A marginal facies of the Jurassic Todilto Formation salina basin near Thoreau, New Mexico

Karl Krainer and Spencer G. Lucas

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A MARGINAL FACIES OF THE JURASSIC TODILTO FORMATION SALINA BASIN NEAR THOREAU, NEW MEXICO

KARL KRAINER[1] AND SPENCER G. LUCAS[2]

[1]Institute of Geology and Paleontology, University of Innsbruck, Innsbruck A-6020, Karl.Krainer@uibk.ac.at;
[2]New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104, spencer.lucas@state.nm.us

ABSTRACT—We present a petrographic study of a measured section of the Luciano Mesa Member of the Jurassic Todilto Formation near Thoreau, New Mexico. This section represents a marginal facies of the Todilto salina, characterized by laminated limestone that formed by precipitation of carbonate minerals and the settling out of eolian sediment that was blown into the salina from the adjacent erg. This is in contrast to the basinal facies of the Luciano Mesa Member where the laminated limestone is commonly composed of organic-rich microbial mats (stromatolites), and where windblown sediment is present in smaller amounts.

INTRODUCTION

The Jurassic Todilto Formation crops out and is present in the subsurface across much of northwestern New Mexico and part of southwestern Colorado, over an area of about 100,000 km^2 (Anderson and Kirkland, 1960; Lucas et al., 1985; Armstrong, 1995; Kirkland et al., 1995). Throughout its extent, the Todilto overlies the Middle Jurassic Entrada Sandstone and is overlain by the Upper Jurassic Summerville Formation. Regional stratigraphic relationships indicate that the Todilto Formation is homotaxial with the marine Curtis Formation of Utah (e.g., Kocurek and Dott, 1983; Anderson and Lucas, 1996). The regional rise in base level reflected in the transgression of the Curtis seaway and the ensuing highstand produced an extensive waterbody in northern New Mexico–southwestern Colorado, just southeast of the seaway. Deposition of this waterbody has been interpeted by a diverse literature as either a marine embayment, saline lake or paralic salina.Yet, despite the extensive discussion of Todilto deposition in the literature, little petrographic study of the unit has appeared in print (exceptions include Ulmer-Scholle, 2005; Lucas et al., 2014; and Kocurek et al., 2018). Here, we present a petrographic study of a Todilto Formation section near Thoreau, New Mexico (Fig. 1). This study documents lacustrine and eolian deposition along the margin of the Todilto depositional basin.

LOCATION AND METHODS

We measured a section of the Todilto Formation approximately 8 km NE of Thoreau (Fig. 1). Thin sections were prepared from nine hand samples collected in the field to examine the sediments under a polarized microscope. The amount of terrigenous particles (quartz, feldspars) of individual layers was calculated by point counting (using the program JMicroVision). Thin section photographs (Figs. 2-4) were prepared for documentation of the different sediment types.

LITHOSTRATIGRAPHY AND LITHOLOGY

Across northern New Mexico, the Todilto Formation is divided lithostratigraphically into the Luciano Mesa Member and the overlying Tonque Arroyo Member (e.g., Anderson and
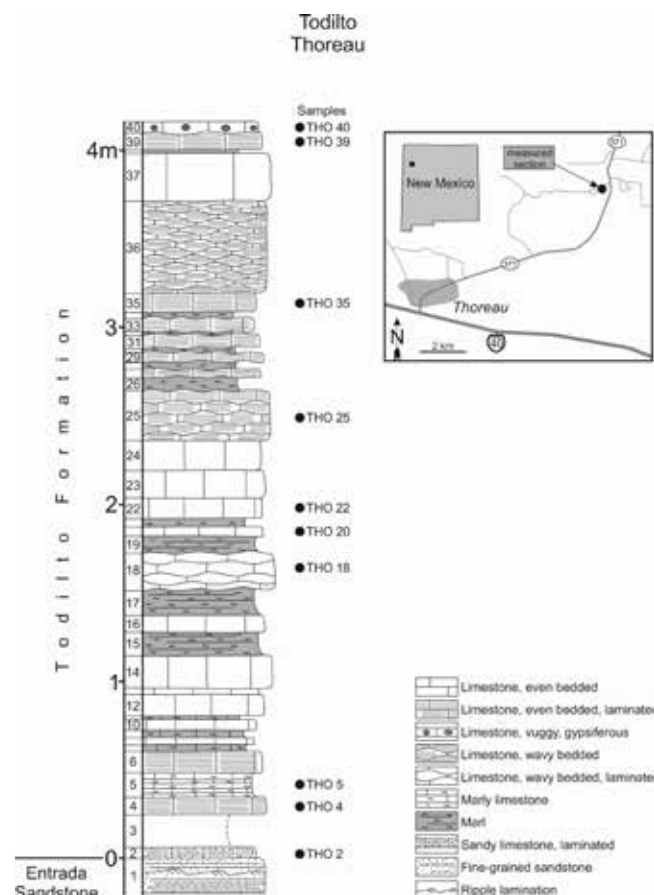

FIGURE 1. Measured section through the Luciano Mesa Member and map showing location of the section near Thoreau. The location of the section in UTM coordinates is zone 12, 759503E, 3925904N, datum NAD 83.

FIGURE 2. Outcrop photograph of the studied section of the Todilto Formation (Luciano Mesa Member) near Thoreau. For location see Fig. 1.

