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THE TRACE FOSSIL *ZOOPHYCOS* FROM MIDDLE PENNSYLVANIAN STRATA AT GUADALUPE BOX, JEMEZ MOUNTAINS, NEW MEXICO

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Abstract—*Zoophycos* is a distinctive trace fossil, interpreted as the deposit-feeding trace of a marine worm that is found in marine deposits throughout the Phanerozoic, but it has rarely been reported from New Mexico. We describe an extensive assemblage of *Zoophycos* traces from the Middle Pennsylvanian (Atokan) Sandia Formation at Guadalupe Box in the Jemez Mountains. These are simple helicoidal and circular forms with subhorizontal spreiten that have diameters up to 190 mm. Based on lithology and associated fossils, the *Zoophycos*-bearing bed was deposited in shallow water but below wave base. *Zoophycos* gives its name to an archetypal ichnofacies originally characterized as being deposited in deep or at least dysaerobic/anaerobic bottom water. However, the Guadalupe Box record conforms well to many other Paleozoic occurrences of *Zoophycos* in shallow marine deposits that support the idea that the *Zoophycos* ichnofacies should be used in the Mesozoic-Cenozoic but not the Paleozoic.

INTRODUCTION

Invertebrate trace fossils are applied to the interpretation of sedimentary environments through the ichnofacies model, which proposes that many trace fossils reflect the presence of organisms and their behaviors specific to certain depositional environments (lithofacies). The ichnofacies model, created by Seilacher in the 1960s, originally identified different water depths as the primary control of trace fossil distribution. However, this was shown to not work well (Byers, 1982; Ekdale, 1988), and now the ichnofacies are thought to reflect more broadly conceived depositional facies, not just bathymetry.

The trace fossil *Zoophycos* gives its name to an archetypal ichnofacies originally characterized as being deposited in deep or at least dysaerobic/anaerobic bottom water. There are only a few published reports of *Zoophycos* from New Mexico (DuChene, 1974; Cooper and Dutro, 1982; Lane and Ormiston, 1982; Kues, 2005; Lucas et al., 2010, 2023; Lerner et al., 2011; Lucas and May, 2024), and these are primarily from Carboniferous strata and of isolated occurrences. *Zoophycos* has its most extensive New Mexican occurrence in the Middle Pennsylvanian (Atokan) Sandia Formation at Guadalupe Box in the Jemez Mountains (Figs. 1–3). Guadalupe Box is a narrow, rocky reach of the Guadalupe River developed in the Proterozoic basement. Here we document the geological context and the *Zoophycos* ichnofossils and briefly discuss their significance for recognition of the *Zoophycos* ichnofacies. In this paper, NMMNH refers to the New Mexico Museum of Natural History and Science in Albuquerque, New Mexico.

GEOLOGY

Lithostratigraphy

At Guadalupe Box, the Sandia Formation is ~30–35 m thick and rests unconformably on the Lower Pennsylvanian (Morrowan) Osha Canyon Formation and is conformably overlain by the Middle Pennsylvanian Gray Mesa Formation (Duchene, 1973, 1974; Duchene et al., 1977; Krainer and Lucas, 2005, 2013; Krainer et al., 2005). The stratigraphic section we measured at the *Zoophycos* locality is 34 m thick, so it represents essentially all of the Sandia Formation (Fig. 2). The Sandia Formation here represents a well-developed, fining-upward succession (transgressive sequence) composed of a basal sandstone interval A, a middle shale-siltstone interval B, and an upper shale-limestone-sandstone interval C.

