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New Mexico Geological Society Guidebook, 67th Field Conference, Geology of the Belen Area, 2016, p. 369-376.

# ON THE ORIGIN OF CARBONATE NODULES IN THE BURSUM FORMATION AT CIBOLA SPRING, SOCORRO COUNTY, NEW MEXICO

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Abstract—A single half-meter-thick bed in the upper part of the Bursum Formation near Cibola Spring contains abundant carbonate nodules with distinctive knobby surface texture. These structures are shown to consist of the remains of a diverse assemblage of organisms, mainly foraminifers, which encrusted skeletal substrates and built finger-like columns with intervening uncolonized areas. The nodules are similar to previously described ones of comparable age from Kansas, Texas, southern New Mexico and other areas (variously termed "*Osagia*", "*Ottonosia*"or "osagid grains"). However, they differ greatly from most "oncolites" or "algal biscuits" in lacking through-going laminations as well as lacking predominant macroscopic or microscopic algal contributors. The Bursum nodules are inferred to have formed in moderately deep waters (below normal wave base) in an open shelf setting.

## INTRODUCTION

This paper focuses on a single half-meter-thick bed in the upper part of the Bursum Formation near Cibola Spring (Socorro County, New Mexico) that contains unusual carbonate nodules (commonly, although incorrectly, referred to as oncolites, algal nodules or algal biscuits). Numerous studies on the Bursum Formation have been done over the years, starting with Wilpolt et al. (1946), who initially named and mapped the Bursum Formation in central New Mexico. More recently, a number of papers have been written, defining the stratotype or refining the stratigraphy and invertebrate paleontology of the unit (e.g., Kues et al., 2000; Lucas et al., 2000; Kues, 2001, 2002; Lucas et al., 2002; Wahlman and Kues, 2004; Krainer and Lucas, 2009; Allen et al., 2013; Krainer and Lucas, 2013).

## GEOLOGIC FRAMEWORK

The Bursum Formation is a latest Pennsylvanian (latest Virgilian) to earliest Permian (early Wolfcampian) deposit (Krainer and Lucas, 2013). It is a synorogenic, mixed terrigenous/carbonate unit that is transitional between underlying marine limestones of the Atrasado Formation and nonmarine strata of the overlying Abo Formation. As with essentially all marine to marginal-marine strata from this Late Pennsylvanian-Early Permian time interval, the Bursum sediments are characterized by cyclic sedimentation associated with well-documented climate variations and associated, 80-meter and greater, glacioeustatic sea-level fluctuations (Ross and Ross, 1987; Rygel et al., 2008; Krainer and Lucas, 2009). In addition, Ancestral Rockies tectonics played a significant role in Bursum sedimentation. The clastic redbeds of the Bursum were derived from exposed nearby basement uplifts, including the large Pedernal massif and possibly also smaller, local highs. These granite-cored structures shed substantial amounts of coarse- and fine-grained, quartz- and feldspar-rich detritus (conglomerates to shales), primarily during sea-level lowstands. During transgressive and highstand intervals, thinner units of fully marine to marginal marine limestones formed, and it is one of those carbonate beds that are the subject of this paper.

## LOCATION AND STRATIGRAPHY

The outcrop area for these nodules (Fig. 1) is located on one of many fault blocks along the eastern flank of the Rio Grande rift in which Pennsylvanian and Permian strata are well exposed. Three closely spaced stratigraphic sections, shown on Figure 1 and logged on Figure 2, have been measured in the Cibola Spring area, within the Sevilleta National Wildlife Refuge (Allen et al., 2013). All three sections include a roughly 0.5-meter-thick calcareous nodule bed located within the uppermost 7 to 10 meters of the Bursum Formation. The bed is poorly exposed, however, because the nodular character of the constituents fosters rubbly weathering of that interval. Nonetheless, it is possible to collect reasonably in-situ nodules and even some slabs of nodule-bearing limestone.

## PREVIOUS STUDIES OF PENNSYLVANIAN-PERMIAN CALCAREOUS NODULES

Studies on the nodules in the Bursum or roughly age-equivalent units have been quite limited. Kues (2002) and Lucas et al. (2002) identified Bursum "algal biscuits" as "microstromatolitic communities" of *Ottonosia* algae on bioclast fragments, analogous to the biscuits described by Toomey et al. (1988) in Permian beds of Kansas and Oklahoma. Allen et al. (2013)

are the first to have cited that the Cibola Spring area Bursum nodules are actually complex foraminiferal-microbial communities (comparable to those described by Toomey et al., 1988) based on initial observations by P. Scholle. Toomey (1983) also described red algal nodules from the Laborcita Formation near Tularosa, NM, a unit that is now considered to be part of (or at least age-equivalent to) the Bursum Formation. Those nodules, however, have a distinctive concentric structure produced primarily by shingled, platy thalli of *Archaeophyllum lamellosum*, not at all comparable to the more northerly Bursum oncolites discussed in this paper.

