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Folding in the Middle Jurassic Todilto Formation, New Mexico-Colorado, USA

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Key words: Jurassic, Todilto Formation, salina, microfolding, stromatolites, tepee-structures.

Abstract. The Middle Jurassic (Callovian) Todilto Formation of northwestern New Mexico–southwestern Colorado, USA, is a carbonate/evaporite lithostratigraphic unit that was deposited in a large paralic salina culminated by a gypsiferous evaporitic lake. Intraformational folds of the limestone-dominated lower part of the Todilto Formation (Luciano Mesa Member) range in scale from millimeters to meters, and many of the large folds are the loci of uranium mineralization. A diverse literature has attributed the formation of intraformational folds of the Todilto Formation to several causes, including syndepositional or postdepositional tectonics, soft-sediment deformation due to sediment loading or gravity sliding, diagenetic alteration (primarily the hydration/crystallization of gypsum/anhydrite), the growth of stromatolitic bioherms or the formation of tepee-like structures. We examine in detail two characteristic outcrops of intraformational folds in the Todilto Formation, in west-central New Mexico, to conclude that folds and domal structures present in the Todilto limestone facies at different stratigraphic levels and at different scales have resulted from varied processes that produced dome-like stromatolitic mounds, tepee-like structures, small-scale enterolithic folds and large-scale folds of likely diagenetic origin.

INTRODUCTION

One of the most distinctive Jurassic lithostratigraphic units in the American West is the Todilto Formation of northwestern New Mexico and southwestern Colorado (Fig. 1). This relatively thin unit (less than 75 m maximum thickness, but typically much thinner) is dominantly carbonate (limestone) and evaporite (anhydrite/gypsum) intercalated in Middle Jurassic siliciclastic strata that are mostly eolianites. The Todilto Formation is extremely significant economically as a source rock for uranium, petroleum, building stone and gypsum (*e.g.*, Weber, Kottlowski, 1959; Vincelette, Chittum, 1981; Chenoweth, 1985; Austin, Barker, 1998; Berglof, McLemore, 2003). Within the Todilto Formation, folding of thinly laminated limestone beds occurs on a range of scales, from millimeters to tens (and rarely hundreds) of meters. A diverse literature exists discussing the genesis (origin) of the folds in the Todilto Formation, particularly because much uranium mineralization is associated with the folds. Here, we review this discussion and examine in detail two outcrops of the Todilto Formation in west-central New Mexico where characteristic folds are present. We conclude that diverse processes created the intraformational folds in the Todilto Formation.

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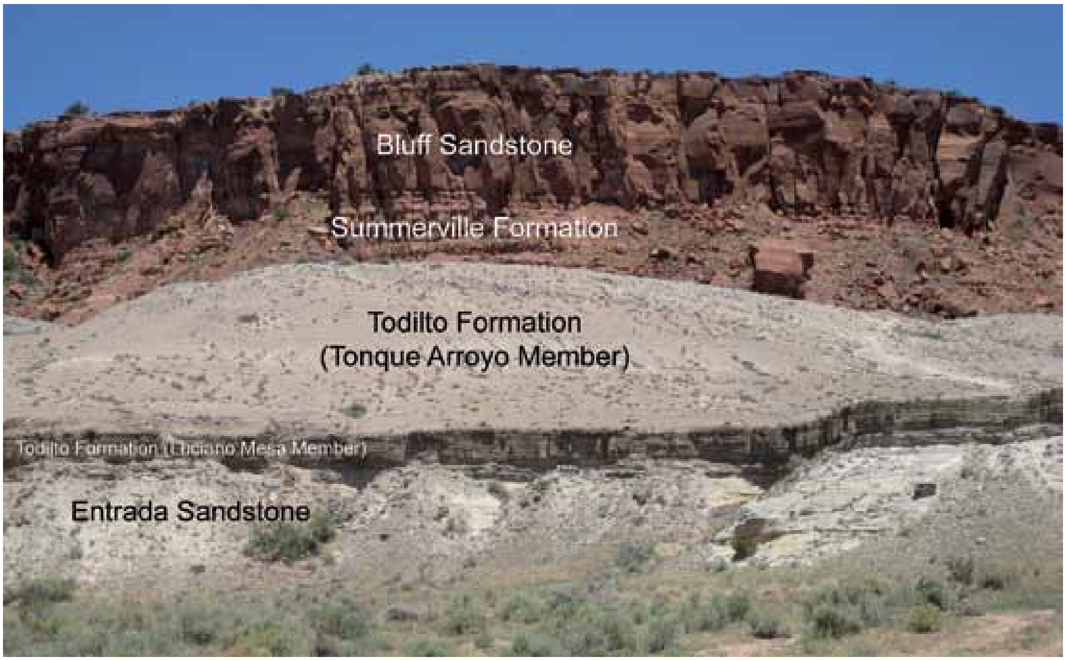

Fig. 1. Photograph of characteristic outcrop of Todilto Formation, underlying and overlying strata, at Mesita in west-central New Mexico

CONTEXT

The Todilto Formation crops out and is present in the subsurface across much of northwestern New Mexico and part of southwestern Colorado (Fig. 2), covering an area of about 100,000 km^2 (Anderson, Kirkland, 1960; Lucas *et al.*, 1985; Lucas, Kietzke, 1986; Armstrong, 1995; Kirkland *et al.*, 1995). Throughout its extent, the Todilto disconformably overlies the Middle Jurassic Entrada Sandstone and is overlain disconformably by the Middle–Upper Jurassic Summerville Formation (Figs 1, 3).

Two members of the Todilto Formation are recognized: the lower, limestone-dominated Luciano Mesa Member and the overlying, gypsum-dominated Tonque Arroyo Member (Figs 1, 3). Maximum thickness of the Luciano Mesa Member is 13.3 m, and it is mostly thin-bedded, microlaminated, kerogenic limestone. Anderson and Kirkland (1960) identified the microlaminae as varved couplets to estimate a duration of about 14,000 years for deposition of the Luciano Mesa Member, but Kirkland *et al.* (1995) suggested 30,000–100,000 years as a more likely estimate, if the duration of the evaporitic basin is considered. The Tonque Arroyo Member is up to 61 m thick and consists mostly of massive and brecciated gypsum. The Luciano Mesa Member has a continuous distribution across the Todilto depositional basin, whereas the Tonque Arroyo Member represents evaporation of the Todilto waterbody in a much smaller basin (Fig. 2).

Fossils are not common in the Todilto Formation. No megafossil plants or palynonomorphs have been found. Algal structures (stromatolites) have been identified on outcrop by various workers (*e.g.*, Ulmer-Scholle, 2005), and dasycladacean algae have been identified in thin section at one locality in west-central New Mexico (Armstrong, 1995). Invertebrate fossils are limited to the ostracod *Cytheridella* and various aquatic insects from one locality in central New Mexico (Kietzke, 1992; Kirkland *et al.*, 1995; Lucas *et al.,* 2000). Fossil vertebrates are three species of holostean fishes, which are locally abundant (Fig. 4) (Schaeffer, Patterson, 1984; Lucas *et al.*, 1985).

Regional stratigraphic relationships indicate that the Todilto Formation is homotaxial with the Callovian-age, marine Curtis Formation of Utah (*e.g.*, Kocurek, Dott, 1983; Anderson, Lucas, 1992, 1994). Both units occur between the Entrada and Summerville formations, and both have thin layers of pebbly sediments (transgressive lag deposits) at their bases. The regional rise in base level reflected in the transgression of the Curtis seaway and the ensuing highstand produced a paralic salina in northern New Mexico–southwestern Colorado, just southeast of the seaway (Imlay, 1980; Kocurek, Dott, 1983; Lucas *et al.*, 1985; Anderson, Lucas, 1994; Kirkland *et al.*, 1995; Lucas, Anderson, 1996, 2000).