Lucas, 1996; Lucas, 2020). The Luciano Mesa Member is up to 13 m thick and composed of light- to medium-gray, commonly microlaminated, bituminous micritic limestone. The Tonque Arroyo Member is a succession of nodular and indistinctly laminated gypsum as much as 61 m thick.

The measured section near Thoreau that was examined is 4.4 m thick and assigned to the Luciano Mesa Member (Figs. 1, 2). The Todilto Formation strata overlie fine-grained calcareous sandstone of the Entrada Sandstone that partly displays ripples that are poorly developed, and internal laminae were not observed. We interpret these ripples to be of eolian origin. The top of the Todilto Formation and its contact with the overlying Summerville Formation has been eroded away at the location measured. However, nearby outcrops indicate that less than 1 m of the uppermost Todilto Formation is missing at the top of the section.

At the measured section (Figs. 1, 2), the basal bed of the Luciano Mesa Member of the Todilto Formation is a thin (5 cm thick), laminated sandy limestone bed. Above a covered interval (20 cm thick), two limestone beds are exposed (10 and 12 cm thick) that are separated by marly limestone (13 cm thick).

The overlying succession (172 cm thick) is composed of muddy limestone beds with even bedding planes (4-19 cm thick) and one wavy bedded limestone (22 cm thick) and thin intercalations of marl (2-13 cm thick). The next interval (83 cm thick) is composed of wavy bedded, laminated limestone (beds are 4-28 cm thick), one laminated limestone bed with even bedding (12 cm thick) and marl intercalations (2-8 cm thick).

This interval is overlain by a thicker, wavy bedded and laminated limestone unit (52 cm thick), followed by a massive, muddy limestone bed (27 cm thick), a thin marl intercalation (2 cm thick) and a laminated limestone bed (10 cm thick). The topmost limestone bed is vuggy and gypsiferous (6 cm thick).

SEDIMENTARY PETROGRAPHY

Laminated Sandy Limestone

The laminated sandy limestone bed that forms the base of the Luciano Member (Fig. 1, unit 2) is composed of up to about 1- mm-thick, fine-grained sandstone layers that alternate with recrystallized carbonate layers (microsparite) that contain small amounts of silt-sized detrital grains (quartz, rare feldspar). The sandstone layers are well-sorted and contain subrounded to rounded detrital grains cemented by blocky calcite (Fig. 3A). Detrital grains are dominantly monocrystalline quartz. Polycrystalline quartz and feldspar grains (perthite, microcline) are present in small amounts.

Laminated Limestone

Laminated limestone of unit 4, under the microscope, appears as indistinctly laminated mudstone that contains small, angular to subangular quartz grains and a few detrital feldspar grains (Fig. 3B). The amount of detrital grains (determined by point counting) is 13.2-14.4%. Detrital quartz and feldspar grains float in recrystallized, silty carbonate matrix.

The laminated limestone of unit 25 is composed of laminated mudstone to siltstone with intercalated thin laminae that contain abundant quartz and, subordinately, feldspar grains and rare mica (muscovite). Also present as single grains are small tourmaline, zircon and opaque grains (Fig. 3H). Individual laminae are very thin (0.05-0.1 mm thick), and some other laminae are up to several mm thick. Thicker laminae are composed of 41% quartz grains, 8% feldspar grains and 51% calcite cement (Fig. 4A-F).

The limestone of unit 35 is composed of laminated mudstone to siltstone. Thicker layers are nearly free of quartz and do not show any internal lamination. Intercalated thin laminae (0.1-0.5 mm thick) contain many quartz and feldspar grains that often form thin lenses (Fig. 5A). One thin mudstone-siltstone layer displays an erosive base (Fig. 5B). Individual mudstone to siltstone layers contain ostracods (Fig. 5C).

The laminated limestone near the top of the section (unit 39) is an ostracod wackestone (Fig. 5D-E). Many of the ostracods are preserved as paired valves that are filled with cal-