Interval A is 9.1 m thick and is composed of 4.1 m of coarse-grained, conglomeratic sandstone with multistorey cross-bedding (Fig. 2, unit 2) scoured into underlying gray shale with limestone nodules of the uppermost Osha Canyon Formation, overlain by finer-grained, tabular-bedded sandstone with poorly developed horizontal lamination. Interval B is 17.5 m thick and composed of shale-siltstone that is mostly gray to dark gray, subordinately yellow, reddish-brown, and variegated yellow and gray. Shale is commonly laminated, partly thinly laminated ("paper shale") with plant fragments (unit 9). In the upper part (units 14, 15), shale contains hematitic platelets (concretions?). In the lower part, two thin sandstone intervals are intercalated. The lower sandstone is 0.2 m thick and quartzose and displays horizontal lamination. The upper sandstone is 0.1 m thick, fine grained, greenish, and micaceous. In the middle of interval B, another thin (0.2 m), fine-grained sandstone bed (unit 11) is intercalated.

Interval C is 7.9 m thick and composed of gray calcareous shale with intercalated limestone and fine-grained sandstone. Limestone intervals are 0.2–0.8 m thick and include crinoidal limestone (crinoidal wackestone to packstone), micritic limestone with even bedding planes (bioclastic wackestone), and nodular micritic limestone (bioclastic wackestone). Fossils observed on outcrops are brachiopods, crinoidal frag-

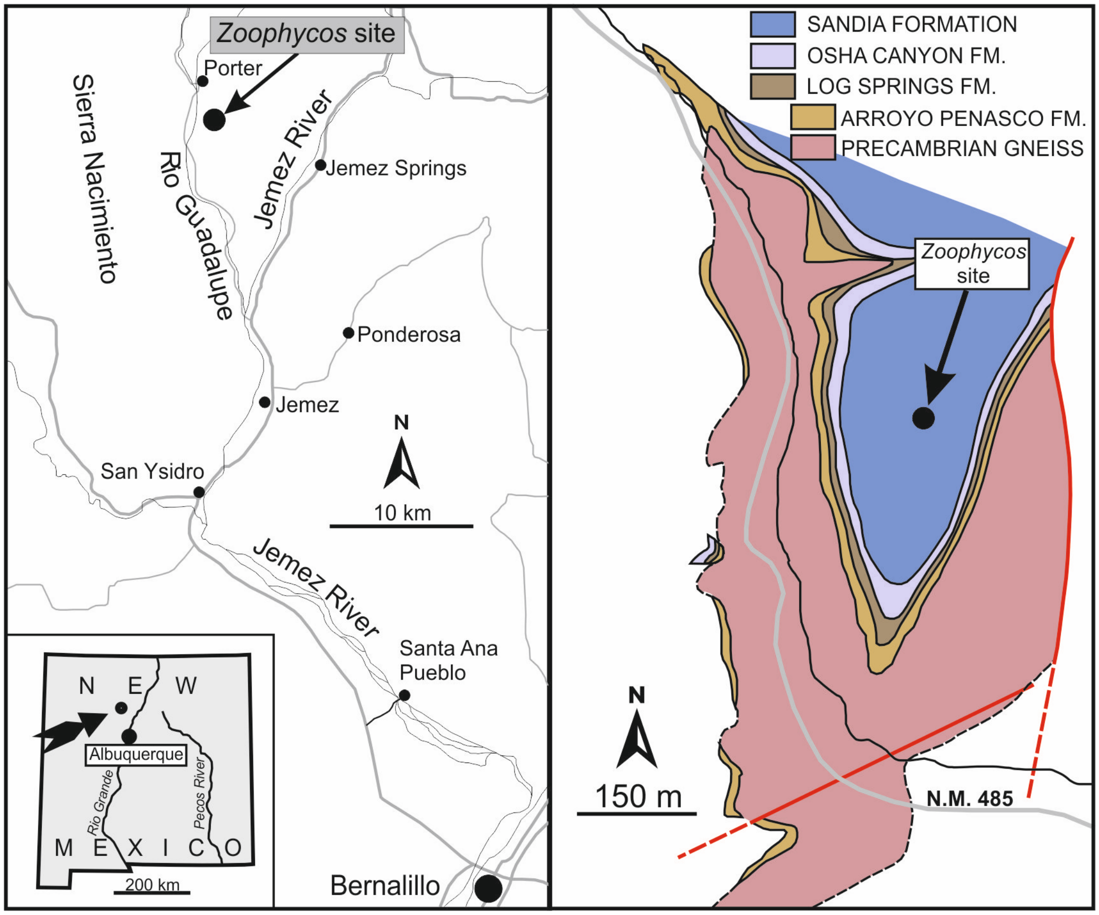

FIGURE 1. Maps of the area around the *Zoophycos* locality at Guadalupe Box (after DuChene et al., 1977).