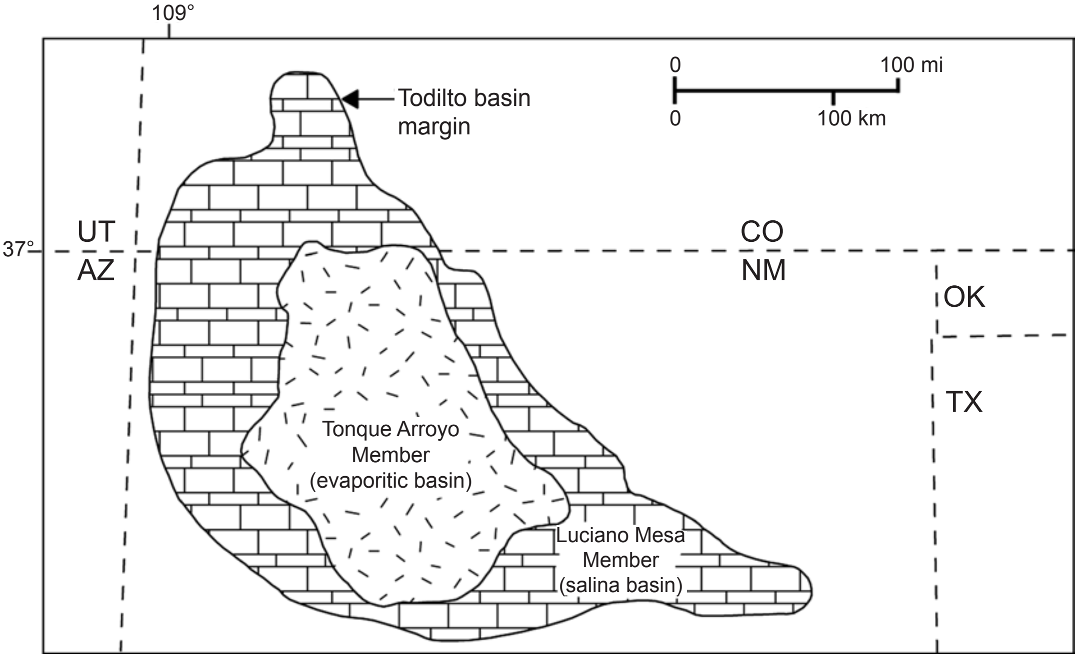

Fig. 2. Map of Middle Jurassic Todilto depositional basin showing distribution of limestone facies (Luciano Mesa Member, entire basin) and gypsum (Tonque Arroyo Member) that defines a smaller evaporitic basin (after Lucas, Anderson, 1996)

Early workers had regarded Todilto deposition as having taken place in a marine embayment of the Curtis seaway (*e.g.*, Harshbarger *et al*., 1957). However, more recent studies of stratigraphy, paleontology and geochemistry indicate that any marine connection to the Todilto basin was short-lived and/or intermittent (Lucas *et al*., 1985; Kirkland *et al*., 1995). Thus, Todilto deposition took place in a vast paralic salina culminated by a gypsiferous evaporitic lake. Three lines of evidence support this conclusion:

1. No direct continuity of Todilto strata and marine Jurassic strata exists as the Todilto pinches out around its basin periphery into eolianites (*e.g.*, Kocurek, Dott, 1983; Lucas *et al*., 1985; Anderson, Lucas, 1992; Lucas, Anderson, 1998; Lucas, 2004).

2. No normal marine flora or fauna are present in the Todilto Formation. Instead, a low-diversity invertebrate and fish fauna characteristic of salina lakes (*e.g.*, Barbour, Brown, 1974) is present, and is strikingly similar to that found in Quaternary salinas in Australia (Warren, 1982; Warren, Kendall, 1985). Dasycladaceans are blue-green algae that tolerate a wide range of salinities, so Armstrong's (1995) claim that their presence in the Todilto Formation indicates marine deposition can be rejected.

3. Carbon and sulfur isotope ratios calculated for Todilto limestone samples have a wide range of values compatible

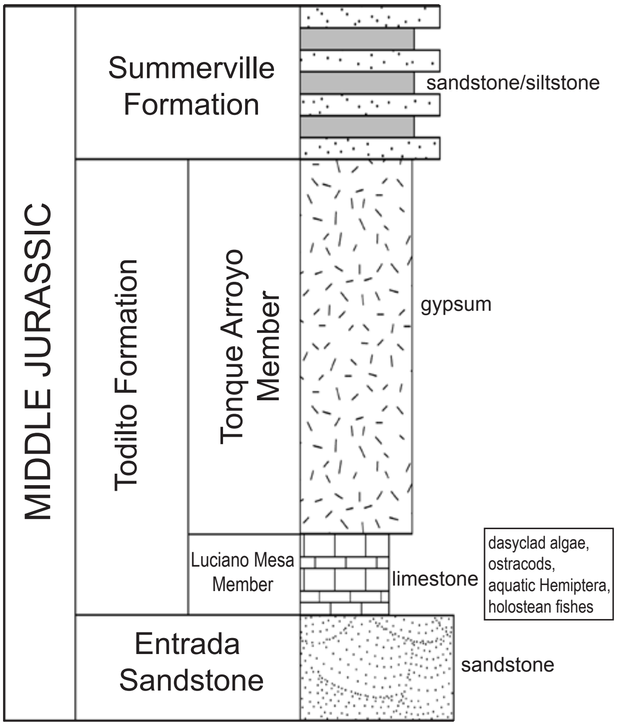

Fig. 3. Generalized stratigraphy of the Todilto Formation

Lithology explained in text

Fig. 4. Artist's view of Todilto waterbody with low diversity of holostean fishes (by Ely Kish, courtesy of New Mexico Museum of Natural History)

with a marine, nonmarine or mixed waterbody. However, strontium isotope ($^{87}Sr/^{86}Sr$) ratios for the Todilto Formation do not match those of sediments deposited by normal marine Callovian seawater (Kirkland *et al.*, 1995).

Todilto deposition thus began with initial flooding of marine waters across the Entrada erg during transgression of the Curtis seaway (Benan, Kocurek, 2000). After this initial flooding, base level must have dropped so that across the Four Corners the erg separated the seaway from its initial embayment, which then became a coastal salina. Freshwater runoff, influx of seawater by seepage through the erg and possible short-term overtopping of the erg maintained the Todilto salina for perhaps as much as 100,000 years. Then, increased aridity promoted evaporation, which produced a smaller evaporitic basin in which gypsum precipitated.

TODILTO FOLDS

OVERVIEW

Folds and fold-like features on several scales affect limestone-dominated strata of the Todilto Formation and have been one of the most interesting and puzzling features of the mineralized portions of the formation (*e.g.*, Rapaport, 1952; Rapaport *et al.*, 1952; Bell, 1963; Perry, 1963; Moench, Schlee, 1967; Hilpert, Moench, 1968; Hilpert, 1969; Kirkland, Anderson, 1970; Rawson, 1980; Green, 1982; Lucas *et al.*, 1985; Gabelman, Boyer, 1988; Armstrong, 1995; Berglof, McLemore, 2003; Ulmer-Scholle, 2005). Perhaps most intriguing are the remarkable variety and scale of intraformational folds (Fig. 5) that were recognized in the earliest studies of Todilto uranium deposits, the origin of which has remained controversial. Intraformational folds clearly localize many Todilto uranium deposits, but not all folds are mineralized. However, most relatively unoxidized uranium deposits in the Todilto are associated with folds.

Thus, mineable uranium ore bodies in the Todilto are generally localized along folds that are predominantly intraformational, ranging widely in size and geometry (Berglof, McLemore, 2003). Several types of folds and fold-like structures, on different scales, are present within the Todilto Formation in the Grants uranium district of west-central New Mexico, although not all are known to have influenced the location of uranium mineralization. These include: regional large-scale folds affecting the Todilto and units above and below it; large-scale, intraformational folds with mappable axes; mounds or dome-like structures within the limestone; and several types of small-scale intraformational folds (Fig. 5). The latter include sharp folding of varve-like thin