FIGURE 3. Thin section photographs of limestone and sandstone of the Luciano Mesa Member (Todilto Formation) near Thoreau. A and D under polarized light, B, C, E-H under plane light. Scale bar for A, D = 0.2 mm, all others = 1 mm. **A**) Fine-grained, well-sorted sandstone composed of abundant detrital monocrystalline quartz, subordinately of polycrystalline quartz and feldspar grains. The detrital grains are cemented by blocky calcite. Sample THO 2. **B**) Indistinctly laminated mudstone containing small amounts of detrital grains (quartz, feldspar). Sample THO 4. **C**) Siltstone to fine-grained sandstone containing abundant small, detrital grains of quartz and feldspar. Sample THO 5. **D**) Detail of C showing detrital quartz and feldspar grains embedded in recrystallized micritic matrix. Sample THO 5. **E**) Indistinctly laminated mudstone containing few detrital quartz and feldspar grains. Sample THO 20. **F**) Indistinctly laminated siltstone/fine-grained sandstone containing abundant detrital quartz and feldspar grains and few large intraclasts ("flat pebbles"). Sample THO 20. **G**) Indistinctly laminated siltstone to fine-grained sandstone containing abundant detrital grains and rare larger intraclasts ("flat pebbles"). THO 22. **H**) Laminated mudstone with thin laminae that contain abundant detrital quartz and a few feldspar grains. Sample THO 25.
