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STROMATOLITES IN THE TODILTO FORMATION?

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ABSTRACT.—The Middle Jurassic Todilto Formation is found in northern New Mexico and southwestern Colorado. In the Ambrosia Lake uranium district, previous workers have identified the large fold-like features in the Todilto Formation as intraformational folds that were produced by loading of the overlying Middle-Upper Jurassic eolian Summerville Formation on the water-saturated sediments of the Todilto Formation or by later structural deformation. A re-interpretation of the outcrops of Green (1982) near Mesa Montañosa, based on preliminary field data, suggests that these features are large, domal stromatolites or bioherms. The composition and morphology of these structures indicate microbial growth rather than loading as the source of the mounds. While similar structures elsewhere in the Todilto Formation have been attributed to intraformational or tectonic deformation, this study suggests that there may be more than one mechanism capable of producing fold-like structures in the Todilto Formation, and a reassessment of previously identified structures may be needed.

INTRODUCTION

The Middle Jurassic Todilto Formation is found in northern New Mexico and southwestern Colorado where it forms well-exposed outcrops of gypsum and limestone. Economically, the Todilto Formation has one of the largest and most productive limestone-hosted uranium deposits in the world (Chenoweth, 1985a, 1985b; McLemore and Chenoweth, 1992). Since limestones are normally unlikely hosts for uranium deposits, numerous studies on the Todilto Formation have investigated its deposition and diagenesis as well as the possible uranium sources and the unusual conditions that must have existed to form these ore deposits (Armstrong, 1995; Bell, 1963; Berglof and McLemore, 1996; Berglof and McLemore, 2003; Ellsworth and Mirsky, 1952; Green, 1982, Gabelman and Boyer, 1988; Gruner et al., 1951; Hines, 1976; Huffman and Lupe, 1977; McLemore and Chenoweth, 2003; Rawson, 1980a; Rawson, 1980b).

In the Ambrosia Lake uranium district of northwestern New Mexico (Fig. 1), previous work on the Todilto Formation has described small- to large-scale, fold-like structures in the unit (Green, 1982). These features have been identified as intraformational folds that formed as a result of differential sediment loading or structural deformation (Armstrong, 1995; Berglof and McLemore, 2003; Ellsworth and Mirsky, 1952; Finch and McLemore, 1989; Gabelman and Boyer, 1988; Green, 1982; Hines, 1976; Huffman and Lupe, 1977; McLemore and Chenoweth, 2003).

Biologic origins for these structures have also been suggested (Perry, 1963; Rawson, 1980b), but that has been disputed by Lucas et al. (2003). Armstrong (1995) suggested that the Todilto folds had many characteristics in common with tepee structures, but indicated that a definitive case could not be made for any model to date.

This paper will present some preliminary findings that once again point to a non-structural, biological original for some of the fold-like features previously described by Green (1982). The features consist of large, sub-aqueous stromatolites probably forming in the restricted waters of the Todilto salina.

STRATIGRAPHY

Dutton (1885) first described the rocks that later Gregory (1916; 1917) would designate with the name Todilto Limestone. In the past, the Todilto Limestone has been assigned as a member of the Morrison, Entrada, or Wanakah Formations, but a revision of the stratigraphic nomenclature by Lucas et al. (1985) elevated it to the Todilto Formation.

The sediments of the Todilto Formation cover an area of approximately 100,000 km² and form a large, elliptical enclosed

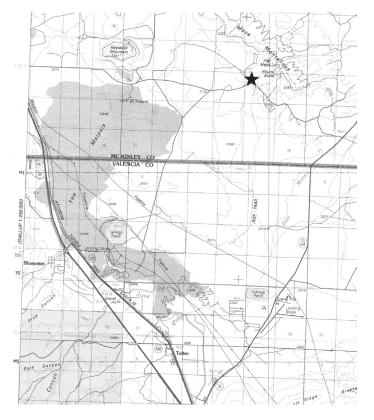


FIGURE 1. The study area within the Ambrosia Lake uranium district, New Mexico.

basin (Fig. 2). It is conformably underlain by the eolian, Middle Jurassic Entrada Sandstone and overlain by the lacustrine and sabkha deposits (Kirkland et al., 1995) of the Middle-Upper Jurassic Summerville Formation (Fig. 3). The Todilto Formation ranges in thickness from 10 to almost 40 m and consists of two members: the lower limestone Luciano Mesa Member and the upper gypsum Tonque Arroyo Member (Fig. 3).

