THE ORIGIN OF CHERT IN THE CONCHA LIMESTONE (PERMIAN) OF SOUTHEASTERN ARIZONA

by

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APPROVAL BY THESIS DIRECTOR

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DATE
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ABSTRACT

Biogenic silica (opal-A) from the dissolution of sponge spicules is thought to have been the major source of silica for the chert in the Concha Limestone (Permian) of southeastern Arizona. Minor sources included the underlying sandstones of the Scherrer Formation and from calcite replacement of eolian sand. The mixing zone model of chertification (Knauth, 1979) best explains the two-dimensional aspect and great lateral extent of the chert zones; and the presence of almost limpid dolomite rhombs and well-preserved sponge spicules in the chert nodules. Concha chert precipitated as microcrystalline quartz and penecontemporaneously with sediment deposition prior to lithification. Decaying organic matter provided numerous sites for quartz crystallite nucleation and served to localize chert precipitation. Contacts between areas of differing porosity-permeability also localized chert formation.
INTRODUCTION

Chert nodules in carbonate rocks have been studied since the late 1800's. Most of these earlier studies lacked understanding of carbonate depositional and diagenetic processes and silica solution chemistry. The questions of timing, silica source, and diagenetic environments of chertification have been addressed only in the past 28 years (Ireland, 1959; Meyers, 1977).

Bryant (1951) is the most significant work on the Concha Limestone. The Concha Limestone and its included chert, therefore, have not been studied using modern carbonate petrology and other tools of present-day science.

Location

The Concha Limestone crops out in Pima, Santa Cruz, and Cochise counties in southeastern Arizona (Fig. 1) and extends into New Mexico and Chihuahua, Mexico. In southeastern Arizona, the known western limit of the Concha Limestone is Kohtkohi Hill at the extreme northeastern corner of the Papago Indian Reservation, 6 miles west of Silver Bell in central Pima County. The known eastern limit is Dunn Springs Mountain located between and to the east of the Dos Cabezas Mountains and the Chiricahua Mountains in eastern Cochise County.
Fig. 1. Concha Limestone outcrops in southeastern Arizona.
The emphasis of this study is in the Waterman Mountains, Pima County, Arizona, approximately 42 miles west of Tucson, Arizona. The Waterman Mountains are easily accessible from Tucson and contain a complete Concha Limestone stratigraphic section with excellent chert development and fossil preservation. Reconnaissance studies were also conducted in the Gunnison Hills, Cochise County; and in the Mustang Mountains, Canelo Hills, and Montosa Canyon in Santa Cruz County; and in the Helvetia area in Pima County (Fig. 1).

**Purpose and Scope of Research**

The Concha Limestone (Permian) contains abundant chert as nodules, in pseudobeds, and as "networks of seams" (Bryant, 1951). The purpose of this study is to determine the source and probable precipitation mechanism for this chert and other silica within the Concha Limestone.

Both field and laboratory work were performed to determine the source and mechanism of chertification. The field work included reconnaissance, measuring stratigraphic sections, mapping, and sampling. The laboratory work included petrographic thin section analysis, preparation of insoluble residues, X-ray diffraction, and scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDXA) of selected samples.
Study Methods

The two measured stratigraphic sections (Appendix A) were taken on the East Hill in the W^NE¼ sec. 31, T. 12 S., R. 9 E. and on the west-facing slope of the Front Range in the NE¼NE¼ sec. 31, T. 12 S., R. 9 E. of the Silver Bell Peak Quadrangle (Fig. 2). These informal place names are those of McClymonds (1957). The sections were measured with a tape and Brunton compass.

Five areas of one square meter (1 m²) were mapped within selected units of the East Hill measured section (Appendix B) at a 1:10 ratio. Such detailed mapping is able to show the relative proportions and relationships of fossils, chert nodules, and limestone in a representative area of the unit. It is effective in visually presenting relationships that cannot be adequately described or photographed.

Extensive sampling was done throughout the formation. Samples of both chert and carbonate were taken at regular intervals (Appendix A). These samples were then subjected to standard geological laboratory procedures.

Sixty-five samples were used to make petrographic thin sections. These thin sections were stained using a standard Alizarin Red S (ARS) solution, which stains calcite and aragonite red to pink and ferroan dolomite and calcite purple, but leaves dolomite and silica unstained.
Fig. 2. Study area in the Waterman Mountains, Pima County, Arizona.
Twenty-one samples were processed for their insoluble residues using hydrochloric acid (HCl) to dissolve the carbonate. The insoluble residues were divided into greater than four phi (> 4Ø) and less than four phi (< 4Ø) size fractions. Four phi (62 μm) is the boundary separating very fine sand from silt-sized material. The <4Ø fraction was further separated into silt-size and clay-size fractions. The >4Ø and silt fractions were examined visually with a microscope. The clay fractions of three selected samples were X-rayed to identify their constituents.

Scanning electron microscopy (SEM) was conducted on seven selected samples. These samples were prepared using three different procedures. Six of the silt fractions from the insoluble residues were coated with a mixture of gold and palladium in a sputter coater. Flakes from one chert nodule were coated manually with either carbon alone or with gold covering a carbon undercoat. Electron dispersive X-ray analysis (EDXA) was also conducted on the chert nodule samples.
Previous Studies

Significant previous studies are those of James Gilluly, J. R. Cooper, and J. S. Williams (1954); Donald L. Bryant (1951); and Donald L. Bryant and Neal McClymonds (1961). Table 1 lists other workers and their contributions to the stratigraphy and paleontology of the Concha Limestone.

Gilluly et al. (1954) designated and described the type section for the Concha Limestone from Concha Ridge in the Gunnison Hills, Cochise County, Arizona (Fig. 1). The Concha Limestone at the type locality consists of 130 feet (40 m.) of limestone with an eroded top. Williams concluded that the fossils were Leonardian to Guadalupian age and suggested that the Concha Limestone is equivalent to the Beta Member of the Kaibab Limestone of northern Arizona.

Bryant (1951) mapped the Cave Creek Formation (Concha Limestone) and described its stratigraphic section in the Mustang Mountains, Santa Cruz County, Arizona. Bryant also performed an extensive paleontological study (Appendix C). He identified 34 species of brachiopods, 27 species of gastropods, seven species of pelecypods, two species of bryozoa, two species of sponges, two species of ammonites, and one horn coral. His thesis contains numerous excellent photographic plates of these fossils.
Table 1: Summary of Significant Previous Studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ransome, 1904</td>
<td>Identified and named the Naco Group.</td>
</tr>
<tr>
<td>Stoyanow, 1926</td>
<td>Mapped the Chiricahua Limestone in the Chiricahua Mountains and correlated it to the Kaibab Limestone.</td>
</tr>
<tr>
<td>--------, 1936</td>
<td>Mapped the Snyder Hill formation, Pima County.</td>
</tr>
<tr>
<td>Johnson, 1941</td>
<td>Mapped in Helvetia area, Santa Rita Mountains.</td>
</tr>
<tr>
<td>Jones, 1941</td>
<td>Mapped in Helvetia area, Santa Rita Mountains.</td>
</tr>
<tr>
<td>Feth, 1948</td>
<td>Mapped in Canelo Hills, Santa Cruz County.</td>
</tr>
<tr>
<td>Bryant, 1951</td>
<td>Mapped in Mustang Mountains; identified fossils; measured stratigraphic section.</td>
</tr>
<tr>
<td>--------, 1955</td>
<td>Correlated Concha Limestone across southeastern Arizona.</td>
</tr>
<tr>
<td>-------- and McClymonds, 1961</td>
<td>Designated a reference section in the Mustang Mountains.</td>
</tr>
<tr>
<td>McClymonds, 1957</td>
<td>Mapped in the Waterman Mountains, Pima County.</td>
</tr>
<tr>
<td>--------, 1959</td>
<td>Mapped in Kohtkohl Hill, Pima County.</td>
</tr>
<tr>
<td>Sabins, 1957</td>
<td>Identified Leonard age and Guadalupe age fusulinids from the Chiricahua Mountains, Cochise County.</td>
</tr>
<tr>
<td>Sulik, 1957</td>
<td>Mapped in Montosa Canyon, Santa Rita Mountains.</td>
</tr>
</tbody>
</table>
Bryant and McClymonds (1961) proposed the 570 feet (174 m.) thick stratigraphic section in the Mustang Mountains as a reference section for the Concha Limestone because the type section is incomplete. The Concha Limestone reaches its maximum known extent in the Mustang Mountains.
STRAITIGRAPHY

Gilluly et al. (1954) formally named the Concha Limestone. Prior to their work, other workers used various informal names for the Concha Limestone. Ransome (1904) included it as the youngest member of the Naco Group of southeastern Arizona. Stoyanow referred to the Concha Limestone as either the Chiricahua limestone (1926) or as the Snyder Hill formation (1936). Bryant (1951) mapped it as the Cave Creek Formation.

Paleogeography

The Concha Limestone was deposited in the Pedregosa Basin of southeastern Arizona, southwestern New Mexico, and northern Chihuahua, Mexico (Fig. 3). It is one of the youngest formations preserved within the basin (Table 2). Deposition of the Concha Limestone marks the known maximum extent of the Permian sea in southeastern Arizona (Butler, 1971).