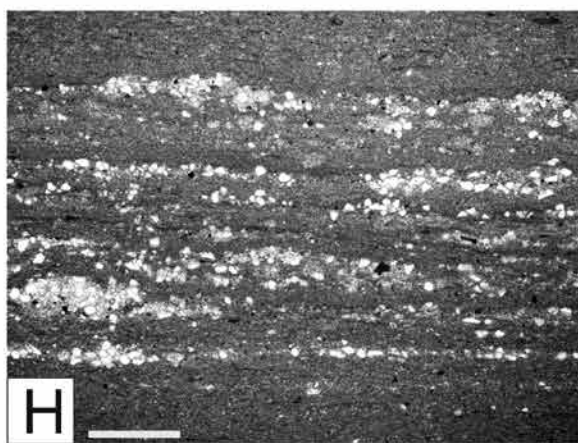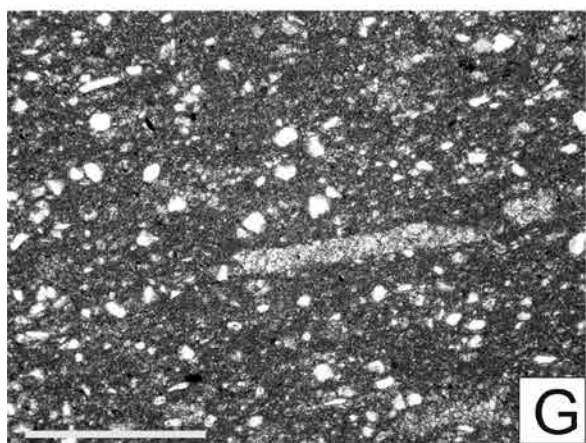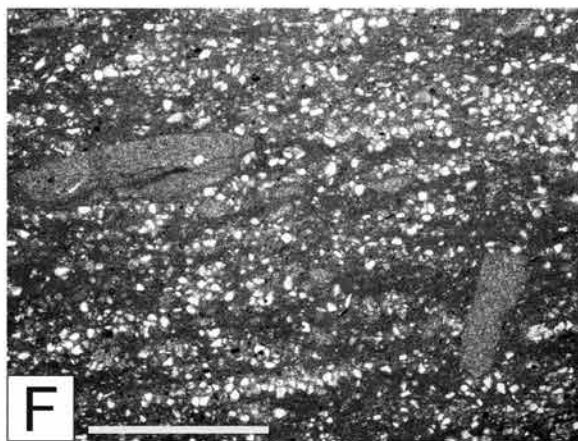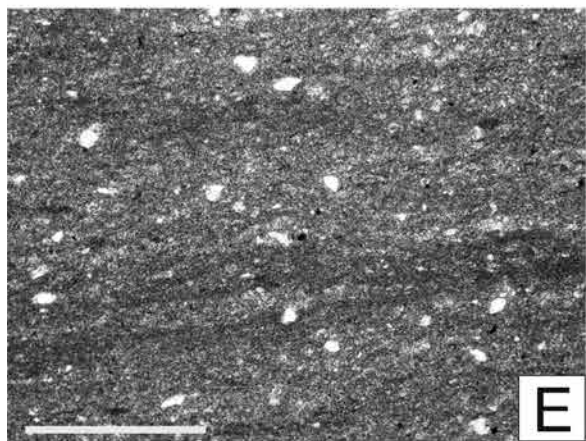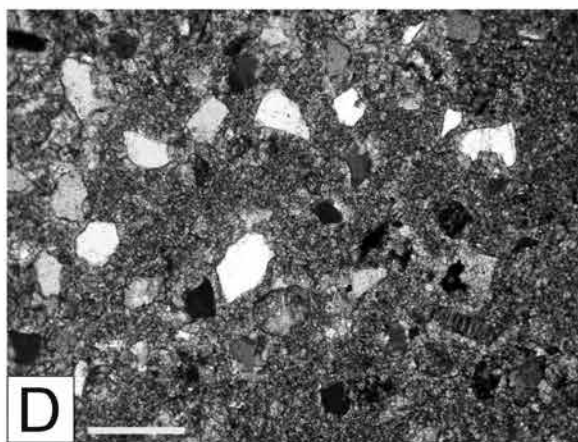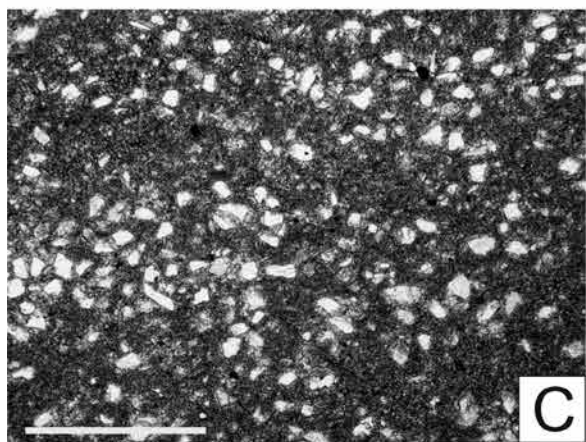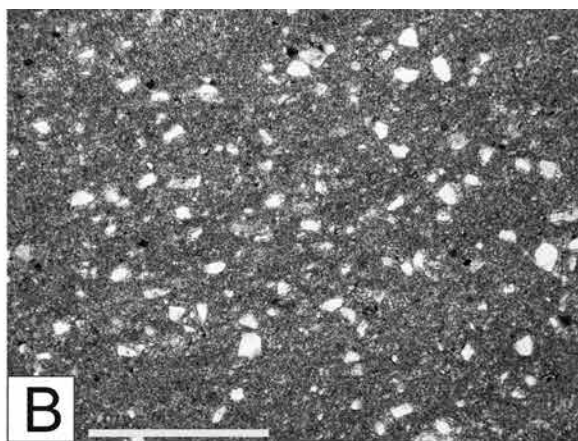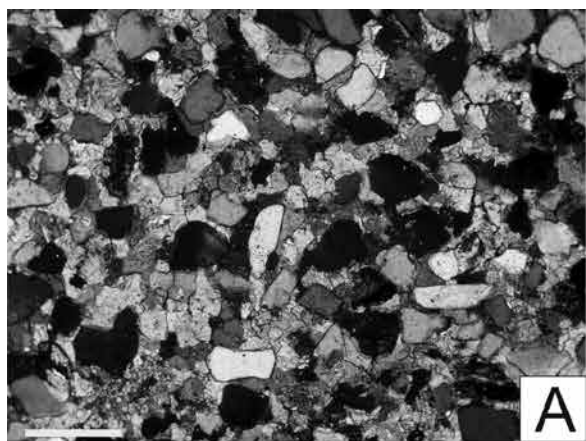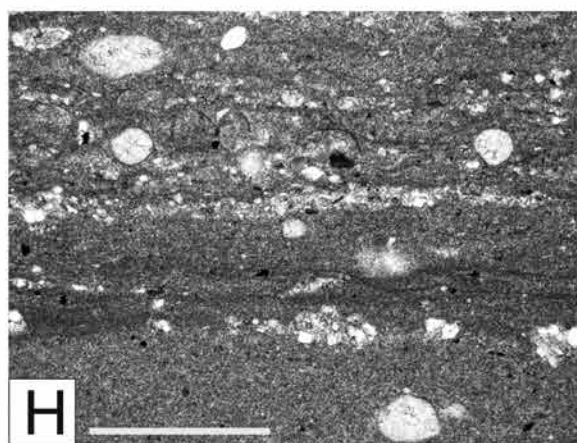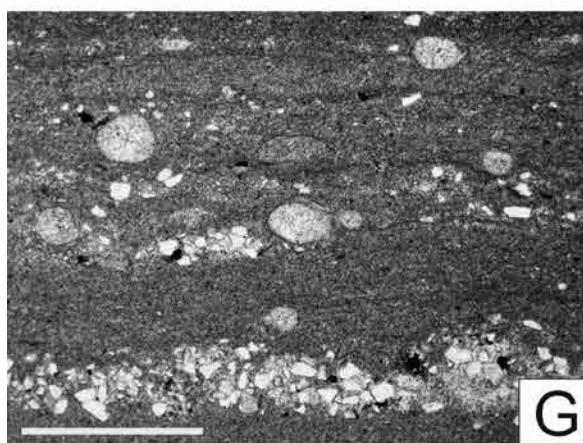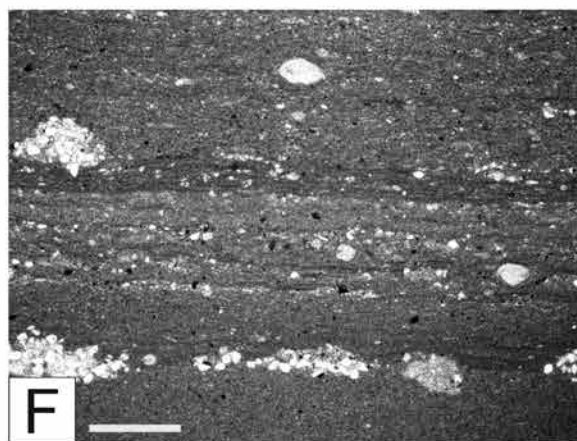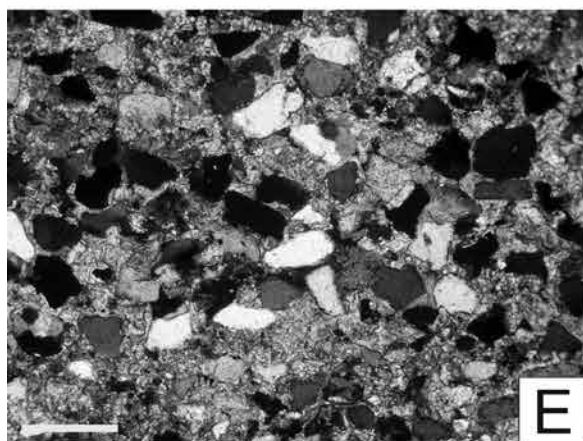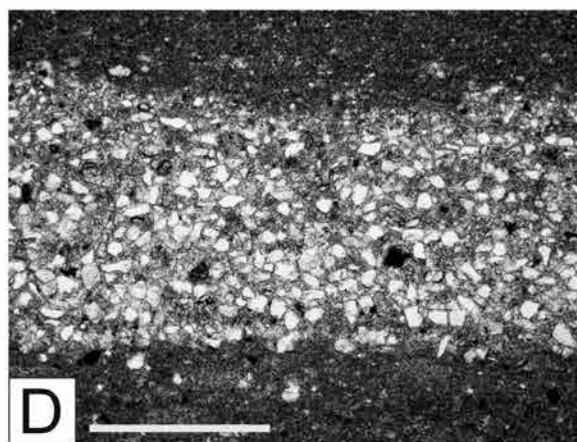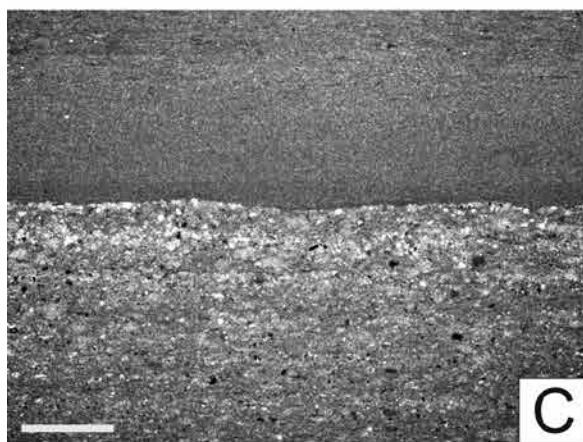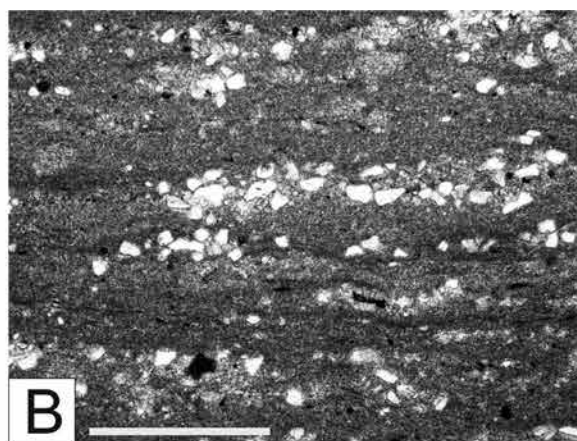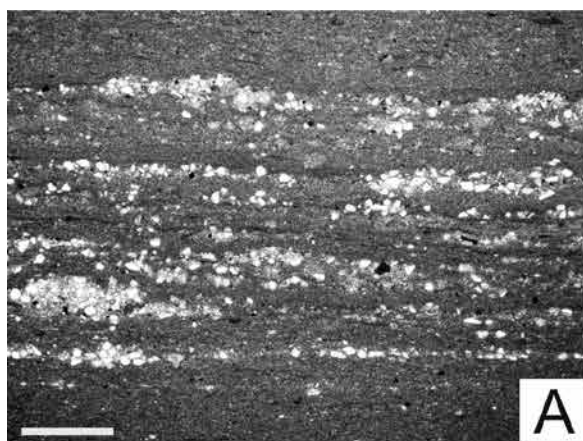
cite cement. Ostracods show little compaction and range in size from 0.1 to 0.6 mm long. Single-valved ostracods are also abundant. The ostracods seem to belong to one species and are very similar to the ostracod *Cytheridella todiltoensis* (Swain, 1946), which was described from a Todilto outcrop very close to the studied section (Kietzke, 1992). The wackestone contains small amounts of small quartz grains.