Many thousands of papers have been written on carbonate nodules in general, and most cite blue-green, green and/or red algae (or more generalized "microbes") as the primary builders of irregularly crenulated, laminated nodules. Some authors have noted an association or consortium between algal/microbial components and foraminifers or other organisms in forming nodules (e.g., Peryt and Peryt, 1975; Peryt, 1977). Terms such as "*Osagia*" and "*Ottonosia*" (Twenhofel, 1919) or "*Somphospongia*" (Beede, 1899) were coined to reflect such "intimate intergrowths" of different types of microorganisms (Johnson, 1946). Those terms were used particularly for grains that combined concentric laminations in the overall nodule structure (primarily *Girvanella* and other microbial growths) with smaller-scale "stromatolitic" or columnar growth forms within the nodules. The columns were attributed, at least partly, to the growth fabrics of tubular encrusting foraminifers from genera such as *Ammovertella* or *Tolypammina*, coupled with other subordinate encrusters such as spirorbid worms (Toomey and Cys, 1977; Toomey et al., 1989). The origin of the concentric laminations in such nodules is almost always attributed to episodic rolling or overturn of the grains, repeatedly exposing new growth surfaces for organic encrustation. In most cases, the origin of stromatolitic or columnar growth is either not explained or is ascribed to external processes such as boring by annelid worms, barnacles and other organisms (e.g., Toomey et al., 1988). The major importance of encrusting foraminifers and the lesser importance of algae/microbes, however, was at least implicated as a partial cause (together with borings) of the columnar structures of what were then termed "osagid grains" (Toomey et al., 1989).

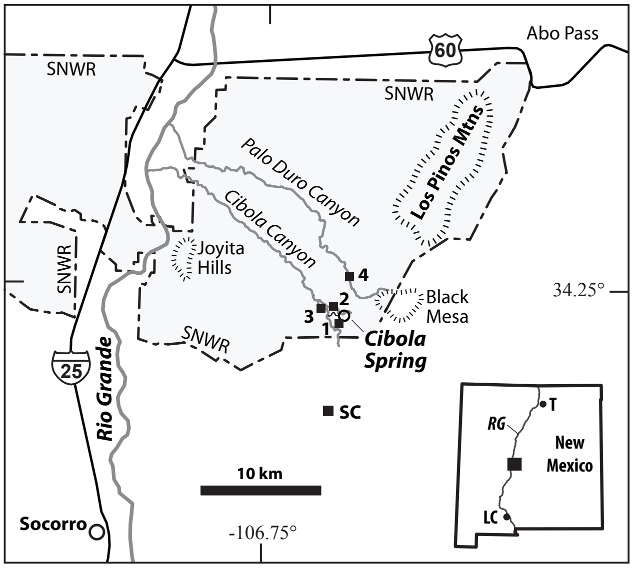

FIGURE 1. Map showing location of measured stratigraphic sections of the Upper Pennsylvanian Bursum Formation near Cibola Spring in which the foraminiferal-microbial nodule bed is exposed. Outline labeled SNWR is the Sevilleta National Wildlife Refuge boundary. In the inset map, T is Taos, LC is Las Cruces, and RG is the Rio Grande. Adapted from Allen et al. (2013)—GPS coordinates for the sections are shown in the appendix to that paper.

## STRUCTURE OF THE BURSUM NODULES AT CIBOLA SPRING

As noted earlier, the Cibola Spring oncolite beds (as opposed to individual oncoids) are not well exposed because of friability of the nodular rock and the softness of the micritic matrix between nodules. The weathered-out individual nodules have very distinctive morphologies (Fig. 3). Their shape is consistently biscuit-like, forming flattened or oblate spheroids. Typical nodules are 4-5 cm in diameter by 2-3 cm in height; exceptionally small ones are 2.5-3 cm in diameter and exceptionally large ones can reach 8 cm. Each nodule is formed by organic encrustations that surround a single shell, and the shapes of the nodules are thus, at least partially, a reflection of the shape of their nuclei. The most common nuclei are small, relatively equidimensional brachiopod and bivalve shells that yield round to ovoid nodules; elongate or triangular nodules are produced via overgrowth of mytilid bivalves, oddly-shaped brachiopods such as *Derbyia* sp., cephalopods, or broken shell fragments. One side of the nodule (the side formed primarily on convex surfaces of shells) has a similarly uniformly convex-upward shape; the opposite side typically has a flat or slightly concave surface, commonly with a distinct central depression. That geometry is, in most cases, a result of the concavo-convex shape of the underlying shell fragment (Fig. 3).

