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TYPE SECTION OF THE LOWER PERMIAN GLORIETA SANDSTONE, SAN MIGUEL COUNTY, NEW MEXICO

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ABSTRACT—In central New Mexico, the Lower Permian Glorieta Sandstone is a relatively thin (<100 m thick), prominent, sandstone-dominated stratigraphic unit near the top of the Permian section. It generally consists of yellowish brown to light gray, very fine to fine-grained, well-sorted quartzose sandstone that is often crossbedded but also includes beds that are ripple laminated and/or tabular bedded. The type section of the Glorieta Sandstone is on Glorieta Mesa near Rowe, NM, in San Miguel County. Here, the Glorieta Sandstone is 51 m thick, entirely composed of sandstone, including the following: trough-crossbedded sandstone representing eolian sand dunes, ripple-laminated sandstone representing wind ripples, and horizontally laminated sandstone and massive sandstone, also representing eolian deposits. In the lower part crossbedded sandstone of eolian sand dunes alternates with ripple- and horizontally laminated sandstone interpreted as interdune deposits. The upper part of the type section is dominated by ripple-laminated, horizontally laminated and massive sandstone, interpreted as eolian sand sheet deposits, with subordinate, intercalated crossbedded sandstone representing eolian dunes. Sandstone of the Glorieta Sandstone at its type section is characterized by high textural (well-sorted and rounded to well-rounded grains) and compositional maturity (mainly quartz arenite, subordinately subarkose).

INTRODUCTION

In central New Mexico, one of the most distinctive Permian stratigraphic units is the Glorieta Sandstone. Usually much less than 100 m thick, the Glorieta is dominantly yellowish brown, very mature quartzarenite that forms a cliff or ledge near the top of the local Permian section. Here, we present the first detailed description of the type section of the Glorieta Sandstone and interpret its depositional environments.

PREVIOUS STUDIES

Keyes (1915a, b) first used the term Glorieta Sandstone as the "main body of the Dakotan around the southern end of the Rocky Mountains." He thus considered it to be of Cretaceous age, and evidently took the name from Glorieta Mesa in eastern Santa Fe-southwestern San Miguel Counties (Fig. 1). However, other workers rapidly recognized the Glorieta Sandstone (usually as the upper member of Lee's [1909] Yeso Formation) as of Permian age (e.g., Rich, 1921). Note, though, that Baker (1920) regarded the Glorieta Sandstone as of Triassic age (he correlated it to the Upper Triassic Santa Rosa Formation), an incorrect correlation rejected by Rich (1921), among others.

Darton (1928) was unable to consistently separate the Yeso and San Andres Formations of Lee (1909) and the Glorieta Sandstone of Keyes (1915a, b). He, instead, combined them into the Chupadera Formation, a unit that has since be abandoned (Lucas, 2009). Keyes (1935) first recommended abandoning the term Chupadera Formation. However, what really undermined the Chupadera Formation were U.S. Geological Survey maps in central New Mexico that distinguished and separately mapped the Yeso, Glorieta and San Andres Formations (Kelley and Wood, 1946; Wilpolt et al., 1946; Wood and Northrop, 1946; Wilpolt and Wanek, 1951).

Needham and Bates (1943) designated a type section of the Glorieta Sandstone on Glorieta Mesa near Rowe in San Miguel County (Figs. 1, 2). Here, they described it as 41 m of white, gray and buff quartzose sandstone above Yeso strata and below limestone of the San Andres Formation. Needham and Bates (1943, p. 1664) concluded that "on account of its wide distribution, persistence of lithology, bold topographic expression, and stratigraphic importance, the Glorieta is considered to be a formation."