Non-Laminated Limestone

The non-laminated limestone bed of unit 18 is a mixed siliciclastic-carbonate siltstone to fine-grained sandstone that is indistinctly laminated and contains abundant quartz grains, a few feldspar grains and very rare micas (muscovite) and chert grains. Present are a few blocky carbonate grains that probably represent replaced feldspar grains. The quartz and feldspar grains are floating in micritic to silty carbonate matrix, resulting in a "mud-supported" texture. Embedded are a few recrystallized, resedimented mudstone "chips" that are up to a few cm in size (mostly < 1 mm; Fig. 3F).

The limestone bed of unit 20 is indistinctly laminated mudstone with a small amount of quartz grains, rare feldspar grains and micas that constitute 3.2% of the total rock (Fig. 3E).

Limestone bed unit 22 contains mixed siliciclastic-carbonate siltstone to fine-grained sandstone that contains abundant quartz grains, a few feldspar grains and rare micas that float in recrystallized micritic to silty matrix. The sediment contains a few reworked mudstone clasts. Quartz and feldspars are 12.4% of the total rock (Fig. 3G).

Marly Limestone

The marly limestone interval (unit 5) is nonlaminated, mixed siliciclastic-carbonate siltstone to fine-grained sandstone (Fig. 3C, D) containing quartz and some feldspar grains, a few opaque grains and rare grains of zircon, tourmaline, garnet and apatite (grain-size of the accessory minerals is approximately 0.05 mm). The terrigenous grains that constitute 17-20% of the total rock are embedded in recrystallized micritic to silty matrix ("matrix-supported texture").

Vuggy, Gypsiferous Limestone

The uppermost bed (unit 40) of the measured section is composed of ostracod wackestone that is indistinctly laminated and contains abundant, up to several cm diameter nodules of coarse, blocky calcite (most likely representing replaced gypsum nodules). Ostracod wackestone contains paired, and more abundant single valves of ostracods, and a few small quartz grains (Fig. 5F, H).

Terrigenous Particles of Limestones

Terrigenous particles are dominantly quartz grains, among which monocrystalline quartz is much more abundant than polycrystalline quartz. Detrital feldspars are mostly alkali-feldspars, including microcline and perthite (Figs. 3A, D, 4E). Many feldspar grains are altered and partly replaced by calcite. Other terrigenous particles include opaque grains and single grains of transparent heavy minerals such as zircon, tourmaline and rare garnet and apatite.