The age of the Todilto Formation, based on fossil evidence compiled by Lucas et al. (1985), is Middle Callovian (~159 Ma). Berglof (1992) considers the uranium ores to be syndepositional. Isotopic ages for uraninite within the Todilto Formation provide an age of 150 to 155 Ma. Paleogeographic and paleoclimatic reconstructions (Fig. 4, Scotese et al., 2005) for this time period place the Todilto Formation at approximately 20°N latitude in an arid climatic belt.

Over the years, a significant debate has existed over the Todilto's depositional environment. Some authors suggested that the carbonates and evaporates are marine (Baker et al., 1947; Evans and Kirkland, 1988; Harshbarger et al., 1957; Imlay, 1952; Ridgley and Goldhaber, 1983), others proposed a non-marine, lacustrine origin (Anderson and Kirkland, 1960; Rapaport et al., 1952; Tanner, 1970), and yet others proposed a coastal salina that may have been periodically flooded by marine waters (Anderson and Lucas, 1993; Armstrong, 1995; Lucas et al., 1985; McCrary, 1985). Kirkland et al. (1995), based on paleontology, sedimentology and the isotopic data (carbon, strontium and sulfur), concluded that the Lucas et al. (1985) model of a coastal salina with a complex interplay of both marine and freshwaters best explains the Todilto deposits. More recently, Benan and Kocurek (2000), based on the Todilto Formation filling the remnant topography preserved on the Entrada Sandstone in the Ghost Ranch area (northeast of the study area), have called for a "catastrophic flooding" event that buried the Entrada dune forms with minimal reworking and in deep enough water that wave-generated features are minimal to non-existent. Overall, because of the Todilto's high organic content and the lack of bioturbation and/or ripples or other waveformed features, the Todilto waters had to be relatively deep, poorly-oxygenated and possibly chemically stratified.

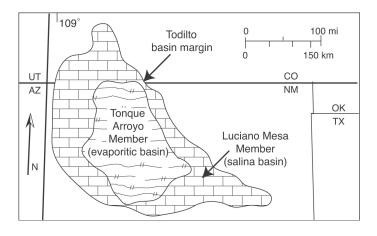


FIGURE 2. Map of the aerial extent of Todilto Formation (Lucas and Anderson, 1997).

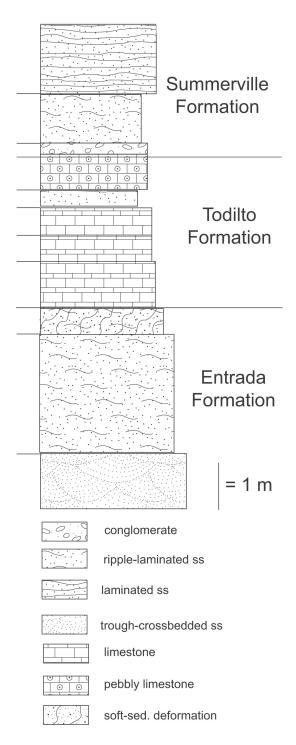


FIGURE 3. The stratigraphy of the Todilto Formation (modified from Lucas and Heckert, 2003).

THE LUCIANO MESA MEMBER

The Luciano Mesa Member of the Todilto Formation is a thin (<10 m), micro-laminated, kerogen-rich limestone. Anderson and Kirkland (1960) considered the laminae (alternating layers of calcite, clastics and organics) to be varves and, based on the number of varves, estimated that deposition occurred over a period of