ments, and rare fusulinids. The lowermost limestone bed (unit 16) contains some poorly developed *Zoophycos*. Intercalated sandstone beds are 0.2 and 1 m thick and fine grained. The lower sandstone bed (unit 18) is 0.2 m thick, contains *Zoophycos*, and is referred to hereafter as the "*Zoophycos* bed." The upper sandstone interval is 1 m thick, greenish, thin bedded, laminated, and contains some shale intercalations. A fusulinid packstone (unit 22) 1.5 m above the *Zoophycos* bed is full of *Fusulinella*, indicative of an Atokan age.

Petrography and Microfacies

The basal sandstone (units 2, 3) of interval A is moderately sorted (Fig. 4A, B), and sandstone of unit 7 is well sorted (Fig. 4C). The detrital grains are mostly subrounded. Sandstone is composed of high amounts of quartz (mono- and polycrystalline quartz) and moderate amounts of detrital feldspars, dominantly potassium feldspars. Other grain types such as rock fragments and micas are rare. Sandstone of units 2 and 3 is cemented by quartz in the form of authigenic overgrowths on detrital quartz grains as well as some opaque cement. Locally, calcite cement is present (Fig. 4A, B). The sandstone of unit 7 of interval B contains matrix and small amounts of calcite cement (Fig. 4C). In the classification scheme of Pettijohn et al. (1987), these sandstones plot into the field of subarkose.

Sandstones of units 11 (interval B) and 18 (*Zoophycos* bed; interval C) are fine grained and contain high amounts of matrix (32–52%), monocrystalline quartz grains, a few polycrystalline quartz grains, and rare detrital feldspars and other grain types (Fig. 4D). In unit 18, burrows, probably of *Zoophycos*, are present.

Siltstone of unit 24 (interval C) is composed of brownish matrix that contains many small quartz grains, few micas, and opaque grains. Siltstone of unit 28 (interval C) is mixed siliciclastic-carbonate in composition, bioturbated (burrows), and composed of small recrystallized fossil fragments, mainly echinoderm fragments and shell debris, small quartz grains, and few micas.

The lowermost limestone bed (unit 16) is a packstone to rudstone containing abundant echinoderm (crinoid) fragments up to 5 mm in diameter, many brachiopod shell fragments, bryozoans, and subordinately foraminifers, ostracods, brachiopod spines, and rare phosphatic shell fragments (Fig. 4E). Small amounts of detrital quartz grains (0.1–0.2 mm) are present. The packstone to rudstone is poorly washed and contains micritic matrix as well as calcite cement. The thin limestone bed of unit 20 is a bioclastic floatstone with a similar fossil content as the lowermost limestone bed. Larger echinoderm (crinoid), brachiopod, and bryozoan fragments float in a wackestone "matrix" (Fig. 4F). The floatstone contains small amounts of detrital quartz grains (2–3%) and displays burrows, probably of *Zoophycos*. The limestone bed of unit 22 is a fusulinid wackestone to packstone with a diverse fossil assemblage (Fig. 4G). Limestone of unit 26 is a bioclastic floatstone composed of abundant brachiopod shell fragments, subordinately of bryozoans, echinoderms (crinoids), brachiopod spines, fusulinids, smaller foraminifers, and ostracods (Fig. 4H).