All nodules, regardless of their core grains, have a distinctively knobby exterior surface texture on all sides. This fabric is essentially identical to that described by Twenhofel (1919), Johnson (1938 and 1950) and Toomey et al. (1988 and 1989). The fabric of small (millimeter-scale), lumpy or knobby, dome-like structures separated by lower-lying interstitial areas reflects the presence of numerous underlying, vertical, isolated stromatolite-like columns formed by encrusting organisms that grew on the core shell substrate. The regular spacing of the surface knobs shows the equally regular 3-D distribution of the "columnar stromatolites" within the underlying nodule (Fig. 4A-B).

The "stromatolitic" columns represent complex communities of primarily encrusting organisms that attached initially to a shell substrate and then to other encrusters as they built and expanded upward forming tapered (upward-broadening) structures (the microbial equivalents of human high-rise condos). The encrusting organisms here, as in the Kansas examples shown by Toomey et al. (1988 and 1989), are dominated by calcareous-walled as well as arenaceous (agglutinating) foraminifers (detailed below) with only very subordinate cyanobacterial or microbial tubules and micritic precipitates. Also

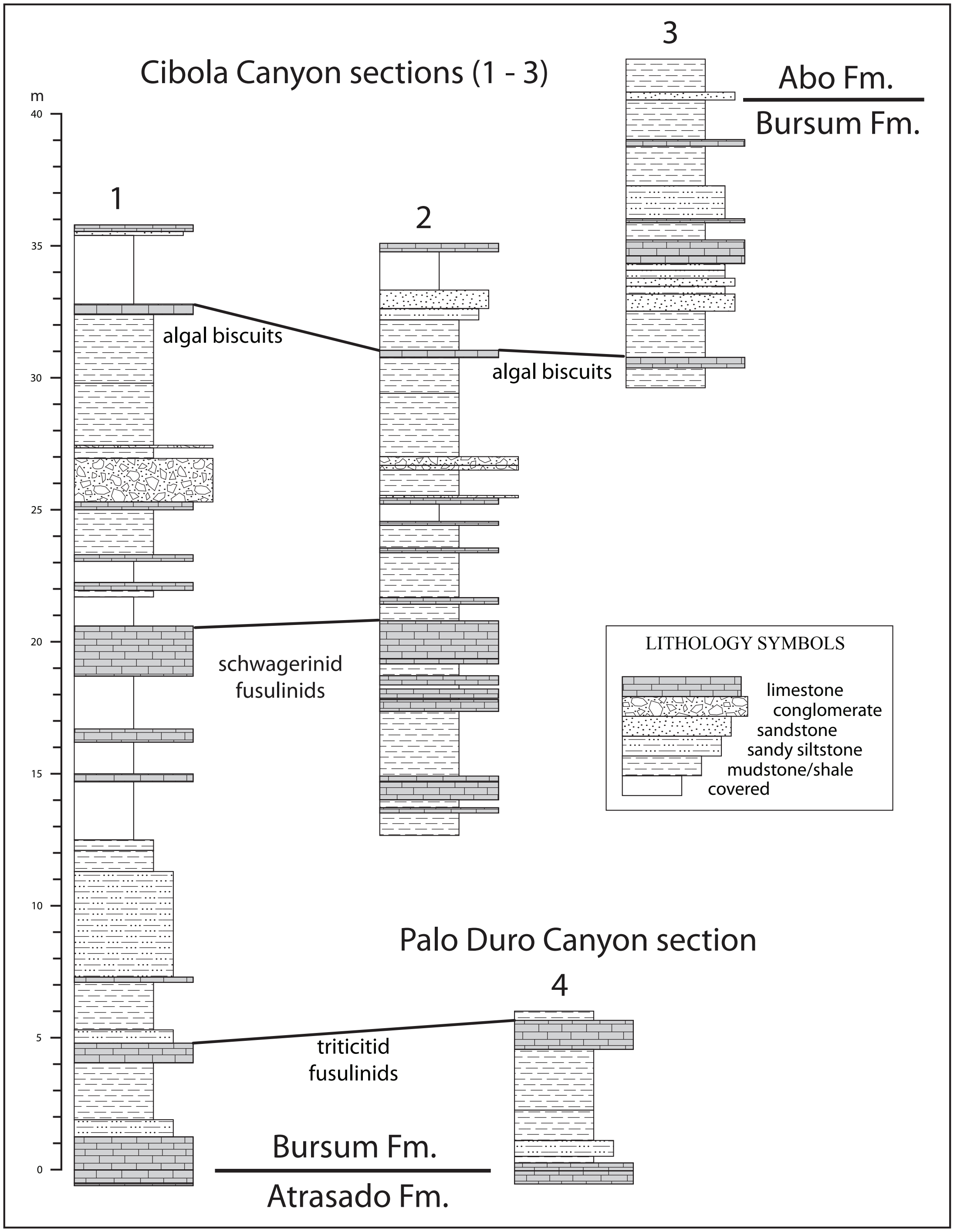

FIGURE 2. Generalized stratigraphic sections of the Bursum Formation near Cibola Spring. Tie lines indicate units that can be readily traced throughout the area, including the nodule zone that is the subject of this article. Section locations are shown in Figure 1. Adapted from Allen et al. (2013).

present, but far less common are trapped sedentary or grazing epizoans (spirorbid worms, gastropods and others).

