portion of the Colina Limestone (161–235 m above the base) is composed primarily of medium- to thick-bedded, light-gray lime mudstone with scattered, distinctive silicified horizons of abundant. These fossiliferous horizons are also mollusc dominated, similar to the lowermost interval, but brachiopods appear to be relatively more common (though still low in taxonomic diversity) in the upper interval. A prominent interval of locally well-developed cryptalgal laminations, approximately 13 m in thickness, is developed in the middle portion of the uppermost part of the Colina Limestone. The scattered and frequent mollusc-dominated fossiliferous horizons indicate that most of the upper part of the unit was deposited in a very shallow water environment in an inner carbonate platform setting, with periodic further shallowing represented by the cryptalgal laminations that probably indicate upper intertidal to supratidal conditions.

3.3. Epitaph Dolomite

The Colina Limestone is conformably overlain by 11.2 m (37 ft) of light-gray lime mudstone and dolostone, assigned here to the Epitaph Dolomite. The formation consists of inter-bedded thin- to medium-bedded, light-, yellowish-, and even reddish-gray weathering lime mudstone and dolomudstone. These rocks commonly contain cryptalgal lamination. The base of the unit is defined by the abrupt change from the more massive, thick-bedded, light-gray weathering lime mudstone of the uppermost Colina Limestone to the markedly thinner bedding of the Epitaph Dolomite, with its prominent reddish gray hues and common cryptalgal lamination. The contact with the overlying Scherrer Formation is denoted by the first appearance of reddish colored sandstones typical of the overlying unit (Fig. 6(D)). No fossils were noted from exposures of the Epitaph Dolomite in the Rancho La Cueva area. The presence of common cryptalgal lamination, together with the absence of marine fauna, suggests that the Epitaph probably was deposited in a warm, very shallow water setting that probably ranged from intertidal to supratidal.

3.4. Scherrer formation

The Epitaph Dolomite is succeeded by 58.8 m (193 ft) of red-colored, thin-bedded sandstone and gray lime mudstone, assigned here to the Scherrer Formation (Fig. 6(D)). Reddish to maroon weathering, fine- to medium-grained orthoquartzite and siltstone are the dominant lithologies, commonly marked by ripple cross-lamination. Locally, chert-pebble conglomerate is present near the base in discontinuous beds up to 1 m thick. Horizontal, tubular-shaped burrows were observed locally in the sandstone. Minor gray weathering, lime mudstone, and calcareous dolomudstone is interlaid with the clastic rocks in the unit. The uppermost beds of the Scherrer Formation exposed in the Rancho La Cueva area consist of well-bedded, light-gray weathering, lime mudstone. The upper carbonate-dominated part of the Scherrer lacks visible fossils, except for minor silicified bryozoans observed near the base of this uppermost interval. Overall, the Scherrer Formation comprises upward-thickening cycles that appear to decrease in thickness and grain size upward within the unit. The presence of calcareous lithologies, burrows, and bedforms suggests deposition occurred in a transgressive shallow marine environment. The base of the Scherrer Formation indicates a sequence boundary, with the low stand represented by the dolomitization observed in the underlying Epitaph, followed by the onlap of coarse clastic sediments of the basal Scherrer.

3.5. Volcaniclastic deposits

Mostly poorly exposed dark-gray tuff breccia, with minor light-gray tuff, rests unconformably on the Permian carbonate and clastic sequence. The volcaniclastic rocks consist predominately of unsorted or poorly sorted tuff breccia and are several hundred meters thick. Clasts in the tuff breccia are pebble to boulder size and consist of plagioclase–clinopyroxene–hornblende phyric mafic andesite. The main basal breccias are monolithologic, matrix-supported, and massively bedded, ranging from 1.5 to 3–5 m thick, with the larger sizes the norm. Clasts are poorly sorted, subrounded to subangular, and dominantly coarsely plagioclase porphyritic amygdaloidal andesite. Clasts range in diameter from 2–3 cm to 1.5 m. Matrices are poorly sorted, coarse grained, recrystallized arkosic sands and pebbly sand. In most units, the clasts are angular and matrix supported in a comminuted volcanic matrix. The tuff breccia consists of multiple depositional units of sediment gravity flow deposits that can be 100 m thick. In one area northeast of the La Cueva stratigraphic window, an interval of light-