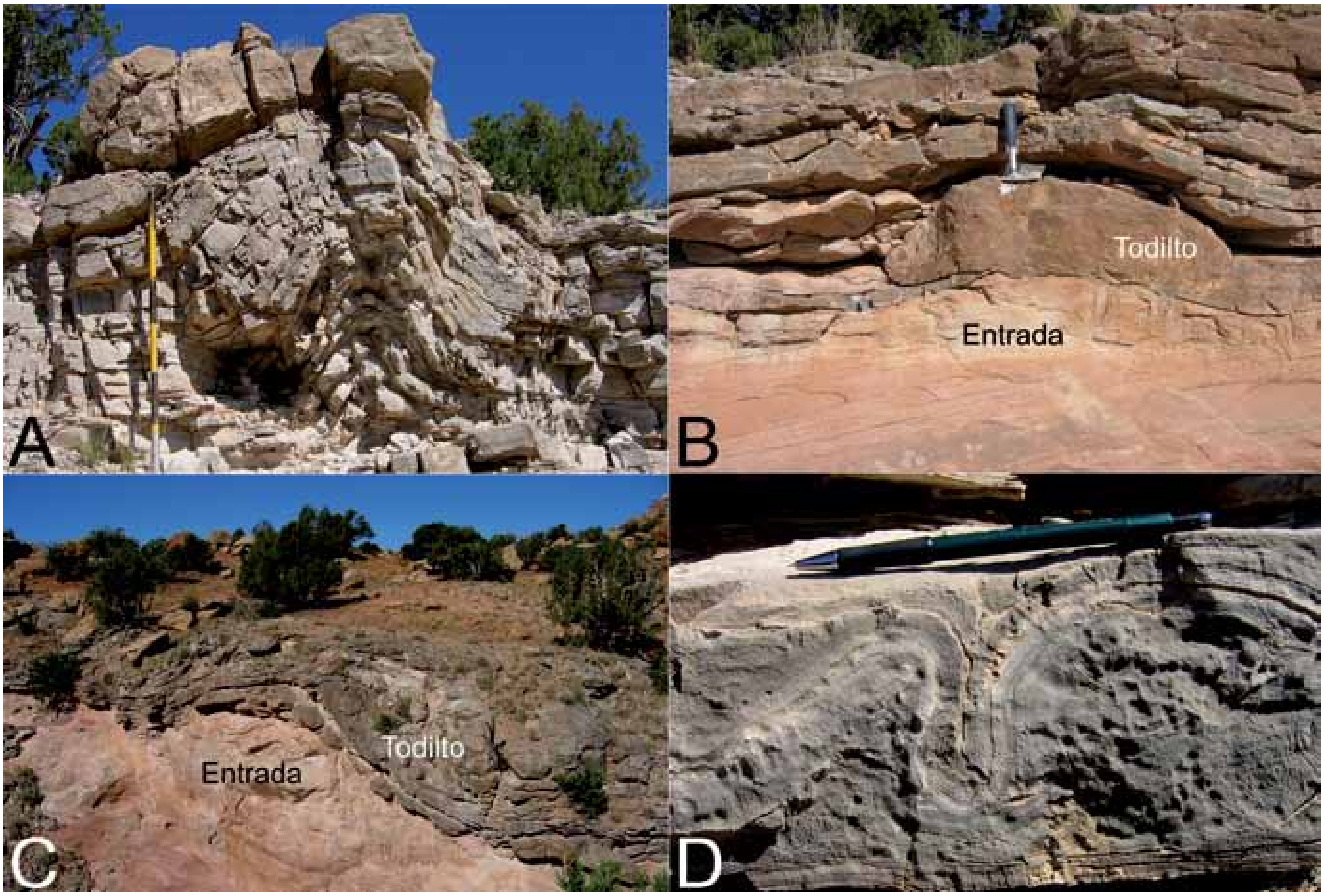

Fig. 5. Various folds in the Todilto Formation in the Haystack Butte area of west-central New Mexico (see Fig. 7 for location)

A. Very large fold (staff is 1.5 m long). **B**. Small, stromatolitic bioherm at base of Todilto Formation (under hammer, which is 28 cm long). **C**. Base of Todilto Formation displaying drape fold over dune form at top of Entrada Sandstone. **D**. Small-scale fold (pencil is 14 cm long)

bedding; within-layer folds resembling those described elsewhere as "enterolithic;" and microfolding of thin layers, including the "crinkly" bedding common in the middle and upper portions of the Luciano Mesa Member of the Todilto Formation.

The large-scale intraformational folds have clearly influenced the location of uranium deposits in the Todilto, presumably by providing zones of permeability through which mineralizing solutions moved (Berglof, McLemore, 2003). Not all of the folds are mineralized, but almost all primary uranium deposits in the Todilto are associated with the folds. Many folds were exposed in underground or surface mines that are now inaccessible; others are exposed on rim outcrops (Fig. 5). In New Mexico, uranium deposits in the Laguna district and small deposits distant from Grants (Sanostee, Box Canyon) also were associated with folds of this type.

A diverse literature offers essentially five explanations (causes, genesis) of the Todilto folding: tectonics, soft-sediment deformation (due to varied causes), diagenetic alteration, stromatolitic bioherms and tepee-like structures. Here, we review these five explanations and note that a combination of multiple processes may have produced some of the Todilto intraformational folds.

TECTONICS

In early studies, Rapaport (1952) and Rapaport *et al.* (1952) suggested two contrasting explanations of the Todilto folds. One was by slumping and soft-sediment deformation early in the history of the formation (possibly related to earthquakes). Then they suggested instead that the folds formed in the Todilto by slippage between the relatively

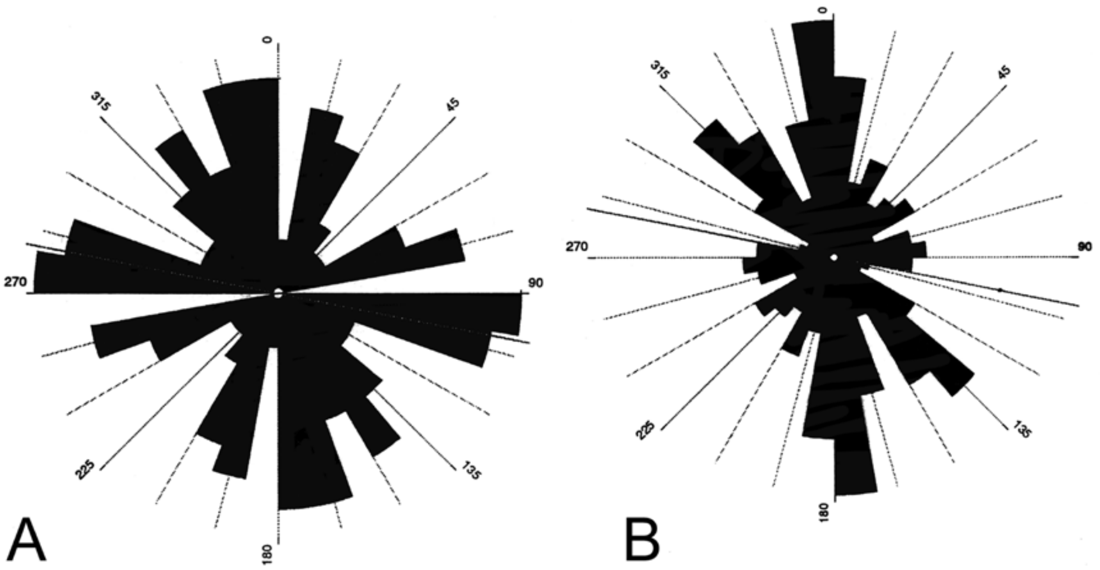

Fig. 6. Rose diagram of axes of Todilto fold directions at two uranium mines in west-central New Mexico

A. Folds in Todilto at the Section 25 mines. **B.** Folds in Todilto at the Flat Top mine. For A, n = 258; for B, n = 90

competent Entrada and Summerville/Bluff formations during later, presumably Laramide (Late Cretaceous–Eocene) deformation; *i.e.*, an unusual type of tectonic origin. The second conclusion was said to be based on supposed detailed compilations of fold trends, which unfortunately were never published. Boggs (2009) has referred to a mechanism similar to that proposed by Rapaport (1952) and Rapaport *et al.* (1952) as deformation of incompetent beds caught between competent sandstone or carbonate beds during tectonic folding, noting that such deformation might be misinterpreted as penecontemporaneous slump folding.

Kirkland and Anderson (1970) studied microfolds (mm scale) in the Todilto Formation near Laguna in west-central New Mexico. They identified these folds as enterolithic folds formed by "shortening by layer-parallel compression" (p. 3275). They posited a tectonic event that mildly folded the Todilto and adjacent Entrada and Summerville formations prior to deposition of the Upper Cretaceous Dakota Sandstone.

Nevertheless, an origin of the Todilto folds by tectonic deformation that significantly postdates Todilto deposition is inconsistent with U-Pb age data on uranium deposits suggesting an age of primary mineralization close to the age of the formation (*e.g.*, Berglof, McLemore, 2003). Indeed, measurement and compilation of more than 1000 intraformational fold axis trends by one of us (WB) also has not supported a tectonic origin of the folds (Fig. 6). The relationships in these diagrams are typical; in some areas (or mines) the folds exhibit a preferred orientation (Fig. 6B), whereas in others the trends yield a nearly random pattern (Fig. 6A). Similar variability in fold trends in the Laguna district of west-central New Mexico is shown in 534 readings compiled by Moench and Schlee (1967). Thus, the available fold-orientation data for the Todilto do not uniquely support a tectonic origin of all of the Todilto folds.

