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ORIGIN OF SANDSTONE CASTS IN THE UPPER TRIASSIC ZUNI MOUNTAINS FORMATION, CHINLE GROUP, FORT WINGATE, NEW MEXICO

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Abstract—Elongate (m-scale), cylindrical sandstone casts are common in the Upper Triassic Zuni Mountains Formation (basal Chinle Group) in a section near Fort Wingate, west-central New Mexico. Previous authors suggested that these features were formed by the burrowing activity of lungfish. Following abandonment of this hypothesis, it was proposed that the casts are the fossilized burrows of crayfish. We find evidence for this origin (crayfish body fossils and characteristic wall structures) lacking at this site. We propose alternatively that the casts are rhizoliths formed by the deep tap roots of the sphenopsid *Neocalamites*.

INTRODUCTION

Dubiel et al. (1987) reported the occurrence of elongate cylindrical structures at various locations on the Colorado Plateau in formations of the Upper Triassic Chinle Group. One of the locations where they described these features, which they interpreted as the aestivation burrows of lungfish, is the section near Fort Wingate, New Mexico, where lowermost Chinle strata (Zuni Mountains and Bluewater Creek formations) rest unconformably on the Moenkopi Formation (Fig. 1). The structures were described by Dubiel et al. as "generally straight and ...vertical to near vertical in orientation," cylindrical in cross-section, and up to 1.6 m in length, but almost never completely preserved. On the basis of a stated lack of ornamentation of the walls and the distinct lack of a terminal chamber, the authors eliminated the burrowing activity of fresh-water decapods as a mode of formation, and further discounted rhizoliths due to the general lack of branching. Dubiel et al. estimated that they examined the contents of several hundred of these structures without finding fossil remains. Nonetheless, they maintained the probable origin through the burrowing of lungfish on the basis of a comparison with the morphology of modern and accepted fossil lungfish burrows.

The lack of supporting fossil evidence caused McAllister (1988) to question this interpretation. Additionally, McAllister demonstrated that the frequency and dimensions of the Chinle Group structures fall outside the limits generally known for the burrows of lungfish, although he offered no alternative interpretation of their origin. Hasiotis and Mitchell (1989) continued the discussion by describing the occurrence of decapod fossils within burrows somewhat similar to those described by Dubiel et al. (1987) in Chinle strata at a location in southeastern Utah. Hasiotis and Mitchell further speculated that many, but not necessarily all, of the structures described by Dubiel et al. as lungfish burrows were in fact constructed by decapod crustaceans (crayfish).

Indeed, Hasiotis and Dubiel (1993) reexamined the section near Fort Wingate originally mentioned by Dubiel et al. (1987) and reinterpreted the cylindrical structures at this location specifically as the burrows of crayfish. In their report, they describe a number of surficial features claimed to be diagnostic of this origin and also describe the length of most of the cylinders as greater than 2 m. Notably, these observations are in contrast to those reported by Dubiel et al. (1987). Alternatively, the structures at this location have been interpreted as the deeply penetrating taproots of monopodial vegetation (Lucas and Hayden, 1989; Tanner, 2003, Tanner and Lucas, 2006).

For this report, we reexamined the Fort Wingate outcrop (Fig. 1) in an attempt to resolve lingering questions regarding the origin of these pervasive structures and address the attendant implications toward the interpretation of trace fossils.

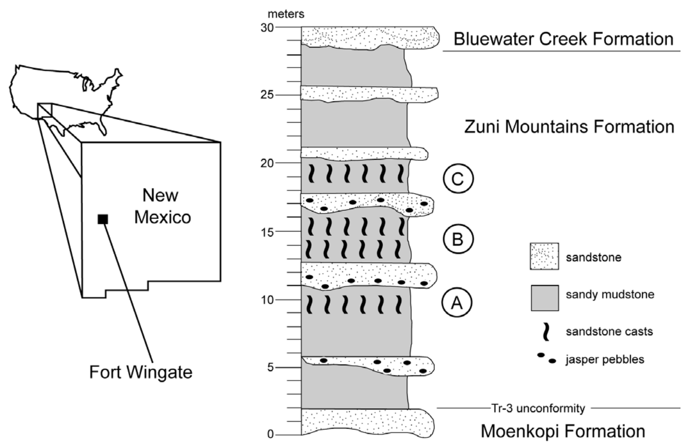

FIGURE 1. Location map of the study area and stratigraphic section of the Zuni Mountains Formation of the Chinle Group at Fort Wingate, showing the three horizons of sandstone casts. Base of section at UTM zone 12, 723153E, 3926330N and top at 723159E, 3926328N (NAD 27).