Sedimentation

The Sandia Formation strata at the *Zoophycos* locality (Fig. 2) represent a well-developed fining-upward succession that

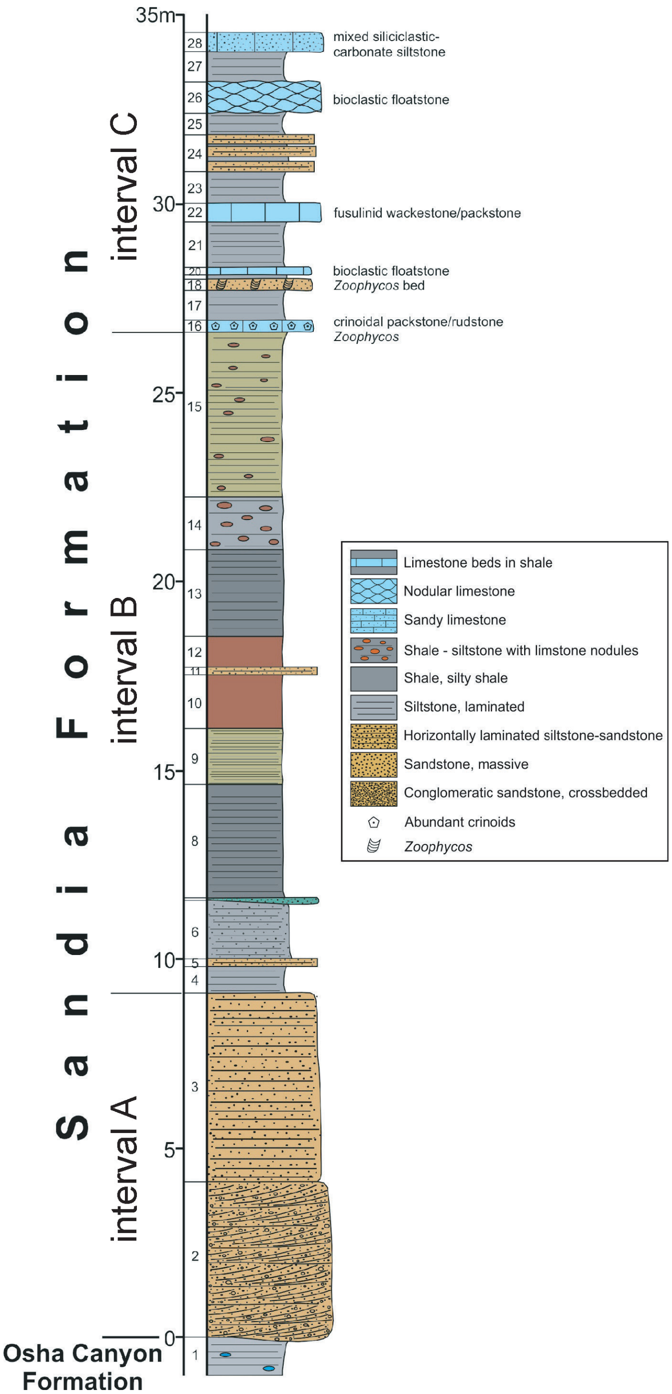

FIGURE 2. Measured stratigraphic section at the *Zoophycos* locality, NMMNH locality 12916.

can be divided into three intervals based on lithology. The lower interval A, 9 m thick and composed mostly of coarse sandstone, is interpreted to be fluvial (Fig. 2, units 2–3). The middle interval B, 18 m of interlayered shale and siltstone (units 4–15), was initially deposited on a coastal plain that became inundated as sea level rose. The upper interval C, 8 m of intercalated gray calcareous shale, limestone, and sandstone, was deposited below sea level (units 16–28). The lowermost bed of the upper interval, a grain-supported crinoidal limestone, documents the continuation of transgression and was deposited in a shallow, open marine setting under moderate to high turbulence. Deepening continued as deposition dropped below wave base, producing limestones with a muddy texture and a diverse fossil assemblage, pointing to deposition in a low-energy but shallow marine environment as long as siliciclastic input was absent. During periods of terrigenous input, calcareous shale was deposited. The *Zoophycos* bed and the other thin, fine-grained sandstone strata may represent distal storm layers. The thin *Zoophycos* bed contains well-preserved brachiopods (apparently not transported far, if at all) and is of light yellowish-orange color. Thus, it does not appear to have been deposited under dysaerobic or anaerobic conditions; instead it was deposited in a relatively shallow marine setting with a fair degree of oxygenation.