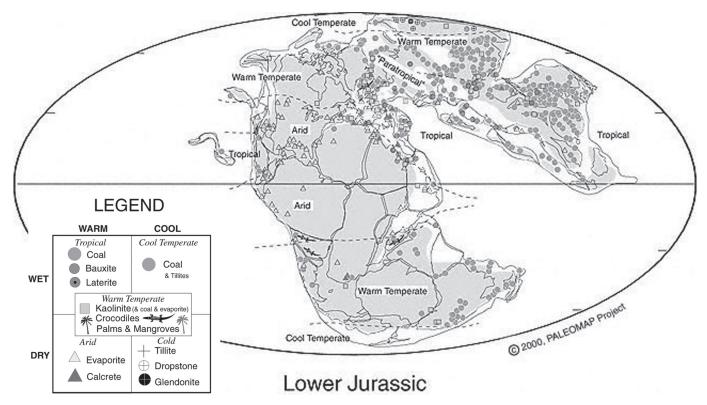


FIGURE 4. Paleogeographic and paleoclimatic reconstruction of early Jurassic time (Scotese, 2002).

14,000 years. This carbonate member is informally subdivided into a "platy," basal, organic-rich, thinly-laminated mudstone (2-5 m thick), followed by a wavy, crenulated, "crinkly" zone (1-3 m thick) with scattered domal structures, and capped by a recrystallized, massive carbonate (0-5 m thick) that appears to be brecciated in places and also contains large domal structures.

Within the middle "crinkly" and upper massive units, large, domal features (Fig. 5) have been attributed to intraformational deformation or folds (Rapaport, 1952; Rapaport et al., 1952), algal reefs or bioherms (Perry, 1963) or stromatolites (Rawson, 1980b).

ORIGIN OF THE "INTRAFORMATIONAL FOLDS"

Rapaport (1952) first described the features as intraformational folds and attributed them to deformation within the upper two units of the Luciano Mesa Member. Rapaport et al. (1952) believed that the structures formed due to basinward creep of sediments during gentle uplift and warping of the area just after deposition, when the sediments were still behaving plastically. Rapaport et al. (1952) modified this earlier model to have the folds produced by slippage brought on by the Todilto being squeezed between the eolian Entrada and Summeville Formations.

Green (1982) presented another variation on the sediment-loading model. As Summerville dunes migrated across the Todilto surface, the carbonates deformed or flowed to interdunal areas were there was less loading. As the dunes continued to migrate across the surface, smaller folds, fractures and faults formed in response to the differential loading. To explain why the

deformation was localized in the Ambrosia Lake District, Green (1982) called on differential water retention within the Todilto Formation. The Todilto carbonates in the Ambrosia Lake area had dewatered less than in other areas within the basin; therefore the strata behaved plastically when the Summerville sands migrated across the surface.

Other workers on the fold-like structures have concluded that syndepositional uplift was occurring (Moench and Schlee, 1967), deformation was post-depositional, sub-Dakota deposition (Hilpert, 1969), early to middle Cretaceous tectonic movement produced a series of orthogonal folds (Gabelman and Boyer, 1988) and/or earthquake activity during Todilto deposition causing slumping and folding (Lucas et al., 2003).

Major drawbacks to a structural origin for these fold-like features are the lack of preferential structural axes exhibited by the folds (Berglof and McLemore, 2003; Hines, 1976), which should be present if regional uplift or other structural deformation was involved. In addition, the sediment-loading model of Green (1982) would require geologically instantaneous loading of the Todilto Formation by Summerville dunes to generate the early, large fold features in the interdunal areas. Otherwise, the carbonates should have acted like toothpaste as the dunes marched across the Todilto surface, displacing the water-saturated carbonates as they were loaded. Also, the area that contains the most folds, along the edge of the basin, should have been exposed longer than the carbonates forming more basinward. This area should have dewatered at least to the same degree, if not more, than the rest of the carbonates in the Todilto Formation that do not contain folds.

Diagenetic alteration within the Todilto strata has also been suggested as an origin for these structures. Gabelman (1956) suggested dehydration and recrystallization of the mudstones. Bell (1963) thought that hydrating anhydrite to gypsum formed the crinkle lamination and the large folds within the Todilto carbonates and subsequent dissolution and calcitization of gypsum formed the porosity and the coarsely crystalline calcite.

Perry (1963) suggested that the folds were formed due to the deposition of Luciano Mesa reefs or bioherms, based on their distribution in outcrop and mine sections. An algal origin was suggested due to the presence of wavy and crinkly lamination and the lack of any other macrofauna besides a few ostracods. Based on their appearance in outcrop as well as comparing them to modern environments, Rawson (1980) suggested that the features were stromatolites deposited in a sabkha environment.