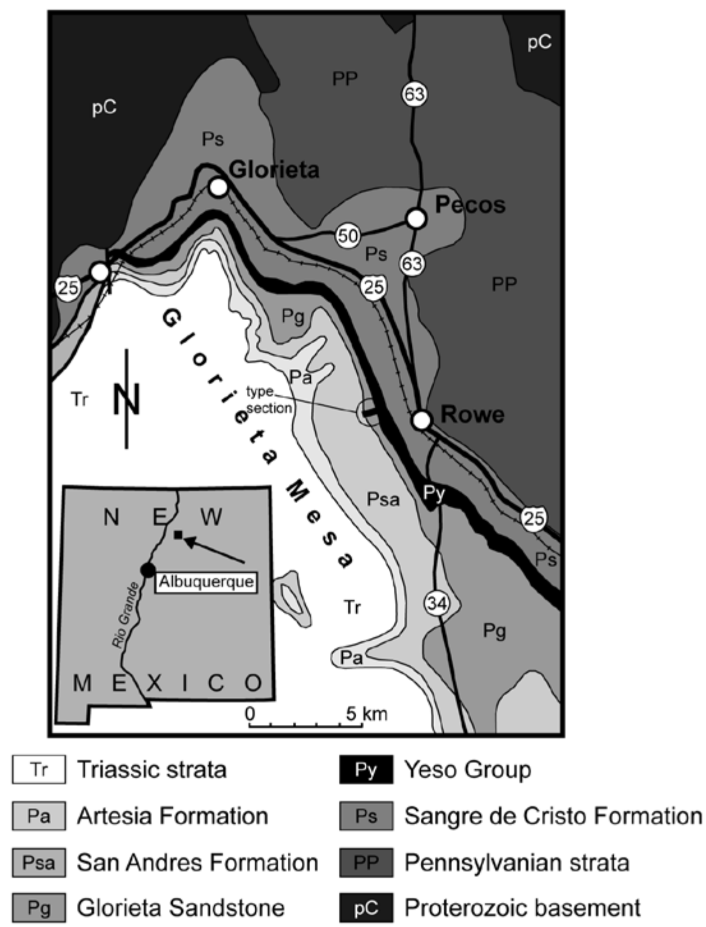

FIGURE 1. Map showing location of type section of the Glorieta Sandstone near Rowe in San Miguel County.

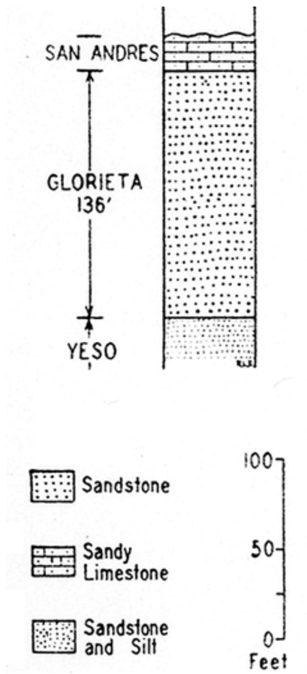

FIGURE 2. Type section of the Glorieta Sandstone (from Needham and Bates, 1943, fig. 2).

Subsequent workers briefly mentioned the type section of the Glorieta Sandstone (Read et al., 1944; Baltz et al., 1956; Foster et al., 1972; Dinterman, 2001; Lucas et al., 2013a) but provided no information about it other than location and overall thickness. Here, we provide a detailed description and analysis of the stratigraphy, and sedimentology of the Glorieta Sandstone at its type section.

LITHOSTRATIGRAPHY

The type section of the Glorieta Sandstone (Figs. 3, 4) is on a north-trending promontory of Glorieta Mesa in the SW ¼ sec. 29, T15N, R12E (UTM zone 13, 436870 E, 3927970 N, datum NAD 83, San Miguel County). Here, the Glorieta Sandstone is 51 m thick and consists totally of sandstone. About one third of the section is trough-crossbedded sandstone, including a few beds up to 1.3 m thick with large (1–3 meter scale) foresets. A little more than one-quarter of the section (27%) displays wind-ripple cross stratification. Thinly laminated sandstone (15%) and thick, tabular sandstone beds (16%) represent the remainder of the section, except for two massive sandstone beds near the top (Fig. 4, units 169 and 171). Many of the sandstone beds are strongly cemented and so well indurated that they have the texture of a metaquartzite. Typically, the sandstone is yellowish brown to light gray.