GUADALUPE BOX *ZOOPHYCOS*

At Guadalupe Box, dozens of *Zoophycos* are present in a bed of fine-grained sandstone (NMMNH locality 12916; Figs. 2, 3). Approximately 20–30 cm thick, the trace-bearing layer is sporadically exposed to the north of the best exposure for at least 300 m. At the best exposure, approximately 5 m^2 of trace-bearing surface is visible (Fig. 3). Bedding within the *Zoophycos*-bearing sandstone is close to horizontal and 3–5 cm

FIGURE 3. Outcrop photograph of part of the main assemblage of *Zoophycos* at NMMNH locality 12916. Note the indurated and joint fractured *Zoophycos* bed.

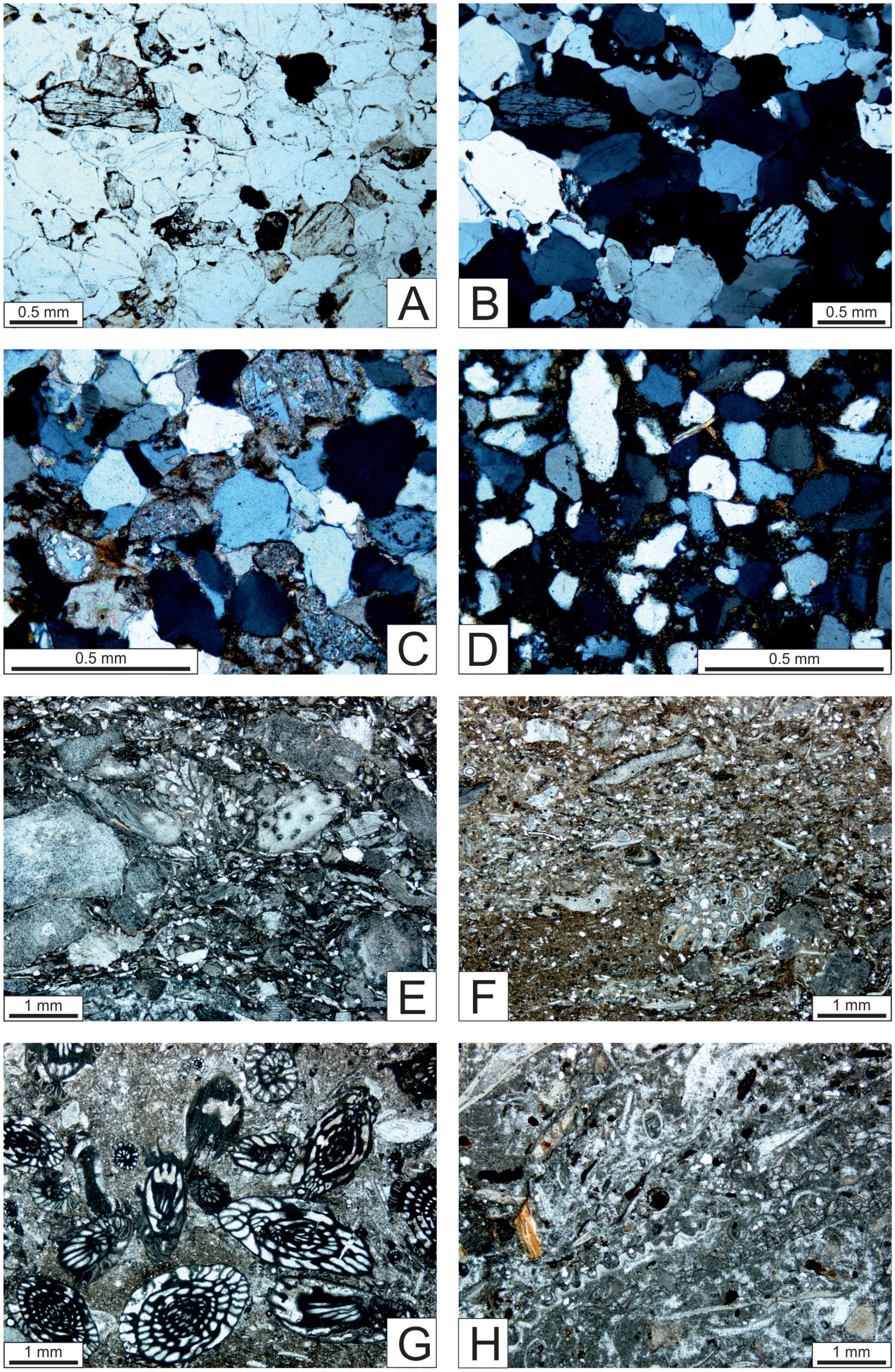

FIGURE 4. Thin section photographs of sandstone and limestone of the Sandia Formation in the stratigraphic section at the *Zoophycos* locality (Fig. 2). **(A, B)** Moderately sorted sandstone composed of high amounts of quartz and moderate amounts of feldspars (subarkose). Quartz grains display authigenic overgrowths. (A) is under plane light; (B) is under polarized light (unit 2). **(C)** Sandstone composed of quartz and feldspar grains. Feldspars are largely replaced by calcite. The sandstone is cemented by calcite. Polarized light (unit 7). **(D)** Fine-grained sandstone composed mostly of monocrystalline quartz, rare polycrystalline quartz, and rare detrital feldspar grains. The sandstone contains high amounts of matrix. Polarized light (unit 11). **(E)** Packstone to rudstone containing large fragments of crinoids, bryozoans, and