Armstrong (1995) noted that some of the folds occurred on Entrada paleo-highs and had many features in common with carbonate tepee structures. Tepee structures are polygonal expansion features, and their name comes from their inverted-V shape. Tepee structures appear to form in a variety of settings ranging from caliche/soils to submarine submarine springs (Assereto and Kendall, 1971; Dunham, 1969; Kauffman et al., 1996; Kendall and Warren, 1987; Klappa, 1980; Warren, 1985), but they are most commonly associated with peritidal to supratidal depositional environments (Assereto and Kendall, 1977; Ferguson et al., 1982; Handford et al., 1984; Kendall and Warren, 1987; Lugli et al., 1999; Neese, 1989; Smith, 1974; Warren, 1982). Their shape is the most diagnostic characteristic of tepee structures, but other features that may be present, depending on the depositional environment, include pisolites, brecciation, fractures, cements, erosional truncation, and fenestral fabrics. The features that Armstong (1995) cited as possible tepee fabrics include the termination of the features at the Todilto/Summerville boundary, the upper surface showing signs of erosion and brecciation (Fig. 5), similar depositional environments, syndepositional deformation on the flanks, fault-looking fracture systems, no preferential strain or fold axes, and the fractures are filled with material derived from the other overlying unit. According to Armstrong (1995), the major drawback to describing these features as tepee structures is the lack of pisolites within the unit; although pisolites are not found in all tepee structures.

STROMATOLITES

Stromatolites form as a result of the metabolism of bacteria, cyanobacteria or algae that create laminated, benthic microbial mats and biofilms composed. Stromatolites come in a variety of shapes and sizes and form in a wide variety of depositional environments (i.e., lacustrine, shallow marine, travertines and tufas, and others).

Stromatolites have been described elsewhere in the Todilto Formation, especially at the type section at Todilto Park, New Mexico (Fig. 6). However, Lucas et al. (2003) stated that the structures at Todilto Park have been erroneously identified as stromatolites (Fig. 6) and ascribed intraformational folding to their formation. The features are low-relief, domal, elliptical

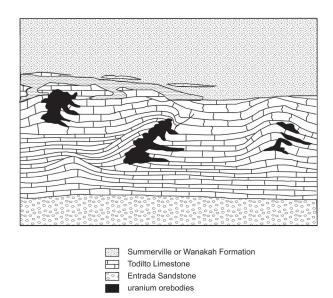


FIGURE 5. A schematic cross section through one of the intraformational "folds" (Berglof and McLemore, 2003; Finch and McLemore, 1989; McLemore and Chenoweth, 2003).

bodies that stick up through the overlying sediments. The upper surfaces, where exposed, have a mottled (light and dark carbonate) and lumpy appearance. While intraformational deformation is a possibility, these same features could easily result from the growth of stromatolites.

Modern and ancient depositional environments analogous to the proposed salina model for the Todilto Formation contain stromatolites; therefore, it would not be unrealistic to expect stromatolites in the Todilto deposits (Bradley, 1929; Duane and Al-Zamel, 1999; Bradley, 1929; Eardley, 1938; Halley, 1976; Monty and Hardie, 1976; Surdam and Wray, 1976; von der Borch, 1976; Walter, 1976). The Todilto depositional environment, with its interplay of marine and fresh waters making the coastal salina environment inhospitable for most invertebrates, would have provided ideal localities for the development of microbial mats and stromatolites. Ancient stromatolites often show a preferred growth orientation (Carozzi, 1962; Dill et al., 1989; Förster and Wachendorf, 1977; Playford and Cockbain, 1976; Wright and Wright, 1985) and form rounded to elliptical domes. In addition to the exterior morphologies, the clotted appearance of the structure is also very typical of stromatolites due to the alternation of clean lime mud (gray) and the more organic-rich mucilaginous mats or bacterial clusters (dark).

In the Ambrosia Lake District, very similar looking structures occur but at a significantly larger scale than the Todilto Park example (Fig. 7a). Here, the domal features can reach over two meters in height and over six meters in length, and their spacing is roughly twice their length (Fig. 7b). The structures all occur within the middle and upper members of the Luciano Mesa Member. The domes do not continue into the overlying Summerville Formation but end at the Todilto/Summerville contact.