At the type section, the Glorieta Sandstone rests with evident conformity on gypsiferous sandstone at the top of the Lower Permian Yeso Group. These Yeso strata belong to the San Ysidro Formation (Lucas et al., 2005, 2013b). The San Andres Formation overlies the Glorieta Sandstone at the type section with apparent conformity. It is a thin unit (4.3 m thick locally) of limestone capped by a breccia-filled karst filled by red-bed siltstone of the overlying Artesia Formation (cf. Lucas and Hayden, 1991). Regionally, the Yeso Group and San Andres Formations are of Early Permian age (Brose et al., 2013; Lucas et al., 2013b), thus constraining the age of the Glorieta Sandstone to Early Permian.

At the type section (Fig. 4) the following lithotypes in the Glorieta Sandstone are distinguished:

1) Sandstone with large-scale trough crossbedding. Sandstone beds are 0.9 and 1.3 m thick. This lithotype is rare.
2) Sandstone with trough crossbedding. Intervals of stacked trough crossbeded sandstone beds are 0.5–3 m thick. Trough crossbedded sandstone is coarser grained than the other sandstone types. The crossbedded sandstones show tabular geometries, and we did not observe any channel geometries. Note that Mack and Bauer (2014) describe planar crossbedded sandstone as a common lithotype of the Glorieta Sandstone, which they interpret as eolian dune deposits. Small-scale trough crossbedded sandstone is reported by Mack and Bauer (2014) and interpreted as deposits of broad, shallow channels of a probable braided stream environment.
3) Sandstone intervals with ripple lamination, 0.5–3.8 m thick. Ripple geometry is crudely developed in this type, and ripple crossbedding is not preserved. This type is the rippled sandstone of Mack and Bauer (2014).
4) Thinly laminated sandstone, 1.7 m thick.
5) Sandstone with horizontal lamination, 0.9–3 m thick. Thinly laminated and horizontally laminated sandstone is finer grained than the other sandstone types. Thinly laminated sandstone and sandstone with horizontal lamination was not reported in the Glorieta Sandstone by Mack and Bauer (2014).
6) Massive sandstone beds lacking any sedimentary structures, 1.5–2 m thick. This type is the same as the mottled sandstone of Mack and Bauer (2014) in which they locally observed root traces and feeding burrows. Mack and Bauer (2014) suggest an eolian origin, and that the primary sedimentary structures were destroyed by pedoturbation and bioturbation.

Mack and Bauer (2014) listed gray silty shale beds, fenestral dolostone and fossiliferous dolostone locally intercalated in the Glorieta Sandstone. These lithotypes are absent at the type section.

The type section of the Glorieta Sandstone can be divided into a lower part (~23 m) and an upper part (~28 m) (Fig. 4). The lower part is composed of alternating crossbedded and ripple-laminated sandstone. The upper part is composed of alternating ripple-laminated, horizontally laminated, thinly laminated and massive sandstone intervals. Trough crossbedded sandstone is rare. In the uppermost part, thin sandstone beds are present. The lower part of the Glorieta Sandstone is generally coarser-grained than the upper part.

PETROGRAPHY

At the type section, crossbedded sandstone in the lower part of the Glorieta Sandstone is characterized by high textural and compositional maturity. The sandstones are fine grained, well sorted and composed of dominantly rounded to well-rounded grains

(Fig. 5A-D). The dominant grain type is monocrystalline quartz, whereas polycrystalline quartz is present in small amounts. Detrital feldspars are rare, and other grain types such as rock fragments and mica are absent. The detrital grains are cemented by quartz that occurs as authigenic overgrowths. These overgrowths are often not visible due to the lack of dark rims around the detrital grains. The sandstones are classified as quartzarenite according to the scheme of Pettijohn et al. (1987).

In the upper part of the Glorieta Sandstone at the type section, a higher amount of detrital feldspars (~20%) is observed (Fig. 5E-F). Potassium feldspars, including untwinned grains, microcline and some perthitic feldspars, dominate. In the upper part, the sandstones also contain small amounts of granitic rock fragments. The detrital grains are cemented by authigenic quartz overgrowths and coarse blocky calcite cement. This sandstone type plots in the field of subarkose.