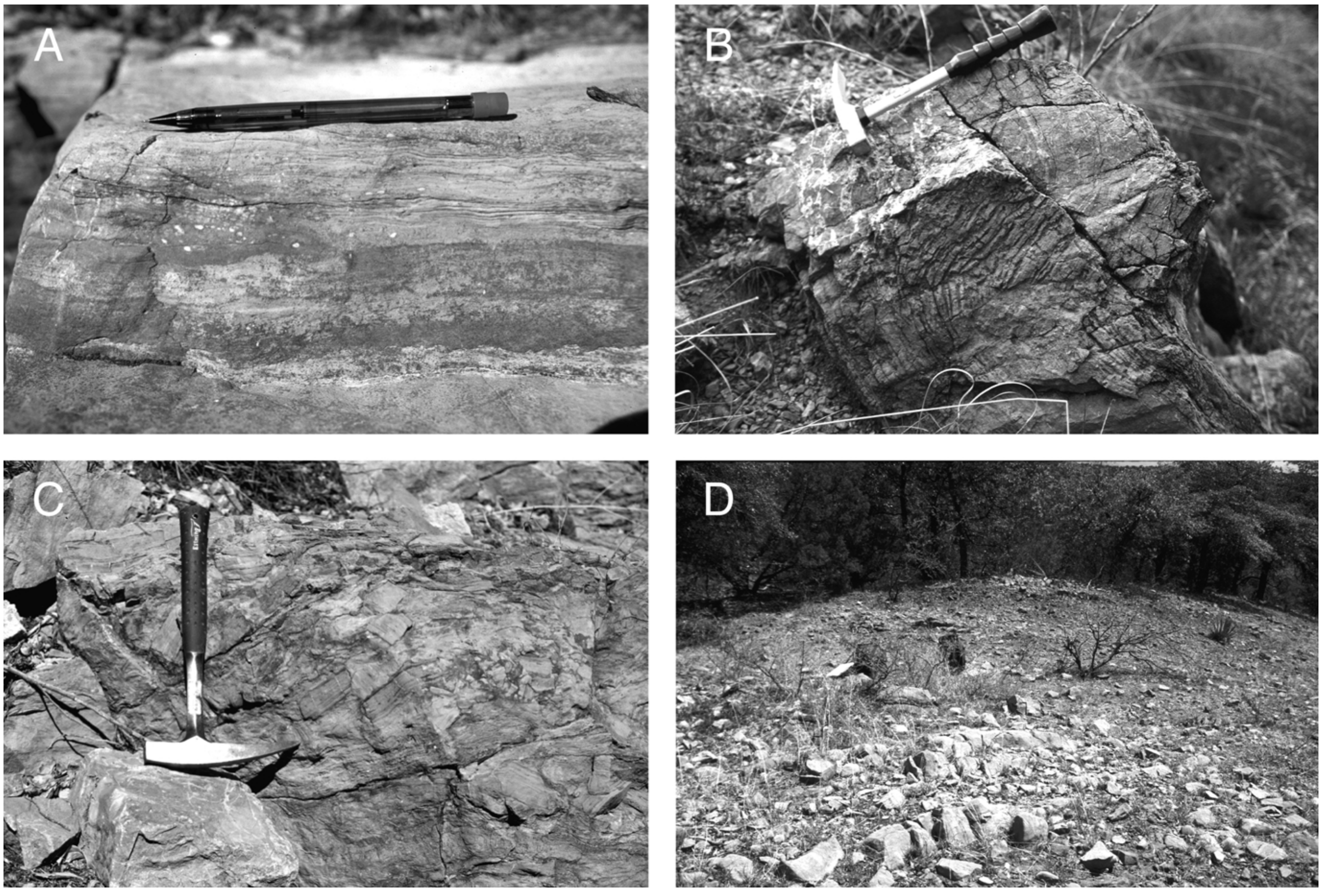

Fig. 6. (A) Bird's-eye texture in limestone of the lower part of the Colina Limestone. The bird's-eye texture and cryptalgal lamination indicate intertidal to supratidal depositional environments for parts of the Colina Limestone. (B) Deformed cryptalgal lamination in limestone in the Colina Limestone. (C) Solution collapse breccia in the lower part of the Colina Limestone. (D) Contact between Epitaph Dolomite (foreground) and overlying Scherrer Formation (beyond backpacks).

gray to white tuff up to 30 m thick (tuff shown in Fig. 2) is inter-bedded with the volcaniclastic deposits. The tuff consists of medium- to coarse-grained devitrified shards of volcanic glass with quartz, plagioclase, and biotite crystals and pumice fragments. The top of the tuff is capped by a 1 m, brick red layer that is here interpreted as a paleosol.

Where exposed, the contact of the volcaniclastic deposits on the Permian sequence is marked by a breccia up to 1 m thick that is composed entirely of angular carbonate clasts. A thick unit of dark-gray volcanic breccia rests sharply on top of the carbonate breccia. The carbonate breccia is interpreted as a regolith present at the time of burial by the volcaniclastic deposits. The contact transects the stratigraphy in both the underlying Permian rocks and the overlying volcaniclastic section. This suggests that the volcaniclastic rocks were deposited on a surface with pre-existing topographic relief in a buttress unconformity.

The volcaniclastic deposits were probably deposited mainly by lahars and/or other non-marine sediment gravity flows. The tuff interval that is interlayered with the volcaniclastic deposits indicates that the tuff breccias constitute at least two distinct depositional units in our map area. The paleosol at the top of the tuff represents a disconformity that a lengthy period of time passed between deposition of the two units. The sequence is interpreted as deposited by debris flows and tephra turbidite from proximal subaqueous volcanic eruptions. The autolithologic nature of this unit and widespread distribution suggest that it was derived from local convergent, coeval eruptive centers. No age data were derived directly from this thick sequence; however, biotite tuff intercalated with plagioclase porphyritic andesite flows approximately 7 km to the east are stratigraphically correlated with this sequence and yield $^{40}Ar/^{39}Ar$ ages of 73.4 ± 0.18 and 71.1 ± 0.35 Ma. Unconformably overlying volcanic rocks exposed on the southwestern side of the limestone body consists of plagioclase–biotite–amphibole andesite flows and breccias with $^{40}Ar/^{39}Ar$ ages of 26.3 ± 0.2–25.0 ± 0.3 Ma (Gray et al., 2002). This broad gap in age (unconformity) has been noted throughout the volcanic section around Cananea as far south as Arizpe, Sonora, some 75 km to the south (González-León et al., 2000; Gray et al., 2002).