The external morphology of the features supports a biological origin for these structures. The overlying units thin or pinch out



FIGURE 6. Outcrop view of Todilto stromatolites at Todilto Park (from Lucas et al., 2003). Note the lumpy, clotted looking surface; this is typical of stromatolites found elsewhere in the geologic record.

over the crests of the mounds or bioherms and thicken on the flanks, indicating that the mounds were positive features during Todilto deposition. At the contact of the Todilto and Summerville Formations, many of the upper surfaces of the mounds show evidence of multiple episodes of subaerial exposure (Fig. 7c). A drop in the water level in the salina interrupted later mound growth (Fig. 7c, units C and D). This produced a highly irregular surface on unit C that was later filled in by unit D. The upper units are irregular due to dissolution, and breccia clasts formed on the tops and flanks of the mounds (Fig. 8). The presence of breccia clasts indicates that the features were positive features before Summerville deposition and that the sediments were cemented and relatively rigid. Todilto deposits not associated with mound growth fill surface irregularities on the mounds (Fig. 9) with subsequent units being flat bedded.

Many of the bioherms or mounds consist of a large central mound with smaller mounds adjacent to the main body (Fig. 9). These appear to be satellite mounds growing off the main mound or bioherm. Also, some of the mounds appear to have multiple episodes of mound growth, either as satellites (Fig. 9) off to the side or as later growth on established highs (Fig. 7c). In Figure 7c, early mound (A) growth was asymmetrical with a fold-like morphology. The exposed surface of the mound has a mottled, clotted, lumpy appearance typical of microbial mat fabrics. Due to changing depositional environments, the mound was probably drowned due to rising water levels resulting in the deposition of fine-grained, finely laminated carbonates on top of the feature. Another environmental change (shallowing?) resulted in the reestablishment of mound growth (C and D).

Internally, the mounds consist of finely to very coarsely crystalline, recrystallized calcite (Fig. 10a). Within the mounds or bioherms, low- and high-relief microbial laminations are visible both on weathered and fresh outcrop surfaces (Fig. 10b). The high-relief laminations form reticulate patterns (Figs. 10a, b) similar to: those described by Wright and Wright (1985) in





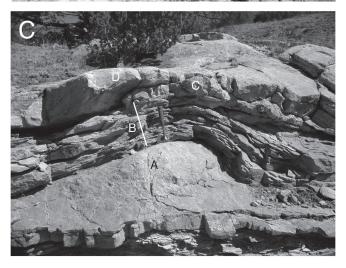


FIGURE 7. A) A large, partially exposed mound in the streambed. Note how the higher beds drape and thin over the mound crest and thicken slightly on the flanks. This structure is approximately 5.5 m wide by 2.2 m high. B) A photograph looking over several large mounds (arrows) exposed in the arroyo. The large mounds are best exposed in the arroyos, but are visible throughout the outcrop area. C) A photograph of one of the smaller stromatolitic mounds (A). This mound exhibits more than one episode of active stromatolite growth. On top of Mound A, finer-grained, laminated sediments (B) drape the mound. These sediments thicken slightly onto the flanks. After deposition of the laminated units, mound growth continued (units C and D). Due to the relief on the upper surface of C, there may have an exposure event before D was deposited. Hammer for scale on top of mound. Photograph courtesy of Spencer Lucas.



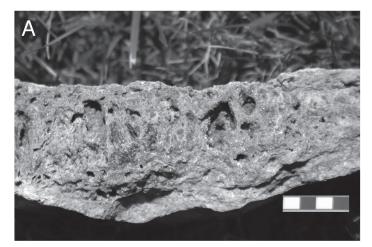
FIGURE 8. An upper surface on one of mounds consisting of cemented breccia clasts. Scale is 5 cm long.