LITHOSTRATIGRAPHY AND SEDIMENTOLOGY

In the Four Corners region, basal Chinle Group strata rest unconformably (the Tr-3 unconformity) on strata of the Moenkopi Formation. Stewart et al. (1972) used the informal designation "mottled strata" to describe alluvial sediments (mudstones, sandstones, and conglomerates) at the base of the Chinle Group that exhibit strong pedogenic mottling. These strata underlie or are laterally equivalent to the basal strata of the Shinarump Formation (Lucas et al., 1997). Heckert and Lucas (2003) proposed the name Zuni Mountains Formation for these strata in west-central and north-central New Mexico. These same authors also noted that locally the Shinarump Formation may be absent, in which case the Zuni Mountains Formation is overlain by the Bluewater Creek or equivalent Monitor Butte Formation.

At the type location of the Zuni Mountains Formation, near Fort Wingate, New Mexico (Fig. 1), the section comprises 21.4 m of mainly sandy mudstone, muddy sandstone and coarse pebbly sandstone between the Tr-3 (Moenkopi) surface and strata of the conformably overlying Bluewater Creek Formation. Muddy sandstone forms beds up to 2.8 m thick, displays a blocky fabric, is mottled chocolate brown to orange and contains coarse sandstone lenses and thin drab root traces up to 25 cm long. The sandy mudstone is slope-forming and mottled gray-purple to light greenish-gray, contains pedogenic slickensides and forms beds up to 3.2 m thick. Coarse, pebbly sandstone occurs in beds up to

1.3 m thick. The beds display crude trough cross-bedding, gray-white to orange mottling, and contain jasper pebbles. The cylindrical casts that are the subject of this investigation are hosted by the sandy mudstone beds and occur immediately below the pebbly sandstones at three stratigraphic levels (labelled A, B and C in Figure 1).

Accumulation of lower Chinle sediment during the Carnian stage initially was limited to paleovalley systems incised in the Moenkopi (Tr-3) surface (Stewart et al., 1972; Blakey and Gubitosa, 1983). The incised paleovalleys and associated tributaries had paleorelief of tens of meters, so deposition by streams of the Zuni Mountains, as well as the Shinarump and the lowermost strata of the Cameron/Monitor Butte/Bluewater Creek formations, was limited to these topographic lows, and thin to absent between (Stewart et al., 1972; Blakey and Gubitosa, 1983; Demko et al., 1998). Tanner and Lucas (2006) noted the obvious pedogenic alteration of these strata (gley colors, mottling, pedoturbation, the kaolinitic composition of the clays, and the presence of hematite-cemented horizons) and concluded that the sediments accumulated as forest/floodplain soils under conditions of abundant but very seasonal precipitation, i.e., as composite gleyed spodosols.

DESCRIPTION OF THE CASTS

In the Zuni Mountains Formation at Fort Wingate, the cylindrical casts are distributed at three principal stratigraphic horizons in the section (Fig. 1). As described above, each of these horizons is overlain by a bench-forming pebbly sandstone bed (Fig. 2A). The casts vary in length from less than 40 cm to 2.2 m (Fig. 2B), and in width from 5 to 20 cm. Shorter casts (<60 cm) clearly taper downward and commonly display small branching segments (Fig. 2C). Longer casts typically maintain a nearly uniform diameter for much of their length. Most casts are essentially straight and have a near-vertical orientation, although a minority are inclined and/or sinuous (Fig. 2D). Casts rarely bifurcate upward (Fig. 2E), and more commonly branch downward (Fig. 2F). In some instances, the sandstone at the top of the casts appears to contain a tabular layer that connects several casts laterally (Fig. 3A). The uppermost portions of some larger casts broaden upward towards the overlying sandstone bed, increasing in diameter from 10 to 20 cm (Fig. 3B). Definitive lower terminations typically are not apparent (Fig. 3C).