4. Biostratigraphy

Megafossils are present at two stratigraphic levels in the Colina Limestone exposures in the Rancho La Cueva area (Fig. 5). The lowermost faunal horizon is mollusc dominated and situated 39.6–45.6 m (130–150 ft) above the base of the measured section. It contains the following gastropods: *Straparollus* sp., cf. *Apachella*? *arizonensis* Winters, *Worthenia* sp., *Amaurotoma* sp. (= *Yunnania* of some authors), *Anomphalus* sp., *Trachydomia* sp., *Glyptospira sonorensis* n. sp. (Fig. 7(A)–(I)), and a subulitid. Bivalves from this horizon include *Edmondia* sp. and undetermined bivalves; brachiopods include *Meekella* sp. and undetermined small, smooth brachiopods. Bryozoans are also present but remain unstudied. Calcareous green algae, probably identifiable as *Mizzia*? sp., are also present. This horizon is thought to be of late Wolfcampian age because of the presence of a new gastropod species (*G. sonorensis* n. sp.) that is extremely close to *Glytospira arelela* Plas. The form from Rancho La Cueva is very similar but differs in that it lacks the well-developed subsutural shelf found in the Nevadan species. In nearly all the other shell characteristics, including the prominent color bands, it appears virtually identical. The latter species is probably from late Wolfcampian-age strata in the Arrow Canyon Range, Clark County, Nevada (Plas, 1972).

The upper faunal interval is separated from the lower by a poorly exposed sequence of extensively silicified limestone beds (with both nodules and siliceous veinlets) along the traverse of the measured section. These beds are much better exposed along the creek east of the measured section and appear to be represented there primarily by limestones with abundant cryptalgal laminations and bird's-eye texture. No megafossils were recognized from this intermediate interval. The upper interval is also mollusc dominated, but unlike the lower, it contains more brachiopods, notably productids and the rhynchonellid *Pontisia* n. sp. aff. *P. stehli stehli* (Fig. 8(A)–(F)). The lowest collection from the upper faunal interval is an isolated silicified shell of *Euomphalus kaibabenis* Chronic, found 173.7 m (570 ft) above the base of the section. The next collection occurs 183.8–184.4 m (603–605 ft) above the base of the measured section and contains the gastropods: *Bellerophon* sp., *Euomphalus kaibabensis*? Chronic, *Cibecuia*? sp., *Goniasma* sp., and *Orthonema* sp. Bivalves from this horizon include *Palaeonucula* sp., *Aviculopinna* sp., *Astartella subquadrata* Girty, *Schizodus* sp., and many undetermined bivalves. Brachiopods consisting of an undetermined dictyoclostid, trilobite free cheeks, and pygidia are also present. The next collection is situated at 191.1 m (627 ft) in the measured section. Gastropods from this collection include *Bellerophon* sp., *Euphemites* sp., *Euomphalus kaibabensis* Chronic, *Euomphalus* sp., *Straparollus* sp., *Naticopsis* sp., *Goniasma terebra* (White), an undetermined ornate gastropod, and another undetermined gastropod. Bivalves include *Palaeonucula* sp., *Astartella subquadrata* Girty, *Schizodus* sp., *Sanguinolites*? sp., and undetermined bivalves. The scaphopod *Plagioglypta* is present, as is an undetermined dictyoclostid brachiopod and pelmatozoan ossicles. Two more silicified collections occur just above the latter, one at 192.6 m (632 ft) and the other at 195.1 m (640 ft) above the base of the section. The collection at 192.6 m (632 ft) includes the gastropods *Warthia* sp. (Fig. 8(I)–(K)), *Euomphalus kaibabensis* Chronic, and *Oncochilus insolitus* Chronic (Fig. 10(F)). The collection at 195.1 m (640 ft) includes the gastropods *Bellerophon* sp. (Fig. 8(G) and (H)), *Warthia* sp., *E. kaibabensis* Chronic (Fig. 9(A)–(E)), *Worthenia* cf. *W. crenulata* Batten (Fig. 10(E)), *Glyptospira* sp., *G. terebra* (White), *Cibecuia cedarensis* Winters, the bivalves *Sanguinoilites*? sp. (Fig. 9(G) and (H)) and *Aviculopinna* sp., and echinoid plates and spines (Fig. 10(G) and (H)).

The uppermost collection (JS-96-39) from the upper faunal horizon of the measured Colina Limestone section occurs 214.9–216.5 m (705–710 ft) above its base. Gastropods from this collection include *Euomphalus kaibabensis* Chronic, *Apachella* sp., *Kinishbia* sp., and *Glyptospira* sp. Brachiopods include *Peniculauris* cf. *P. subcostata* (R.E. King) (see Fig. 10(A)–(D) for views of this species from locality 97RB21, which is situated west of the measured section), *Pontisia* n. sp. aff. *P. stehli stehli* Cooper and Grant sp., *Dielasma*? sp., and undetermined smooth small brachiopods. Also common in this collection are pelmatozoan ossicles. To the east of the measured section are several other localities that contain rich silicified faunas. JS-96-45, which, according to its fauna, is undoubtedly at the same horizon as JS-96-39 (situated 400 m southeast of JS-96-39), contains the gastropods *Bellerophon* sp., *E. kaibabensis* Chronic (Fig. 9(F)), *Kinishbia nodosa* Winters, *Baylea* sp. 1, *Baylea* sp. 2, *Worthenia*? or *Platyworthenia*? sp. (cf. genus et sp. indet. 1 of Winters (1963)), and *Glyptospira* sp. Brachiopods include *Meekella* sp. and *Pontisia* n. sp. aff. *P. stehli stehli* Cooper and Grant (Fig. 8(A)–(F); same species as JS-96-39). Also present are the bivalve *Bakevellia* sp., undetermined bryozoans, and echinoid plates.

The gastropods suggest a Leonardian (late Early Permian) age for this horizon, because many of the species previously have been recorded from the Leonardian Supai Group and Kaibab Formation of northern and central Arizona. The most abundant gastropod in the upper part of the Colina Limestone at Rancho La Cueva is *Euomphalus kaibabensis* Chronic (Fig. 9(A)–(F)). This relatively large gastropod is easily to recognize in the field, and it provides a guide fossil to the upper part of the Colina. It is also reported in Arizona and West Texas (Chronic, 1952; Yochelson, 1956; Winters, 1963; Batten, 1964). Brachiopods also compose a prominent part of the upper Colina Limestone fauna but consist of relatively few species. Notable among this element of the fauna are productoids (especially the genus *Peniculauris*) and the rhynchonellid genus *Pontisia*. These species show closest affinities with Leonardian-age species from West Texas.

