Reference section of the Lower Permian San Andres Formation, Sierra County, New Mexico

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REFERENCE SECTION OF THE LOWER PERMIAN SAN ANDRES FORMATION, SIERRA COUNTY, NEW MEXICO

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Abstract—In the northern San Andres Mountains, Sierra County, New Mexico, the reference section of the Permian San Andres Formation is a better exposed section than the nearby type section, also located in the San Andres Mountains. At the reference section, the San Andres Formation is ~ 130 m thick, has an eroded top and overlies a very thin Glorieta Sandstone. We divide the reference section of the San Andres Formation into a lower, hydrocarbon-bearing bedded-limestone interval, a middle thicker-bedded and massive limestone interval and an upper interval of bedded limestone with some chert. Petrographic study reveals that the most common microfacies of the San Andres Formation at the reference section is bioclastic wackestone, and that muddy textures dominate the section. Ammonoids indicate that the reference section of the San Andres Formation is of late Leonardian age. Our data, particularly detailed lithostratigraphy and petrography, do not support a previous interpretation of the reference section as a transgressive systems tract overlain by a highstand systems tract, both composed of numerous parasequences. Instead, our data suggest that limestone was deposited in a normal marine environment of dominantly low to moderate water turbulence within the photic zone with open circulation. Well washed grainstones formed under high-energy conditions are rare, and only a few shallowing-upward parasequences are developed. The reference section of the San Andres Formation is an incomplete section of the lower Rio Bonito Member of the formation. It records the initial transgression of the San Andres seaway over the Glorieta-Coconino erg, followed by the development of shallow marine platform environments across much of New Mexico. Hydrocarbons are restricted to the lowermost San Andres westerly to the New Mexico/Arizona border, but the mechanism by which they were sealed is not certain. It may have been the high-energy dispersal of clays into the Northwest Platform of the Delaware Basin during late Leonardian time.

INTRODUCTION

In the regional Permian stratigraphic section exposed in New Mexico and West Texas, the San Andres Formation is an important unit both economically and in understanding regional stratigraphic correlation, sedimentation and paleogeography. Named by Lee (1909), the type section of the San Andres was located in Rhodes Pass in the northern San Andres Mountains of Sierra County, New Mexico. Needham and Bates (1943) fixed the type section at the same location and provided a more detailed description of the location and stratigraphy. However, Kottlowski et al. (1956) later described a better exposed section (a reference section) about 1.6 km west of the type section, also in the San Andres Mountains, and Lindsay (1994) restudied this reference section, placing it into a sequence stratigraphic framework (Fig. 1). Here, we describe the stratigraphy, microfacies and paleontology of this reference section of the San Andres Formation using thin section analyses of samples derived from the reference section to interpret its depositional environments, sequence stratigraphy and significance to regional deposition of the San Andres lithosome.

PREVIOUS STUDIES

Lee (1909, p. 12) named the "San Andreas limestone" as the uppermost unit of the Manzano Group of Herrick (1900). He took the name from "San Andreas Mountain, at the north end of which it is typically developed, as described in the section on page 29" (Lee's, 1909, fig. 7; see our Fig. 2). Lee (1909, p. 12) described the "San Andreas limestone" as "essentially marine limestone,

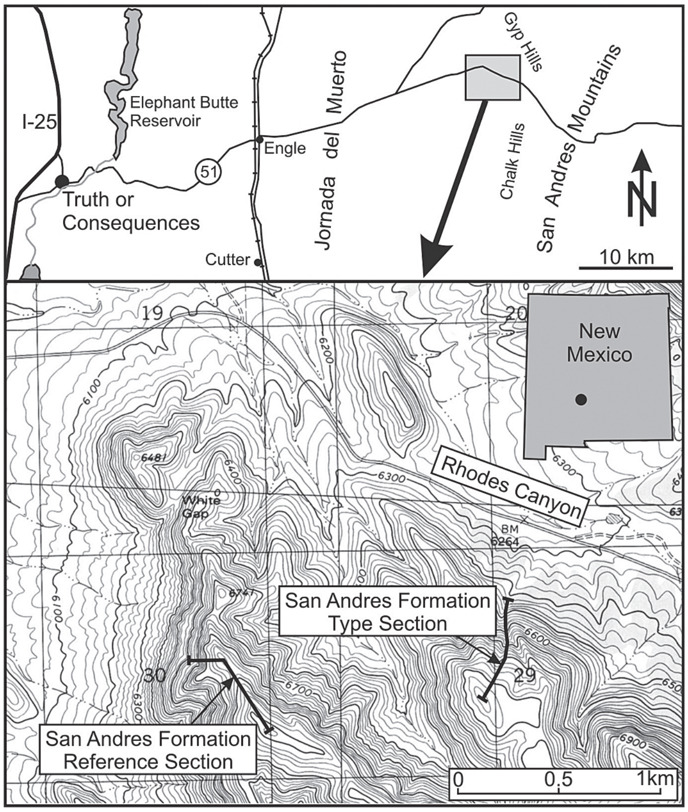


FIGURE 1. Location of type and reference sections of the San Andres Formation in the northern San Andres Mountains, Sierra County, New Mexico.