The casts are commonly lighter colored than the host rock, but this is not always the case. In some cases, the casts are almost white and surrounded by a contrasting grayish to reddish-purplish halo that diffuses outward into the host matrix (Fig. 3D). The casts consist of fine-grained sandstone that is coarser and more resistant than the surrounding host rock, causing the casts to weather out with such spectacular relief. In cross-section, the casts are typically circular and lack any internal structure, i.e., mud or lag linings, although a crude concentric rim is apparent in a few specimens (Fig. 3E). The outer surfaces of the casts lack any distinctive ornamentation, and generally display an irregular surface. In some instances, the surface appears to display crude, irregularly spaced horizontal ridges (Fig. 3F), but as similar textures may be observed in the adjacent host rock, these features appear to be the result of differential weathering.

CRITERIA FOR INTERPRETATION

Much of the current literature on fossil crayfish burrows derives from studies of modern burrowing activity. In particularly, the work of Hobbs (1981) is commonly cited. He described three basic types of crayfish burrowers: primary burrowers who build architecturally complex structures that are not attached to bodies of water; secondary burrowers, whose tunnels are attached to open water; and tertiary burrowers who live in open water, but burrow to avoid desiccation. *Fallicambarus devestator* is an interesting example of a primary burrower; demonstrating tremendous adaptation to seasonality, *F. devestator* lives on the prairies of East Texas and excavates burrows up to 3 m deep in order to maintain a dwelling below the water table in the dry season (Hobbs and Whiteman, 1991). These subvertical tunnels have multiple entrances and terminate in an enlarged chamber. Conversely, *Cambarus diogenes diogenes* is an example of the last (tertiary) type of burrower; Grow and Merchant (1980) described the burrows of *C. diogenes diogenes* as up to 5 m deep, typically with multiple entrances that are inclined and converge at shallow depth. *Procambarus clarkii*, described by Correia and Ferreira (1995), is another tertiary burrower. Most burrows of this crayfish are less than 0.5 m deep, but depth may exceed 4 m. Generally, the burrows have a single entrance and terminate in a single chamber.

Of necessity, the interpretation of ancient burrowing activity from trace fossils relies more on the morphology of the preserved structures than on the paleohydrology, which may be unclear. Hasiotis and Mitchell (1993) and Hasiotis et al. (1993), for example, described three morphologies of structures they interpret as crayfish burrows in Upper Triassic (Chinle) strata in southeastern Utah. Their Type I burrows have a complex architecture of branching tunnels and chambers, which they refer to the work of the primary burrowers of Hobbs (1981). Type II encompasses less complex burrows, but typically includes upward branching tunnels and a terminal chamber or chambers, which they compare to the secondary burrowers of Hobbs (1981). Type III refers to simple vertical tunnels, probably comparable to the tunnels of Hobbs' tertiary burrowers. Hasiotis and Mitchell (1993) erected the ichnogenus *Camborygma* to include the structures they interpreted as the burrows of crayfish, including Types I, II and III.

The morphology of the burrow wall or surface is emphasized by Hasiotis (1993), Hasiotis and Dubiel (1993), Hasiotis and Mitchell (1993) and Hasiotis and Honey (2000). These authors stress the importance of recognizing and identifying the following features formed during burrow construction that they consider diagnostic of crayfish burrows: scrape marks, which are horizontal cm-scale ridges produced by the chelae; scratch marks, the sub-vertical, mm-scale scratches caused by the telson and uropods; mud and lag liners, which are concentric layers of matrix material added to the burrow walls during construction; knobby and/or hummocky surfaces that are formed by the pereiopods during excavation; pleopod striae; and body impressions. No single one of these criteria, or combination thereof, is cited as essential to identification of a trace fossil as a crayfish burrow, but the implication is that the occurrence of some combination of these features in any location is diagnostic of the burrowing activity of crayfish.