The grain size of terrigenous particles is mostly between 0.05 and 0.1 mm, and the maximum grain size is 0.2 mm. Quartz and feldspar grains are mostly subangular to subrounded, and, subordinately, rounded grains are present. In general, the terrigenous particles float in the micritic to silty carbonate matrix, forming a mud-supported texture. Only in a few thin layers terrigenous particles are so abundant that they form a grain-supported texture (Figs. 3A, 4E). In general, the amount of terrigenous particles (quartz, feldspars) decreases from base to top.

DEPOSITIONAL ENVIRONMENTS

Three models have been proposed for the deposition of the Todilto Formation:

1. Evaporitic lake model (e.g., Rapaport et al., 1952; Anderson and Kirkland, 1960; Kocurek and Dott, 1983) of a lake or playa lake that became increasingly evaporitic.

2. Marine embayment model (e.g., Harshbarger et al., 1957; Armstrong, 1991) suggesting a hypersaline marine embayment of the Curtis sea.

3. Salina model proposed by Lucas et al. (1985) of an isolated basin that was filled with marine water from the Curtis sea by seepage through the Entrada sand dunes along the western margin of the basin (also see Kirkland et al., 1995). The salina had no direct connection to the Curtis sea. Freshwater entered the salina in the form of streams that were possibly of intermittent nature.

Anderson and Kirkland (1960) interpreted the microlaminae in limestones of the Todilto Formation as varves. This cyclic sedimentation was probably caused by seasonal variations in water temperature, the rate of evaporation, amount of rainfall, or the amount of inflow of freshwater from the hinterland, as well as photosynthesis of phytoplankton (see also Kirkland et al. 1995). According to Anderson and Kirkland (1960), the