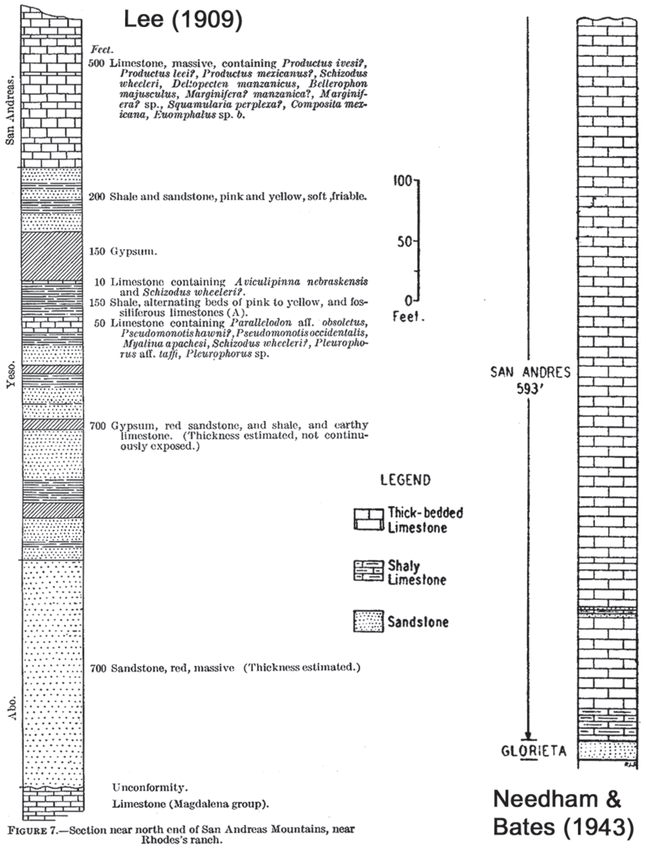


FIGURE 2. Type section of the San Andres Formation, from Lee (1909) and from Needham and Bates (1943).

which is often cherty and poorly fossiliferous, although several localities were found where fossils are abundant." He recognized its distribution across much of central New Mexico, from Mesa del Yeso in Socorro County through the Fra Cristobal, Caballo and San Andres Mountains of Sierra County.

The original spelling of San Andres as "San Andreas" by Lee (1909) was corrected by Darton (1928). However, Darton (1928) was unable to separate the Yeso and San Andres formations regionally, so he combined them in his Chupadera Formation, a stratigraphic concept abandoned in the 1940s (Lucas, 2009).

Needham and Bates (1943), in one of the classic articles of New Mexico geology, properly regarded Lee's (1909, fig. 7) section as the type section of the San Andres Formation. Lee (1909, p. 29) gave the location of this section in the northern San Andres Mountains as "in the canyon through which the road passes from Engle to Rhodes's ranch." Needham and Bates (1943, p. 1665) fixed the type section there in a small canyon south of the road, providing a specific location in sec. 29, T12S, R 2E (Fig. 1). Needham and Bates (1943, p. 1665) described the type section of the San Andres Formation as 181 m of limestone with two thin (0.6 m thick) sandstone beds near its base, overlying the Glorieta Sandstone (Fig. 2). Significantly, the top of the San Andres Formation is eroded at the type section, so it is not a complete section of the formation. Needham and Bates (1943) also noted the presence of numerous brachiopods (*Dictyoclostus*, etc.) in the type section. They were aware of a much broader geographic extent of the San Andres Formation than was Lee (1909), probably due mostly to the work of Darton (1928).

Kottlowski et al. (1956, p. 60-62, 89-90, fig. 11) described in detail a section of the San Andres Formation located ~ 1.6 km west of the type section (Fig. 1). Here (center E1/2 sec. 30, T12S, R2E), the San Andres Formation is reported to be 174 m thick, also has an eroded top and is much better exposed than at the type section. Lindsay (1994, p. 133) therefore referred to it as "a much better exposed reference section," and redescribed the reference section and interpreted it as a transgressive systems tract overlain by a highstand systems tract divisible into 47 shallowing upward parasequences and 13 parasequence sets. We also refer to it as the reference section of the San Andres Formation. Here, we present a very different interpretation of the sequence stratigraphy of the reference section of the San Andres Formation than did Lindsay (1994).

LITHOSTRATIGRAPHY

At the reference section (Figs. 3-4), the San Andres Formation is ~ 130 m thick and overlies massive, gray dolomite containing abundant small vugs filled with gypsum and calcite (uppermost strata of the Yeso Group) overlain by 2.1 m of fine-grained Glorieta Sandstone.

Glorieta Sandstone

At the type section of the San Andres Formation in Rhodes Pass, the Glorieta Sandstone is fine-grained (0.1-0.3 mm), well rounded, well sorted and grain supported (Fig. 5A). The sandstone is a quartzarenite composed of dominantly monocrystalline quartz and rare polycrystalline quartz and chert. The detrital grains are cemented by quartz and calcite. Quartz cement occurs as thin authigenic overgrowths on detrital quartz grains, and the remaining pore space is filled with coarse blocky calcite cement that locally replaces quartz and probably detrital feldspar grains. At the reference section, the Glorieta Sandstone displays similar texture and composition, but locally the quartz grains float in indistinctly laminated micrite, which also contains a few poorly-preserved foraminiferans (Fig. 5B-C).

San Andres Formation

The entire reference section of the San Andres Formation is an incomplete section of the formation and can be referred to the Rio Bonito Member of Kelley (1971). At the reference section, the San Andres Formation can be lithologically divided into three parts: (1) lower, ~ 30 m thick (units 5-22); (2) middle, ~ 33 m thick (units 23-62); and (3) upper, ~ 67 m thick (units 63-126).

Lower part (~ 30 m thick, units 5 – 22)

The lower part of the San Andres Formation is composed of massive limestone beds (1.2-3.7 m thick), indistinctly bedded