The nature of a burrow-maker is truly unambiguous only when the remains of the burrower are found in association with the burrows. This is true only for the Type I burrows of Hasiotis and Mitchell (1993), in which case crayfish body fossils were found in these architecturally complex burrows in the Petrified Forest and Owl Rock formations in southeastern Utah. No body fossils have been found associated with either Type II or Type III burrows.

In comparison, the recognition of rhizoliths is relatively unambiguous. Rhizoliths are highly variable in size and orientation, reflecting the greatly varied rooting strategies of plants, which range from deep, vertical tap roots to tabular patterns. Nevertheless, rhizoliths commonly display certain features that facilitate their identification, such as cylindrical shape, circular cross-section, the common presence of secondary rootlets, a pattern of downward bifurcation, and downward tapering shape (Klappa, 1980).

DISCUSSION

In contrast to Hasiotis and Mitchell (1993), we find that unambiguous rhizoliths are not rare in the Fort Wingate section; smaller casts (< 0.5 m in length) commonly display a pattern of either bifurcation or rootlets that facilitates their recognition (Fig. 2C). However, the identity of the larger casts is the subject of this discussion.

Hasiotis and Dubiel (1993) stated that the majority of the casts in the Fort Wingate section are greater than 2 m long, and that most of the structures exhibit lower terminations that either branch laterally or end in