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FIGURE 4. Thin section photographs of limestone and fine-grained sandstone of the Luciano Mesa Member (Todilto Formation) near Thoreau. E under polarized light, all photos under plane light. Scale bar for E = 0.2 mm, all others = 1 mm. **A**) Laminated mudstone with intercalated thin laminae that contain abundant detrital quartz and some feldspar grains. Sample THO 25. **B**) Detail of A. **C**) Siltstone layer containing small amounts of small detrital grains, overlain by a mudstone layer that is almost free of detrital grains. Sample THO 25. **D**) Fine-grained sandstone layer intercalated in silty mudstone. Sample THO 25. **E**) Detail of fine-grained sandstone layer composed of abundant monocrystalline quartz, and, subordinately, polycrystalline quartz and feldspar grains. Detrital grains are cemented by calcite. Sample THO 25. **F**) Laminated mudstone/siltstone containing a few detrital quartz and feldspar grains, and a few ostracods. Locally, detrital grains are concentrated in small lenses. Sample THO 25. **G, H**) Laminated mudstone with ostracods and intercalated thin laminae that contain abundant detrital quartz and feldspar grains. Sample THO 35.
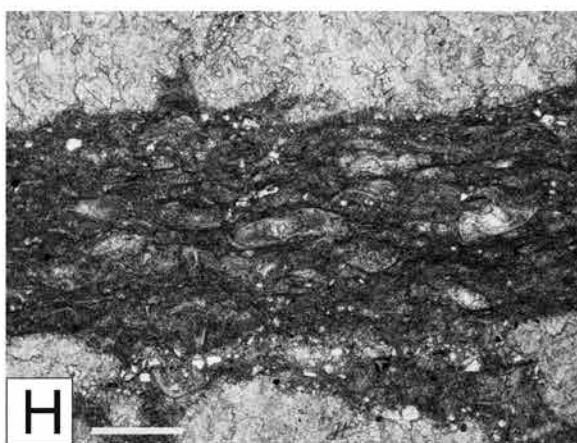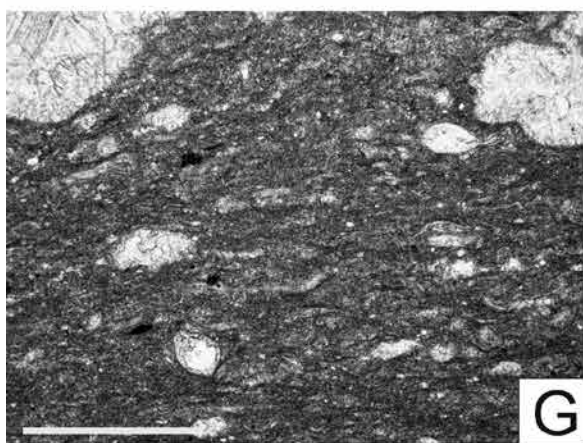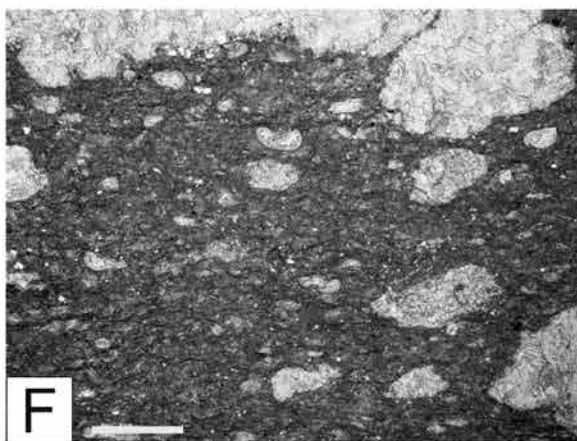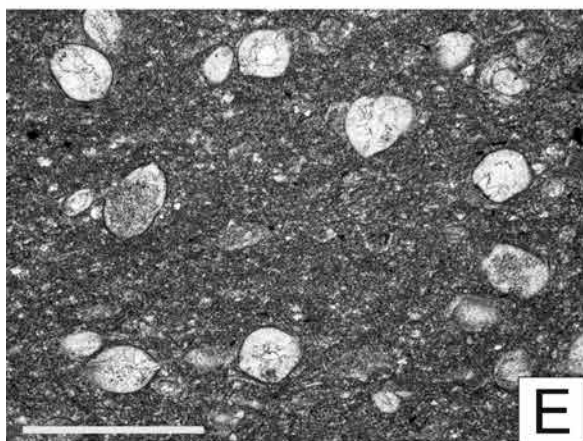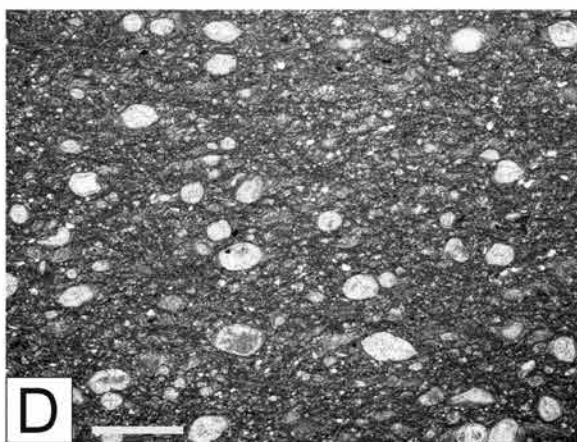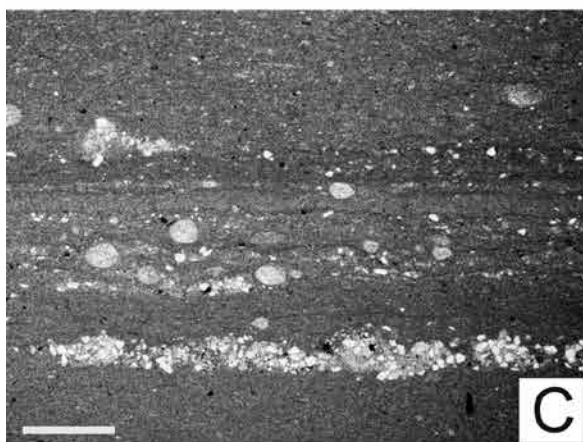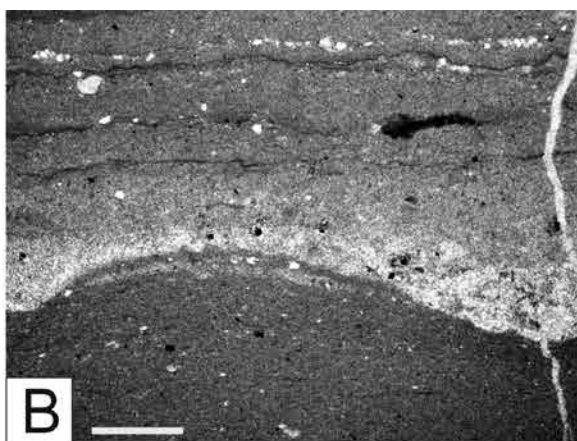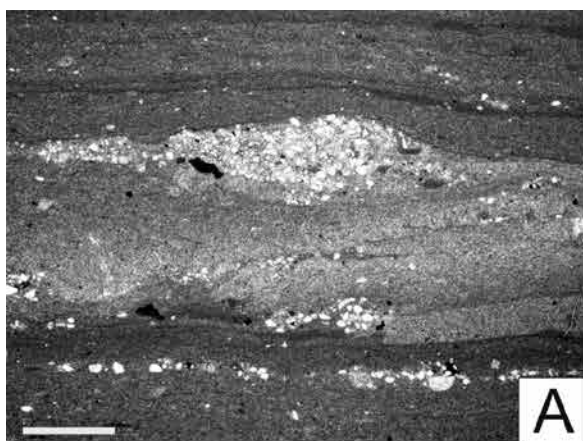
siliciclastic grains were probably transported into the salina by both wind and inflowing streams. Eolian transport of silt- to fine-grained sand in a desert basin is to be expected and the fresher water from inflowing streams would have produced overflows of the more saline water and distributed the suspended sediments more or less uniformly over the salina. From the number of varve couplets, Anderson and Kirkland (1960) estimated a time-span of about 14,000 years for deposition of the microlaminated limestones. According to Armstrong (1995), the calcite lime mudstone of the Todilto Formation derived primarily from an aragonite mud precursor that was diagenetically overprinted by neomorphism. He concluded that the Todilto represents the change from a restricted marine embayment with an ephemeral connection to the Curtis sea to a completely enclosed salina/playa and shrinking body of gypsiferous water. Gypsum was deposited in the central part of the basin during the final salina phase.

Kirkland et al. (1995) concluded that evaporation in the Todilto sea led to precipitation of laminated carbonate sediments and gypsum. The Todilto Formation was deposited in a coastal body of sea water (salina). After initial flooding by marine water, the salina was maintained by inflow of freshwater from streams and by influx of seawater by seepage through the Entrada sand dunes. Isotope studies indicate a marine origin, but the isotope data are also compatible with nonmarine or mixed water (Kirkland et al. 1995).