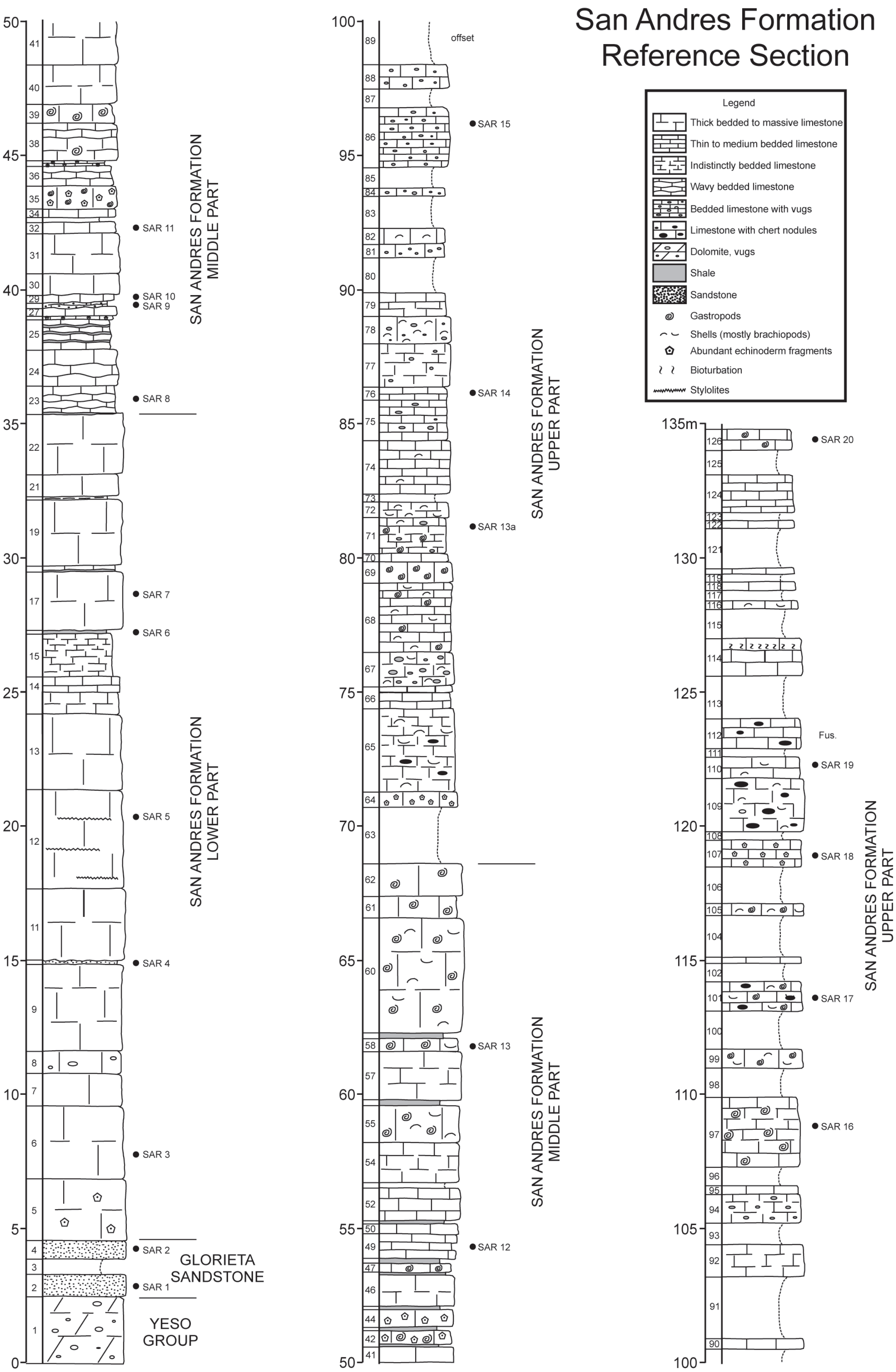


FIGURE 3. Reference section of the San Andres Formation. See Figure 1 for location of section.

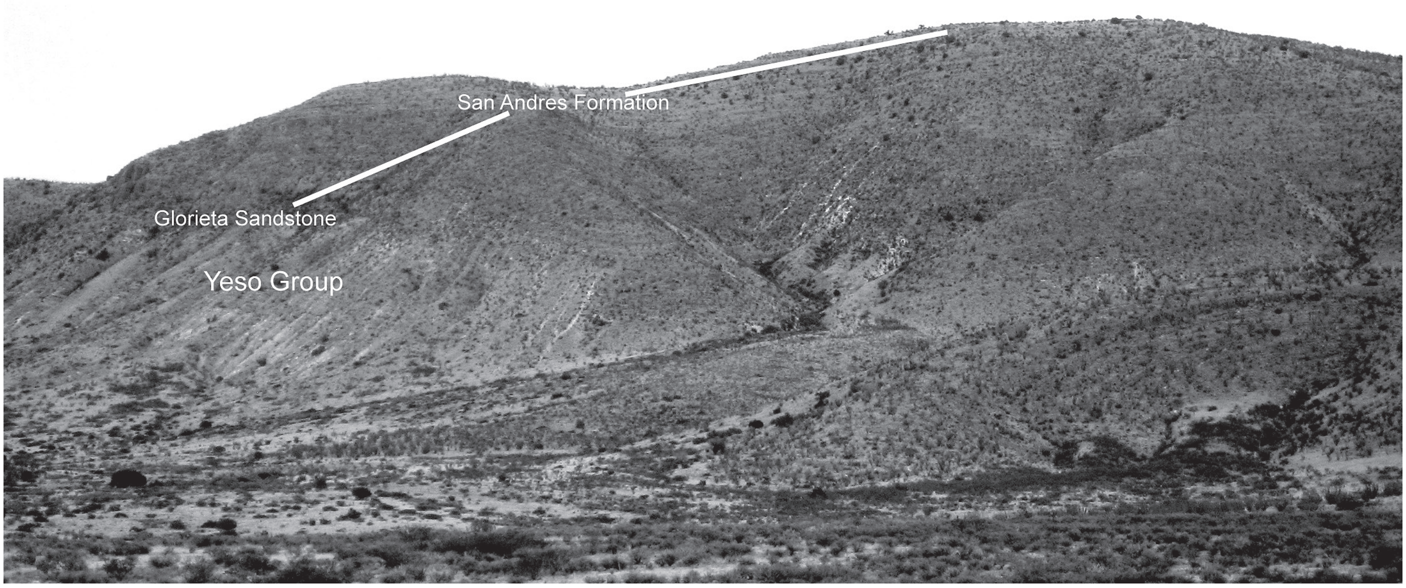


FIGURE 4. Overview photograph of the reference section of the San Andres Formation.

limestone and rare, thin limestone beds (0.2-0.8 m thick). The limestone is gray to dark gray, muddy, partly bituminous and in the lower part contains crinoidal debris. The limestone bed of unit 8 contains a few vugs, up to 5 cm in diameter filled with calcite (originally probably infilled with evaporite minerals such as gypsum). Stylolites oriented parallel to the bedding plane are common in the massive limestone of unit 12. Several thin (1-10 cm) brownish siltstone layers (?) are intercalated with the limestone beds.