brachiopods and small amounts of detrital quartz grains. Plane light (unit 16). **(F)** Bioclastic floatstone composed of large fragments of bryozoans, brachiopods, and echinoderms floating in fine bioclastic matrix. Plane light, (unit 20). **(G)** Fusulinid wackestone to packstone. Plane light (unit 22). **(H)** Bioclastic floatstone containing fragments of brachiopods, bryozoans, and crinoids embedded in fine bioclastic matrix. Plane light (unit 26).

thick, with each bed bearing numerous, closely packed *Zoophycos* traces (Fig. 5).

The Guadalupe Box *Zoophycos* (Fig. 5) are helical (spirally coiled), subhorizontal spreiten with both a cylindrical marginal tunnel (tube) and a vertical axial tunnel. The spreiten layers are thin laminae (2–3 mm transversely) furrowed by numerous curved lamellae, and the marginal tube has a diameter of about 5 mm. Lobes are round to J-shaped and have a range of lengths between 60 and 190 mm and widths between 50 and 170 mm. Lobes converge to apices well displayed on a few specimens (e.g., Fig. 5D). The Guadalupe Box *Zoophycos* are thus relatively simple, planar to subplanar forms with the laminae parallel to the bedding plane. The laminae are asymmetrically arranged in two lobes around a strongly curved central area.

Numerous ichnospecies of *Zoophycos* are in the literature, and a revision of the ichnogenus is needed (e.g., Zhang et al., 2015). Hence, we make no attempt at an ichnospecific identification of the Guadalupe Box *Zoophycos*.