Tectonic activity during or immediately after Todilto deposition is a possible cause of some of the Todilto folds. Indeed, active folding appears to have influenced the geometry of mineralized sandstones in the younger, Upper Jurassic Morrison Formation. Some Todilto folds resemble folds in the Pleistocene Lisan Formation along the Dead Sea in Israel and Jordan (Marco, Agnon, 1995), believed to be a sedimentological analogue of the Todilto in a different tectonic setting. The Lisan folds apparently formed at least in part from seismogenic processes. Therefore, a tectonic (including seismogenic) origin of the Todilto folds finds little support unless the tectonism took place during or immediately after Todilto deposition.

SOFT-SEDIMENT DEFORMATION

Evidence of soft-sediment deformation is prominent within some of the Todilto intraformational folds, consistent with their early formation. One hypothesis is that the weight of encroaching sediments of the overlying Summerville

Formation deformed the soft lime muds of the Todilto (*e.g.*, Green, 1982). Jones (1972) proposed a similar mechanism for the formation of deformational folds in siltstone of the Upper Devonian Langra Formation in the Black Hill Range, central Australia. He suggested that lateral pressure produced by overloading from an overlying sandstone caused the folding and deformation.

Slumping under the influence of gravity is also a possible mechanism for the formation of folds, but it is not clear if paleoslopes in the Todilto depositional basin were sufficient to initiate such movement. Earthquakes occurring during sedimentation are increasingly recognized as a possible cause of soft-sediment deformation, producing "seismites," which can develop even on gentle slopes. Therefore, soft-sediment deformation caused by various processes, including syndepositional seismic activity, seems a possible mechanism to have formed some of the Todilto folds. Note that syndepositional seismicity is most plausibly invoked if there were fault systems in the region that might have been active in the Jurassic. Indeed, causation by tectonics and soft-sediment deformation overlap if the former caused the latter.

DIAGENETIC ALTERATION

Hydrating anhydrite to gypsum results in expansion, and dehydrating lime mudstone results in contraction. Dissolution of gypsum could lead to contraction, and subsequent recrystallization of sparry calcite in the voids that dissolution produced could result in expansion. Both Gabelman (1956) and Bell (1963) suggested that these processes underlie some of the Todilto folds at various scales, particularly the crinkly limestone often found in the Luciano Mesa Member. Indeed, as discussed below (also see Armstrong, 1995), such diagenetic alteration may provide the best explanation of some of the largest intraformational folds in the Todilto Formation, like the fold illustrated in Figure 5A.

STROMATOLITIC BIOHERMS

Several authors (Perry, 1963; Rawson, 1980; Ulmer-Scholle, 2005) have advocated that at least some of the Todilto "folds" are domal stromatolites (bioherms). Perry (1963) referred to such fold-like features as "reefs." Indeed, Ulmer-Scholle (2005) argued that the "folds" at Dos Lomas described below are large stromatolitic bioherms that grew by microbial processes subaqueously. Our data and those of some others identify small domal stromatolites in the Todilto Formation, so some of the "folds" are of stromatolitic origin.

TEPEE-LIKE STRUCTURES

Armstrong (1995, p. 30–33) first pointed out that some of the intraformational folds in the Todilto Formation have many of the attributes of tepee structures (also see Berglof *et al*., 2009). Tepee structures are antiformal structures that form by the buckling and fracturing of carbonate sediment (Assereto, Kendall, 1977). Some of the Todilto folds resemble tepee structures in shape, erosional truncation of their tops and the presence of fractures and fenestral carbonate fabrics (Armstrong, 1995). However, the genesis of tepee structures typically requires subaerial exposure and early cementation, processes not always inferable for the Todilto folds. Nonetheless, we describe folds that resemble tepee structures at Dos Lomas near Grants, New Mexico, below.

CONCLUSIONS

The variety of folds and fold-like structures in the Todilto Formation suggests that they have multiple origins. Indeed, in some cases it is difficult to establish the relative importance of the various processes that may have contributed to the formation of these structures. Furthermore, no one of the five proposed processes explains all of the Todilto intraformational folds. And, some of the Todilto folds may reflect a combination of processes, such as syndepositional tectonics causing soft-sediment deformation. The characteristic Todilto folds described below, and their analysis, well demonstrate the diverse processes behind the folding.

TODILTO FOLD EXAMPLES

INTRODUCTION

Here we present detailed analyses of Todilto folds at two locations in west-central New Mexico, Dos Lomas and Haystack Butte (Fig. 7).

DOS LOMAS

The Todilto folds at Dos Lomas (Figs 8–9) have been discussed by Green (1982) and by Ulmer-Scholle (2005). Green attributed them to soft sediment deformation caused by sediment loading during deposition of the overlying Summerville Formation. In contrast, Ulmer-Scholle identified them as large, domal stromatolites (bioherms). Before describing and discussing the folds we present a sedimentological description of the Todilto Formation at Dos Lomas.

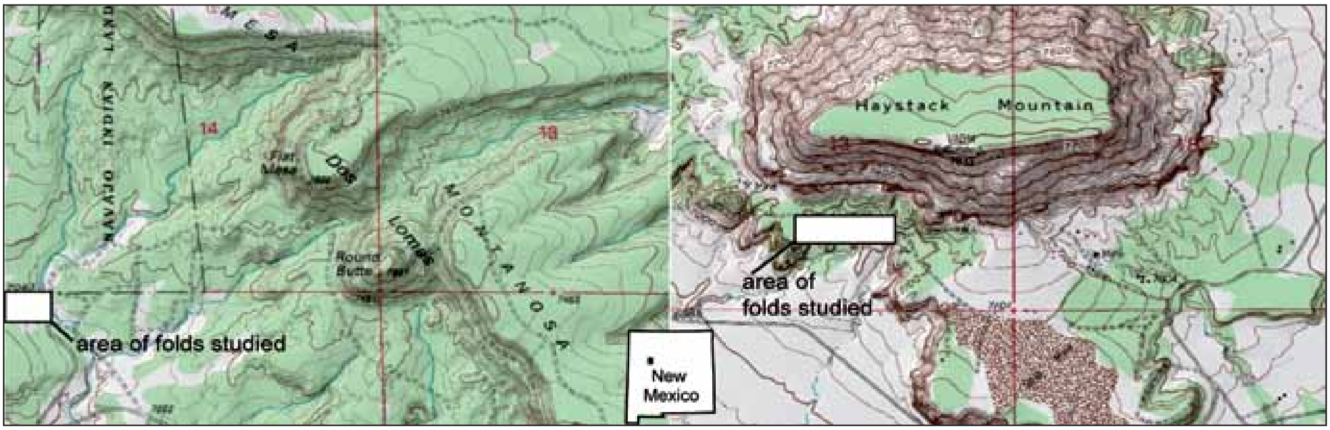

Fig. 7. Location map of Todilto Formation folds studied at Dos Lomas and Haystack Butte in west-central New Mexico. Index map shows location in New Mexico

The Todilto Formation at Dos Lomas is 4.2 m thick and overlies eolian, crossbedded sandstone of the Entrada Sandstone (Fig. 8). Near its top, the Entrada Sandstone is composed of fine-grained sandstone (0.1–0.3 mm), which is moderately to well-sorted and contains subrounded to rounded grains. Detrital grains are dominantly monocrystalline quartz with small amounts of detrital feldspars, chert grains and polycrystalline quartz. The detrital grains are cemented by coarse calcite (Fig. 10A). Here, the Todilto Formation can be divided into three distinct facies:

1. The lower 2.1 m (Fig. 8, units 2–11) are composed of gray lime mudstone beds, 4 to 32 cm thick, partly wavy, in the upper part laminated, intercalated with dark gray, partly micaceous and bituminous lime siltstone. Lime mudstone is indistinctly laminated, locally bioturbated and contains small quartz grains and rare ostracods (Figs 10F, 11B). In the upper part of this interval thin layers and lenses of fibrous calcite (most likely representing replaced gypsum crystals) are intercalated. The lime siltstone contains small, subangular to subrounded monocrystalline quartz grains, rare polycrystalline quartz grains, detrital feldspar and opaque grains that constitute up to 30–40% of the rock volume (Fig. 10E, G). Grain size of the detrital grains is 0.05–0.2 mm. The intercalated dark gray siltstone contains small quartz grains with diameters up to 0.1 mm, and rare micritic intraclasts up to several mm in diameter float in the siltstone (Fig. 11B).