The Pennsylvanian-Permian Pedregosa Basin was a northwest trending embayment that plunged to the southeast (Peirce, 1976). It was bounded on the northwest by the Mazatzal Uplift and on the southeast by the Marathon-Ouchita tectonic belt. The Diablo Uplift separated the
Fig. 3. Pedregosa Basin. Boundary drawn where Pennsylvanian-Permian rocks exceed 2000 feet in thickness. Figure is from Greenwood et al., 1977.
Table 2: Pennsylvanian-Permian Formations Within the Pedregosa Basin

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Description (Bryant, 1968)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Prince Limestone</td>
<td>Morrowan</td>
<td>Dominantly light gray limestone with a pinkish tinge; basal 20-30 feet is red-maroon shale; green-mottled red shale beds.</td>
</tr>
<tr>
<td>Horquilla Limestone</td>
<td>Morrowan</td>
<td>Light to dark gray, cherty limestone pink-gray in many places; Some beds are predominantly crinoid debris; red and green shale.</td>
</tr>
<tr>
<td>Earp Formation</td>
<td>Virgilian to Wolfcampian</td>
<td>Thin, vari-colored (pinkish, yellowish, greenish gray) shaley limestones with sandstones, siltstones, and shales.</td>
</tr>
<tr>
<td>Colina Limestone</td>
<td>Wolfcampian to Leonardian</td>
<td>Dominantly thick-bedded to massive dark gray to black limestone.</td>
</tr>
<tr>
<td>Epitaph Formation</td>
<td>Leonardian</td>
<td>Dolomite with limestone, mudstone, and dolomite in the upper part.</td>
</tr>
<tr>
<td>Scherrer Formation</td>
<td>Leonardian</td>
<td>Dominantly sandstone with limestone and siltstone.</td>
</tr>
<tr>
<td>Concha Limestone</td>
<td>Leonardian to Guadalupian</td>
<td>Thick bedded to massive, very cherty, very fossiliferous limestone; medium gray.</td>
</tr>
<tr>
<td>Rainvalley Formation</td>
<td>Guadalupian</td>
<td>Thinner, vari-colored, dolomitic limestone with minor sandstone.</td>
</tr>
</tbody>
</table>
Pedregosa Basin from the Permian Basin of western Texas and, the Burro, Florida, Moyotes, and Huerco Uplifts separated the Pedregosa Basin from the Orogrande Basin of New Mexico (Greenwood, Kottlowski, and Thompson, III, 1977) (Fig. 3).

The Pedregosa Basin was formed during the Pennsylvanian Period as a result of intraplate deformation associated with formation of the Ancestral Rockies by the Ouchita orogeny. The Ouchita collision orogeny joined Laurasia and Gondwanaland to form the Pangea supercontinent. "Irregularities in the shape of the pre-collision Ouchitan margin served to guide stresses along preferred paths across the transcontinental arch. The Pedregosa Basin was part of a broad platform belt that had previously closed around the nose of the transcontinental arch" (Dickinson, 1981) (Fig. 4).

**Concha Limestone Lithologies**

The Concha Limestone may be divided into three members on the basis of topographic expression, color, chert nodule content and character, and fossil assemblages. These members are continuous, where exposed, throughout southeastern Arizona but, their thicknesses vary according to their location within the Pedregosa Basin. Bryant and
Fig. 4. Paleogeography of southwestern North America from the Pennsylvanian to Mid-Triassic Periods. (Dickinson, 1981)
McClymonds (1961) and Vaag (personal communication, 1983) recognized similar informal members. See the two measured sections in Appendix A for detailed lithologic descriptions including the fossil content of each unit.

Lower member:

In the Waterman Mountains, the lower member is 113 feet (34 m.) thick with 90 feet (27½ m.) forming a massive cliff and the remaining 23 feet (7 m.) consisting of slope-forming units at the base and top of the cliff. Units 1 through 12 of the measured sections form the lower member with Unit 12 grading into the middle member. Contact with the underlying Scherrer Formation is conformable.

Lithology as determined by field and microscopic examination is a biomicrosparite (Folk, 1959). The rock exhibits porphyroid aggrading neomorphism (Folk, 1965). The micrite groundmass is from 1 to 4 μm in size while the microspar patches grade from 4 μm along the edge to 12 μm in the center. There are a few units of microsparite present. These lithologies are predominantly medium gray (N5) on fresh surfaces and weather to medium light gray (N6) (Goddard, 1948). Sedimentary structures seen in the lower member are channel fills, burrows, laminations, and convoluted bedding. Dolomitic patches occur in certain units.
The chert nodule content is 33 percent for the lower member as a whole but varies from 0 to 60 percent in certain units. Nodules range from 1 to 36 inches (2½-91½ cm.) in length and from 1 to 18 inches (2½-46 cm.) in thickness. Exterior surfaces weather predominantly moderate yellowish brown (10 YR 5/4); interiors are generally gray calcite and silica intermixed.

The lower member is the most fossiliferous of the three informal members. Fossils are also well-preserved and diverse. In addition to the large productid brachiopods Rugatia occidentalis and Peniculauris bassi (formerly Dictyoclostus sp.), echinoid spines, bryozoans, Actinocoelia meandrina Finks, and "fossil hash" dominate the fauna.

Middle member:

Units 13 through 18 of the measured sections comprise the middle member. It is a cliff-former 165 feet (50 m.) thick but is slightly less resistant than the lower member. The member is a biomicrosparite. Microscopic examination revealed porphyroid aggrading neomorphism but less well-developed than the lower member. The micritic matrix consists of 1 to 3 µm grains with coarser patches grading to 5 µm. Some units (13 and 17) contain beds of pelmicrite. The pelloids are about 48 µm measured on their long axes. Lithologies are uniformly medium
dark gray (N4) on fresh surfaces and weather medium light gray (N6). Channel fills were the only sedimentary structures observed.

Chert nodule content is 6 percent for the entire member, but ranges from 0 to 10 percent in certain units. Nodule dimensions are smaller than those in either the lower or upper members. Length ranges from $\frac{1}{2}$ to 6 inches (1-15 cm.); thickness varies from $\frac{1}{4}$ to 2 inches ($\frac{1}{2}$-5 cm.). Nodule exteriors weather from grayish brown (5 YR 3/2) to dusky brown (5 YR 2/2); interiors are dark gray to black and well-silicified.

Fossils are abundant but less so than in the lower and upper members. Brachiopods are more diverse than in the lower member but are of smaller genera than the large productids found in the lower member. Gastropods first occur in the middle member and become more abundant toward the top of the member. *Actinocoelia* sp., locally abundant in the lower member, is found only rarely in one unit of the middle member. Complete silicified bryozoans and echinoid spines are present in great abundance. "Fossil hash" is the dominant organic remains.
Upper member:

Units 19 through 32 of the measured sections make up the upper member. It consists of 240 feet (73 m.) of resistant, massive to thinly bedded limestone. Contacts with the middle member and with the overlying Rainvalley Formation are gradational.

The upper member is the most variable of the three members in both lithology and color. The lithologies include biomicrosparites and microsparites with 1 to 3 μm groundmass and 5 to 7 μm patches of porphyroid aggrading neomorphic calcite. A few units have beds containing 15 percent well-rounded, bimodal sand grains (100 μm and 60 μm). Many of the units have a yellowish or pinkish tinge on both fresh and weathered surfaces. However, the upper member is predominantly medium dark gray (N4) and weathers to medium light gray (N6). Sedimentary structures observed include hummocky bedding planes, channel fills, convoluted bedding, laminations, and rip-up clasts.

Average chert nodule content is 19 percent for the member but ranges from 1 to 40 percent. Nodule dimensions are from 1 to 12 inches (2½-30 cm.) in both length and thickness. Exteriors weather mainly light brown (5 YR 6/4) to moderate brown (5 YR 4/4). Interiors consist of gray calcite and silica intermixed. Nodules in the top units may have hollow, quartz-lined vugs.
Fossils within the upper member are both abundant and diverse. Horn corals were first observed within the upper member in the Waterman Mountains, Pima County, Arizona. Brachiopods are most diverse in the upper member. Fusulinids occur in two thin beds near the top of the upper member (McClymonds, 1957). Other fossils present are similar in occurrence to those in the other two members.

**Paleoecology and Paléontology**

Many of the physical parameters were similar to those of modern environments. Permian organisms filled ecological niches similar to modern niches and, therefore, these fossil species each had a set of environmental limiting factors that defined their respective niches. Limiting factors are those "physical, chemical, and biological properties of an environment that limit the distribution of any given species" (Raup and Stanley, 1971). These factors limit "either through restriction of immigration and reproduction or through increased death and emigration rates (Beerbower, 1968).