Compared to the Glorieta Sandstone, sandstones of the underlying Yeso Group display a lower textural and compositional maturity (Fig. 5G-H). Yeso Group sandstones are moderately to well-sorted and composed of dominantly subangular to subrounded grains. Sandstones of the Yeso Group contain less monocrystalline quartz, more polycrystalline quartz and substantial amounts of detrital feldspars. Granitic rock fragments are also common. Yeso Group sandstones thus plot in the field of subarkose to arkose.

There is a distinct change in mineralogy and textural maturity between the lower and the upper Glorieta Sandstone. This difference can be explained, at least in part, by the evident change in depositional environment. Thus, the lower Glorieta Sandstone contains more deposits of sand dunes, which contain better sorted, more texturally mature sand grains. In contrast, the upper Glorieta Sandstone is mostly eolian sheet deposits, which are less well sorted and therefore texturally less mature. The change in mineralogy also likely reflects a change in source area, suggesting a more proximal source area during deposition of the upper Glorieta Sandstone.

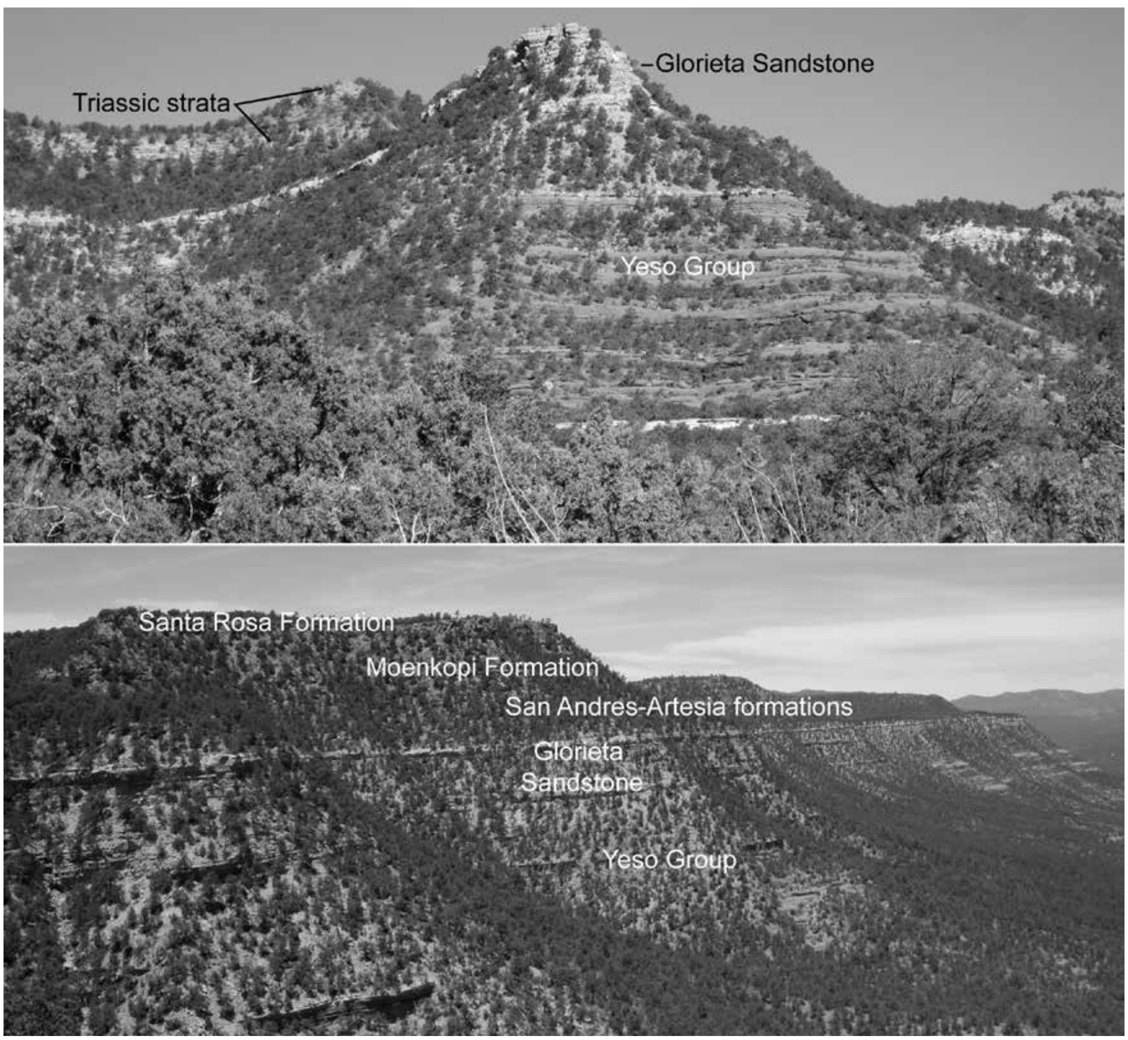

FIGURE 3. Overview of type section of Glorieta Sandstone (above) at Glorieta Mesa near Rowe, and view to west along Glorieta Mesa escarpment from type section (below). Note that Glorieta Mesa is locally capped by outliers of Triassic strata (Moenkopi and Santa Rosa Formations). Most of the mesa slope is Yeso Group strata, and the Glorieta Sandstone forms a bold, light-colored rim above those strata. A thin interval composed of the Permian San Andres and Artesia Formations separates the Glorieta Sandstone from the Triassic strata. (See also Color Plate 13)