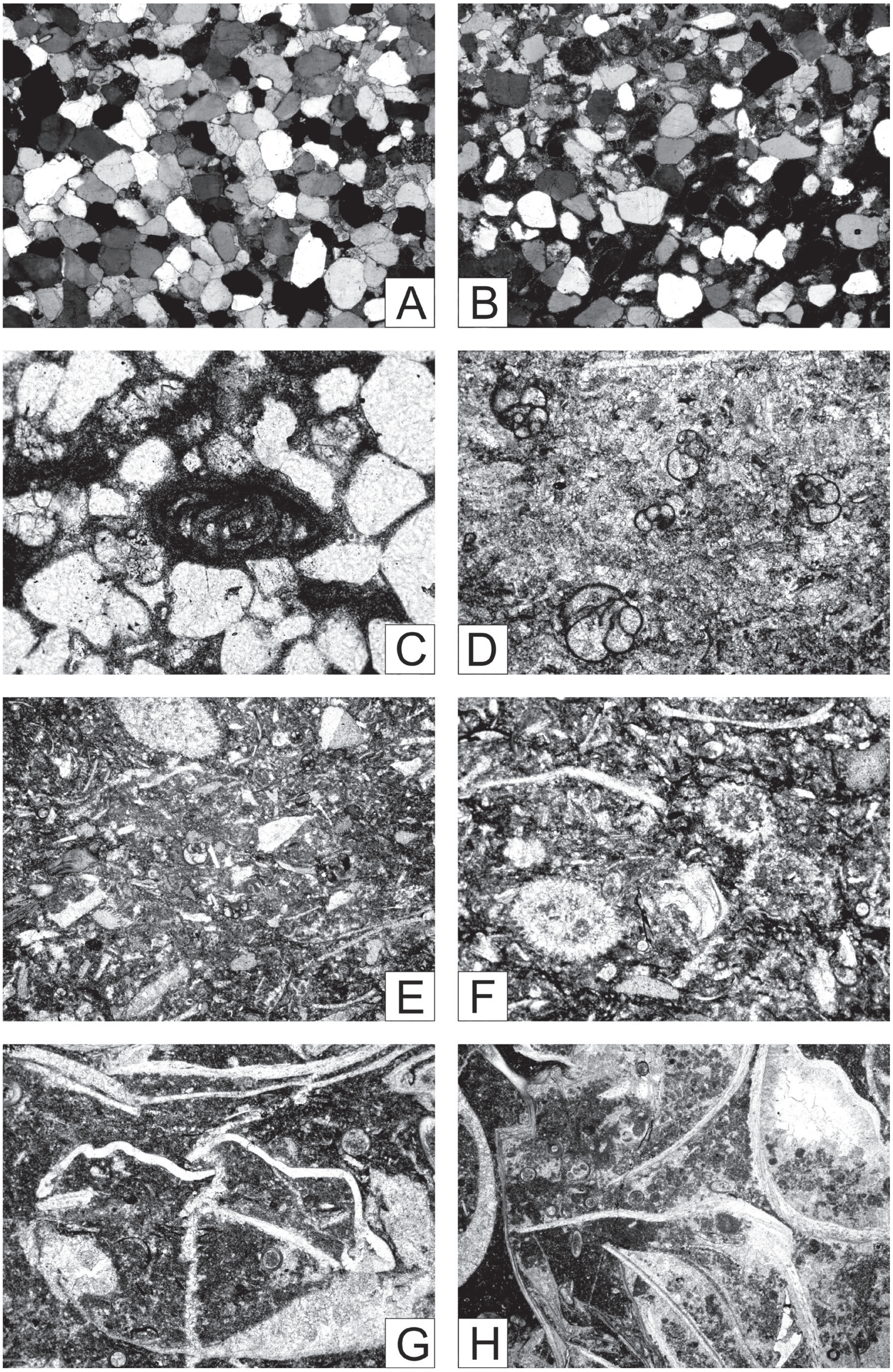
Middle part (~33 m thick; units 23-62)

The middle part of the San Andres Formation consists of thin- to thick-bedded limestone (10 cm-1 m) and massive limestone (beds up to 4.3 m thick). Bedding is mostly even; wavy bedding is rarely observed. A few thin shale layers are intercalated in bedded limestone in the lower portion of the middle part. As in the lower part, limestone is gray to dark gray, muddy and commonly bituminous. A few beds contain abundant crinoidal debris. Vugs with diameters up to 20 cm occur in a few limestone beds. In the middle and upper part, gastropods and other shell fragments are present in many limestone beds. Brachiopods are rarely observed.

Upper part (~ 67 m thick, units 63-126)

The upper part of the San Andres Formation is composed of medium- to thick-bedded, partly indistinctly bedded limestone, which in the lower part contains vugs filled with calcite. Limestone is commonly muddy (mudstone to wackestone) and colored light to dark gray. A few limestone beds contain abundant crinoidal debris (crinoidal wackestone). Shell debris is common. Many limestone beds contain large gastropods. Less common are brachiopods, bryozoans, and, in the uppermost part, nautiloids. Burrows, which are partly filled with calcite, occur in the upper part of unit 114. A few cherty limestone beds are present containing silicified fossils and chert nodules. Limestone intervals are 0.2-3.1 m thick and separated by covered intervals (possibly shale) that are 0.3-2.1 m thick.