Table 3 lists environmental factors present within the Concha Limestone depositional regime. Table 4 lists the requirements of the organisms found within the Concha Limestone. The Concha Limestone was deposited in the subtidal zone, in waters of normal salinity, low turbidity,
Table 3: Environmental Factors during deposition of the Concha Limestone

<table>
<thead>
<tr>
<th>Factor</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year length</td>
<td>390 days (Wells, 1963)</td>
</tr>
<tr>
<td>Day length</td>
<td>21 hours (Stokes, 1973)</td>
</tr>
<tr>
<td>Basin latitude</td>
<td>± 7° of equator (Poole, 1964)</td>
</tr>
<tr>
<td>Climate</td>
<td>Hot, arid (Nairn, 1964; Poole, 1964; Butler, 1971)</td>
</tr>
<tr>
<td>Light:Darkness ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Seasonal variability</td>
<td>None significant</td>
</tr>
<tr>
<td>Wind directions</td>
<td>Trade winds blowing from north or northeast to south or southwest (Poole, 1957; 1964)</td>
</tr>
<tr>
<td>Water depth</td>
<td>Subtidal, 100-150 feet (Bryant, 1951; Butler, 1971)</td>
</tr>
<tr>
<td>Salinity</td>
<td>Normal marine (Bryant, 1951)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Low</td>
</tr>
<tr>
<td>Energy</td>
<td>Low to moderate</td>
</tr>
<tr>
<td>Substratum</td>
<td>Firm to hard</td>
</tr>
<tr>
<td>Species diversity</td>
<td>High (Bryant, 1951)</td>
</tr>
</tbody>
</table>
Table 4: Ecological Constraints of Organisms (Ladd, 1957; McAlester, 1977; Heckel, 1972; Dodd and Stanton, 1981)

<table>
<thead>
<tr>
<th>Brachiopoda</th>
<th>Bryozoa</th>
</tr>
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<tbody>
<tr>
<td>Euryhaline</td>
<td>Stenohaline</td>
</tr>
<tr>
<td>Soft to firm substrate</td>
<td>Firm to hard substrate</td>
</tr>
<tr>
<td>Low energy</td>
<td>Low to moderate energy</td>
</tr>
<tr>
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and low to moderate energy. The species present are those of a diversified deeper-water shelf fauna (Butler, 1971).

As noted in the previous section, the fossils present in the Concha Limestone can be divided into three assemblages based on either abundance or occurrence of a particular fossil group. These assemblages are the productid brachiopod-Actinocoelia assemblage in the lower member; the gastropod-bryozoa assemblage in the middle member; and the horn coral-brachiopod assemblage in the upper member.

The productid brachiopod-Actinocoelia assemblage is based on the abundance of the large productid brachiopods Rugatia occidentalis and Peniculauris bassi and the lithistid Demospongea Actinocoelia meandrina Finks. Prior to the work of Muir-Wood and Cooper (1960), the brachiopods were classified as Dictyoclostus paraindicus McKee. These organisms are found in the middle and upper members but not in as great an abundance as in the lower member. In Quadrat 1 (Appendix B), 20 "Dictyoclostus" brachiopods were counted in one square meter. Ten sponges were counted in Quadrat 2. Other fossils are also abundant, making the lower member the most fossiliferous of the members.

The gastropod-bryozoa assemblage is found in the middle member where it is defined on the first occurrence of gastropods and the presence of especially well-preserved
trepostome bryozoa. Although gastropods also occur in the upper member, they are most abundant in the middle member. The middle member is least fossiliferous.

The horn coral-brachiopod assemblage is based on the first occurrence of horn corals and the great diversity of brachiopods. Bryant (1951) found horn corals in the middle member of the Concha Limestone in the Mustang Mountains. The horn corals are only found in the upper member in the Waterman Mountains.

Although, in general, all three assemblages indicate the same broad environmental conditions, clearly there were important differences. The lower member was deposited under generally transgressive conditions. This is evident by the succession of lithologies. The Scherrer sandstones are in conformable contact (Gilluly et al., 1954; Bryant, 1951; McClymonds, 1957) with the silty, dolomitic units of the basal lower member. These units are followed by limestones deposited in more open marine conditions.

The middle member was deposited under generally regressive conditions. The darker color, sandy and dolomitic units; units with pelmicrite beds; and the abundance of gastropods indicate deposition under more restricted conditions than that of the lower member. Shell debris is the dominant fossil constituent.
The upper member was deposited under more varied conditions. The characteristics of the units (Appendix A) indicate deposition mainly during marine transgression, but several of the units indicate possible regression. The upper member grades into the Rainvalley Formation which was deposited generally during marine regression (Vaag, 1984)
SILICA OCCURRENCES

Silica in the form of chert nodules occurs in great abundance in the Concha Limestone. Factors necessary to the formation of chert are an adequate source of silica; solutions capable of transporting silica to the site of deposition; an environment at this site that inhibits silica solubility and promotes carbonate solubility; and reaction rates that cause carbonate dissolution to be roughly equal to silica precipitation (Lovering, 1972).

Silica Types

Silica in the Concha Limestone occurs in four mineralogical and/or textural varieties: chalcedony; "chert" in nodules, veinlets, and fossil replacement; authigenic quartz crystals; and sand grains.

Folk (1980) divides sedimentary quartz into three forms:

"(1) megaquartz, a general term for quartz overgrowths, crystals, geode and vein fillings, composed of equant to elongated grains larger than 20 microns; and (2) microquartz, divided into (2A) microcrystalline quartz, forming a pinpoint-birefringent aggregate of equidimensional grains usually ranging from 1-5 microns in diameter (but ranging from a fraction of a micron—in the apparently isotropic cherts—to 20 microns, the arbitrary upper limit); and (2B) chalcedonic quartz, forming sheaf-like bundles of radiating extremely thin fibers, which average about
0.1 mm long but may range from 20 microns to a millimeter long. All three types are transitional in some degree."

Chert is composed chiefly of microcrystalline quartz, and may contain chalcedonic quartz in significant amounts. Minor amounts of megaquartz and impurities (clay and carbonate minerals, pyrite, and organic matter) may also occur.

Chalcedony:

Microcrystalline quartz is the principal constituent of Concha cherts. Chalcedony is usually but not always found in the chert nodules. More often the chalcedony occurs as vug fillings or linings within the nodule, and fossil replacements. Spherical fans of chalcedony in fossil body cavities sometimes have as their nucleus, hematite pseudomorphs after pyrite (Fig. 5). The chalcedony is length-fast (Fig. 6). At least two episodes of chalcedony vug/cavity lining may be recognized in thin sections (Fig. 7). Many of the vugs also contain microcrystalline quartz grading to megaquartz in their centers. Some chalcedony show dolomite rhomb ghosts.

Chert:

The term "nodule" as applied to the chert in the Concha Limestone is a misnomer. "Nodule" implies a discrete, rounded, roughly spherical body (Bates and Jackson, 1980).
Fig. 5. Spherical chalcedony fans in fossil body cavity. Fans have hematite pseudomorphs after pyrite as nuclei. Plane light. 150X
Fig. 6. Length-fast chalcedony vug-filling. Upper photograph—crossed nicols; lower photograph—crossed nicols with gypsum plate inserted. 150X
Fig. 7. Two episodes of chalcedony cavity linings. Best seen on upper edge of cavity. Cavity is filled with mega-quartz. Upper photograph--plane light; lower photograph--crossed nicols. 150X
The nodules in the Concha Limestone, when viewed perpendicular to bedding, appear to be elongated, rounded, and flattened bodies subparallel to bedding (Fig. 8). In plan view, the nodules are seen to form an anastomosing, three dimensional web (Quadrat 4, Appendix B). However, the term "nodule" will be used for lack of a better term.

Chert nodules are the most abundant form of silica in the Concha Limestone. For the formation as a whole, the chert nodules amount to 19 percent. The lower, middle, and upper members contain 33, 6, and 19 percent chert nodules respectively. Certain units have a maximum of 60 percent chert nodules while others possess no chert nodules. The nodules vary considerably in size among the three members, but the sizes are fairly consistent within a member.

The colors of the chert nodules are also fairly consistent within a member although the colors are various shades of brown on the weathered surface; unweathered interiors of the nodules are various shades of gray and vary from very light gray to very dark gray.

The brownish colors are due to the presence of minute quantities of iron oxide contained in the chert nodules. Less than 1 percent iron oxide is sufficient to color chert (Lovering, 1972). EDXA, which has a
Fig. 8. Chert nodules exposed perpendicular to bedding. Waterman Mountains, Pima County, Arizona. Photograph courtesy of Myra K. Vaag.
resolution of 1 percent, showed only silicon, calcium, and magnesium (Fig. 9). EDXA does not analyze for carbon or oxygen.

The chert nodules consist of varying proportions of microcrystalline quartz and calcite. Minor amounts of dolomite, hematite, ilmenite, leucoxene, chalcedony, megaquartz, and clay also occur. Calcite as fossil remains is abundant.

The microcrystalline quartz occurs both as a replacement of included fossils and as groundmass not obviously associated with fossil remains (Fig. 10). The quartz bodies average 10 \( \mu \text{m} \) in fossil replacement and less than 3 \( \mu \text{m} \) in the groundmass.

Calcite occurs as either original limestone, neomorphic microspar, original fossil material, or as late stage sparry calcite vein-fillings. The calcite crystals are generally larger in the chert nodule than in the surrounding limestone.

Dolomite occurs as two populations. The most abundant group consists of large (12-163 \( \mu \text{m} \), average 50 \( \mu \text{m} \) in diameter) rhombs with abundant inclusions (Fig. 11). These rhombs show two growth zones, and some have been dedolomitized. They are found in both limestone and chert. In nodules, they occur as patches and single rhombs in the
10000

SI
KA

X-RAY LINE ENERGIES:

MG/KA - 1252 KEV
SI/KA - 1730 KEV
CA/KA - 3690 KEV
CA/KB - 1012 KEV.