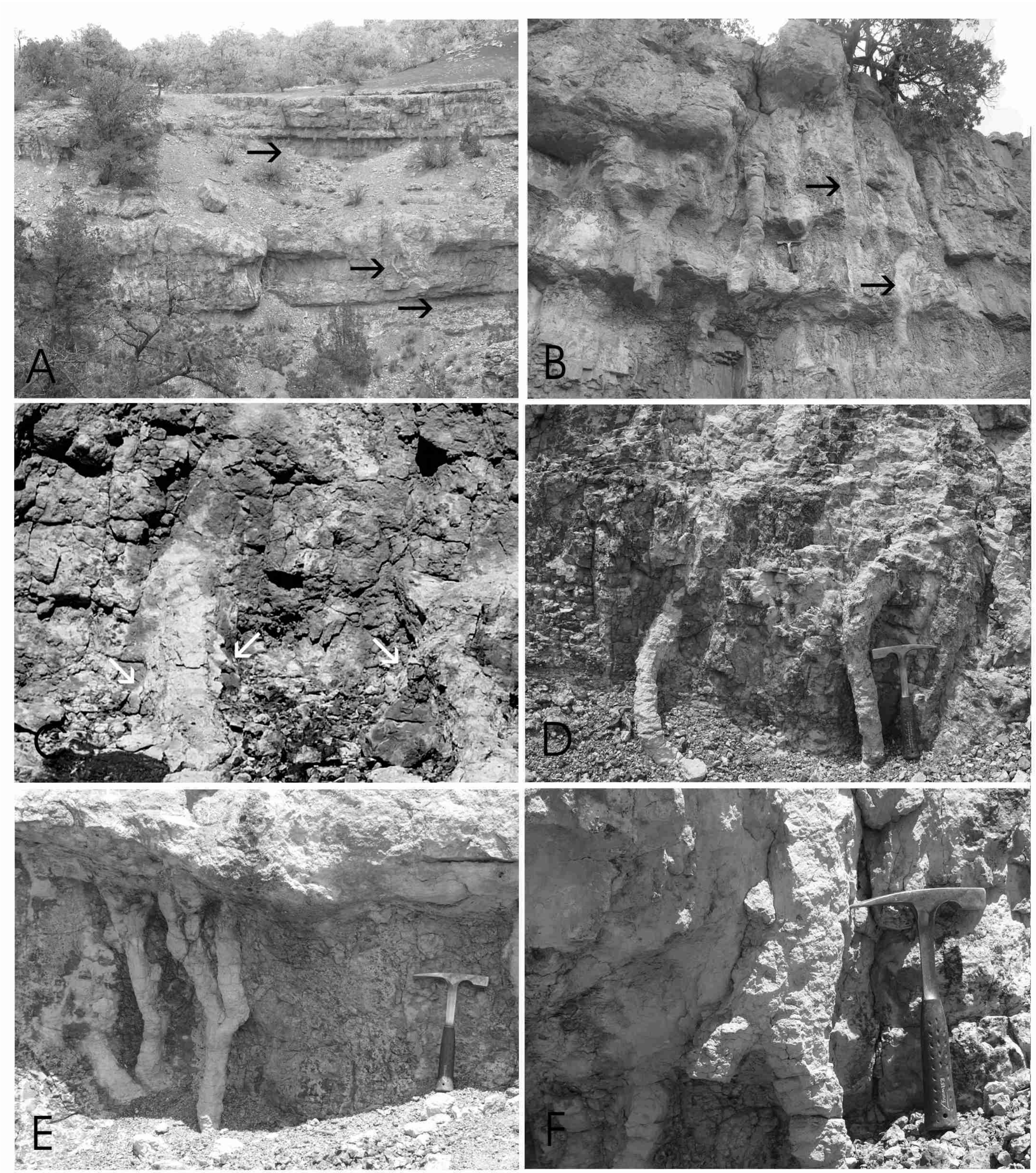

FIGURE 2. Features of the Zuni Mountains Formation section near Fort Wingate. Hammer for scale in most views is 27 cm long. **A**, Overview of the section illustrating several cylindrical cast-bearing horizons (arrows) interbedded with course sandstone beds. **B**, The longer casts (arrows) exceed 2 m in length. **C**, Rootlets (arrows) are visible branching from the main rhizolith body. **D**, Although most casts are mainly straight, a few display extensive curvature. **E-F**, Upward branching of the casts occurs very rarely in this section (**E**). Most casts are unbranched or bifurcate downward (**F**).