FIGURE 5. Thin section photographs of sandstone of the Glorieta Sandstone at the type and reference sections and limestone of the San Andres Formation at the reference section. **A**, Well-sorted, well-rounded, calcite-cemented Glorieta sandstone of the type section composed of monocrystalline quartz grains, many of them displaying authigenic overgrowths. Sample GL 1, polarized light, width of photograph is 3.2 mm. **B**, Moderately- to well-sorted, calcite- cemented Glorieta sandstone containing abundant quartz grains, micritic matrix and calcite cement. Sample SAR 1, polarized light, width of photograph is 3.2 mm. **C**, Glorieta sandstone containing a foraminiferan (center), quartz grains, some micritic matrix (dark gray) and calcite cement. Sample SAR 1, plane light, width of photograph is 1.2 mm. **D**, Recrystallized wackestone containing many foraminiferans (*Globivalvulina*). Sample SAR 3, plane light, width of photograph is 3.2 mm. **E**, Wackestone containing a diverse fossil assemblage of echinoderms, brachiopod shells and spines, bryozoans, calcareous algae, smaller foraminiferans, ostracods and abundant recrystallized skeletons. Sample SAR 7, plane light, width of photograph is 3.2 mm. **F**, Wackestone containing many gymnocodiacean algae, brachiopod shells and spines, smaller foraminiferans, a few bryozoans and many recrystallized fossil fragments. Sample SAR 8, plane light, width of photograph is 3.2 mm. **G-H**, Rudstone composed of abundant brachiopod shells, a few echinoderm fragments, bryozoans, smaller foraminiferans and trilobite fragments floating in peloidal micritic matrix (**G**). Locally brachiopods display geopetal structures (**H**, upper right). Sample SAR 9, plane light, width of photograph **G** is 3.2 mm, of **H** is 6.3 mm.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Microfacies

The dominant microfacies type of the San Andres Formation is bioclastic wackestone containing a diverse fossil assemblage (Figs. 5D-F, 6F). Fossils float in peloidal micrite. Wackestones may grade into packstones. A common microfacies is crinoidal wackestone to packstone, diverse, poorly sorted and strongly recrystallized. Besides crinoid fragments, other fossil debris are present in small amounts. Peloidal mudstone is rare and contains abundant small vugs filled with calcite cement and very rare crinoid fragments and other skeletons.

Rudstone is composed of abundant brachiopod shell fragments and spines, bivalves, few echinoderm fragments, bryozoans and other skeletons (Fig. 5G, H, Fig. 6A, B, D, E). The matrix is peloidal micrite. A few shelter and interparticle pores occur that are filled with calcite cement. Very rare are geopetal structures (Fig. 5H). Bivalved shells are commonly filled with micrite and peloidal micrite, rarely with calcite cement.

Floatstone-rudstones containing large skeletons that are encrusted by cyanobacteria to form oncoids are present in the upper part (Fig. 6E). This microfacies type contains many coated grains, abundant peloids and a few micritic intraclasts.

Grainstones observed in the uppermost part are fine-grained, poorly sorted and composed of abundant peloids and small intraclasts. Recrystallized skeletons, ostracods, foraminiferas and shell fragments float in the peloidal grainstone matrix (Fig. 6H).

The most abundant fossils observed in thin section are echinoderm fragments (mostly crinoid fragments). Bryozoans (trepostome forms: Fig. 6A, B, G), brachiopod shells (Fig. 6H) and spines, bivalves and gastropods are common in many limestone beds. Recrystallized gymnocodiacean algae are locally abundant (Fig. 5F). Smaller foraminiferans are represented by *Globivalvulina*, which is common in distinct limestone beds (Fig. 5D). Less common are *Eotuberitina, Tuberitina, Syzrania, Nodosinelloides* and tubular porcelaneous foraminiferans (hemigordiids, calcivertellids). A few samples contain rare trilobite fragments (Fig. 5G). Ostracods and recrystallized skeletons of unknown origin occur in all studied samples. The limestone is commonly recrystallized and thus poorly preserved, and many fossil fragments are completely recrystallized, which makes definitive identifications difficult.

PALEONTOLOGY

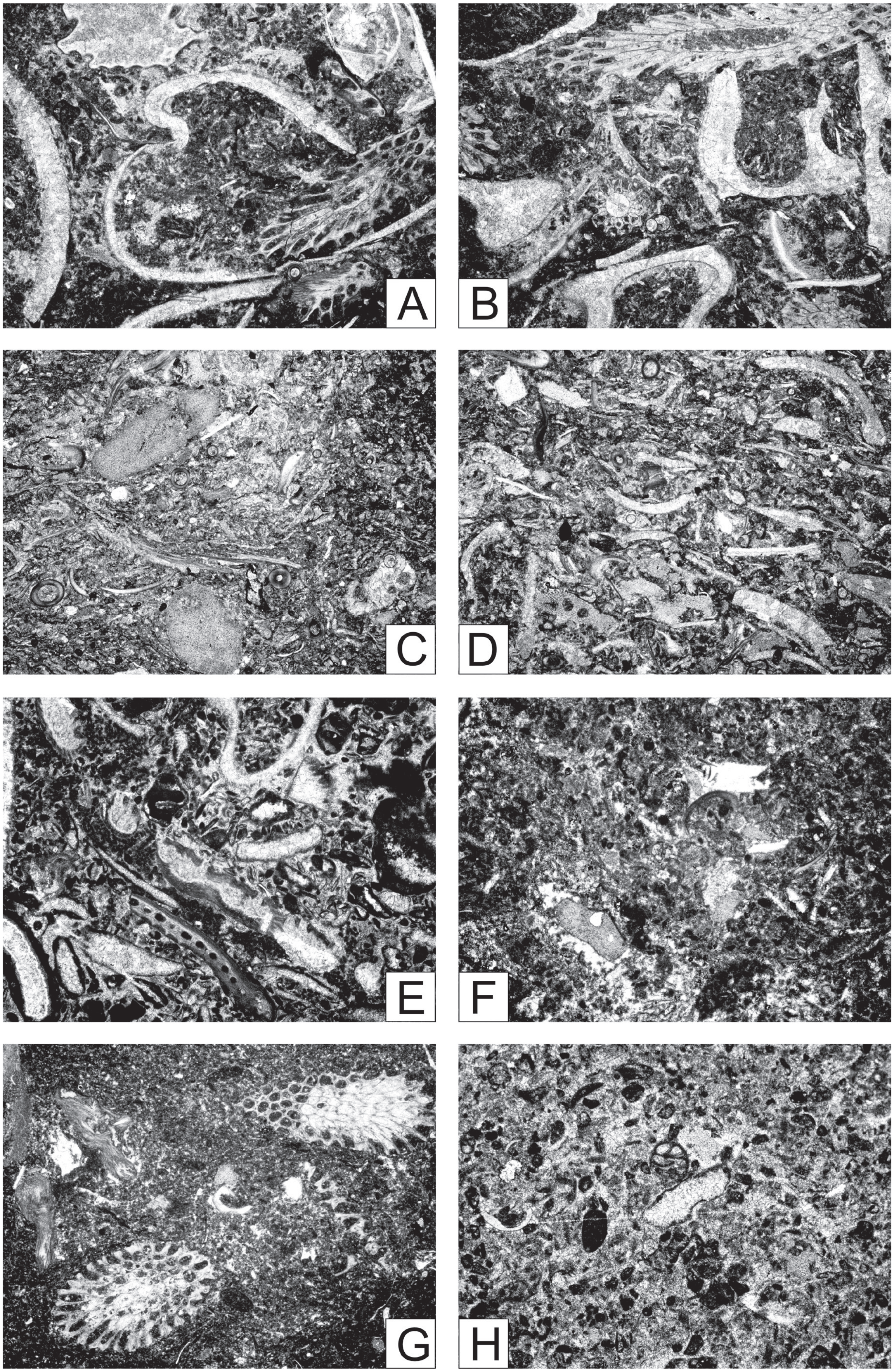
Kottlowski et al. (1956, p. 61) provided a brief summary of the paleontology of the San Andres Formation in the area of the type and reference sections. They noted that the lower part of the formation produced primarily productid brachiopods (*Dictyoclostus* spp.), and that the upper part yields a more diverse molluscan fauna that includes numerous nautiloids (*Domatoceras, Stearoceras, Stenopoceras, Pseudorthoceras, Morreaceras,* etc.). It also yields the ammonoids *Perrinites* and *Pseudogastrioceras*, indicative of a late Leonardian age. This is significant, as the upper part of the San Andres Formation (not preserved in the Rhodes Pass area) in the Delaware basin of southeastern New Mexico-West Texas yields fusulinids and conodonts of Guadalupian (Middle Permian) age (e.g., Kerans et al., 1993).