Fig. 9. EDXA graph of chert nodule composition.
Fig. 10. Pervasive chert replacement of limestone. Crossed nicols. 150X
Fig. 11. Dolomite rhombs lining vug and in groundmass. Crossed nicols. 150X
groundmass and concentrated along fractures. The second group consists of small, clear rhombs with few inclusions (Fig. 12). They average 20 μm in diameter, range from 12 to 40 μm in diameter, and are only found in chert. They are often associated with fossils. Both populations show minor and occasional replacement by microcrystalline quartz.

Hematite is found as pseudomorphs after pyrite. It occurs as cubes and dodecahedra associated with fossils, as chalcedony nuclei, and independently in limestone and chert (Figs. 5 and 13). Iron-stain haloes are seen around some grains. Ilmenite altering to leucoxene occurs only rarely.

Clay is not abundant; it was difficult to obtain enough for X-ray diffraction. The clay-size fraction consists of illite, quartz, pyrophyllite/talc, and an unidentified mineral.

The chert nodules exhibit no internal structure except that some few nodules have concentric bands of alternating silica and calcite. SEM viewing shows the chert to be of the novaculite type (Folk and Weaver, 1952). Figure 14 illustrates the polyhedral, blocky crystals typical of the microcrystalline quartz.
Fig. 12. Clear dolomite rhombs in chert. White areas are chert; brown areas are limestone. Plane light. 150X
Fig. 13. Ostracod showing complex replacement.

Cubic, opaque grains are hematite pseudomorphs after pyrite; grains are concentrated along the outer and inner surfaces of the shell and found primarily in chert. From the exterior surface of the shell to the inner body cavity, the replacement sequence is as follows: 1) chert (3 µm) in a zone 8 µm wide; 2) neomorphic calcite (1 µm); 3) micritic shell material (1 µm); 4) neomorphic calcite (1 µm); 5) chert (same geometry as no. 1 above); 6) two populations of sparry calcite void-fill; 7) megaquartz from 13 µm to 195 µm in center of body cavity.
Fig. 13. Ostracod showing complex replacement. Upper photograph—crossed nicols; 40X. Lower photograph is an enlargement of the lower right area of the ostracod. Crossed nicols. 150X
Fig. 14. SEM photographs of chert surface texture.

Cherts are of the novaculite type. Rightmost scale bar is equal to 0.1 microns.
Fig. 14. SEM photographs of chert surface texture. Rightmost scale bar is equal to 0.1 micrometers.
In these nodules, the boundary between the nodule and the enclosing limestone appears diffuse under the petrographic microscope. However, they are resistant enough to be exposed to a height of 4 inches (10 cm.) above a weathered limestone surface.

Fossils are abundant in the nodules and include intact brachiopods, whole sponges, complete bryozoa, intact ostracods, complete horn corals, whole gastropods, fragments of the above fossils, echinoid (sea urchin) spines, productid brachiopod spines, and sponge spicules. The fossils are generally composed of original shell material as evidenced by the structure of the fossil. Most of the fossils show only partial replacement by microcrystalline quartz if any (Fig. 15). There is no preferred orientation within the chert.

Chert is also found as veinlets or wispy seams in certain units. The veinlets are usually less than 3 mm in thickness, but can extend for a meter or more. Occasionally, the veinlets are associated with nodules, but they are more often independent. The veinlets show no single preferred orientation within the formation; however, there is a preferred orientation within a unit. They may be subparallel to bedding or at an angle to bedding. There is no obvious association with fossils.
Fig. 15. Fossils exhibiting partial replacement by chert. White/light areas are chert. Plane light. 40X
Replacement of fossils by microcrystalline quartz also occurs outside chert nodules. A preferred order of silicification among the fossil groups may be recognized. The siliceous sponge *Actinocoelia* sp. is the most susceptible followed by horn corals, brachiopods, echinoid spines, bryozoa, crinoid columnals, and gastropods. In the Concha Limestone if any fossils are silicified, they are from the most susceptible groups followed in order by the remaining groups. This can be seen in the field and microscopically.

The order of silicification is influenced but not wholly dependent on original fossil structure and mineralogy. Others (Schmitt and Boyd, 1981; Cooper and Grant, 1972; Meyers, 1977) have found different orders of silicification than the hierarchy found in the Concha Limestone. Hintze (1953) found that the order of silicification within the same fossil assemblage to vary with the fossil assemblage's position within the basin of deposition.

The sponge, *Actinocoelia* sp., was made of small (2-875 μm) siliceous spicules embedded in protoplasm. The spicules, which were originally biogenic opal, have been replaced by microcrystalline quartz (Fig. 16). The axial canal is still present in some spicules (Fig. 17). The complete sponge is often found included within chert.
Fig. 16. Sponge spicules replaced by microcrystalline and megacrystalline quartz. Crossed nicols. Upper photograph--40X; lower photograph--150X.
Fig. 17. SEM photograph of sponge spicule. Note morphology of chert in remainder of insoluble residue and presence of clay crystal "book" in lower right corner. Leftmost scale bar is equal to 1 micrometer.
nodules (Fig. 18). This is evidence that chert replacement was rapid and penecontemporaneous with the organism's death for those sponges included within nodules.

Brachiopods possess two valves composed of low magnesian calcite. In the Concha Limestone, the brachiopods frequently are still articulated and some possess attached spines. The shell is filled with micrite while the surfaces of the valves are replaced by chert and chalcedony. The valve interiors have been replaced by sparry calcite in the cases of the large productid brachiopods. Other brachiopod valve fragments show the wavy original shell structure and are replaced by chert and authigenic quartz in an irregular fashion (Fig. 15).

Horn corals are always replaced by chert in the Waterman Mountains. Their skeletons were originally composed of low magnesian calcite. They are found both in and outside of chert nodules. Except for a few units, they are not abundant.

Permian bryozoans were composed of high magnesian calcite although probably containing less magnesium than present species (Richter and Fuchtbauer, 1978). Complete bryozoans are found included in chert nodules and as silicified fossils outside nodules. Bryozoans are also found as unsilicified fragments in units containing bryozoa
Fig. 18. *Actinocoelia* sp. sponge included in chert nodule. Gunnison Hills, Cochise County, Arizona. Photograph courtesy of Myra K. Vaag.
in chert nodules. The bryozoa skeleton in chert nodules and independent of nodules may be only partially replaced by chert. In nodules, the skeletal pores are often filled by chert and dolomite while the skeleton remains calcite.

Echinoid (sea urchin) spines and crinoid columnals are both composed of high magnesian calcite. Echinoid spines have a lacy structure while crinoid columnals are single calcite crystals. Silicification usually occurs on the outer surfaces, along cleavage planes, or along some break in the structure. Echinoid spines are much more susceptible to silicification than are crinoid columnals.

Gastropods are very rarely silicified. Permian forms had shells composed of either aragonite or low magnesian calcite depending on the species. Even when the body cavities are lined with chalcedony or filled with chert, their shells are usually not silicified.

Petrographic evidence (Figs. 16 and 19) indicates some of the fossils underwent a moldic stage prior to replacement by chert. Schmitt and Boyd (1981) recognized five patterns of silicification in their studies. Patterns I, II, and III, indicative of an open void stage, were found in the Concha Limestone.
Fig. 19. Fossil exhibiting moldic-stage replacement. Crossed nicols. 150X
Pattern I consists of megaquartz lining and filling the void (Fig. 16). Pattern II has microcrystalline quartz lining the void, followed by hemispherical fans of chalcedony with megaquartz filling the interior of the void (Fig. 19). Pattern III is essentially the same as pattern II, but the chalcedony forms a continuous lining with the long axes of the fibers perpendicular to the void wall.

Authigenic quartz:

Authigenic quartz is found throughout the Concha Limestone. It accounts for the bulk of the insoluble residue and occurs predominantly as disseminated crystals. Authigenic quartz crystals are also found in chert nodules, in fossil replacement, vugs, and in veins.

The crystals are often doubly-terminated, idiomorphic, pitted, and contain abundant carbonate inclusions (Fig. 20). Some of the crystals have quartz sand grains as nuclei but most do not. The crystal size ranges from 750 μm to silt-size; average size is 75 to 100 μm in length by 25 μm in width.

Sand grains:

Sand grains are scarce in the Concha Limestone except for certain units in the middle and upper members where sand grains comprise 15 percent of the rock.
Fig. 20. Authigenic quartz crystals. Upper photograph--plane light; lower photograph--crossed nicols. 150X
The grains are well-rounded, bimodal (60 and 100 µm) and are believed to be of eolian origin. Thin section studies show many of the quartz grains partially replaced by calcite.

Silica Sources

There are three possible sources for the silica contained within the Concha Limestone. The primary source is biogenic; the other two sources are inorganic.

Dissolution of siliceous sponge spicules is the primary source of the silica. Evidence to support this supposition is the presence of siliceous sponges (Fig. 18) and their spicules in chert nodules (Fig. 17), and the occurrence of spicules within the limestone (Fig. 16). The fossil sponge, *Actinocoelia* sp., occurs abundantly in the lower member and sporadically in the middle member. Monaxon and possible polyaxon siliceous spicules are present in all three members.

Another source of the silica is the sandstones of the underlying Scherrer Formation. Their proximity to the lower member and the great abundance of chert in the lower member lend circumstantial support to this proposal.