2. Above follow 1.3 m of evenly bedded, thinly laminated gray lime mudstone (Fig. 8, units 12–15). The lime mudstone is indistinctly laminated and contains a few small quartz grains, rare feldspar and opaque grains, a few large micritic intraclasts and, locally, ostracods (Fig. 11C).

3. The uppermost 80 cm (Fig. 8, units 16–19) consist of even, commonly wavy, laminated, stromatolitic, partly vuggy limestone beds (microbial crusts), 14–28 cm thick. The lower part (unit 16) is composed of indistinctly laminated mudstone with a few small quartz grains up to 0.2 mm in diameter, and indistinctly laminated mudstone containing ostracods and a few quartz grains (Fig. 11D). The overlying bed (unit 17) is composed of laminated mudstone containing ostracods, a few detrital quartz grains and abundant calcite nodules. These calcite nodules are most likely replacements of evaporite minerals (gypsum). In the upper part, this unit displays a nodular texture composed of calcite nodules (replaced gypsum) up to 1 cm in diameter embedded in indistinctly laminated mudstone that contains rare ostracods and small detrital quartz grains. Unit 18 is similar, again characterized by a nodular texture. In thin layers calcite nodules are densely packed (Fig. 11E–F). The uppermost, stromatolitic bed (unit 19) is about 30 cm thick and forms a distinct horizon that laterally contains abundant domal structures (Figs 8–9).

The stromatolitic bed is composed of recrystallized micritic laminae that contain a few small quartz grains and ostracods, and intercalated layers composed of calcite. These calcite layers locally display a fibrous texture indicating replacement of gypsum crystals. Locally, the micritic stromatolite layers display desiccation cracks (Fig. 11G–H). The stromatolitic facies is overlain by greenish, gypsiferous siltstone and shale of the basal Summerville Formation.

At Dos Lomas, the domal structures (Figs 8–9, here considered tepee-like) are 0.7–2.2 m high and measure 1.5–8.0 m in width (n = 16). Their base is formed by horizontal beds of evenly laminated or more commonly of stromatolitic limestone (Figs 8–9). The core of the domal structures is up to about 50 cm thick and about 1 m in width at the base and consists of intensively folded or brecciated limestone and evaporites, overlain by a decimeter-thick "crust" of stromatolitic limestone, which may be vuggy and may contain a thin bed of gray micritic limestone.

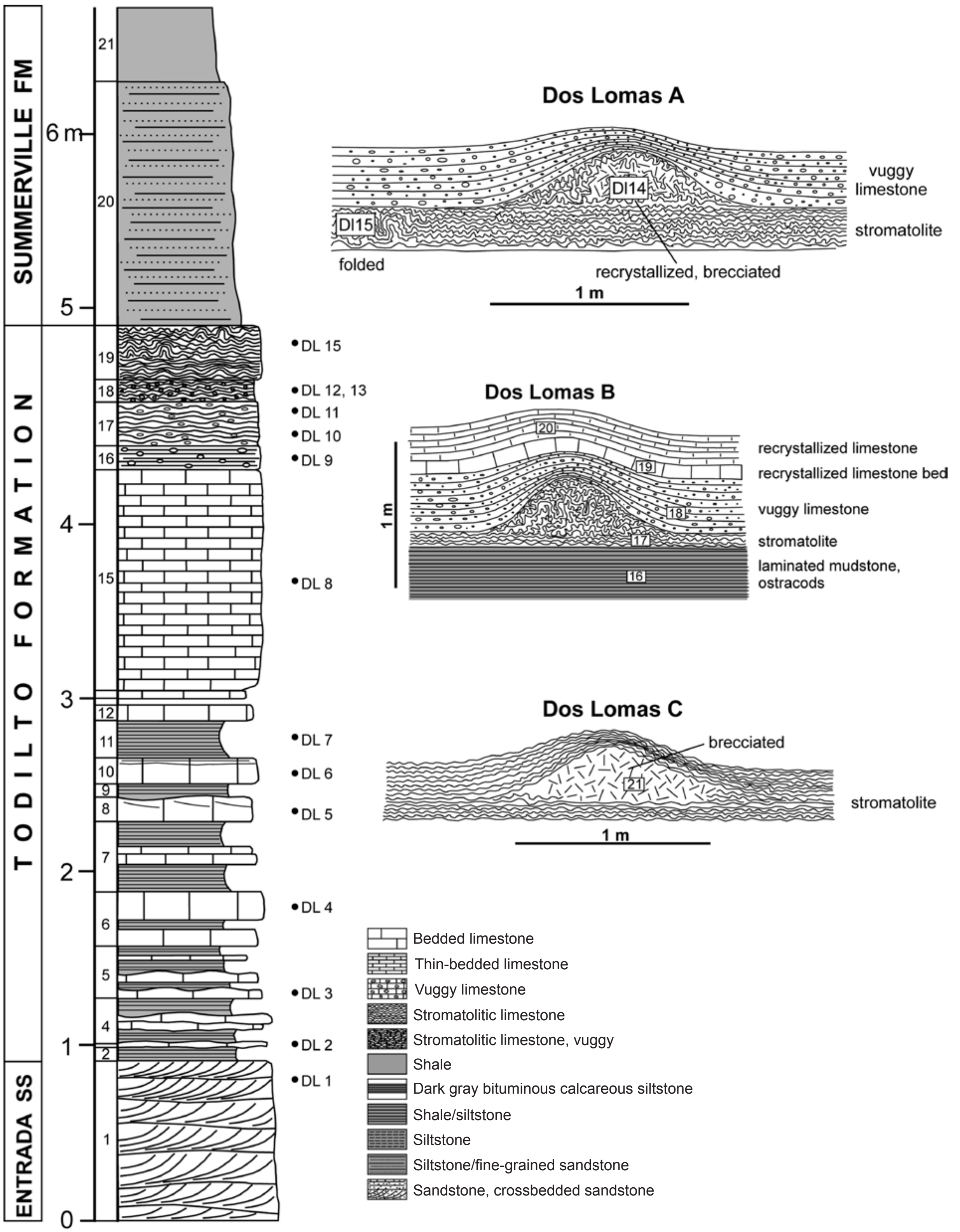

Fig. 8. Stratigraphic section of Todilto Formation and adjacent strata at Dos Lomas and details of three domal structures in upper part of Todilto Formation (units 17–19). Numbers 16–20 in Dos Lomas B and 21 in Dos Lomas C indicate position of samples DS 16–DS 21