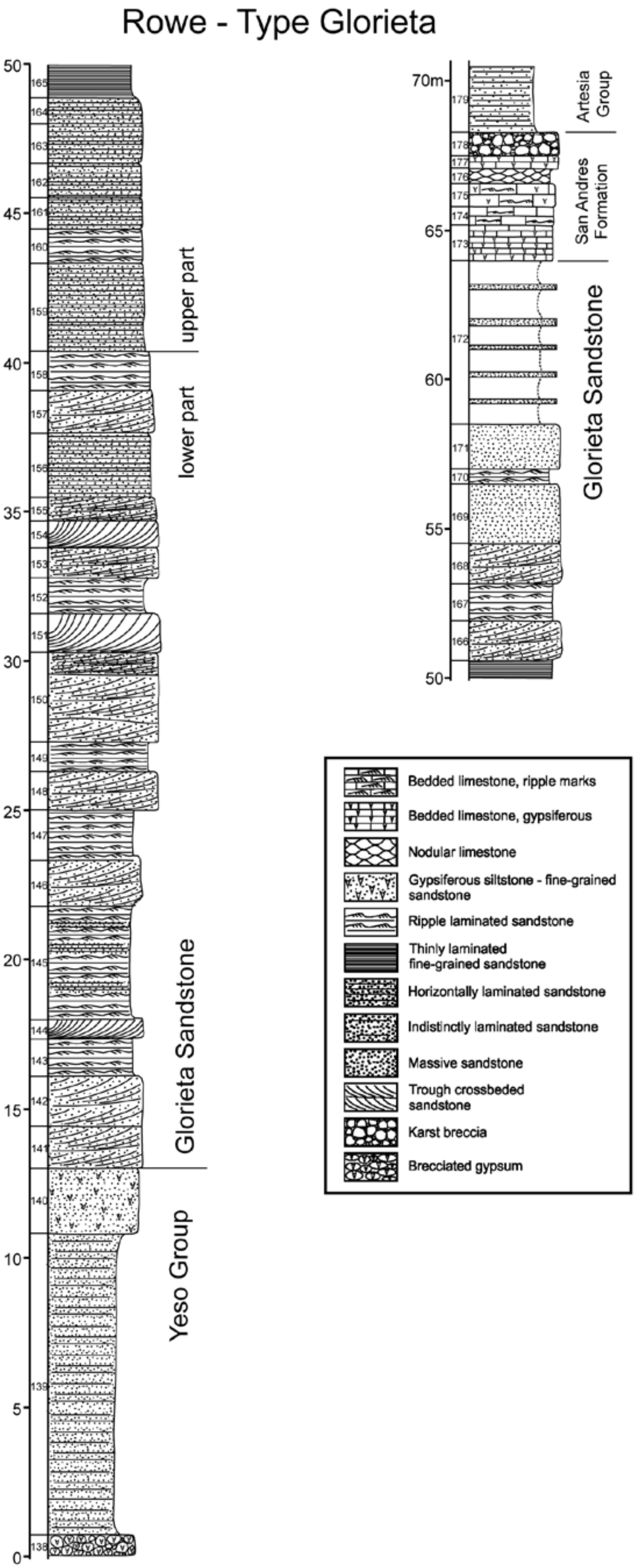

FIGURE 4. Measured stratigraphic type section of the Glorieta Sandstone.

DEPOSITIONAL ENVIRONMENTS

The Glorieta Sandstone has been interpreted as either deposits of a dominantly shallow marine environment (e. g., Baars, 1961, 1962, 2000; Kelley, 1971; Milner 1978; Dinterman, 2001) or as dominantly eolian deposits (e.g., Bauer, 2011; Bauer and Mack, 2011; Lucas et al., 2013a; Mack and Bauer, 2014). Baars (1961, 1962, 1974, 2000) correlated the Glorieta Sandstone with the Coconino Sandstone of northeastern Arizona. He pointed to the similar facies, although he noted that sedimentary structures of the Glorieta Sandstone indicate that most of it was deposited in a subaqueous environment. According to Baars (2000), the sediment of the Glorieta Sandstone was derived from the Mazatzal uplift in north-central Arizona. Recently, Mack and Bauer (2014) listed a number of differences between the Glorieta and Coconino Sandstone with regard to thickness and facies.

According to Milner (1978), cross-stratification, ripples and parallel stratification are the common sedimentary structures of the Glorieta Sandstone in Lincoln County, eastern New Mexico. Milner (1978) interpreted the Glorieta Sandstone there as sediments deposited along the coastline. Crossbedded sandstones formed in foreshore to upper shoreface, coastal dune and tidal channel environments. Sea-level rise caused deposition of carbonate sediments in tidal flat, restricted, open marine and evaporitic environments (see discussion in Lucas et al. 2013a).