The fabric of regularly-spaced "stromatolitic" columns produced by these organisms comes, in part, from the clear pattern of preferential colonization of "highs" by initial encrusters. That is, initial growth took place on surface shell sculptural features—ridges or ribs, beads or tubercles, spine attachment sites and other high-standing points on shells (including attached worms, barnacles or other organisms)—at least where such points were available (Fig. 4C-D). But, it is likely that other ecologic factors also played a role in fostering growth of finger-like "stromatolitic" columns. Perhaps micro-scale patterns of water circulation, nutrient supply or organic competition helped to foster such a completely consistent pattern of isolated column formation. Toomey et al. (1988) cited barnacle borings as an additional and important factor in isolating columns. Although a few such borings are present in the Cibola Spring nodules, they are so scarce that they cannot be of major influence in this case.

It should also be noted that, unlike most oncoids, there are few through-going concentric laminations (that is, banding that is correlatable from one finger-like column to adjacent ones). That absence of banding presumably reflects infrequent rotation of grains, although the presence of "stromatolitic" fingers on all sides of grains reflects at least a few episodes of rotation for most of these nodules.

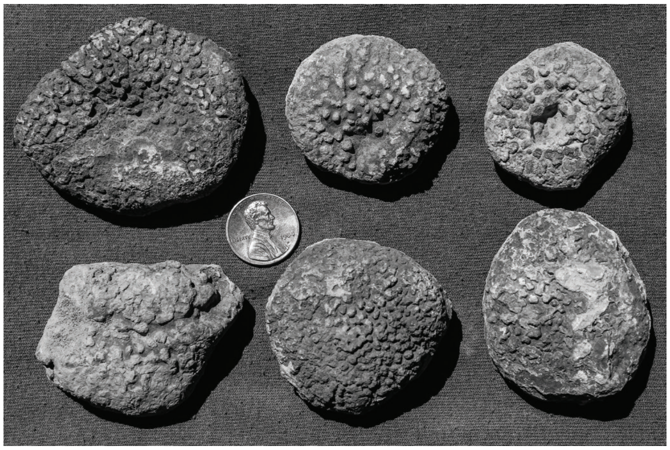

FIGURE 3. Six average-sized nodules showing characteristic shapes and knobby surface textures. The nodule at lower left has a somewhat triangular shape reflective of a mytilid bivalve core; the three nodules at top are oriented to show the underside or lower surface with various degrees of depression of the central area. Coin is 19 mm in diameter.

## CONSTITUENTS OF THE CIBOLA SPRING NODULE COATINGS

Although the makeup of each stromatolite-like column is different in terms of the proportions of constituent organisms, there is an overall similarity in the diversity of organisms present. Most columns are dominated by a few species of encrusting foraminifers, especially those of the genera *Ammovertella*