A third and quite minor source of the silica is eolian sand. Several units in the middle and upper members contain up to 15 percent sand grains in various stages
of replacement by calcite. The small size (very fine sand to silt-size) plus the distance from land of the depositional site point to an eolian source. Land sources were probably to the north.

Precipitation Mechanism

Knauth's (1979) mixing zone theory of chert formation best accounts for the features observed in the Concha cherts. He proposes that mixing of fresh and marine waters can lead to the creation of a geochemical environment favorable to chert formation. Water moving as a result of compaction or sea-level change may become saturated with silica as it passes through a sediment pile containing siliceous spicules (or other siliceous microfossils). Figure 21 illustrates this situation.

Biogenic silica (amorphous opal, opal-A) from sponge spicules is believed to be the major source of silica in the Concha Limestone. Siliceous sponges produce spicules from sea water undersaturated [0.1 to 14 ppm silica (Krauskopf, 1959; Williams and Crerar, 1985)] with respect to both opal-A [solubility 100 to 140 ppm (Jones and Segnit, 1971)] and quartz [solubility 6 ppm (Morey, Fournier, and Row, 1962)] possibly by a process of enzyme catalysis. After the organism's death, the spicules are subject to dissolution by the undersaturated waters.
Fig. 21. Mixing zone model of chert formation. Sediments are carbonate containing significant amounts of biogenic silica. Figure from Knauth (1979).
Biogenic opal-A is thought to convert to quartz under progressive diagenesis. "The generalized diagenetic sequence is: opal-A (siliceous biogenic ooze) → opal-A' (secondary amorphous silica) → opal-CT (opal-cristobalite/tridymite) → reordered opal-CT → cryptocrystalline quartz or chalcedony → microcrystalline quartz" (Williams and Crerar, 1985). However, only silica phases showing opal-A, opal-CT, and quartz ordering have been observed to form. Williams, Parks, and Crerar (1985) propose that the opal-A → opal-CT → quartz transformations follow a dissolution-reprecipitation pathway.

"The diagenetic pathway of silica is controlled mainly by aqueous solubility of the phases, which is primarily a function of crystal structure and particle size and shape" (Williams et al., 1985). Silica concentration in pore waters is also influenced by pH of the water; temperature and pressure; type and concentration of other dissolved silica species; and other minerals in the sediment. Of these factors, only pH is likely to have been involved in the Concha chert formation. The Concha Limestone has never been buried deeply since no indication of regional metamorphism has been seen. It consists of essentially monomineralic biomicrosparite.
Modern sea water is supersaturated with respect to calcite, and there is little reason to think Permian seas were not. However, it is possible for two waters, each saturated as to calcite, to be undersaturated when mixed if the original waters differed in either carbon dioxide (CO₂) gas partial pressure or in temperature (Knauth, 1979). Therefore, in the mixing zone of meteoric and marine waters, the resultant water can be simultaneously undersaturated with respect to calcite and supersaturated with respect to quartz and amorphous silica leading to carbonate dissolution and silica precipitation.

Features of the Concha cherts explained by Knauth's model are the generally two-dimensional aspect and great lateral extent of the chert zones; the presence in chert nodules of almost limpid dolomite rhombs which indicate slow crystal growth in waters of very low salinity to fresh waters; and the well-preserved spicules observed in chert nodules.

Given the extremely gentle slope (less than one foot per mile, .02 percent) of epeiric sea floors (Irwin, 1965), small changes in sea-level can result in large expanses of sediment being exposed or covered (Fig. 22).
Fig. 22. Effect of porosity-permeability on the thickness of the chertification zone. Relatively porous and permeable shoreline sediments prograde over offshore sediments of low porosity and low permeability. The mixing zone is effectively confined to a narrow interval above the contact of these contrasting sediments to produce a relatively thin horizon of silicification. Figure from Knauth (1979).
This, of course, affects the lateral extent of the meteoric-marine mixing zone. This zone is the site of chert formation and can cover many thousands of square kilometers (Back and Hanshaw, 1970). Regression is probably responsible for initiating chert precipitation since shelf carbonates tend to be exposed to freshwater recharge during regression.

Siliceous spicules preserved in chert nodules retain their axial canal (Finks, Yochelson, and Sheldon, 1961) (Fig. 17) while spicules outside the nodules have undergone a moldic stage before being replaced by microcrystalline quartz grading to megacrystalline quartz (Fig. 16). Biogenic silica in waters supersaturated with respect to opal-A would not dissolve and would thus be preserved intact within the nodules (Knauth, 1979).

Knauth's model does not explain the strong association of fossils with chert nor does it address kinetic questions of nucleation and the rate of crystalline silica precipitation from supersaturated solutions. Field and petrographic evidence indicate that decaying organic matter served to localize chert formation (Figs. 13 and 18) in many instances; although, in other cases (Quadrat 4), porosity-permeability contrasts served to localize chert formation. Oehler (1976) showed that decaying organic
matter provides numerous chemically reactive sites for quartz crystallite nucleation. Intact fossils are frequently silicified while fragments are not. Intact fossils were more likely to have organic matter associated with them at deposition than fragments which had been mechanically and biologically processed before their deposition. Hematite pseudomorphs after pyrite are closely associated with fossil remains (Fig. 13). The pyrite probably formed through bacterial action associated with organic decay.

Field observations show that chert formation occurred prior to lithification and penecontemporaneous with sediment deposition. The abundance of life, current activity, and well-oxygenated bottom conditions preclude any great time span between organism death and inclusion in chert nodules—especially for the sponges.

Knauth (1979) states that it is possible for much of the mixing zone to be saturated with regard to quartz (solubility 6 ppm) but undersaturated with respect to biogenic opal (100 to 140 ppm solubility). Therefore, the silica phase precipitated would be quartz because amorphous silica would be subject to dissolution.

Schmitt and Boyd (1981) also suggest that chert precipitated as microcrystalline quartz rather than as amorphous silica. Their mechanism involves the migration
of interstitial waters of normal pH (approximately 8) and that skeletal dissolution resulted in silica concentrations of 20 to 30 ppm. Pore waters would thus be supersaturated with regard to quartz but undersaturated with respect to amorphous silica. At high silica concentrations, precipitation was relatively rapid giving rise to microcrystalline quartz and chalcedony. Megaquartz precipitated at slower rates during periods of lower dissolved silica concentration in the pore waters.

Although authors have seen, via SEM and TEM, evidence of opal-A $\rightarrow$ opal-CT $\rightarrow$ quartz transformations in their Paleozoic rocks, no evidence of this has been seen in the Concha Limestone. It seems most likely that chert in the Concha Limestone precipitated as microcrystalline quartz in a mixed marine-meteoric water zone.
SUMMARY AND CONCLUSIONS

1) The Concha Limestone can be divided into three informal members—lower, middle, and upper—on the basis of topographic expression; color; chert content and character; and fossil assemblages. The lower member is medium gray (N5) and weathers to medium light gray (N6) in color. It contains the most chert (33 percent) and is most fossiliferous. The productid brachiopod—Actinocoelia assemblage is found in the lower member. The middle member forms a cliff as does the lower member but, is darker in color—medium dark gray (N4) on fresh surfaces weathering to medium light gray (N6). The middle member contains the least chert (6 percent) and fossils with most of the fossils consisting of "fossil hash." The fossil assemblage present is the gastropod-bryozoan assemblage. The upper member forms massive to thinly bedded, resistant beds. Its colors are more variable than that of the other members. The unit exhibits pinkish to yellowish tinges on both fresh and weathered surfaces. It is intermediate between the lower and middle members in chert content (19 percent) and fossil content. The fossil assemblage is the horn coral-brachiopod assemblage.
2) Limestone lithologies are predominantly biomicrosparites with minor units and beds of microsparite and pelmicrite. Many units, especially chert-rich ones, have irregular patches of dolomite within them. All lithologies exhibit porphyroid aggrading neomorphism. The micritic groundmass is from 1 to 3 \( \mu \text{m} \) in grain size while the patches grade from about 4 \( \mu \text{m} \) along the edge to as much as 12 \( \mu \text{m} \) in the center. Neomorphic calcite is best developed in the lower member.

3) Chert nodules are composed of microcrystalline quartz and calcite with minor amounts of dolomite, hematite, clays, chalcedony, megaquartz, and abundant fossil remains. Grain size of the cherts is from less than 1 \( \mu \text{m} \) (average 3 \( \mu \text{m} \)) in the groundmass to 10 \( \mu \text{m} \) in fossil replacement.

4) Biogenic silica from the dissolution of sponge spicules is believed to be the major source of silica. Silica from the underlying sandstones of the Scherrer Formation and from replacement of eolian sand by calcite is a minor additional source of silica for the cherts.

5) Chertification occurred prior to lithification and penecontemporaneously with sediment deposition. Features such as differential compaction around nodules and intact sponges and other fossils within chert nodules support this interpretation. Petrographic evidence supports belief that at least two episodes of chertification/dolomitization occurred.
6) Mixing of marine and fresh waters in a coastal setting (Knauth, 1979) is the most probable precipitation mechanism. Undersaturated waters (with respect to silica) moving through the sediment would dissolve siliceous spicules increasing the concentration of dissolved silica. In a chemically favorable region such as a mixing zone, it is possible to have waters simultaneously undersaturated with respect to calcite and saturated with regard to quartz (or amorphous silica). Therefore, calcite would dissolve and silica would precipitate.