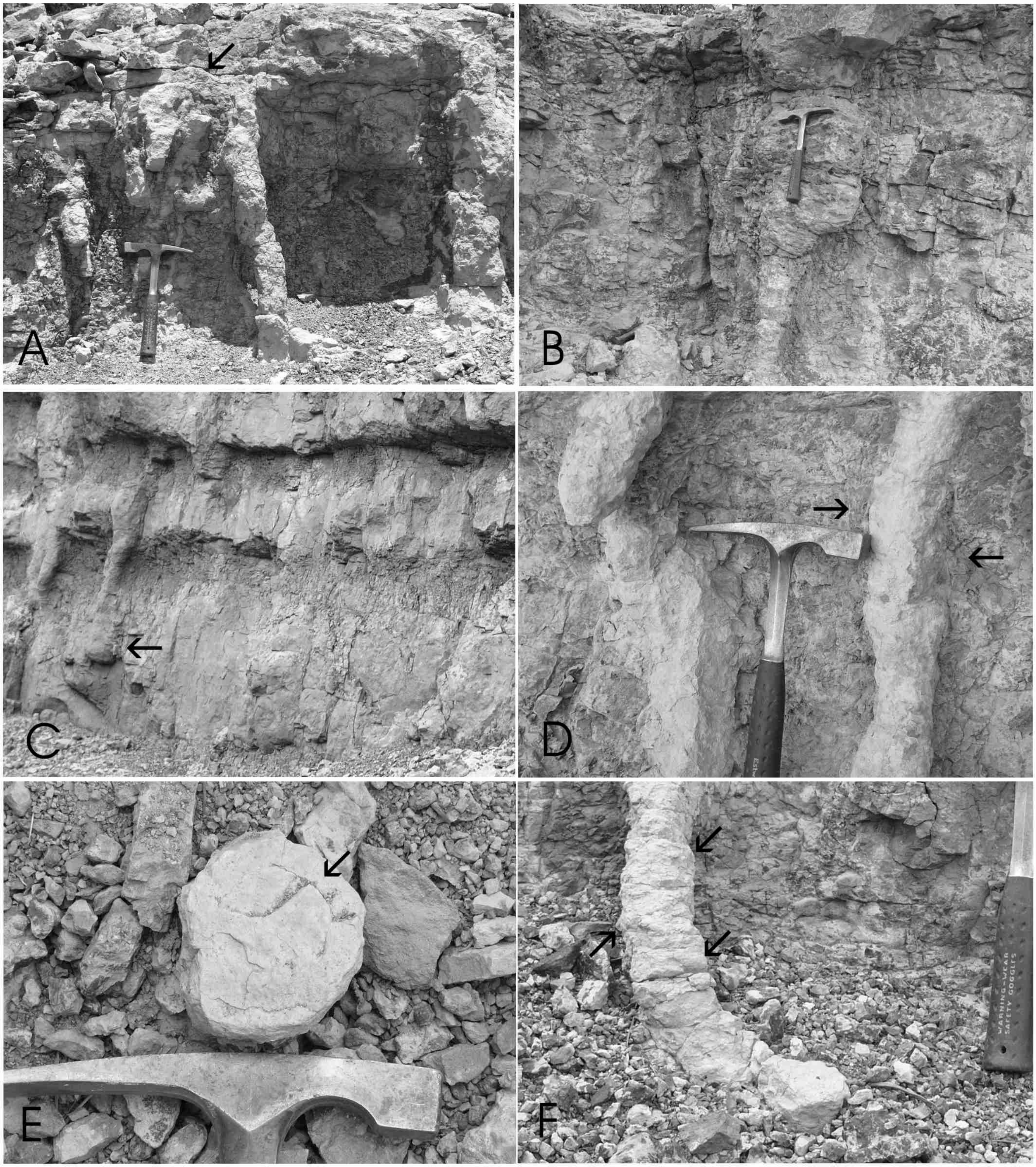

FIGURE 3. Additional features of the Zuni Mountains Formation casts. **A**, The top of the cast in the center of the photograph appears to branch laterally at the base of the sandstone bed (arrow). **B**, The cast on which the hammer rests appears to increase in diameter from about 10 cm to 30 cm near the top. **C**, An enlarged, rounded chamber (arrow) occurs at the terminus of one cast, the only such occurrence observed in the section. **D**, The casts in this photograph have a bleached appearance and are surrounded by a dusky blue-purple halo (arrows) that diffuses outward into the host matrix. **E**, The outer rim of the cast (arrow) is about 1.5 cm thick and is the same grain size as the interior of the cast. **F**, The wall of this cast displays crude cm-scale ridges, but this texture appears similar to that of the weathered host rock behind.