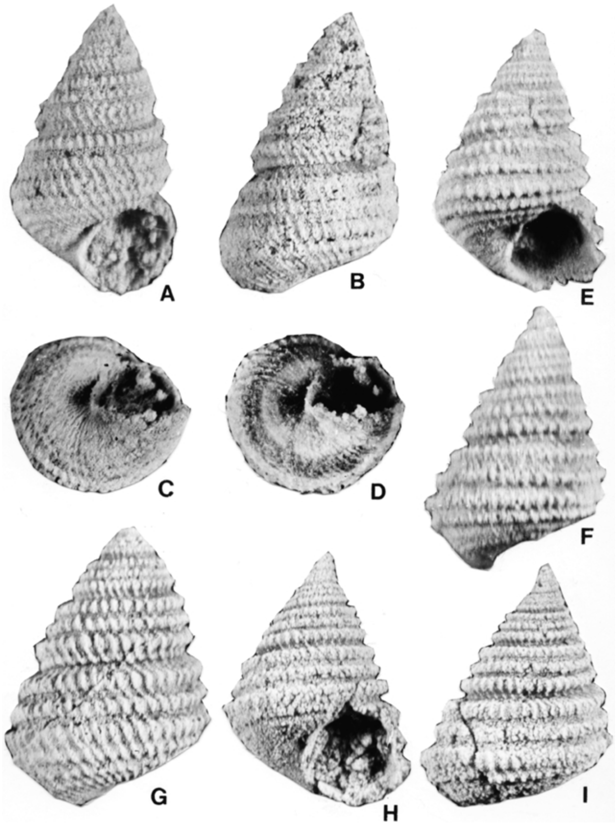

Fig. 7. *Glyptospira sonorensis* n. sp. from the lower part (39.6–45.6 m (130–150 ft), probably of late Wolfcampian age) of the measured section in Colina Limestone at Rancho La Cueva, all views ×4. (A–D) Holotype, ERNO-2465, apertural, abapertural, basal, and basal (uncoated with ammonium chloride to show color banding) views; (E–F) Paratype A, ERNO-2466, apertural and abapertural views; (G) Paratype B, ERNO-2467, abapertural view; (H–I) Paratype C, ERNO-2468, apertural and abapertural views. Like the closely related *G. arelela* Plas, it possesses well-preserved color bands on its base.

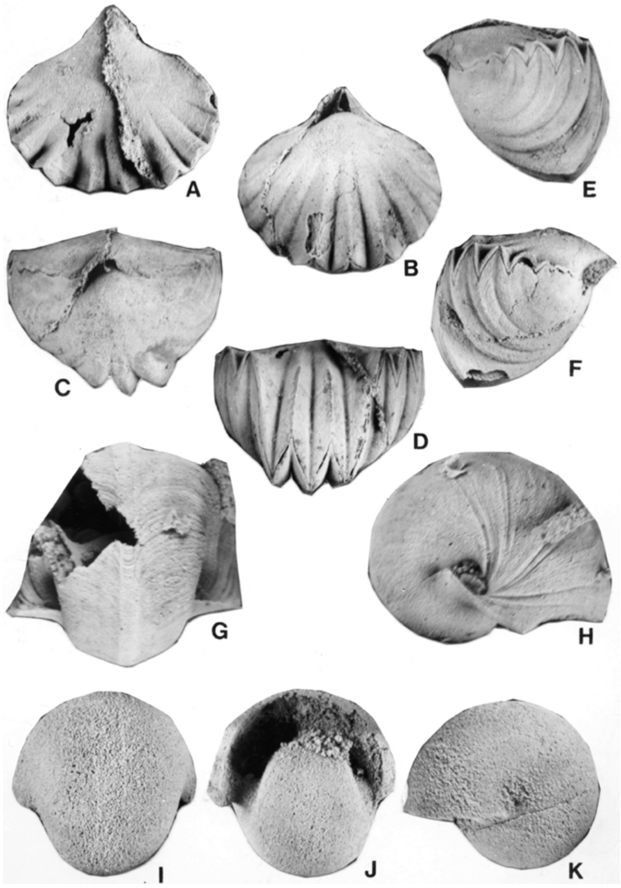

Fig. 8. Lower Permian (Leonardian) brachiopod and gastropods from the upper part of the Colina Limestone at Rancho La Cueva. (A–F) *Pontisia* n. sp. aff. *P. stehli stehli* Cooper and Grant 1976, ERNO-2469 from locality JS-96-45, which is laterally equivalent to the interval 214.9–216.5 m (705–710 ft) above the base of the measured section; ventral, dorsal, lateral, opposing lateral, posterior, and anterior views, ×2 (This new species closely approaches *P. stehli stehli*, but differs primarily in having costae that do not extend as far posteriorly); (G–H) *Bellerophon* sp., ERNO-2470 from 195.1 m (640 ft) above the base of the measured section, anterior and lateral views, ×2; (I–K) *Warthia* sp., ERNO-2471 from 192.6 m (632 ft) above base of the measured section, abapertural, apertural, and lateral views, ×2.

Samples of limestone were acidized from various megafossil-rich horizons throughout the Colina Limestone section at Rancho La Cueva and examined for conodonts. Unfortunately, only a few scrappy, indeterminate conodont fragments were recovered. The dearth of conodonts in the section is probably best attributed to the molluscan-dominated biofacies of the examined rocks, which typically do not contain abundant conodont remains.