DEPOSITIONAL ENVIRONMENTS

The deposits of the San Andres Formation were formed during the late Leonardian-Guadalupian transgression, which was the last major Paleozoic transgression onto the North American craton, producing normal marine environments across large parts of New Mexico and adjoining areas (e. g., Moore and Wilde, 1986; Lindsay, 1994; Kues and Giles, 2004). The San Andres Formation in New Mexico represents deposits of the northwestern shelf of the Delaware Basin (Ward et al., 1986). According to Lindsay (1994), most of the San Andres reference section was deposited in an open marine, shallow shelf environment. At the reference section, Lindsay (1994) recorded 93 bedded intervals of which 2 are rudstones, 15 grainstones, 37 mud-poor packstones, 36 mud-rich packstones, 1 particle-rich wackestone, 1 mudstone and 1 argillaceous dolomitic sandstone. These microfacies types are obviously based on field observations and not on thin section analysis; Lindsay (1994) did not mention any thin sections and also did not report the occurrence of bryozoans, calcareous algae, smaller foraminiferans, ostracods and trilobite fragments, which are only seen in thin sections. Like Kottlowski et al. (1956), we did not observe fusulinids at the reference section of the San Andres Formation, although they were mentioned by Lindsay (1994).

In the reference section of the San Andres Formation, we distinguished 126 intervals (units) (Fig. 3), and according to our

FIGURE 6. Thin section photographs of limestone of the San Andres Formation at the reference section. **A-B**, Rudstone composed of abundant brachiopod and trepostome bryozoan fragments. Subordinate brachiopod spines, smaller foraminiferans, ostracods, small gastropods and many recrystallized skeletons are present. The fossils are embedded in peloidal micrite. Sample SAR 10, plane light, width of photographs is 6.3 mm. **C**, Packstone-floatstone, poorly sorted, composed of echinoderm fragments, brachiopod shells and spines, bryozoans, smaller foraminiferans, ostracods and many recrystallized skeletons. Sample SAR 12, plane light, width of photograph is 6.3 mm. **D**, Rudstone containing abundant recrystallized shell fragments (?bivalves), brachiopod shells and spines, gastropods, smaller foraminiferans, ostracods, calcareous algae, rare bryozoans and trilobite fragments embedded in micritic matrix. Sample SAR 13, plane light, width of photograph is 6.3 mm. **E**, Rudstone containing a diverse fossil assemblage and peloidal matrix. Some skeletons are encrusted by cyanobacteria. Sample SAR 17, plane light, width of photograph is 6.3 mm. **F**, Wackestone, poorly sorted, with a diverse fossil content (echinoderms, bryozoans, shell fragments, ostracods, smaller foraminiferans), containing micritic peloidal matrix. Sample SAR 18, plane light, width of photograph is 6.3 mm. **G**, Floatstone containing large bryozoans and subordinate brachiopods and echinoderms floating in peloidal micrite containing small skeletons. Sample SAR 19, plane light, width of photograph is 6.3 mm. **H**, Fine-grained, poorly-washed, moderately-sorted grainstone containing abundant peloids and small micritic intraclasts, recrystallized skeletons, ostracods, foraminiferans and rare larger skeletons. Sample SAR 20, plane light, width of photograph is 3.2 mm.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field observations and thin section microfacies analysis, muddy textures dominate by far. The dominant microfacies are wackestones and packstones, and grainstones are rare. Dominance of wackestone and packstone textures and the diverse fauna, including brachiopods, bryozoans, echinoderms, smaller foraminiferans, nautiloids, ammonites and calcareous algae, are indicative of shallow, normal marine environments of dominantly low- to moderate-water turbulence within the photic zone with open circulation. Well-washed grainstones formed under high-energy conditions are rare. Limestones containing large (up to several cm) vugs filled with calcite (originally probably infilled with evaporite minerals such as gypsum), are composed of mudstones to wackestones containing a less diverse fossil assemblage. These microfacies suggest deposition in a shallow, restricted environment with increased salinity.