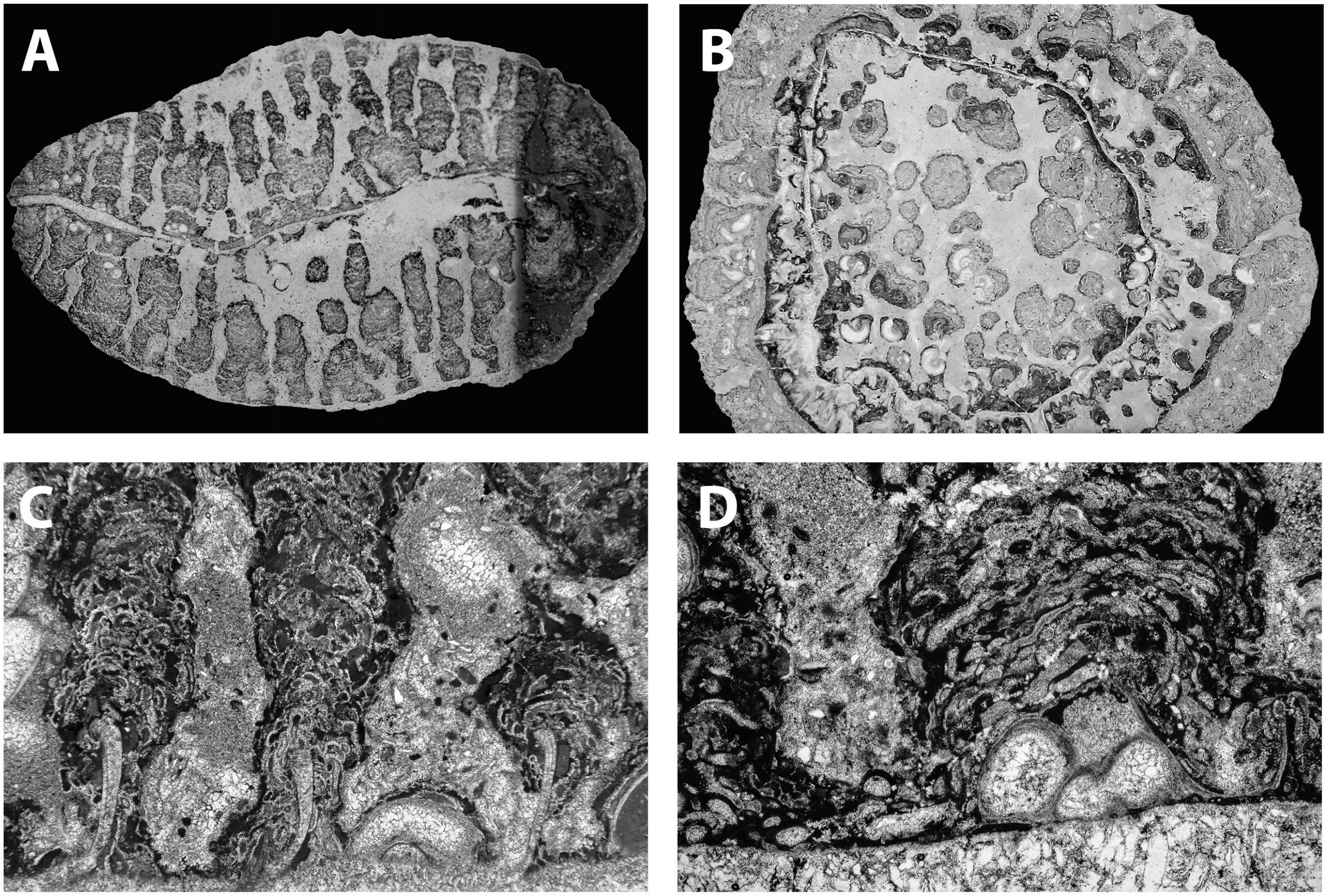

FIGURE 4. **A**) Full thin-section view of a vertical slice through a single nodule. A thin and irregularly shaped shell substrate extends horizontally through the center with "stromatolitic" columns of foraminiferal/algal encrustations extending upward and downward. Some non-encrusting organisms (gastropods and ostracods) are found in sediment between the columns. The dark colored area at the right of the image was stained with Alizarin red and potassium ferricyanide. Horizontal axis (HA) = 51 mm. **B**) A view of a nearly complete thin section showing a horizontal slice through a single nodule. A strongly ornamented brachiopod shell forms the growth substrate here. Numerous early stage encrusting spirorbid worm tubes can be seen in the central area (curved white grains) along with loosely spaced "stromatolitic" columns. More extensive and closer-spaced "stromatolitic" columns are arrayed on and around the external shell surface. HA = 47 mm. **C**) Thin-section view (plane-polarized light) of a partially neomorphosed bivalve shell with large shell plications (bottom edge). Each of the three high-standing plications visible here has acted as the nucleation site for foraminiferal/algal encrustation, thus localizing upward-widening stromatolite-like columns. Inter-column areas have a mixture of micrite (carbonate mud), skeletal fragments and sparry calcite cement. HA = 5.1 mm. **D**) Thin-section view (plane-polarized light) of an encrusting worm tube on a neomorphosed bivalve shell (bottom edge). In this case, the worm tube formed the high-standing substrate for localized foraminiferal/microbial encrustation. HA = 3.8 mm.

and *Tolypaminna*, but also including members of the genera *Diplosphaerina*, *Saccaminopsis*, *Saccamina*, *Tuberitina*, *Carbonella*, *Serpulopsis* (= *Minammodytes*) and others (Fig. 5). It should be noted that all the identified foraminifers are compatible with a latest Pennsylvanian age for this nodule bed (see BouDagher-Fadel, 2008).