Recently, Bauer (2011), Bauer and Mack (2011) and Mack and Bauer (2014) interpreted sandstone with ripple lamination, large-scale planar crossbedded sandstone and massive sandstone of the Glorieta Sandstone to be of eolian origin, and small-scale trough-crossbedded sandstone as deposits of shallow interdunal streams. Based on zircon ages, Bauer (2011), Bauer and Mack (2011) and Mack and Bauer (2014) conclude that the sediment of the Glorieta Sandstone was derived from a transcontinental river system with its headwaters in the Appalachian-Ouachita Orogen and Canadian Shield and a local source in the Uncompahgre and Front Range uplifts.

At the type section of the Glorieta Sandstone, we interpret the crossbedded sandstone intervals as eolian dune deposits. Foresets dip mostly towards the southwest, indicating that the sand dunes formed in a relatively unimodal wind regime. The crossbedded sandstones probably represent transverse or barchanoid dunes (cf. Ahlbrandt and Fryberger, 1982; Fryberger, 1990; Brookfield and Silvestro, 2010). We interpret the horizontally and ripple-laminated sandstones intercalated in the crossbedded sandstone in the lower part of the type section as interdune deposits.

Ripples in the Glorieta Sandstone are poorly preserved, and the ripple foresets observed by Milner (1978) are absent at the type section. During the migration of wind ripples, sand grains are transported by saltation and impact processes, and no avalanching occurs down the lee slope, as is the case in subaqueous ripples (e.g., Reineck and Singh, 1980; Nickling, 1994). Therefore, ripple foresets are commonly absent in wind ripples, and the bedding produced by the migration of wind ripples is commonly horizontally laminated sand (e.g., Schenk, 1990).