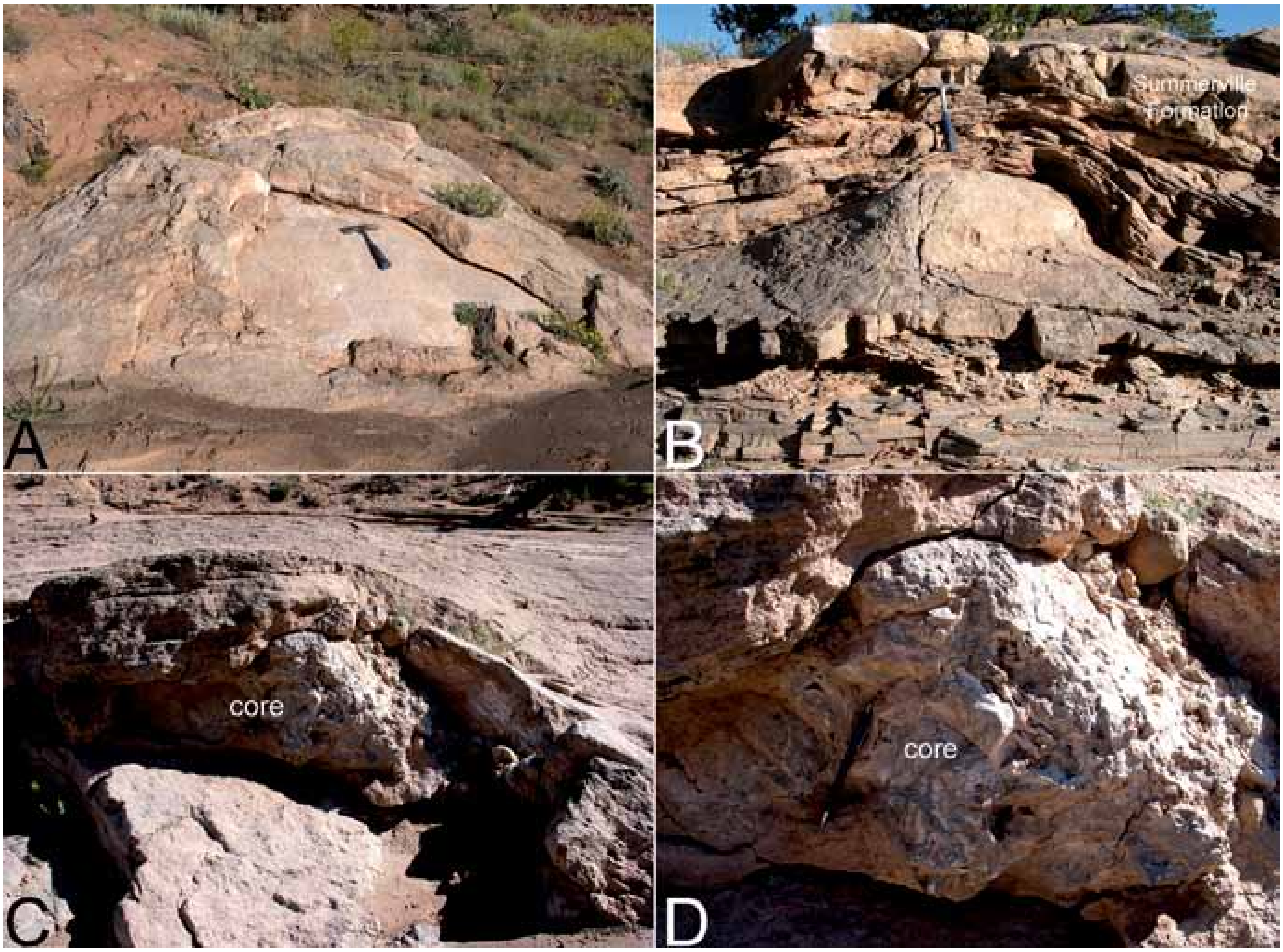

Fig. 9. Todilto “folds” at Dos Lomas

A. Overview of large domal “fold” (hammer is 28 cm long). **B.** View of domal structure in cross-section. **C–D.** Broken dome showing brecciated core

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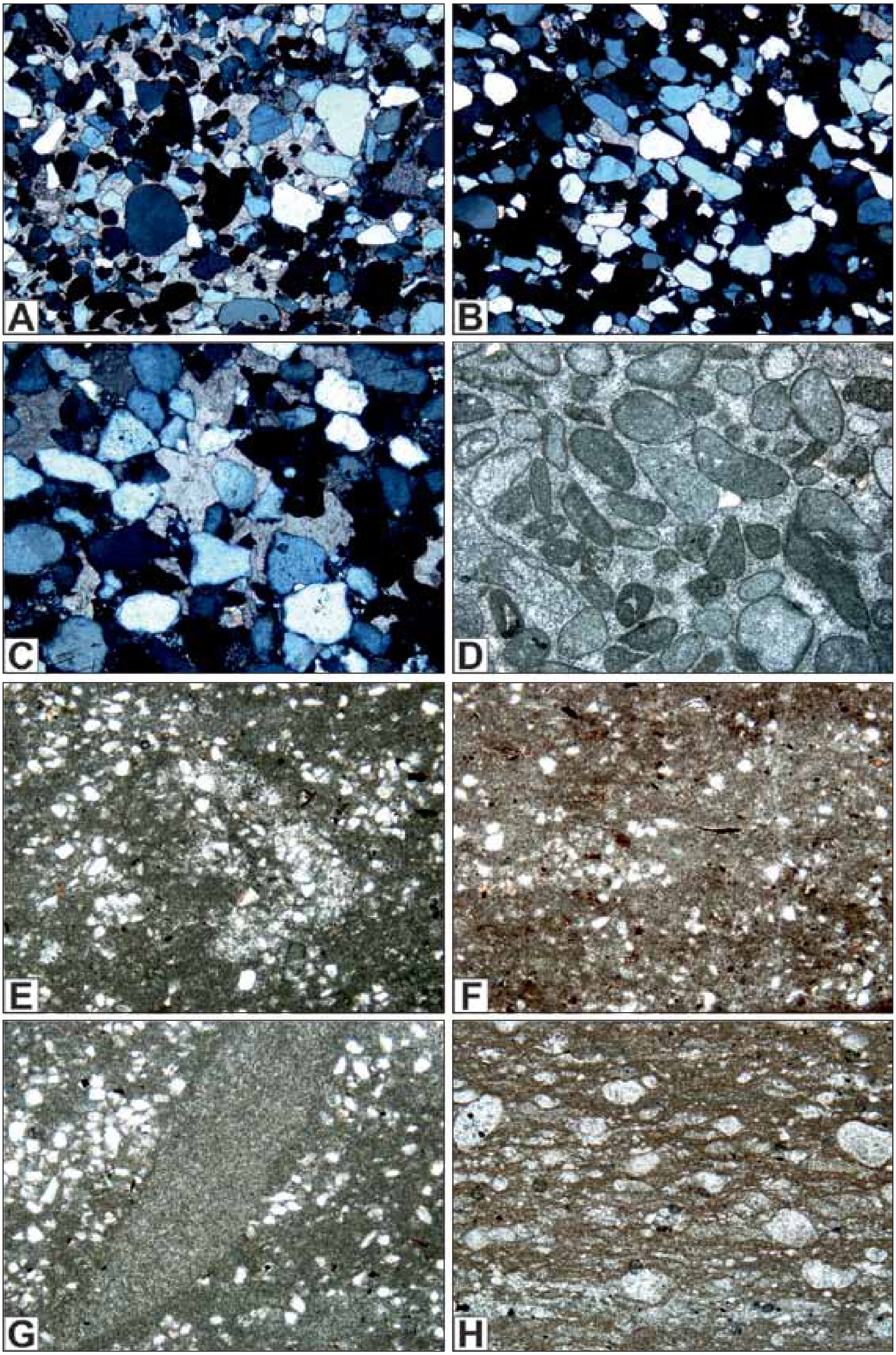
Fig. 10. Thin section photographs of Entrada Sandstone and Todilto limestone (Luciano Mesa Member) from Haystack Butte and Dos Lomas