The wall structures of the foraminifers are varied, with many having arenaceous or silicified walls (e.g., the light-colored chambers in Fig. 5A-B) whereas many others have calcareous or organic walls (generally the darker-colored areas in most of the photographs in Fig. 5). Darker areas, however, also include probable peloidal and filamentous microbial precipitates as well as some possible red algal encrusters. In addition, as noted earlier, some other organisms, including spirorbid worms, gastropods, ostracods and others, are found either attached directly as macro-encrusters in these nodules or simply trapped within or between growth columns.

## PALEOECOLOGY OF BURSUM NODULES

The organisms found in these nodules (either as substrates or encrusters) reflect, in aggregate, a predominantly normal marine, open shelf environment, a conclusion also noted by Toomey et al. (1988) in their Kansas studies. The formation of columnar overgrowths on both the tops and the bottoms of the substrate grains in virtually all nodules (but with no signs of column breakage and with no continuous circumgranular encrustations) requires minimal, but at least episodic, rotation of grains. The rotation of such large-sized nodules (2-8 cm), however, implies that at those infrequent times of rotation, significant energy was required to move the grains. The absence of photic organisms in the faunal assemblage (and especially the red or green algae and cyanobacteria found in many other oncolites of comparable age) further indicates deposition in deeper waters below the euphotic zone. Overall, the most likely scenario for deposition of these nodules is formation on an open-marine shelf or bank at water depths below normal wave base but still subject to impacts from rare major storms.

Support for that model is provided by examination of relatively rarely preserved large samples of this nodule bed—rare, because weathering generally obliterates structure and leaves only individual rubble zones of isolated nodules that are no longer in original position. One small example of an intact layer is shown in Figure 6, and because there is very little contrast between nodules and matrix, the nodule outlines have been enhanced with white lines. Note the lack of any consistent orientation of grains, and the number of grains standing on edge. Storm reworking could have produced this fabric, although bioturbation or other sediment reworking processes also may have played roles.

## NODULE DIAGENESIS

As a final note of interest on these nodules is their complex diagenesis. Bursum terrigenous sediment is arkosic in composition, reflecting immature sedimentary deposits laid down in close proximity to granitic sources. The various arenaceous foraminifers presumably incorporated such grains in varying degrees within their tests and, in addition, those tests were further replaced by silica and feldspar. Thus, many foraminiferal walls show euhedral quartz terminations or euhedral authigenic feldspar crystals that transect the organic walls and extend into surrounding rock. Figure 7 shows an example of such feldspar replacement or overgrowth; microprobe analysis showed the feldspar to be pure albite. Vachard et al. (2010) noted euhedral quartz terminations in arenaceous foraminiferal walls and suggested that many groups of such organisms may have undergone wall replacement rather than having originally siliceous walls. Although that is possible, quartz overgrowths on original detrital arenaceous grains also could produce similar fabrics.

## CONCLUSIONS

Nodules in the Bursum Formation near Cibola Spring consist of distinctive columnar encrustations on bivalves, brachiopods and other shelly fauna substrates by a wide variety of organisms including at least eight genera of foraminifers, predominantly *Ammovertella* and *Tolypaminna*. Additional encrustations by spirorbid worms, barnacles, red algae and microbes (cyanobacteria?) are present, but are only rarely volumetrically important. These nodules are similar in structure and composition to those in other Carboniferous to Permian limestones at several localities in the southern and southwestern United States as well as other areas. However, they differ greatly from the "normal" algal nodules (oncolites or algal biscuits) that have irregular concentric laminations and generally lack any internal columnar fabric.

Normal oncolites require frequent rotation of grains and are associated with constituents that require light for growth. Thus, they typically form in shallow, open marine to marginal marine or even lacustrine settings with relatively high wave or current energy. The Bursum nodules, on the other hand, are interpreted to have formed in a normal marine setting that lay below normal wave base but probably above storm wave base.

Although generally well preserved, the Bursum nodules have undergone substantial diagenetic alteration including carbonate precipitation in intercolumn areas and authigenic quartz and feldspar replacement of encrusting foraminiferal and microbial material.

## ACKNOWLEDGMENTS

The Sevilleta National Wildlife Refuge kindly granted a research permit to allow our investigations on the refuge. We thank Bruce Allen and Dave Johnson for their careful reviews and valuable suggested improvement