7) Chert was probably precipitated as microcrystalline quartz in the Concha Limestone with decaying organic matter and regions of differing porosity-permeability serving to localize chert precipitation.
RECOMMENDATIONS FOR FURTHER STUDY

The Concha Limestone has been extensively studied only in the Mustang Mountains (Bryant, 1951; Bryant and McClymonds, 1961) and in the Waterman Mountains. Field work by the author and work done by others (Table 1) indicate that these above localities are fairly typical of the entire formation. Nonetheless, detailed field and petrographic work should be done to verify this conclusion.

Oxygen and carbon isotope determinations should be done on both the chert and carbonates of the Concha Limestone. The $\delta^{18}O$ and $\delta^{13}C$ values can be used to infer burial depth and water composition at the time of formation for the chert and for the carbonates. Comparison between the values for carbonate and for chert will determine the timing of chertification (Meyers and James, 1978). This would be most valuable in substantiating or disproving the precipitation mechanism proposed for chert in the Concha Limestone.

The lithologies present in the Concha Limestone should also be examined using cathodoluminescent microscopy and fluorescent microscopy. These two techniques
may be useful in determining the timing of chertification and lithification. Fluorescent microscopy is capable of discerning features not apparent by the other techniques (Dravis and Yurewicz, 1985).
APPENDICES
APPENDIX A: STRATIGRAPHIC SECTIONS

Two stratigraphic sections were measured with a tape and Brunton compass. Standard geologic procedures were used to correct for dip and slope angle (Compton, 1962). The color designations are those of the Geological Society of America's Rock Color Chart (Goddard, 1948).

Section 1

Section 1 was measured on the East Hill in the Waterman Mountains, in the W^NE sec. 31, T. 12 S., R. 9 E., Silver Bell Peak Quadrangle, Pima County, Arizona. Informal place names are those of McClymonds (1957) (Fig. 2).

Permian:

Rainvalley Formation:

Limestone (biomicrite), medium dark gray (N4), weathering light gray (N7) to medium light gray (N6); very slightly fetid; white quartz-lined, calcite-filled vugs \( \frac{1}{2} - 2 \) inches \((\frac{1}{2}-5 \text{ cm.})\); whole brachiopods, "fossil hash"......unmeasured

Strike and dip: N. 40° W., 75° NE.

Concha Limestone:

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Description</th>
<th>Unit Thickness</th>
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<tbody>
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<td>32</td>
<td>Limestone (bioclastic), dark gray (N3) to medium dark gray (N4), weathers light gray (N7) with yellowish gray</td>
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(5 Y 8/1) silty layers; very slightly fetid; white calcite-filled vugs ½-2½ inches (1-6 cm.), contain authigenic quartz crystals; chert, 1 percent, contain quartz-filled vugs, 1-3 inches (2½-7½ cm.), weather dark yellowish brown (10 YR 4/2), gray calcite interiors; fossils include horn corals, echinoid spines, productid spines, *Composita*; forms resistant ledges 1-3 feet (.3-1 m.) thick; gradational upper contact ........................................30.0 9.1

31 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6) with yellowish gray (5 Y 8/1) silty layers; slightly fetid; extensive stylolitization; white calcite-filled vugs, 1-4 inches (2½-10 cm.); chert, 10 percent, weathers moderate brown (5 YR 3/4), gray calcite interiors, irregular nodules, 3-12 inches (7½-30½ cm.) in length, 1-3 inches (2½-7½ cm.) in thickness; echinoid spines, productid spines, *Dictyoclostus,* horn corals, *Dielasma, Marginifera,* trepostome bryozoa, and bellerophontid gastropods dominate the fossils; irregular lower contact; forms resistant beds 1-4 feet (.3-1½ m.) thick ........5.0 1.5

30 Limestone (microsparite), medium gray (N5), weathers medium gray (N5); 1-3 inches (2½-7½ cm.) thick silt layers in middle of unit; chert, 20 percent, weathers dark yellowish brown (10 YR 4/2), ½-3 inches (1½-7½ cm.) in thickness, 1-6 inches (2½-15½ cm.) in length, contain quartz-lined vugs ½-2 inches (1-5 cm.); fossils include horn corals, echinoid spines, trepostome bryozoa, *Marginifera,* "Dictyoclostus;"* forms resistant beds 1-4 feet (.3-1½ m.) thick ......................10.5 3.2
29 Limestone (microsparite), medium light gray (N6), weathers very light gray (N8) to light gray (N7); dolomitic areas; chert, 30 percent, well-developed nodules, weathers moderate brown (5 YR 3/4), dark gray silica interiors; fossils include shell fragments, productid spines, echinoid spines; gradational upper contact; thickness irregular; resistant beds 1-4 feet (.3-1 ¼ m.) thick.........................6.0 1.8

28 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6) to pinkish gray (5 YR 8/1); fetid; chert, 10 percent, weathers moderate brown (5 YR 3/4), 1-4 inches (2%-10 cm.) in length, 1-12 inches (2%-30 cm.) in thickness, more abundant at base of unit; fossils include shell fragments, productid spines, crinoid columnals, turreted gastropods, horn corals; channel fills contain coarser fossil debris; resistant beds 2-6 feet (%-2 m.) thick...............................14.0 4.3

27 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6); 3 inches (7½ cm.) thick silt layers; slightly fetid; chert, 5 percent, weathers moderate brown (5 YR 3/4), gray calcite interiors, most abundant at base; fossils include "Dictyoclostus,* fenestrate bryozoa, bellerophontid gastropods, "fossil hash;" crops out as resistant beds 1-3 feet (.3-1 m.) in thickness.................10.5 3.2

26 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6) mottled with yellowish gray (5 YR 8/1) silty patches; chert, 35 percent, weathers moderate brown (5 YR 4/4), 1-7 inches (2½-17 ½ cm.) in length and 1-2 inches (2½-5 cm.) in thickness, found in bands; fossils include bryozoa, "Dictyoclostus,* Composita; resistant beds........................................8.0 2.4
25 Limestone (microsparite), medium light gray (N6) to light brownish gray (5 YR 6/1), weathers light brownish gray (N7); fetid; chert, 40 percent, in pseudobeds, weathers moderate brown (5 YR 3/4), dark gray calcite interiors; Composita, crinoid columnals, shell fragments; resistant, massive...7.5 2.3

24 Limestone (biomicrosparite), dark gray (N3) to medium dark gray (N4), weathers medium gray (N5) grading to yellowish gray (5 Y 8/1) at top of unit; fetid; chert, 2 percent, poorly developed, more abundant at base, weathers moderate yellowish brown (10 YR 5/4); fossils include horn corals, echinoid spines, productid spines, "Dictyoclostus,* turreted and bellerophontid gastropods; 1-4 feet (.3-1 m.) thick resistant beds...30.0 9.1

23 Limestone (biomicrosparite), medium dark gray (N4) to brownish gray (5 YR 4/1), weathers medium light gray (N6) to yellowish gray (5 Y 8/1); chert, 1 percent, weathers light brown (5 YR 6/4); fossils include Composita, Enteles, Marginifera, fenestrate and trepostome bryozoa, crinoid columnals, echinoid spines; forms resistant, 1-3 feet (.3-1 m.) thick beds...11.0 3.4

22 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6); slightly fetid; chert, 20 percent, poorly developed, forms veinlets, weather light brown (5 YR 6/4) to dusky brown (5 YR 2/2); fossils include "Dictyoclostus,* Dielasma, horn corals, crinoid columnals, shell fragments; forms 1-3 feet (.3-1 m.) thick resistant beds...21.0 6.4
21 Limestone (microsparite), medium dark gray (N4), weathers medium gray (N5) mottled light olive gray (5 Y 6/1); chert, 1 percent, weathers light brown (5 YR 6/4); fossils include bryozoa, brachiopods; forms massive bed .............5.0 1.5

20 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6) to pinkish gray (5 YR 8/1) at top of unit; slightly fetid; chert, 20 percent, weathers moderate brown (5 YR 3/2), interiors are calcite, found in bands; fossils include crinoid columnals, Composita, horn corals; forms resistant, 1-6 feet (.3-2 m.) thick beds ..................................................20.0 6.1

Strike and dip: N. 45° W., 59° NE.

19 Limestone (biomicrosparite), medium gray (N5) grading to medium dark gray (N4) in the lower 15 feet (4½ m.), weathers medium gray (N5) to medium light gray (N6) with pinkish gray (5 YR 8/1) areas; fetid; dolomitic; chert, 40 percent, occurs as irregular nodules, 1-24 inches (2½-61 cm.) in length and thickness, weather light brown (5 YR 6/4) to black with medium gray calcite interiors; fossils include a 1-2 feet (.3-½ m.) thick fusulinid zone in the top 2 feet (½ m.) of the unit, crinoid columnals, echinoid spines, "Dictyoclostus,"* Composita, Neospirifer, bryozoa, horn corals; forms resistant beds 1-6 feet (.3-2 m.) thick .........................61.0 18.6

Strike and dip: N. 45° W., 60° NE.