SEQUENCE STRATIGRAPHY

At the reference section of the San Andres Formation, Lindsay (1994) described 47 shallowing-upward parasequences and 14 parasequence sets. He interpreted the lower part of the San Andres as a transgressive systems tract (TST) composed of 40 parasequences and 3 parasequence sets, and the middle part as a highstand systems tract (HST) composed of 7 parasequences, which form one complete parasequence set and one partial parasequence set. According to Lindsay (1994), the uppermost 16 m of the section represents the middle San Andres Formation (early Guadalupian).

Clearly, the San Andres reference section is composed of various alternating limestone types and covered intervals, probably representing shale units. This alternation indicates some cyclic pattern and variations in accommodation space as a result of changing water depths caused by sea-level changes. However, limestone of the lower part, which is massive to indistinctly thick bedded, does not show distinct shallowing upward cycles as described by Lindsay (1994), although several thin intercalated brownish siltstone layers indicate some cyclicity. These siltstone layers may indicate a sudden drop of sea level and probably represent subaerial exposure surfaces (sequence boundaries).

According to Lindsay (1994), the maximum flooding surface (MFS) in the middle part of the TST (transgressive systems tract) coincides with the first occurrence of brachiopods and crinoids. However, crinoid fragments occur in many limestone beds, even near the base of the formation. Indeed, in thin section, crinoid fragments are present in all studied samples. Brachiopods are also present in many limestone beds, which makes it difficult to use this criterion for placing the MFS. According to our observations, grainstone is not the dominant rock type of the uppermost part of the San Andres Formation, which does not differ significantly from the underlying part as mudstone and wackestone are also dominant facies types.

A parasequence is defined as a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces (e.g., Catuneanu et al., 2009). Lindsay (1994) interprets all sharp bed boundaries within the San Andres reference section as flooding surfaces, which are defined as surfaces with a sudden change in facies that may indicate an increase in water depth or a decrease in sediment supply (see Van Wagoner et al., 1988, 1990). Due to the dominance of muddy textures throughout the succession with only minor changes in facies and the rare occurrence of grainstone, we do not accept Lindsay's (1994) subdivision of the section into 47 shallowing-upward parasequences, particularly as this subdivision is only based on field observations. Instead, the quantitative interpretation of shallowing-upward trends and flooding surfaces would require an intensive bed-by-bed microfacies analysis of the entire section.

DISCUSSION

The principal reference section of the San Andres Formation, located in the San Andres Mountains of central New Mexico, is near the easterly margin of the Northwestern Shelf platform environment of the Permian Basin (e.g., Sarg and Lehmann, 1986; Kues and Giles, 2004). The reference section, and similar sections of the Northwestern Shelf platform located westerly across New Mexico to the Arizona border, represent the initial transgression of a Permian sea that covered extensive eolian dune fields along the northern margin of the Gondwana supercontinent during a world-wide rise in sea levels that characterized the Middle Permian (Guadalupian) (e.g., Moore and Wilde, 1986; Ross, 1987; Ross and Ross, 1995, 1998; Kues and Giles, 2004; Brose, 2011).

The dune fields include the Permian Glorieta Sandstone of New Mexico and Permian Coconino Sandstone of Arizona (e.g., Milner, 1978; Peirce, 1989). The Glorieta and Coconino sandstones primarily consist of white to buff, fine- and medium-grained quartz sands. Both the Glorieta and Coconino sandstones are well indurated, with both silica and calcium carbonate cementation. The basal portions of the sandstones may be massive, although their upper parts are typically cross bedded.

At the San Andres reference section and to the northwest, the marine platform environment transgressed across the eolian dune environment. Relative base-level changes controlled sedimentation along the platform and shelf margins, with both progradational and aggradational cycles (e.g., Sarg and Lehmann, 1986). Depending on the location of the shoreline relative to the deeper platform environment, the cyclical base-level changes resulted in subaerial exposures, incision and erosion of the platform margins. Much of the distribution and the ecosystems of the platform margin are unknown or poorly preserved near what is today the western margin of the platform environment (Brose, 2011).

Of more interest, however, is the appearance of routine incursions of detritus from adjacent eolian dune fields of the Glorieta and Coconino sands in layers of variable thickness deposited in the marine environment (e.g., Harbour, 1970; Kelley, 1971; Lucas and Zeigler, 2004; Brose, 2011). These deposits have been the subject of many authors, and have created significant debate regarding both the presence and environmental significance of the sands within the otherwise marine environment. Kelley (1971) used the occurrence of the allochthonous detritus to separate the San Andres into three members (in ascending order), the Rio Bonito Member, the Bonney Canyon Member and the Fourmile Draw Member.

Rio Bonito Member

The Rio Bonito Member consists of a massive, thick-bedded limestone, and the entire reference section described here can be referred to that member. The overlying Bonney Canyon Member is the middle, typically thin-bedded dolomitic and limestone interval of the San Andres Formation, and the Fourmile Draw Member consists of the uppermost, evaporitic portion of the section.

The Rio Bonito Member upper horizon was wisely chosen by Kelley (1971) to develop structure contours separating the "cherty" San Andres from the upper "non-cherty" member(s). This is mainly because the Rio Bonito Member appears to represent the transgression of the San Andres marine platform environment westward, where subsequent hydrocarbon migration to the marginal portions of the platform occurred. Although the central portion of the Rio Bonito Member is relatively massive, the peripheral margins contain routine incursions of eolian and sub-aqueous deposition of allochthonous detritus primarily originating from the underlying dune fields.

The presence of the sands from these peripheral eolian dune fields within the basal portion of the reference section and in similar sections encountered westward to the present New Mexico/Arizona border suggests that the transgressing Northwestern Shelf platform environment was routinely inundated with reworked eolian transported sands deposited on the seafloor. To the west, near the New Mexico-Arizona border, submarine flows have the characteristics of turbidity deposits that include coarse clastic gravels and cobbles, bioturbated sands and bioherm debris, with accompanying channeling and scouring of the seafloor (Brose, 2011). Also, near the westernmost exposure(s) of the Northwestern Shelf platform margins, the basal portion of the San Andres also appears to have been disrupted by high-energy events, with plastic deformation of the San Andres marine deposits accompanied by disruption of underlying beds along previously incised channel boundaries. As noted by Kelley (1971), the Rio Bonito Member becomes finer grained in thinner beds toward the south, away from the western and northern source areas.