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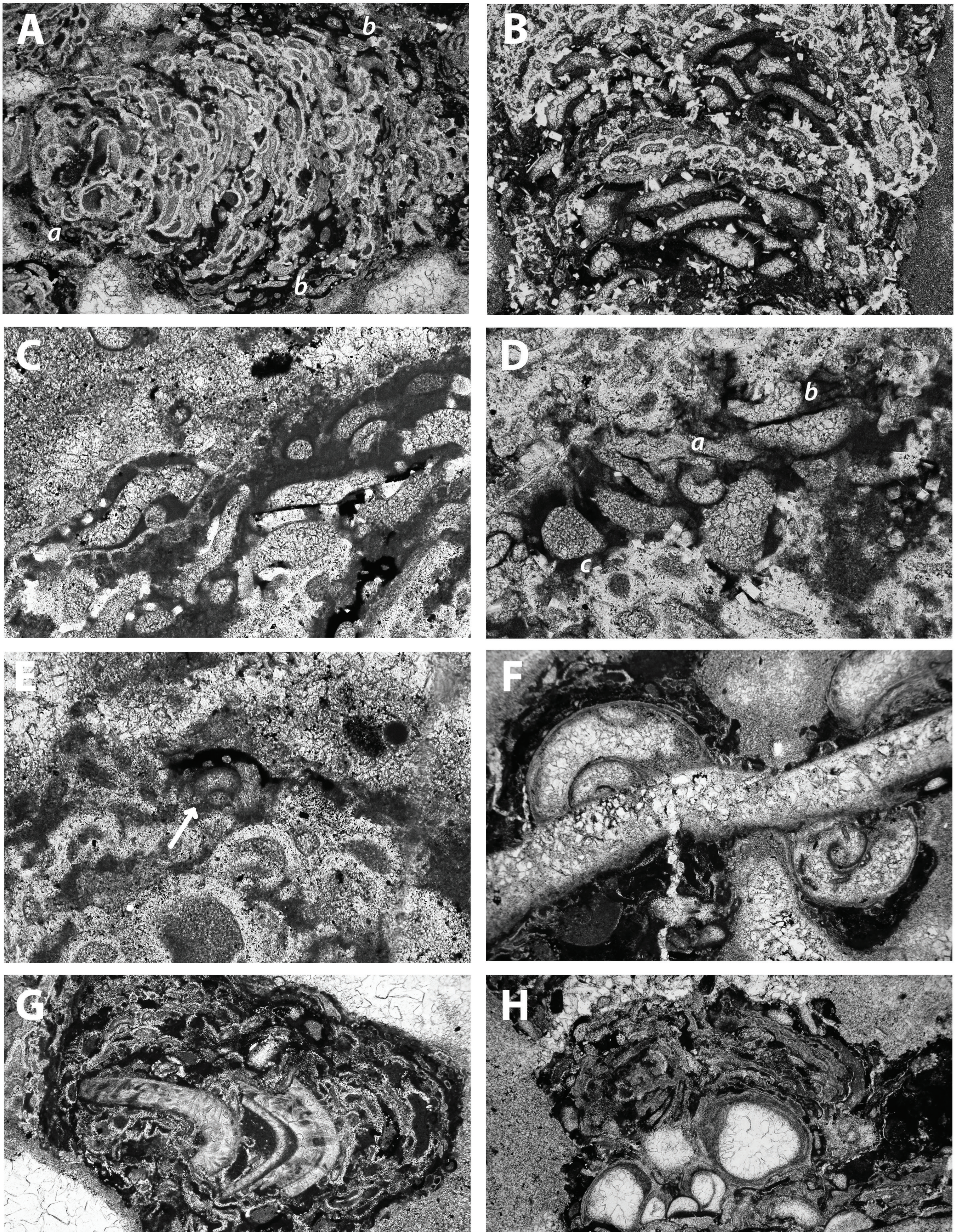
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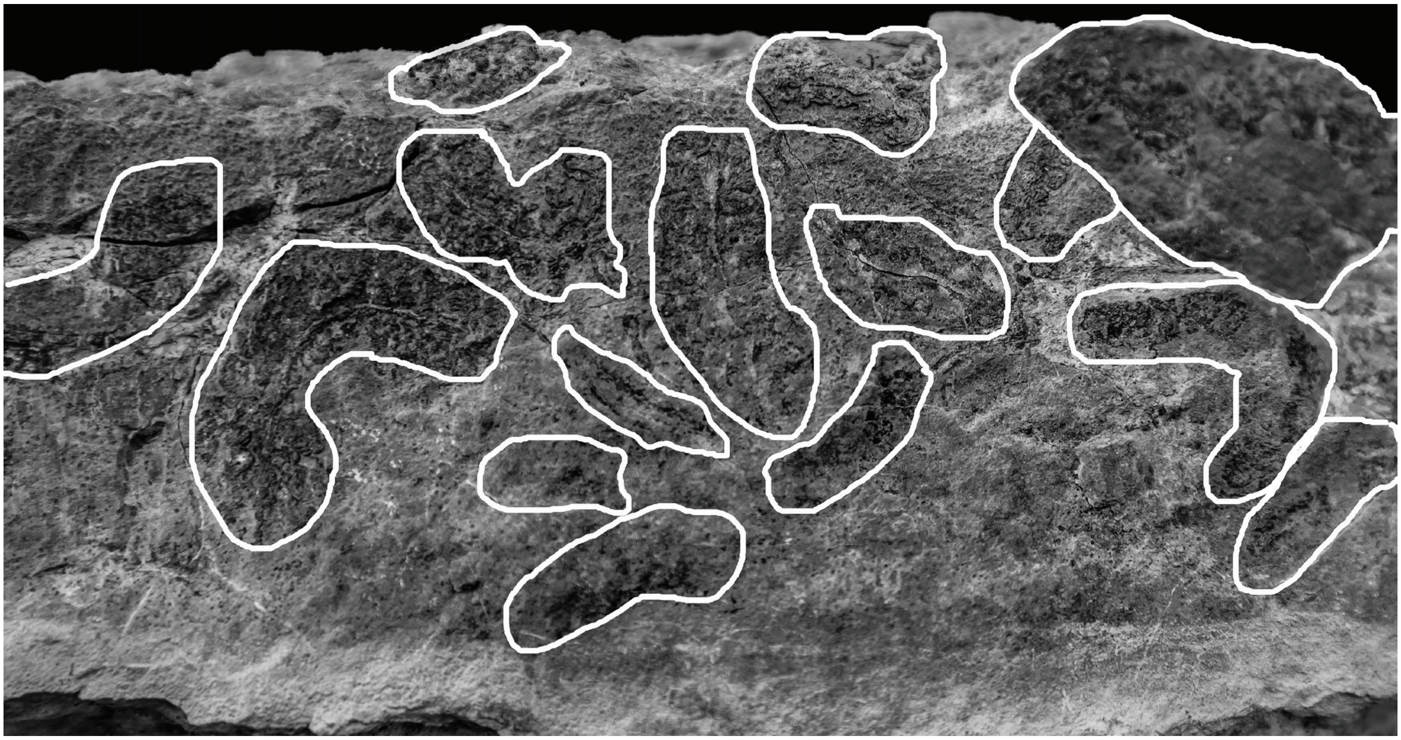