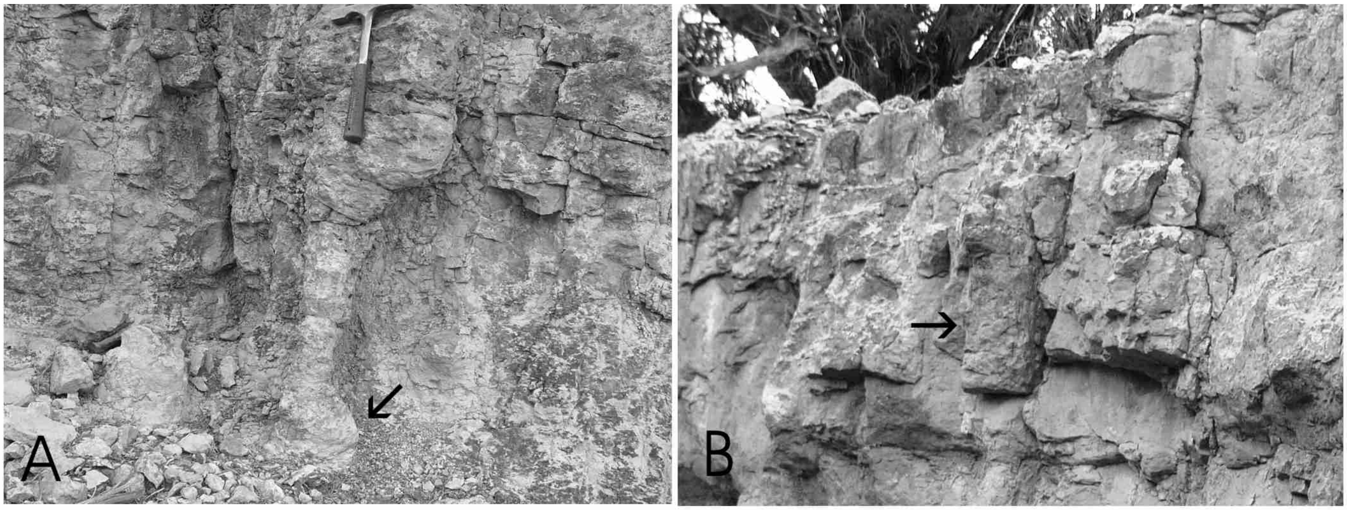

FIGURE 4. Additional features of the Zuni Mountains Formation. **A**, The cast appears to terminate in a chamber structure, but the exposure is incomplete. We believe the enlargement at the base (arrow) marks instead a point of bifurcation. **B**, The vertical cylinder (arrow) appears to be the pith cast of a trunk in life position.

enlarged chambers. Further, Hasiotis and Dubiel wrote that the surfaces of most of these structures display some combination of scrape marks, scratch marks, mud or lag liners, hummocky textures, pleopod striae or body impressions. Hasiotis and Dubiel (1994) assign these structures to the ichnospecies *C. eumekemenos* Hasiotis and Mitchell, 1993. We repeat that the observations of Hasiotis and Dubiel (1993) are contrary to ours and to those of Dubiel et al. (1987), in that, with rare exceptions, most of the casts are in fact less than 1.0 m in length, generally lack wall markings, and lack terminal chambers.

As we describe above, the casts generally lack identifiable surface markings; apparent horizontal ridges occur in places on the walls of the casts, but the nearby matrix often displays a similar weathering pattern. Therefore, we discount the likelihood that these features are scrape marks formed by crayfish chelae. In regard to the lack of terminal chambers, we note an apparent enlarged chamber at the base of one prominent cast (Fig. 3C). Close examination of other apparent occurrences of this type of feature suggests, however, that the enlargement may mark a node where the cast is bifurcating below the exposed base (Fig. 4A).

Ash (1999) described a large and diverse mesic paleoflora from the lower Chinle Group of the Fort Wingate area as dominated by horsetails, ferns and cycadophytes, typical of lowland swampy and riparian environments. Of these, we draw attention in particular to the horsetails. The root systems of the modestly proportioned modern *Equisetum* comprise rhizomes, i.e., lateral adventitious shoots, as well as deep tap (m-scale) vertical tap roots (Walton, 1944), and a similar rhizome system has been demonstrated for the Upper Triassic *Equisetites arenaceus* (Kelber and van Konijnenburg-van Citturt, 1998). The robust sphenopsid *Neocalamites* is well-known from the Chinle strata (Ash, 1999), and we propose here that at least some, if not most, of the casts in the Zuni Mountains section at Fort Wingate are in fact the deep tap roots of *Neocalamites*. The crude concentric layering we note in one cast (Fig. 3E) can be explained as formed by the compression of the matrix material by expansive growth of the tap root. Laterally connecting layers within the sandstone at the tops of some casts may in fact represent the lateral rhizome system of the plants, and the upward thickening pattern of the largest casts probably indicates the base of the plant trunk. We note the occurrence of at least one trunk cast in life position (Fig. 4B) in support of this interpretation.

Both deep tap roots and crayfish burrowing would be possible, perhaps even likely, in regions where meter-scale, water table fluctuations occur regularly. These hydrologic conditions would have been conducive to water-logged soils for humid intervals, but periodic, perhaps seasonal, drawdown of the water table would have resulted in gleying and necessitated deep penetratation by both flora and fauna to maintain moisture levels. Thus, crayfish burrows and rhizoliths are not mutually exclusive interpretations of the structures at Fort Wingate. However, there is no morphological evidence that the vast majority of the sandstone casts at Fort Wingate are crayfish burrows.

CONCLUSION

In attempting to discern the origin of the casts in the Zuni Mountains Formation at Fort Wingate, we find definitive evidence for crayfish burrowing lacking in almost all cases. Although support for this interpretation (i.e., upward branching, terminal chamber) occurs rarely, we support an alternative interpretation that most of the casts are likely the rhizoliths of deep tap roots of the flora known to be abundant at this time. In particular, we suggest that many of these features represent the roots of the sphenopsid *Neocalamites*.

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