Eolian dunes are more common in the lower part of the type section of the Glorieta Sandstone (Fig. 4). Intercalated

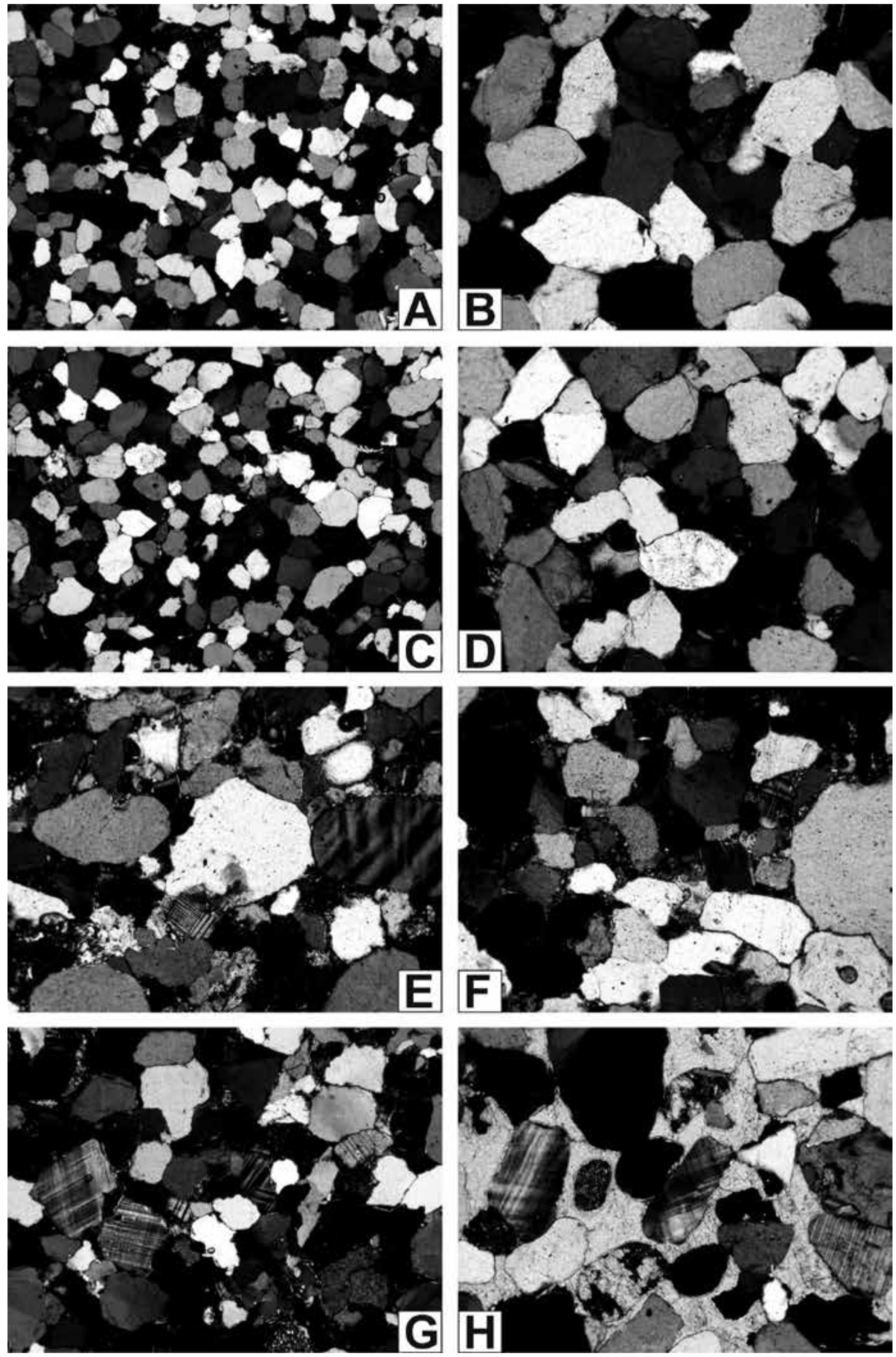

FIGURE 5. Thin section photomicrographs of sandstone from the Glorieta Sandstone and underlying Yeso Group at the Glorieta type section. All under polarized light. A. Fine-grained, well-sorted sandstone (quartzarenite) composed of rounded to well-rounded quartz grains. Lower part of the Glorieta Sandstone (unit 142). Width of photograph is 3.2 mm. B. Fine-grained quartzarenite composed almost entirely of monocrystalline quartz and rare polycrystalline quartz. The detrital grains are cemented by quartz as authigenic overgrowths, which on some grains are poorly visible. Lower part of the Glorieta Sandstone (unit 142), width of photograph is 1.2 mm. C. Fine-grained, well-sorted sandstone composed of monocrystalline quartz, rare polycrystalline quartz and very rare detrital feldspar grains (quartzarenite). Lower part of the Glorieta Sandstone (unit 152), width of photograph is 3.2 mm. D. Detail of C showing abundant mono- and a few polycrystalline quartz grains (quartzarenite), which are subrounded to rounded and cemented by authigenic quartz overgrowths. Unit 152, width of photograph is 1.2 mm. E. Fine- to medium-grained, moderately sorted sandstone containing subrounded grains of mono- and polycrystalline quartz. Detrital feldspar grains are also present (subarkose). The detrital grains are cemented by coarse blocky calcite. Upper part of the Glorieta Sandstone (unit 171), width of photograph is 3.2 mm. F. Fine-grained sandstone composed of mono-and polycrystalline quartz and detrital feldspar grains (subarkose) cemented by calcite. Upper part of the Glorieta Sandstone (unit 171), width of photograph is 3.2 mm. G. Medium-grained, moderately sorted sandstone composed of subangular to subrounded grains including mono- and polycrystalline quartz, abundant feldspar grains and a few granitic rock fragments (arkose). Yeso Group, unit 7 (below section in Figure 4), width of photograph is 3.2 mm. H. Medium-grained sandstone containing mono- and polycrystalline quartz grains, detrital feldspar grains and granitic rock fragments, cemented by coarse poikilitic calcite cement that partly replaced detrital feldspar grains. Yeso Group, unit 44 (below section in Figure 4), width of photograph is 3.2 mm.