5. Systematic paleontology

Only the newly established microdomatid gastropod species, *Glyptospira sonorensis* n. sp., is formally described here. All illustrated specimens are deposited in the collections of the Estación Regional del Noroeste del Instituto de Geología—UNAM, Hermosillo, Sonora, Mexico (ERNO).

Phylum MOLLUSCA
Class GASTROPODA
Order ARCHAEOGASTROPODA Thiele, 1925
Suborder TROCHINA Cox and Knight, 1960
Superfamily MICRODOMATOIDEA Wenz, 1938
Family MICRODOMATIDAE Wenz, 1938
Genus GLYPTOSPIRA Chronic, 1952
Glyptospira sonorensis new species
Fig. 7(A)–(I)

Diagnosis. Small, turbiniform species of *Glyptospira* with three prominent spiral carinae on upper whorl surface and a weaker fourth lower carina just above the sutural boundary, a weakly convex whorl profile between sutures, a minutely phaneromphalous base, and a distinct, broad, spiral color band on the base.

Description. Small, dextral, turbiniform shell of height up to 8.0 mm, with up to seven whorls; sutures weakly impressed; protoconch not clearly discernable due to coarse

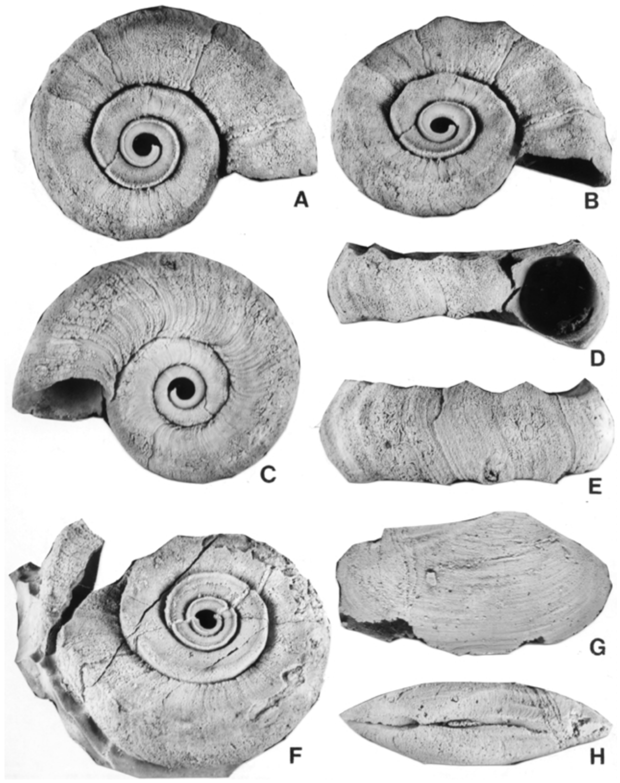

Fig. 9. Lower Permian (Leonardian) gastropod and bivalve from the upper part of the Colina Limestone at Rancho La Cueva. (A–F) *Euomphalus kaibabensis* Chronic 1952; (A–E) ERNO-2472 from 195.1 m (640 ft) above base of measured section, apical, oblique apical, basal, apertural, and abapertural views, × 1; (F) ERNO-2473 from locality JS-96-45, which is laterally equivalent to the interval 214.9–216.5 m (705–710 ft) above the base of the measured section, oblique apical view, × 0.75; (G–H), *Sanguinolites*? sp., ERNO-2474 from 195.1 m (640 ft) above the base of the measured section, right valve exterior and dorsal view of conjoined valves, × 1.5 (a similar, possibly conspecific form occurs in the Supai Group of central Arizona (see Winters (1963), pl. 8, figures 10(a) and (b))).

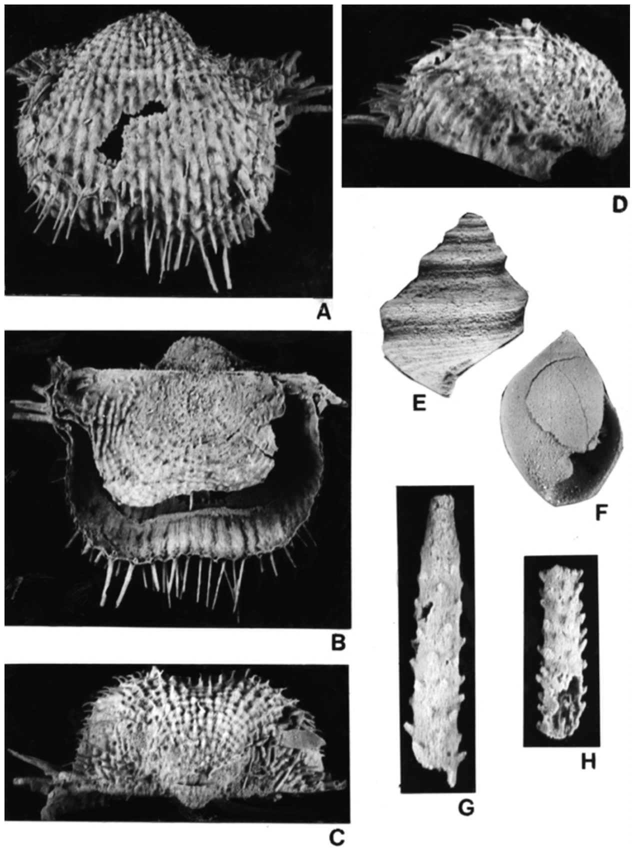

Fig. 10. Lower Permian (Leonardian) brachiopod, gastropods, and echinoid spines from the upper part of the Colina Limestone at Rancho La Cueva. (A–D) *Peniculauris* cf. *P. subcostata* (R.E. King), ERNO-2475, ventral, dorsal, posterior, and lateral views, × 1, from locality 97RB21, which is equivalent to an interval between 183.8 and 195.1 m (603–640 ft) in the section but situated downslope about 150 m west (just above road) of this interval in the measured section; (E) *Worthenia* cf. *W. crenulata* Batten 1989, ERNO-2476 from 195.1 m (640 ft) above base of measured section, abapertural view, × 2.5; (F) *Oncochilus insolitus* Chronic 1952, ERNO-2477 from 192.6 m (632 ft) above the base of the measured section, apertural view, × 2 (this species is also found in the Supai Group and Kaibab Formation of Arizona); (G–H) two echinoid spines, ERNO-2478 and ERNO-2479 from 195.1 m (640 ft) above the base of the measured section, × 1.5.