Photos A–C taken under polarized light, D–H under plane light. **A.** Sandstone composed of subrounded to rounded grains, mostly monocrystalline quartz, rarely polycrystalline quartz, chert, volcanic rock fragments and detrital feldspar. Most grains are 0.1–0.3 mm in diameter, a few grains are larger (0.4–0.5 mm). Grains are cemented by calcite. Haystack Butte, sample HB 5, width of photograph is 3.2 mm. **B.** Well-sorted sandstone composed of subrounded to well-rounded grains, dominantly monocrystalline quartz with small amounts of polycrystalline quartz, chert and detrital feldspars. Haystack Butte, sample HB 6, width of photograph is 3.2 mm. **C.** Fine-grained sandstone (0.1–0.3 mm), moderately to well sorted with subrounded to rounded grains, predominantly monocrystalline quartz, rare polycrystalline quartz, chert and detrital feldspars, cemented by calcite. Dos Lomas, sample DL 1, width of photograph is 1.2 mm. **D.** Intraclast grainstone, moderately to well sorted, composed of subrounded to rounded intraclast grains, many of them displaying thin, dark gray micritic envelopes. The grains are cemented by calcite. Haystack Butte, sample HB 1, width of photograph is 6.3 mm. **E.** Siliciclastic-carbonate siltstone, bioturbated, composed of small detrital quartz grains (~0.1 mm) embedded in micrite. Dos Lomas, sample DL 3, width of photograph is 3.2 mm. **F.** Mudstone containing many small detrital quartz grains with diameters <0.2 mm. Dos Lomas, Sample DL 2, width of photograph is 3.2 mm. **G.** Mixed siliciclastic-carbonate siltstone with a burrow. Dos Lomas, sample DL 3, width of photograph is 3.2 mm. **H.** Ostracod wackestone, laminated, containing many ostracods and a few small detrital quartz grains embedded in micrite. Dos Lomas, sample DL 9, width of photograph is 3.2 mm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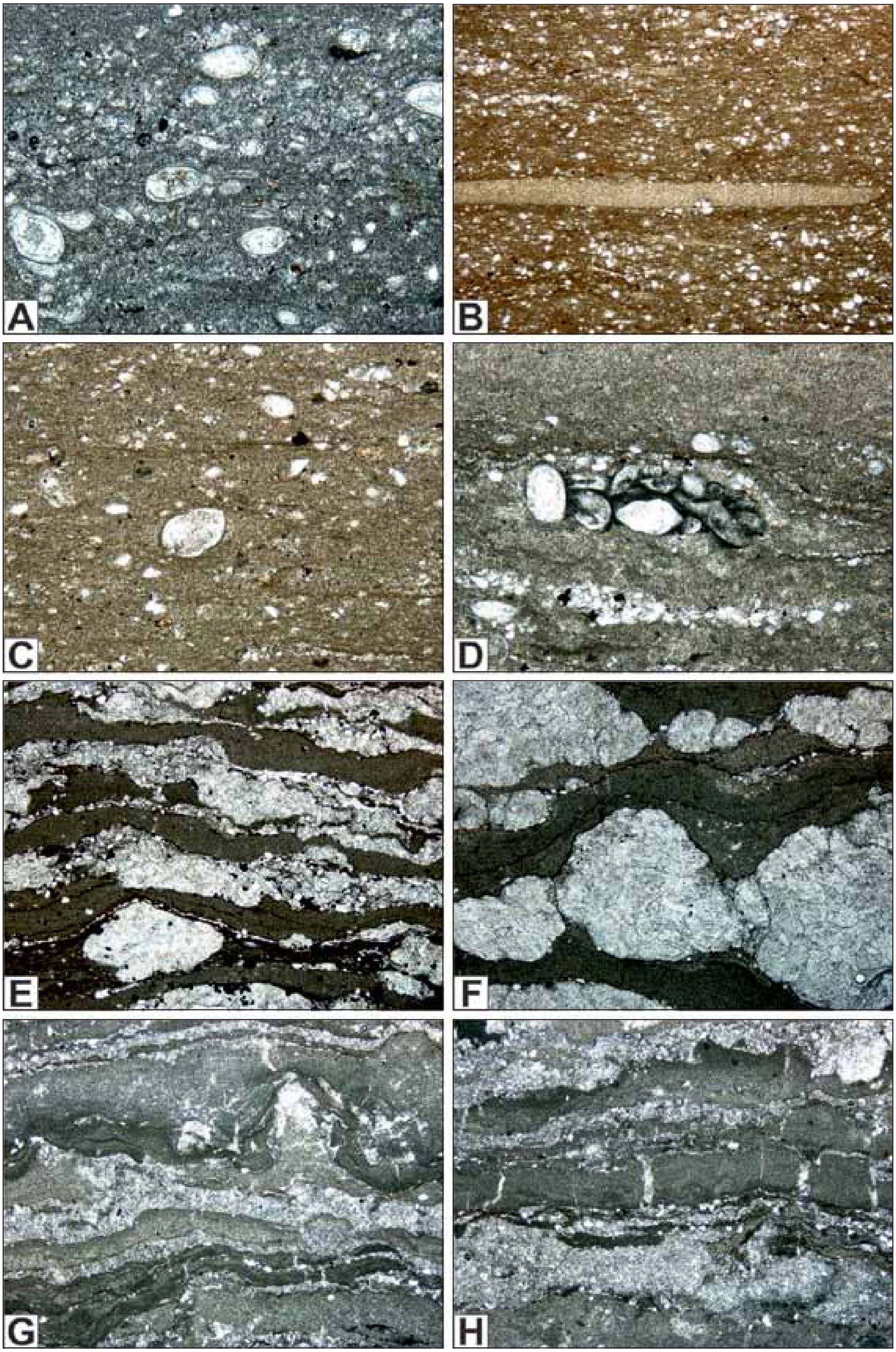
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Fig. 11. Thin section photographs of limestone of the Todilto Formation at Haystack Butte and Dos Lomas (all under plane light)

A. Mudstone containing ostracods and a few small detrital quartz grains. Haystack Butte, sample HB 3, width of photograph is 3.2 mm. **B**. Mudstone-siltstone, indistinctly laminated, containing many small quartz grains (<0.1 mm) and rare mm-large intraclasts (”flat pebbles“). Dos Lomas, sample DL 7, width of photograph is 6.3 mm. **C.** Indistinctly laminated mudstone containing a few ostracods and detrital quartz and feldspar grains. Dos Lomas, sample DL 8, width of photograph is 3.2 mm. **D.** Mudstone with local accumulation of ostracods (center of photograph). Dos Lomas, sample DL 16, width of photograph is 3.2 mm. **E.** Thin layers of mudstone alternating with layers and nodules of calcite (replaced evaporite minerals). Dos Lomas, sample DL 13, width of photograph is 6.3 mm. **F.** Nodular mudstone composed of calcite nodules (up to several mm large) embedded in mudstone. Dos Lomas, sample DL 12, width of photograph is 6.3 mm. **G.** Laminated mudstone, most probably stromatolite, with intercalated laminae of calcite (probably replaced gypsum crystals). Dos Lomas, sample DL 17, width of photograph is 6.3 mm. **H.** Laminated mudstone (stromatolitic) with intercalated layers of calcite. Some mudstone layers display desiccation cracks. Dos Lomas, sample DL 17, width of photograph is 6.3 mm

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At Dos Lomas, we interpret the domal structures to be tepee-like structures overlain and sealed by stromatolites that partly reciprocate the relief formed by the tepees: the stromatolitic layers are thinner above the crest of the tepees; thickness increases down from the crest (Fig. 8). The stromatolitic beds that overgrow the tepees thus display domal, mound-like structures (but do not represent typical mounds or bioherms as claimed by Ulmer-Scholle, 2005). The cores of these domal structures in the Dos Lomas area (Figs 8, 9C–D) are commonly strongly deformed (folded and/or brecciated). Indeed, it is well known that syndepositional cementation may cause early lithification and subsequent expansion of the cemented bed, resulting in the formation of pseudoenterolithic structures (tepees) (*e.g.*, Assereto, Kendall, 1977). So, we conclude that at least some of these domal structures at Dos Lomas are not stromatolitic mounds but the result of such early lithification (note their cores: Fig. 9C–D) and thus some kind of tepee-like structures.

Green (1982) explained the formation of the “folds” at Dos Lomas by differential sediment loading when eolian sand dunes of the overlying Summerville Formation migrated over soft lime mud shortly after deposition. However, at Dos Lomas the Todilto is overlain by a sabkha facies of the basal Summerville Formation, rather than eolian dunes. Furthermore, the domal structures at Dos Lomas are not simply domal stromatolites, as concluded by Ulmer-Scholle (2005). Instead, they have brecciated to massive cores over which stromatolitic limestone layers are draped, forming tepee-like structures.

HAYSTACK BUTTE

At Haystack Butte (Fig. 12), very large folds (meters in scale) and much smaller folds (mm/cm in scale) are present in the Todilto Formation (Figs 5A–C, 12). Here, the top surface of the Entrada Sandstone forms a surface of relief (eolian sand dunes) of up to 1.5–2.0 m, which is capped by the Todilto Formation (*e.g.*, Fig. 5C). This relief causes thickness variations within the Todilto, which is thinner above the Entrada dunes (mostly 1.5–2.0 m) and thicker above interdune deposits (the difference in stratigraphic relief is up to 5.4 m), thus forming drape folds in the Todilto (Fig. 5C). Locally, lenses of crossbedded red sandstone up to about 2 m thick and 8 m in lateral extent are intercalated in the Luciano Mesa Member of the Todilto Formation at Haystack Butte. These lenses represent isolated eolian sand dunes, indicating that during Todilto sedimentation the environment locally was subaerially exposed and isolated eolian sand dunes formed.

Intercalated sandstone in the Todilto Formation is similar in texure and composition to the underlying Entrada Sandstone. Thus, the sandstone is fine-grained, well sorted and composed mainly of rounded detrital grains that are predominantly monocrystalline quartz with a few grains of polycrystalline quartz, detrital alkali feldspars (including microcline), chert, metamorphic rock fragments and opaque grains. Detrital grains are cemented by coarse calcite that randomly replaces detrital quartz and feldspar grains (Fig. 10A–B).