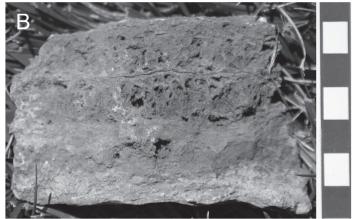
Carboniferous stromatolites of Wales; modern, flabellate *Scytonema* sp. algal stromatolites from freshwater marshes of Monty and Hardie (1976); and box-work boundstones of Warren (1982) in salinas of South Australia. These boundstones are a type of fenestral limestone in which the preferred growth form is upward rather than horizontal. On outcrop, these are the zones that also have highest porosity. Other types of microbial lamination are the finely crystalline, low-relief, parallel laminites (Fig. 10b) and high-relief stromatolites (Fig. 10c). Both of these types of boundstones have the light and dark banding (organic-rich layers are dark) common to most microbial deposits.

Locally, pockets of coarser grained carbonate debris (Fig. 11a) occur within the mounds. Most of the clasts have been leached, but based on their size and shape, the clasts may have been mol-



FIGURE 9. A cross sectional view through one of the mounds. Note the lumpy mound morphology and possible, smaller satellite mounds off to the side (black arrow). Later deposits (white arrow) thin over the top of the mound and fill in the topography on the mound indicating it was a positive feature during Todilto deposition. This mound is approximately 5 m long and 2 m high.





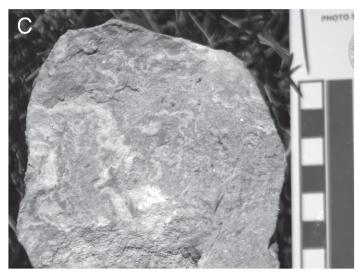


FIGURE 10. A) A photograph of a coarsely crystalline, reticulate or box-work zone within the domal stromatolites. In appearance, these stromatolites are similar to modern freshwater *Scytonema* sp. (Monty and Hardie, 1976). Long axis of sample equals 12 cm. B) A photograph of alternating reticulate/box-work and parallel lamination. Long axis of sample equals 8 cm. C) A sample from one of the mounds exhibiting both the light and dark banding and the convoluted banding common to microbial mats. Sample width is equal to 9 cm.

lusks or mud rip-ups. These zones probably represent storm events during mound formation.

Slightly to the northeast of the large domal mounds, the stromatolites become lower relief. Here, the stromatolites exhibit centimeters rather than meters of relief. The microbial lamination is easily visible on outcrop (Fig. 11b). Like the mounds, microbial growth ranges from mostly horizontal growth forms grading upward into more reticulate varieties (Fig. 11c).

CONCLUSIONS

If the mounds were due to intraformational deformation, one would expect to see more folding throughout the unit due to the movement of the sediments from one area to another. Between the mounds or bioherms, the beds are flat lying with little evidence of deformation or flowage (Fig. 9). As mentioned previously, since there are no preferred deformational fold axes (Hines, 1976), it is unlikely that the mounds are tectonic in origin. If sediment loading by Summerville eolian deposits caused deformation (Green, 1982), the mound spacing appears to be inadequate to account for the size of the dunes responsible to get that degree of flowage. Also, the presence of early brecciation of the mounds indicates that sediments were probably too rigid to permit that amount of plastic flow in the Green (1982) model.

Based on preliminary field data, large, domal, stromatolitic mounds/bioherms formed near Mesa Montañosa. Due to their composition and morphology, these mounds were the result of microbial growth and not to intraformational deformation due to sediment loading (Green, 1982). The mounds started forming during middle Luciano Mesa deposition and remained positive features until the end of Todilto deposition. While similar structures elsewhere in the Todilto Formation have been attributed to intraformational or tectonic deformation, this study suggests that there may be more than one mechanism capable of producing fold-like in the Todilto Formation and a reassessment of previously identified structures may be needed.

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FIGURE 11. A) Within some of the mounds, zones of leached clasts are visible. The clasts may have originally been bioclasts (e.g., mollusks) or rip-up clasts. B) A cross-sectional view of low-relief stromatolites that occur slightly more basin ward of the domal stromatolites. Note the microbial lamination in the section as well as the extremely porous upper 8 cm. The massive bed is approximately 30 cm thick. C) The close-up of the upper unit of Figure 16. Similar reticulate features have been described by Wright and Wright (1985) and Warren (1982). Also visible in the lower half of the photograph are well-developed microbial laminations. Keys for scale.

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