ripple-laminated sandstone in the lower part is interpreted as interdune deposits. In the upper part of the type section, horizontally laminated, ripple-laminated and massive sandstones dominate, which are interpreted as eolian sand sheets. A few crossbedded intervals represent eolian dunes.

We did not recognize marine sandstone deposits within the Glorieta Sandstone at the type section, although in the San Andres Mountains near Rhodes Pass in Sierra County, at the type section of the San Andres Formation, the Glorieta Sandstone is very thin and of shallow marine origin as is indicated by the presence of foraminiferans (Krainer et al., 2012). Herringbone crossbedding in the Glorieta Sandstone observed by Milner (1978) suggests that, at least locally, the sandstone was deposited in a shallow marine, tidally influenced environment.

Mack and Bauer (2014) reported fenestral dolostone in the Glorieta Sandstone that they interpreted as representing a high intertidal to supratidal environment, and fossiliferous dolomite indicating a shallow marine setting. Such shallow marine carbonate intercalations are absent at the type section of the Glorieta Sandstone but have been observed in the Sandia Mountains at Cedar Crest in Bernalillo County (Lucas et al., 2013a).

As already pointed out by Baars (1961, 1962, 1974), the Glorieta Sandstone is an eastward extension of the Coconino erg of northern Arizona (e.g., Kues and Giles, 2004). In the northwestern and western outcrops on the Colorado Plateau portion of New Mexico, and at the type section described here, the Glorieta Sandstone is mainly composed of eolian dune and interdune deposits and eolian sheet sands. To the southeast and east, the Glorieta Sandstone interfingers with shallow marine carbonates of the San Andres Formation, and parts of the Glorieta Sandstone were deposited in marginal marine settings.

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