silicification; pleural angle varying from 45 to 60°; aperture subrounded, about one-third of shell height; whorl profile weakly convex between sutures, strongly rounded on final whorl; spiral ornament consists of three clearly distinct, strong carinae on the spiral whorls, roughly evenly spaced, with the lowermost cord peripherally situated and strongest, and a fourth weakly visible carina discernable just above the suture; final whorl bears two to three additional spiral carinae that are restricted to the upper half of the basal whorl surface and weaken in strength basally; collabral ornament consists of many closely spaced growth lines that are highly inclined and prosocline on the outer whorl surface and weakly opisthocyrt on the basal whorl surface; ornamentation has weakly nodose character at intersection of spiral and collabral elements; base rounded, with a narrow, deep umbilicus; a strong, broad spiral color band is present on base (Fig. 7(D)), nearly centrally situated with respect to the basal whorl surface.

Comparison. The unique combination of characters in the diagnosis clearly distinguishes the new species from all previously established species in the genus *Glyptospira*. The most similar species is *G. arelela* Plas 1972, from beds of probable late Wolfcampian age in the Arrow Canyon Range, Clark County, Nevada, which also possesses well-preserved color bands on its base. The Sonoran species differs in that it lacks the well-developed subsutural shelf found in the Nevadan species and has a broader, more centrally located spiral color band on its basal whorl surface. The new Sonoran species differs from the type species *G. cristulata* Chronic 1952, from the Leonardian of Arizona, in its tendency to have a much broader spired shell and stronger collabral ornament. In addition, it differs from the following species established by Erwin (1988) from the Permian of the southwestern United States as follows: *G. huecoensis* (has a broader spired shell, more spiral carinae on whorl surface), *G. turrita* (stronger development of collabral ornament, more spiral carinae on whorl surface), *G. cingulata* (has broader spired shell, spiral carinae more widely spaced, and collabral ornament stronger), and *G. tricostata* (possession of a minute umbilicus seemingly lacking in *G. tricostata*, more widely spaced spiral carinae).

Stratigraphic occurrence. The species is known only from the Colina Limestone at Rancho La Cueva, where it occurs in great abundance in the interval 39.6–45.7 m (130–150 ft) above the base of the measured section. Approximately 200 specimens present, making it the most abundant species found in this interval.

Types. Holotype, ERNO-2465, paratypes A–C, ERNO-2466-2468.

Etymology. After the State of Sonora, Mexico.

6. Discussion

The Pennsylvanian and Permian section in southeastern Arizona, which totals approximately 1.2–1.5 km in thickness, was assigned to the Naco Group by Gilluly et al. (1954). The type area of the Naco Group is near Tombstone (Fig. 1), where Gilluly divided the group into six formations (Fig. 11). Of these, five contain Permian strata: the upper part of the Pennsylvanian and Permian Earp Formation, the Lower Permian Colina Limestone, Lower Permian Epitaph Dolomite, Lower Permian Scherrer Formation, and Upper and Lower Permian Concha Limestone. We interpret the thick-bedded limestone present in the lower 240 m of our measured section as the Colina Limestone because of its Lower Permian age and lithologic features. Similar to the Colina, as described by Gilluly et al. (1954) and Blakey and Knepp (1989), the limestone near Rancho La Cueva is a resistant unit consisting of thick-bedded, limestone with sandy layers and a locally abundant gastropod and echinoid fauna. Sedimentary structures indicate the Colina of both areas was deposited in a subtidal to supratidal environment. Gilluly et al. (1954) reported that the Colina contains the Wolfcampian–Leonardian stage boundary, which we have found in the lower part of the measured section in the Rancho La Cueva area. The thickness of the Colina in its type area is 193 m (Gilluly et al., 1954), very similar to the minimum thickness we have assigned to the Colina (235 m) at Rancho La Cueva. We conclude that the Colina Limestone extends southwest across the international border into northern Sonora and that carbonate strata exposed at Rancho La Cueva, though incomplete, include nearly the full thickness of that unit.

The thickness of the overlying Epitaph Dolomite as reported by Gilluly et al. (1954), in contrast, is substantially greater north of the international border (238 m) than that part of the section that we have assigned to the Epitaph at Rancho La Cueva (11 m). Gilluly et al. (1954) interpreted dolomites in the Epitaph as of diagenetic rather than primary sedimentary origin, and Blakey and Knepp (1989) described the basal contact of the Epitaph as an irregular dolomitization boundary not confined to a given stratigraphic horizon. Thus, the thin Epitaph at Rancho La Cueva may be an artifact of the fluid rock compositions that led to alteration after deposition and does not reflect the depositional processes that controlled the thickness of the unit.