18 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6); fetid; dolomitic; chert, 10 percent, nodules, weather grayish brown (5 YR 3/2) to dusky brown (5 YR 2/2), dark gray (N3) silica interiors; fossils include echinoid spines, shell fragments; resistant, 1-3 feet (.3-1 m.) thick beds ..................................................57.0 17.4
17 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6); fetid; chert, 10 percent, dark gray interiors, silicified, weather pale yellowish brown (10 YR 6/2); bellerophontid gastropods, Actinocoelia, brachiopods, bryozoa, echinoid spines, crinoid columnals; forms resistant beds 1-4 feet (.3-1¾ m.) thick......................25.0 7.6

16 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6); fetid; chert, 5 percent, nodules smaller than those of unit 17, chert decreases to top of unit, interiors are black, well silicified; fossils include echinoid spines, productid spines, shell fragments, fenestrate and trepostome bryozoa, gastropods; resistant, cliff-former............................11.0 3.4

15 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6); fetid; chert, 1 percent, scattered; fossils include bellerophontid and turreted gastropods, trepostome bryozoa, fenestrate bryozoa, "Dictyoclostus,"* echinoid spines, crinoid columnals, productid spines; white calcite filled vugs 1-3 inches (2¾-7¾ cm.); resistant, cliff-former.............................27.5 8.4

14 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6); fetid; dolomitic; chert, 5 percent, weathers moderate yellowish brown (10 YR 5/4), irregular nodules, increase in abundance toward top of unit, interiors are dark gray, well silicified, ½-6 inches (1¾-15 cm.) in length, ½-2 inches (.8-5 cm.) in thickness; fossils include productid spines, shell fragments, bryozoa, brachiopods, crinoid columnals, Dielasma; gradational upper and lower contacts, resistant, cliff-former.................................12.5 3.8
13 Limestone (biomicroparite), medium dark gray (N4), weathers medium light gray (N6); fetid; minor chert, weather moderate yellowish brown (10 YR 5/4); fossils include productid spines, crinoid columnals, "Dictyoclostus,"* Composita, bryozoa; gradational upper and lower contacts, forms a cliff....................32.0  9.8

Units 13 through 18 form a prominent cliff.

12 Limestone (biomicroparite), medium dark gray (N4), weathers medium light gray (N6); chert, 10 percent, weathers pale yellowish brown (10 YR 6/2), 3-12 inches (7½-30½ cm.) in length, ¾-2 inches (1½-5 cm.) in thickness; fossils include crinoid columnals, echinoid spines, "Dictyoclostus,"* bryozoa; forms saddle, beds ½-2 feet (.2-½ m.) in thickness......12.0  3.7

11 Limestone (biomicroparite), medium dark gray (N4) to dark gray (N3), weathers light gray (N7) to medium light gray (N6); slightly fetid; dolomitic patches; chert, 60 percent, irregular nodules in pseudobeds, weather moderate yellowish brown (10 YR 5/4) to black, smaller at top of unit, interiors increasingly silicified toward top of unit; fossils include Actinocoelia, "Dictyoclostus,"* Fenestrella associated with chert nodules; echinoid spines, productid spines; forms cliff.........................42.0  12.8

10 Limestone (biomicroparite), medium gray (N5), weathers medium gray (N5); slightly fetid; chert, 5 percent, weathers moderate yellowish brown (10 YR 5/4), well-developed nodules, rounded, interiors are intergrown silica and calcite; fossils include Fenestrella, trepostome bryozoa, shell fragments, crinoid columnals; massive, cliff-former with channel fill consisting of bryozoan fragments in middle of unit.................2.5  0.8
72

9 Limestone (microsparite), medium gray (N5), weathers light gray (N7) to medium light gray (N6); slightly fetid; silty; chert, 50 percent, weather moderate yellowish brown (10 YR 5/4), irregular nodules, interiors are intergrown calcite and silica; "Dictyoclostus,"* fenestrate and trepostome bryozoa, not associated with chert; cliff-former........3.0 0.0

8 Limestone (biomicrosparite), medium gray (N5), weathers light gray (N7) to medium light gray (N6); very fetid; dolomitic; silty areas; chert, 40 percent, irregular nodules, weather moderate yellowish brown (10 YR 5/4), mostly gray silica interiors but some with calcite interiors, 1-36 inches (2½-91 cm.) in length, 1-8 inches (2½-20½ cm.) in thickness, contain Actinocoelia, "Dictyoclostus,"* form pseudobeds, silt commonly associated with chert bands; extensive stylolitization; fossils include "Dictyoclostus,"* crinoid columnals, echinoid spines; resistant beds 2-8 feet (½-2½ m.) in thickness.......12.0 3.7

7 Limestone (biomicrosparite), medium light gray (N6) to light brownish gray (5 YR 6/1), weathers light gray (N7) to medium light gray (N6); fetid; chert, 20 percent, in irregular nodules, 1-36 inches (2½-91 cm.) in length, 2-18 inches (5-45½ cm.) in thickness, in bands, weather moderate yellowish brown (10 YR 5/4), contain "Dictyoclostus,"* Fenestrella, and Actinocoelia, many exhibit concentric, alternating bands of calcite and silica; resistant..............8.0 2.4

6 Limestone (biomicrosparite), medium light gray (N6), weathers light gray (N7) to medium light gray (N6); slightly fetid; veinlets of white calcite; chert, 3 percent; fossils decrease in abundance toward top of unit, "Dictyoclostus,"* bryozoa, echinoid spines; resistant, massive......................6.5 2.0
5 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6); slightly fetid; silty with authigenic quartz crystals; dolomitic; chert, 20 percent, in irregular nodules, $\frac{1}{4}$-24 inches (1$\frac{1}{4}$-61 cm.) in length and $\frac{1}{2}$-5 inches (1$\frac{1}{4}$-12$\frac{1}{2}$ cm.) in thickness, weathers moderate yellowish brown (10 YR 5/4), calcite interiors, contain "Dictyoclostus,"* trepostome bryozoa, Actinocoelia; other fossils are echinoid spines, "fossil hash;" forms resistant beds.................................10.5 3.2

4 Limestone (biomicrosparite), medium dark gray (N4), weathers medium light gray (N6), abundant "Dictyoclostus,"* fenestrate and trepostome bryozoa, and productid spines........................................2.5 0.8

3 Limestone (microsparite), medium gray (N5), weathers light gray (N7) to light brownish gray (5 YR 6/1); fetid; fossils are echinoid spines; resistant..............3.0 0.9

Units 3 through 11 form a prominent cliff.

2 Limestone (microsparite), medium light gray (N6), weathers light gray (N7) to pinkish gray (5 YR 8/1); very slightly fetid; bands of dolomite; fossils, 20 percent, include echinoid spines, crinoid columnals, "Dictyoclostus;"* slope-former, beds 1-2 feet (.3-$\frac{1}{2}$ m.) thick........3.5 1.1

1 Limestone (microsparite), medium gray (N5), weathers light gray (N7) to medium light gray (N6); slightly fetid; bands of dolomite; slope-former, beds 1-1$\frac{1}{2}$ feet (.3-$\frac{1}{2}$ m.) thick..........................7.0 2.1

Fault contact

Scherrer Formation:

Quartzarenite, grayish pink (5 R 8/2), weathers grayish orange pink (5 YR 7/2); case-hardened with silica............. unmeasured
Section 2

Section 2 was measured down the west face of the
Front Range in the NE 1/4 NE 1/4 sec. 31, T. 12 S., R. 9 E., Silver
Bell Peak Quadrangle, Pima County, Arizona. Informal place
names are those of McClymonds (1957) (Fig. 2).

Permian:

Rainvalley Formation:

Limestone (biomicrite), medium dark gray (N4), weathers
light gray (N7) to medium light gray (N6); very slightly
fetid; quartz-lined, calcite filled vugs 1/2-2 inches (1.25-
5 cm.); fossils include "fossil hash," and brachiopods
partially replaced by silica.....................unmeasured

Strike and dip: N. 12° E., 27° SE.

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<th>Unit No.</th>
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<td>32</td>
<td>Limestone (biomicrite), dark gray (N4), weathers light gray (N7) to pinkish gray (5 YR 8/1); yellowish gray (5 Y 8/1) silty layers; slightly fetid; white calcite filled vugs 1-2 inches (2.5-5 cm.) contain authigenic quartz crystals; scattered chert nodules, 1-36 inches (2.5-91 cm.) in length, weather dark yellowish brown (10 YR 4/2); fossils include Composita, Dielasma, horn corals, &quot;Dictyoclostus,/* rhynchonellid brachiopods, productid spines, echinoid spines, and bellerophontid gastropods; forms saddle with 1-4 feet (.3-1.2 m.) thick beds.................................</td>
<td>29.0</td>
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31 Limestone (biomicroparite), medium dark gray (N4), weathers medium light gray (N6), yellowish gray (5 Y 8/1) silty layers; slightly fetid; chert, 5 percent, in irregular nodules, weather moderate brown (5 YR 3/4), interiors consist of gray calcite, extensive stylolitization; white calcite vugs 1-4 inches (2½-10 cm.); fossils include Dielasma, "Dictyoclostus,"* Marginifera, productid spines, echinoid spines, trepostome bryozoa, bellerophontid gastropods, horn corals; cliff-former with an irregular lower contact.................................5.0 1.5