The basal Todilto limestone locally consists of moderately to well-sorted intraclast-grainstone, composed of subrounded to rounded micritic intraclasts and a few small quartz grains. Many intraclasts display thin, dark gray micritic envelopes (Fig. 10D). The limestone is commonly laminated lime mudstone that contains ostracods and a few small quartz grains. Locally, layers and lenses up to a few mm thick of fine-grained, calcite-cemented sandstone are intercalated in the mudstone (Fig. 11A). Some laminated lime mudstone beds contain nodules composed of calcite (replaced evaporite minerals).

Locally, small stromatolitic mounds occur on top of eolian sand dunes of the Entrada (Figs 5B, 12: Haystack Butte 1 section). At these locales, the Todilto is thin-bedded and laminated in the lower part, locally containing small stromatolitic mounds near the base. Rare small-scale (cm) synsedimentary folds occur within laminated limestone beds. Larger folds (dm-m scale) occur in the upper part of the Todilto (Figs 5A, C, 12: Haystack Butte 4 section). As the limestone beds below and above the folded horizon are undeformed, these folds are synsedimentary and not of tectonic origin.

In the upper part, the Todilto has crinkly laminated stromatolitic limestones, commonly gypsiferous and containing small gypsum nodules. These gypsiferous stromatolitic limestones cap the folded horizon. Locally, massive limestone forms the top of the Todilto Formation.

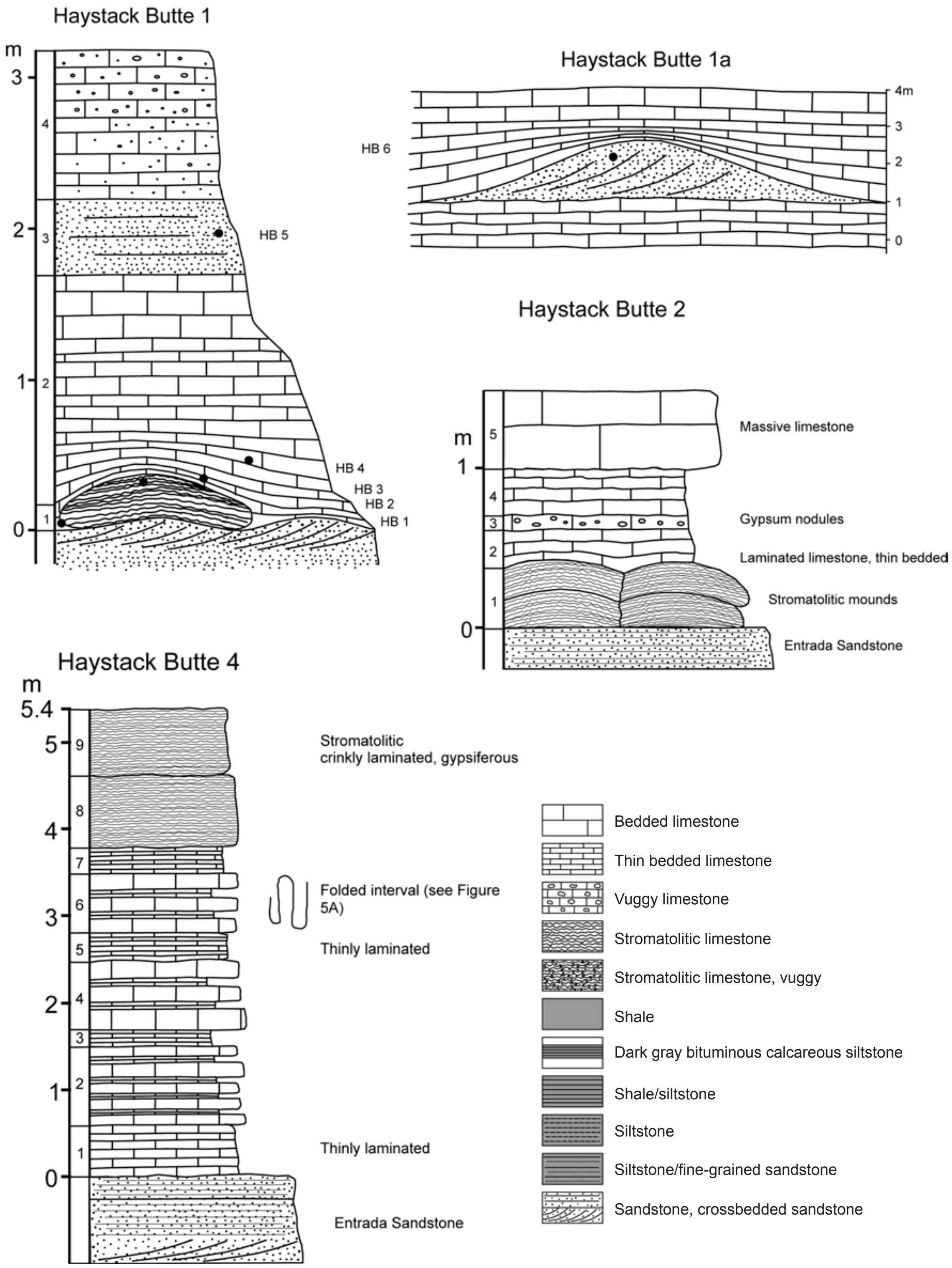

Fig. 12. Stratigraphic sections of Todilto Formation and adjacent strata at Haystack Butte

The sections show drape folds (Haystack Butte 1, 1a), stromatolitic mounds (Haystack Butte 2) and the interval of large folds exemplified by Figure 5A (Haystack Butte 4)

Our analysis of the intraformational folds in the Todilto Formation at Haystack Butte indicates that three scales of fold structures occur within the Todilto:

1. Small, stromatolitic mounds are locally present near the base of the Todilto Formation, forming small domal structures (Figs 5B, 12: Haystack Butte 2 section). These domal structures were formed by the growth of stromatolites (microbialites) and belong to SH-Type (Stacked Hemispheroid) stromatolites, which are domal structures or columns separated by sediment according to the stromatolite classification of Logan *et al*. (1964). These structures are not the product of folding, but are bioherms.

2. Small-scale folds within one limestone bed (thickness approximately 10 cm) occur at scales on the order of mm to cm (Fig. 5D). These folds only occur in individual beds, whereas over- and underlying limestone beds are undeformed. These folds are interpreted as enterolithic folds that probably formed by the transformation of anhydrite to gypsum. Later, gypsum seems to have been mostly replaced by calcite. Such folds may also form by slump events in soft sediment on gently inclined slopes, so we regard their origin as uncertain.

3. Larger-scale folds at meter scale include a thicker part of the entire succession of the Todilto Formation, and are locally associated with thrusts (Fig. 5A), suggesting that folding occurred after lithification of the limestone. It is not totally clear what caused the formation of these folds. The transformation of anhydrite to gypsum in the more central part of the Todilto basin where thick evaporites are present may be one explanation. Such a transformation would cause an increase in volume and produce enough force to form these folds. The fact that no compressional tectonic structures (folds, reverse faults, overthrusts) are present in the underlying Entrada Sandstone and overlying Summerville Formation at Haystack Butte indicates that these folds are not the product of compressional tectonics and crustal shortening related to post-Todilto tectonics.

Thus, the folds at Haysack Butte range from millimeter to meter scale. They include enterolithic folds at the millimeter scale, likely the result of diagenetic alteration. Some of the “folds” are domal stromatolites. There are drape folds in the Todilto over pre-Todilto, dunal topography developed at the top of the underlying Entrada Sandstone, The largest folds in the Todilto were most likely caused by diagenetic alteration (expansion of anhydrite when hydrated to gypsum).

CONCLUSIONS

In northwestern New Mexico, intraformational folds in the Luciano Mesa Member of the Todilto Formation range in size from millimeter to meter scale. No single process explains the formation of the diverse Todilto folds. Five explanations have been offered by an extensive literature: tectonics, soft-sediment deformation, diagenetic alteration, stromatolitic bioherms and tepee-like structures.

Our studies of characteristic Todilto folds in west-central New Mexico identify diagenetic alteration, soft-sediment deformation, stromatolitic bioherms and tepee-like structures. We thus conclude that diverse processes produced the Todilto folds: microbialite growth produced dome-like stromatolitic mounds; tepee-like structures were formed by early cementation and lithification; small-scale enterolithic folds were probably caused by transformation of anhydrite to gypsum or as slump folds; and large-scale folds are of likely diagenetic origin.

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