Similar to the Epitaph, the Scherrer Formation at Rancho La Cueva is much thinner than that reported by Gilluly et al. (1954) and Wrucke and Armstrong (1987) in southeastern Arizona. Near Tombstone, Gilluly et al. (1954) subdivided the Scherrer into three members, including lower and upper rusty red-brown weathering, quartz-rich siltstone and sandstone members and a thick middle limestone member. According to Gilluly et al. (1954), the sandstone and siltstone members, which are rippled and have silica-cemented, quartz-rich compositions, distinguish the Scherrer from all other units in the Naco Group. Because dolomite and algal limestone characteristic of the middle member of the Scherrer is not present in significant thicknesses in the Scherrer at the Rancho La Cueva locality, we conclude that the red-brown weathering, quartz-rich sandstone and siltstone that we have assigned to the Scherrer at the top of the Rancho La Cueva section represent an incomplete section of the lower member of the unit.

The Colina Limestone faunas of the La Cueva area closely resemble those described from the Colina of southeastern Arizona by Gilluly et al. (1954) and Gilluly (1956) in terms of the dominance of gastropods and echinoid spines (Fig. 10(G) and (H)) and a somewhat less dominant position occupied by brachiopods. Visits by Blodgett to the Colina Limestone exposures in the Tombstone Hills area and the Whetstone Mountains of southeastern Arizona confirmed both the lithologic and paleontologic correlations of the La Cueva exposures with those on United States' side of the border. Many of the same gastropod species are recognized in common in the upper horizons of the Colina Limestone of both regions, as well as further to the north in the Supai Group and Kaibab Formation of central and northern Arizona.

The Lower Permian section exposed at Rancho La Cueva indicates that the shallow marine shelf that existed in southeastern Arizona in the Permian extended southwest into Sonora. Although the Paleozoic sections to the east of the Rancho La Cueva area indicate that northeastern Sonora is underlain by a cratonal and covering Paleozoic section, the Permian is poorly represented in the Sierra El Tule and Sierra Los Ajos, the two best exposed Paleozoic successions west of N110°W. In Sierra El Tule, González-León (1986) assigned 140 m at the top of the Paleozoic succession to the Earp Formation and, on the basis of the presence of fusulininds and the weaker presence of gastropods, suggested that the environment of deposition was considerably more open marine than that represented by the Permian at Rancho La Cueva. Although it includes some Lower Permian strata, the Sierra El Tule section does not extend upward in the Naco Group to include any of the formations found at Rancho La Cueva. No Permian strata have been recognized to date in the Sierra Los Ajos. Fig. 11

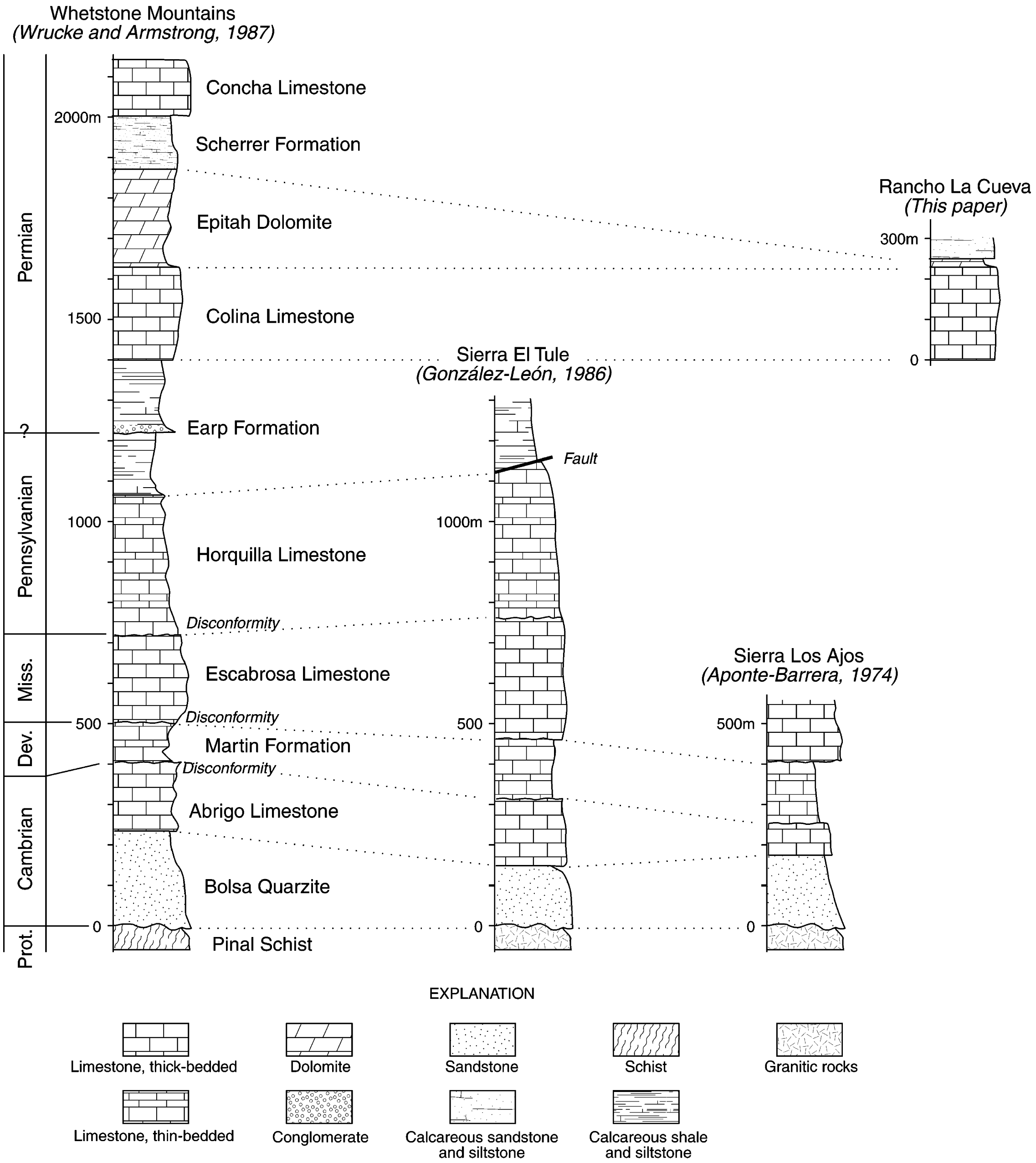

Fig. 11. Comparison of Proterozoic and Paleozoic stratigraphic sections of north central Sonora and southeastern Arizona. The placement of the Pennsylvanian–Permian boundary remains problematic in southeastern Arizona (Blakely and Knepp, 1989). As noted, it has historically been placed with the lower Earp Formation on the basis of fusulinid evidence, but Blakely and Knepp (1989) also note that it falls in the Horquilla Limestone in mountain ranges marginal to the Pedregosa basin facies.