30 Limestone (microparite), medium gray (N5), weathers medium gray (N5); chert, 15 percent, weathers dark yellowish brown (10 YR 4/2), flattened, ½-3 inches (1½-7½ cm.) in thickness, 1-6 inches (2½-15 cm.) in length, contain vugs lined with quartz pyramidal terminations; silty layers 1-3 inches (2½-7½ cm.) in middle of unit; fossils include horn corals, echinoid spines, bryozoa, Marginifera, "Dictyoclostus;"* forms cliff.................................10.5 3.2

29 Limestone (microparite), dolomitic, medium light gray (N6), weathers very light gray (N8) to light gray (N7); chert, 30 percent, well developed nodules, weather moderate brown (5 YR 3/4), silica interiors; fossils include "fossil hash," productid spines, echinoid spines; gradational upper contact, irregular thickness, forms saddle.............6.5 2.0

28 Limestone (biomicroparite), medium dark gray (N6), weathers medium light gray (N6) to pinkish gray (5 YR 8/1); fetid; base of unit contains coarser channel fills; chert, 10 percent, weathers moderate brown (5 YR 3/4), 1-48 inches (2½-122 cm.) in length, 1-12 inches (2½-30½ cm.) in thickness, more abundant at base of unit; fossils include shell fragments, productid spines, crinoid columnals, turreted gastropods, horn corals; forms ledges, beds 2-6 feet
27 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6); chert, 5 percent, scattered, interiors are gray calcite, increase in abundance toward base of unit; silty layers 3 inches (7½ cm.) thick; fossils include bellerophontid gastropods, *Dictyoclostus,* fenestrate bryozoa, fragments; beds form ledges 1-4 feet (.3-1½ m.) thick......................................10.0 3.0

26 Limestone (biomicrosparite), medium gray (N5), weathers medium light gray (N6) with mottled yellowish gray (5 Y 8/1) silty patches; chert, 30 percent, weathers moderate brown (5 YR 4/4), 1-7 inches (2½-18 cm.) in length, 1-2 inches (2½-5 cm.) in thickness; fossils include *Dictyoclostus,* * Composita, bryozoa; massive...............................8.0 2.4

25 Limestone (microsparite), medium light gray (N6) to light brownish gray (5 YR 6/1), weathers light gray (N7); fetid; chert, 40 percent, in pseudobeds, weather moderate brown (5 YR 3/4), gray calcite interiors; fossils include Composita, crinoid columnals, "fossil hash;" massive...7.0 2.1

24 Limestone (biomicrosparite), dark gray (N3) to medium dark gray (N4), weathers medium gray (N5) grading to yellowish gray (5 Y 8/1) at top of unit; fetid; chert, 2 percent, poorly developed, scattered, more abundant at base, weather moderate yellowish brown (10 YR 5/4); fossils include horn corals, echinoid spines, productid spines, *Dictyoclostus,* turreted and bellerophontid gastropods; slope-former, beds 1-4 feet (.3-1½ m.) thick.................................30.0 9.1
23 Limestone (biomicomsparite), medium dark gray (N4) to brownish gray (5 YR 4/1), weathers medium light gray (N6) to yellowish gray (5 Y 8/1); chert, 1 percent, weather light brown (5 YR 6/4); Composita, Entele, Marginifera, fenestrate bryozoa, crinoid columnals, echinoid spines; beds 1-3 feet (.3-1 m.) thick form ledges .........................11.0 3.4

22 Limestone (biomicomsparite), dark gray (N3), weathers medium gray (N5); fetid; chert, 1 percent, weathers light brown (5 YR 6/4), scattered; fossils include bryozoa, echinoid spines, Dielasma, "fossil hash," "Dictyoclostus;"* resistant beds 1-3 feet (.3-1 m.) thick ..........7.0 2.1

Fault contact

Quaternary alluvium:

* Reclassified as Peniculauris bassi or Rugatia occidentalis by Muir-Wood and Cooper, 1960.
Quadrat 1 describes channel fill in the biomicrite of Unit 5. It was taken perpendicular to bedding. The channel contact (lower left corner) is irregular and burrowed. It consists of coarser fossil debris than the limestone of the unit. The chert percentage is consistent in both the channel and the main body of the rock. However, chert nodules are localized along the contact indicating possible porosity-permeability control on chert formation.

Intact fossils are also abundant with 20 "Dictyoclostus" brachiopods, still articulated, included in the chert nodules. Only a few were found independent of the nodules. *Fenestrella* sp. bryozoa were abundant in the limestone; none were included in nodules. Echinoid spines were also present. Except for the brachiopods, the fossils were replaced by white sparry calcite.
Quadrat 2 was taken perpendicular to bedding and describes the boundary area of Units 10 and 11. Unit 11 consists of abundant sponges included into chert nodules in biomicrosparite. Ten sponges (5½-20 cm) were counted in the half-meter area of Unit 11. Limestone lamina bend beneath the chert nodules. The chert is weathered blackish-orange brown and has dark greenish-gray carbonate interiors.

Bryozoans, *Fenestrella* sp. and trepostome, are concentrated in a laterally extensive zone at the base of the quadrat in Unit 10. Their exteriors are replaced by silica and interiors consist of white sparry calcite. The remainder of Unit 10 contains crinoid columnals, bryozoa, and "fossil hash."
Quadrat 3 describes an area near the base of Unit 12. It is perpendicular to bedding.

The unit consists of silty biomicrosparite with chert nodules. The chert is slightly more silicified than that of the lower units. Less resistant lamina are weathering out especially in the left half of the quadrat.

Fossils are abundant consisting primarily of echinoid spines with partial silica replacement of their exterior surface, two species of crinoid columnals, and exceptionally large (10 cm) "Dictyoclostus" brachiopods in the chert nodules.
Quadrat 4 describes a bedding plane in Unit 18 at the contact between silty, coarser patches (M) and the finer biomicrosparite of the unit. The chert has weathered dark orange brown and has dark gray interiors of silica and carbonate. Fossils consist of crinoid columnals and productid brachiopod spines. They have been replaced by silica.
Quadrat 5 describes a bedding plane in Unit 32. It contains abundant hollow, white silica-lined vugs. The vug interiors contain clear quartz crystals, many doubly-terminated. Originally, the vugs may have been fossil molds (McClymonds, 1957). Chert is not abundant.

Fossils consist of bryozoan, echinoid spines, and productid brachiopod spines. The spines have been replaced by silica. "Fossil hash" is abundant in scattered patches of silty, coarse limestone in the biomicroparite of the unit.
APPENDIX C: LIST OF FAUNA (Bryant, 1951)

Brachiopoda

Avonia costata (R. E. King)
Avonia dorsiconcava (McKee)
Avonia signata (Girty)
Camarophorina deloi (King)
Chonetes kaibabensis (McKee)
Composite arizonica (McKee)
Composite mexicana (Hall)
Composite mira (Girty)
Composite subtilita (Hall)
Derbya arizonensis (McKee)
Derbya buchi (d'Orbigny)
Derbya sp.
Dielasma spatulatum (Girty)
Hustedia meekana (Shumard)
Hustedia sp.
Marginifera cristobalensis (Girty)
Marginifera popei (Shumard)
Meekella attenuata (Girty)
Meekella globosa (King)
Meekella grandis (King)
Meekella hessensis (King)
Meekella sp.
Neospirifer pseudocameratus (Girty)
Productus gratiosus occidentalis (Schellwien)
Productus leonardensis (King)
Pugnoides pinquis (Girty)
Pugnoides sp.
Pugnoides swallovianus (Shumard)
Rugatia paraindicus (McKee)
Rugatia occidentalis
Spiriferina hilli (Girty)
Squamularia guadalupensis (Shumard)
Squamularia sp.
Waagenconcha montpelierensis (Girty)
Gastropoda

Baylea sp.
Bellerophon crassus (Meek and Worthen)
Bucanopsis modesta (Girty)
Bucanopsis sp.
Euomphalus sulcifer (Girty)
Euomphalus sulcifer var. angulatus (Girty)
Foordella sp.
Glabrocingulum sp.
Goniasma sp.
Helicospira sp.
Lindstroemia cylindrica (Girty)
Meekospira sp.
Naticopsis sp.
Omphalotrochus sp.
Orthonema socorroense (Girty)
Orthonema sp.
Phanerotrema manzanicum (Girty)
Pseudozygopleura sp.
Shansiella planicostata (Girty)
Shansiella sp.
Soleniscus sp.
Straparolus (Euomphalus) pernodosus
Straparolus (Amphiscapha) reedsi (Knight)
Strobeus sp.
Trepospira sp.
Trepospira sphaerulata
Worthenia sp.

Pelecypoda

Acanthopecten coloradoensis (Newberry)
Allorisma terminale (Hall)
Astartella sp.
Astartella subquadrata (Girty)
Aviculopecten sp.
Nucula levatiformis (Walcott)
Pleurophorus mexicanus (Girty)
Ammonoidea

Paragastrioceras serratum
Popanoceras bowmani (Boese)

Porifera

Heterocoelia beedei (Girty)**
Virgula neptunia (Girty)***

Bryozoa

Dekayella sp.
Polypora mexicana (Prout?)

Coral

Malonophyllum sp.

Scaphopoda

Plagioglypta canna

* formerly Productus (Dictyoclostus) paraindicus (McKee)
  Muir-Wood and Cooper, 1960.

** Girtyocoelia coss. (Laubenfels, 1955).

REFERENCES CITED


Vaag, M. K., 1983, Personal communication: Graduate student, Department of Geosciences, University of Arizona, Tucson.