Together, the outcrops from the western New Mexico border with Arizona easterly through New Mexico to Texas suggest that the Rio Bonito Member was periodically inundated by reworked material(s) near the western and northern margins of the platform from the onset of the marine transgression. Near the central and eastern portion of the platform, such as the reference section, the Rio Bonito Member eventually received detritus from these distant source(s) to the west and north.

Near the central and eastern portion of the shelf-platform environment, where the San Andres reference section is encountered, the marine environment appears to be rich with submarine invertebrate faunal assemblages in a primarily limestone environment. Closer to the shelf margins, the variety and numbers of marine invertebrate species are reduced or completely absent, although the number of invertebrate assemblages increases in the marginal boundaries, especially westerly, as the thickness of the shelf deposits increases and dolomitic conditions prevail. Kelley (1971) has also noted that northward there is a "slight lightening of shades from dark gray to gray or light gray, and lightening overall of the faint brownish tints." We suggest that the same occurrence is observed westerly, where shelf margin(s) interfingered with the adjacent Kaibab sea (Brose, 2011).

Bonney Canyon Member

Kelley's (1971) Bonney Canyon Member is characterized by relatively thin (< 0.5 m) beds of dark gray, grayish brown and light gray sequences of light- to medium-gray and brownish-gray, fine-grained dolomite and limestone. The upper portion of the Bonney Canyon Member also contains numerous silty and sandy carbonate beds of pale yellowish color that are considerably disturbed, suggesting the former presence of anhydrite and gypsum. The Bonney Canyon Member does not appear to be present at the San Andres Mountains reference section, although the basal portion of the Bonney Canyon Member may appear very similar to the upper portions of the Rio Bonito Member.

As described by Kelley (1971), the Bonney Canyon Member of the San Andres transitions upward into alternating sequences of marine and evaporite depositional environments. The upper portion of the Bonney Canyon Member also contains marine invertebrate species characteristic of the adjacent Kaibab Formation, encountered on the Colorado Plateau of Arizona, Nevada and Utah. Thus, trilobites, which are indicative of the Kaibab sea fauna, can be observed in the Bonney Canyon Member of the San Andres Formation as far east as the Guadalupe Mountains.

A close look at the marginal boundaries of the San Andres marine environment provides clues to the presence of these fauna and depositional patterns within the Bonney Canyon Member of the San Andres marine environment. From St. Johns, Arizona eastward, evidence of periodic transgression of the Kaibab marine environment into the San Andres marine environment is present on outcrop. Kaibab transgressive sequences appear to be associated with the earliest San Andres Rio Bonito Member sea floor near the New Mexico/Arizona border, where reworked sands of the underlying dune field(s), shelf margin bioherm environments, and periodic inundation of terrestrial detritus is routinely encountered (Brose, 2011). These incursions appear to have continued into the time of deposition of the Bonney Canyon Member, where it is postulated that the brownish discoloration observed in the otherwise grayish limestone may be the distal muds of turbidity deposits encountered near the platform margin at the New Mexico/Arizona border. The uppermost part of the Bonney Canyon Member that contains silty and sandy carbonates of yellowish color likely represents the distal reach of the Kaibab marine environment easterly across the platform.

Fourmile Draw Member

Kelley (1971) described the Fourmile Draw Member as the upper, evaporitic part of the San Andres. The Fourmile Draw Member consists of gypsum and dolomite, with reddish, pinkish and yellowish mudstone, siltstone and sandstone present both at the type locality in Fourmile Draw of southeasterly New

Mexico and westward, where the reddish, pinkish and yellowish mudstone, siltstone and sandstone become more prevalent. Kelley (1971) also notes that the gypsiferous section(s) become more prevalent to the north and west, suggesting that the shelf margin evaporites likely extended from west to east as base levels declined.

Observations of outcrops consistent with Kelley's (1971) Fourmile Draw Member near the New Mexico/Arizona border suggest that the Fourmile Draw Member may actually represent a final incursion of the Kaibab sea easterly across the retreating San Andres marine environment (Brose, 2011). The presence of similar stratigraphy, combined with the increase in gypsum and anhydrite in the uppermost sections of the Fourmile Draw Member, caps the San Andres near the Arizona/New Mexico border. Eventually, the Kaibab deposits appear to have transgressed across New Mexico with the retreat of the San Andres marine environment bringing not only Kaibab sediments but Kaibab marine fauna as well.

ECONOMIC IMPACTS OF THE NORTHWESTERN SHELF PLATFORM MARGINS

The San Andres Formation is also a major reservoir for petroleum hydrocarbons in the Permian Basin, and it is the reservoir with the greatest production volume of the Northwestern Shelf Platform Play. In the San Andres Mountains, the basal portion of the outcrop at the reference section appears to be hydrocarbon bearing. Similar hydrocarbon-bearing San Andres limestones and dolomitic limestones are encountered near the western shelf boundaries, appearing on outcrop as far west as the Zuni Mountains of northwestern New Mexico. Similar to the reference section, the hydrocarbon reservoir appears to be limited to the basal portion of the section along the western shelf margins.

The causal factors for the capping of the reservoir within the basal portion of the San Andres are speculative. Near Bluewater Lake, within the Zuni Mountains, a reduction in high-energy depositional events is terminated by a thick, dark gray, brachiopod-bearing limestone. The brachiopod-rich section does not appear to be hydrocarbon bearing. Similarly, the reference section in the San Andres Mountains is hydrocarbon-bearing in the basal section, with hydrocarbons apparently disappearing from the upper, brownish-colored limestones (although the marine fauna appears to be distributed evenly throughout the section). It may be possible that the high-energy events occurring at the marginal portions of the platform to the west resulted in the transport of clays across the Northwestern Shelf Platform towards the abyssal deeps, resulting in a greatly reduced primary permeability of the formation on a regional basis.

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Photograph of Mud Mountain in the Mud Springs Mountains shows dark-colored strata of the Cambro-Ordovician Bliss Formation on its lower slopes, overlain by cliff-forming, dolomite-dominated strata of the Ordovician El Paso Group and Montoya Formation.