schematically shows the stratigraphic position of the Rancho La Cueva section compared with the sections south of the international border in Sierra Los Ajos and Sierra El Tule and north of the border in the Whetstone Mountains. The southwestward extension of the middle and lower Paleozoic succession of southeastern Arizona into northern Sonora is apparent from previously published statigraphic relations, but the nature of the Permian section in north central Sonora is uncertain, because this part of the section is not present in the known Paleozoic sections. The new locality at Rancho La Cueva confirms that the Lower Permian units of the Naco Group once extended southwestward into northern Sonora and indicates that they were removed by later erosion in the Sierra El Tule and Sierra Los Ajos sections.

The Rancho La Cueva locality also supports the interpretation that the Paleozoic section extends westward across northern Sonora beneath covering Cretaceous and Tertiary volcanic and sedimentary strata. Although only a small part of the Paleozoic stratigraphic succession is exposed at Rancho La Cueva, it consists of strata from near the top of the Paleozoic section that are virtually identical in lithofacies to their type sections in southeastern Arizona. This implies that the entire underlying Paleozoic and Proterozoic stratigraphic section is present at depth in this area and that the Paleozoic section extends westward in Sonora beneath covering strata to at least the position of Rancho La Cueva. This interpretation substantiates the interpretation of Mulchay and Velasco (1954) that the protoliths of altered quartzite and carbonate rocks at Cananea represent parts of the Paleozoic stratigraphic succession, and it strengthens the interpretation that most or all of north central Sonora north of the hypothesized Mojave–Sonora megashear is underlain by the North American craton and its covering Paleozoic stratigraphic succession.

Finally, our stratigraphic and structural observations provide clues about the subsequent structural history in northern Sonora. The presence of southwest-directed folds that deform the Paleozoic section, though constrained only as post-Permian in age and indicative only of minor displacement, demonstrates that the Rancho La Cueva area experienced an episode of contractional deformation following deposition. The folds have northwest-trending axes that are similar to Laramide structures described in southern Arizona and northern Sonora by Davis (1979). Although most Laramide structures are northeast directed in southern Arizona, Laramide folds and thrusts in the Huachucha Mountains are southwest directed, much like those in the Rancho La Cueva area. These observations suggest that the folds in Rancho La Cueva are probably Laramide structures. Although Davis (1979) argued that the Huachucha Mountains structures root into deep-seated, nearly vertical faults, recent work has indicated that southwest-directed structures of Laramide-type in the Rocky Mountains orogen, such as those in the Huachucha Mountains, are conjugate structures rooted on a detachment deep in the crust in an overall northeast-directed contractional orogen (Krantz, 1989; Oldow et al., 1989, Fig. 1). It is unclear whether the southwest-directed folds in the Rancho La Cueva area are part of the same system of southwest-directed folds and faults in the Huachucha Mountains or whether the Rancho La Cueva structures are parasitic folds to a different system of Laramide structures that is located to the southwest of the Huachucha Mountains, as the north-westward projection of the fold trends would indicate. We note, however, that the presence of uppermost Cretaceous volcanic rocks in unconformable contact on the Permian sections and the absence of the Upper Cretaceous rocks of the Cabullona basin indicate that the Rancho La Cueva area was probably a structural high in the Late Cretaceous. A thick sequence of clastic sedimentary rocks of the Cabullona basin are present in both the northern part of the Sierra Los Ajos and adjoining areas to the northeast and east (Fernandez-Aguirre and Almazán-Vázquez, 1991; González-León and Lawton, 1995). The strata of the Cabullona basin have been interpreted as syntectonic deposits that were shed southwestward from areas uplifted on Laramide thrust faults. It is possible that the Rancho La Cueva area was located in the hanging wall of a Laramide thrust and may have formed part of a highlands for the Cabullona basin in the Late Cretaceous.

7. Conclusions

Three Lower Permian stratigraphic units of the Naco Group (Colina Limestone, Epitaph Dolomite, and Scherrer Formation) are demonstrated in a 2 km^2 stratigraphic window in the vicinity of Rancho La Cueva (north of Cananea) in northern Sonora. Their presence strengthens the stratigraphic ties of this part of Sonora with North American cratonal stratigraphy recognized in southeastern and northern Arizona. These three Lower Permian units are virtually identical in lithofacies with their type sections in southeastern Arizona and represent the westernmost known exposure of the sedimentary cover of the North American craton south of the international border between Mexico and the United States. The molluscan-dominated biofacies (lacking fusulinids) of the Colina Limestone contains a richly diverse fossil assemblage. These are readily separated into two fossiliferous horizons in the stratigraphic window at Rancho La Cueva: a lower horizon of probable late Wolfcampian age and an upper horizon of Leonardian age. Gastropods are notably abundant in this unit and share many species with the Colina Limestone of southeastern Arizona, the Supai Group and Kaibab Formation of northern and central Arizona, and time-correlative strata in west Texas.

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