Recently, Kocurek et al. (2018) stated that the underlying Entrada sand dunes were located in a basin below sea-level that was flooded by marine water. They interpret the laminated limestone of the Todilto Formation as microbial biolaminites. Characteristic features of these microbialites are organic-rich laminae that display structures typical of filamentous microbes. These laminae also contain trapped eolian silt. The laminae are commonly wavy to crinkly, non-parallel and difficult to trace laterally. Locally, the laminae form cm-scale stromatolitic domes. Stromatolitic laminites have also been reported by Armstrong (1995) and described from the Luciano Member at Dos Lomas and Haystack Butte near Grants by Ulmer-Scholle (2005) and Lucas et al. (2014).

The Todilto Formation contains a limited fossil record of a few species of insects, fish, nonmarine ostracods and calcareous algae (Lucas et al., 1985; Kietzke, 1992; Armstrong, 1995; Kirkland et al., 1995). According to Kietzke (1992), the presence of a typical freshwater ostracod supports the salina model. This ostracod, *Cytheridella todiltoensis* (Swain, 1946), probably occupied marginal areas of the Todilto salina, depending on freshwater influx. The type locality of this ostracod species is located about 10 km north of Thoreau on NM Highway 371, very close to the section we studied. The Todilto fish fauna is also inferred to have lived in freshwater so that fish fossils in the Todilto Formation are mostly restricted to nearshore areas with freshwater inflow (see discussion in Lucas et al., 1985).

In the laminated limestones of the studied section near Thoreau, the lamination is even, locally poorly developed and of variable thickness. Organic-rich laminae and crinkled lamination is absent. Desiccation cracks were not observed. Detrital grains of quartz and feldspar are common and occur either dispersed or concentrated in thin laminae and layers. These evenly laminated limestones most likely formed from carbonate precipitation. Microbial mats were not observed.

Lacustrine sediments in general are a mixture of precipitated minerals, such as calcite; detrital, terrigenous material, such as quartz and feldspar grains; and biogenic particles, such as ostracod shells. Finely laminated limestones of variable thickness and lateral extent generally are deposited from sediment that settles out of suspension. Lamination is formed when temporal variations occur in the amount of sediment input when the sediment is not disturbed by bioturbation. Carbonate evaporite precipitation from seawater starts when the water becomes supersaturated in calcium carbonate (aragonite, calcite). Calcite precipitation from seawater through evaporation starts after the loss of 50% of seawater, gypsum precipitation after the loss of 66% of seawater (James and Jones, 2016). Precipitation of carbonate minerals may be induced by microbes and algae. Aragonite and calcite are the most common abiogenic precipitates. Additionally, detrital carbonate grains may be transported into the lake by rivers or by wind, and it is impossible to distinguish detrital carbonate grains from precipitated carbonate minerals, particularly after diagenetic recrystallization processes.

We conclude that the laminated limestones of the studied section formed by both precipitation of carbonate minerals (aragonite according to Armstrong, 1995) and windblown sediment from the adjacent sandy erg composed of dominantly carbonate, quartz and feldspar grains. Precipitated and windblown grains settled down in the water column of the perennial salina forming laminated limestone. Individual laminae are mainly or completely composed of windblown sediment (eolianites). Other laminae that are almost free of detrital quartz and feldspar grains mainly formed from precipitation of calcium carbonate (aragonite) minerals. Biogenically induced precipitation seems to have played no significant role, but, although microbial mats were not observed, this process cannot be completely excluded. Thin microbial mats may not be preserved. In the upper part, individual limestone beds formed by the accumulation of abundant ostracod shells, windblown sediment and probably also precipitated calcium carbonate minerals. Increased salinity finally caused the precipitation of nodular and laminated gypsum in more basinal locations than the section we studied near Thoreau. The studied section was thus located in a marginal part of the Todilto depositional basin, where

FIGURE 5. Thin section photographs of limestone of the Luciano Mesa Member (Todilto Formation) near Thoreau. All under plane light. Scale bar is 1 mm. **A)** Laminated mudstone with a few small detrital grains and intercalated thin laminae and lenses that contain abundant detrital grains. Sample THO 35. **B)** Indistinctly laminated mudstone to siltstone with a few detrital grains and a distinct erosional relief filled with siltstone. Sample THO 35. **C)** Laminated mudstone to siltstone containing a few detrital grains and ostracods, and intercalated lenses rich in detrital grains. Sample THO 35. **D, E)** Ostracod wackestone containing ostracods, partly preserved as paired valves that probably all belong to one taxon. The ostracods are embedded in recrystallized micrite. Sample THO 39. **F-H)** Ostracod wackestone with nodules of blocky calcite. These nodules are gypsum nodules that were replaced by calcite during diagenesis. Sample THO 40.

eolian sediment input was probably higher than in the more basinal part and hampered microbial activity.

CONCLUSIONS

The investigated section of the Luciano Mesa Member of the Todilto Formation near Thoreau represents a marginal salina facies of the perennial waterbody (Todilto salina), characterized by well to indistinctly laminated limestone that formed by the settling out of precipitated carbonate minerals and eolian sediment that was blown into the Todilto salina from the adjacent erg. Microbial mats (stromatolites) are absent. The Luciano Member is thinner than in the more basinal area of Todilto deposition, and the overlying gypsum-rich Tonque Arroyo Member is absent in the marginal facies. This is in contrast to the basinal facies where the laminated limestone is commonly composed of organic-rich microbial mats (stromatolites) and where windblown sediment is present in smaller amounts than in the marginal facies.

ACKNOWLEDGMENTS

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