FIGURE 6. Rock surface from Bursum Formation (with outlines of onclolitic grains accentuated by white lines) showing lack of consistent bedding-parallel orientation of incorporated nodules. Long axis of sample is 18.5 cm.

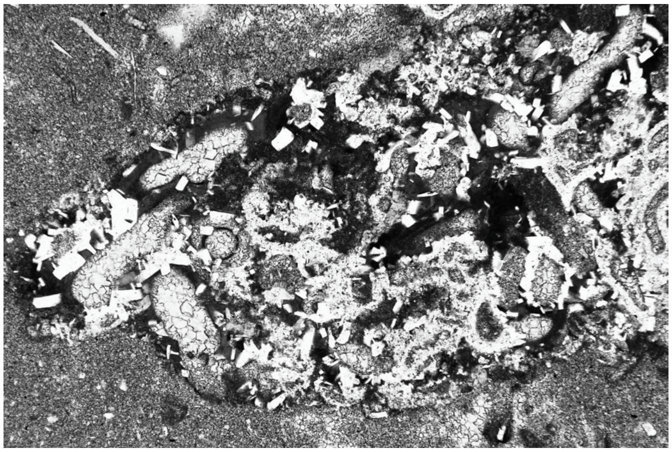

FIGURE 7. Extensive replacement of micritic and possibly also arenaceous foraminiferal walls by authigenic formation of feldspar (albite) and quartz. The feldspar and quartz replacement is specific to the foraminiferal/microbial columns and does not substantially affect the adjacent micritic sediment fills of inter-column areas. Most of the large white crystals in this image are feldspar; quartz constitutes the majority of the small white crystals. Horizontal axis = 2.4 mm.

FIGURE 5: Thin-section photomicrographs (plane-polarized light) of major constituents of Bursum nodules: **A**) Foraminiferal/algal column (top at right) including *Diplosphaerina sphaerica* (a) and *Tolypammina* sp. (b). Horizontal axis (HA) = 3.8 mm. **B**) *Ammovertella* sp. encrustations. HA = 2.6 mm. **C**) *Tolypammina* sp. HA = 5.1 mm. **D**) *Diplosphaerina sphaerica (a)*; *Saccaminopsis fusulinaformis (b)*; *Saccamina* sp. (c). HA = 1.0 mm. **E**) *Diplosphaerina sphaerica* (white arrow) and other foraminiferal encrusters. HA = 0.9 mm. **F**) *Carbonella* sp. encrusting on a neomorphosed substrate shell. HA = 3.8 mm. **G**) Barnacle plates and encrusting foraminifers. HA = 2.9 mm. **H**) Worm tubes and encrusting *Saccaminopsis* spp. HA = 3.8 mm.

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