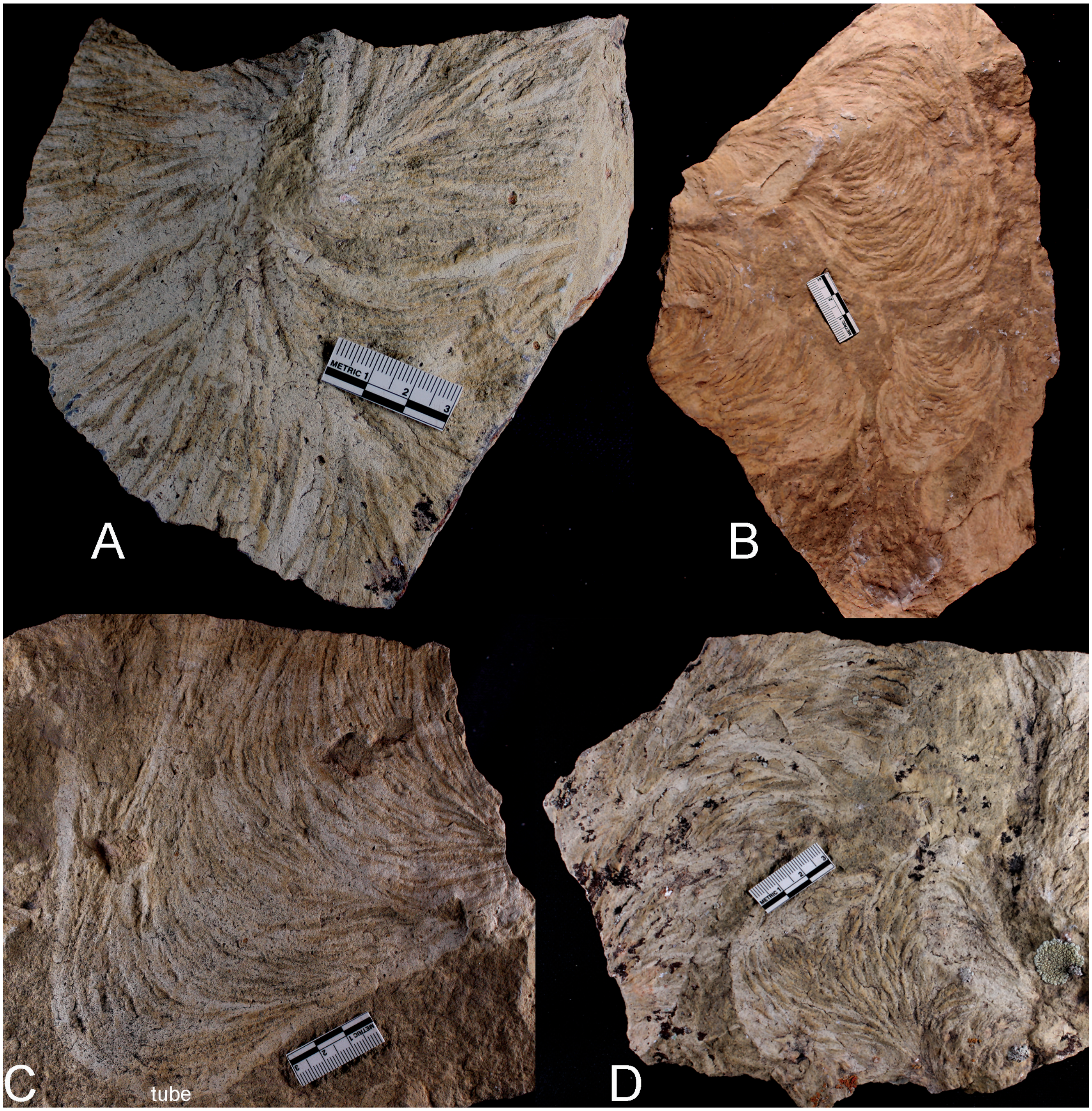

FIGURE 5. Selected specimens of *Zoophycos* from the Sandia Formation at Guadalupe Box, NMMNH locality 12619. (A) NMMNH P-84537, showing the axial tunnel. (B) P-84532, multiple medium-sized specimens. (C) P-84546, a J-shaped specimen with a well-preserved marginal tube. (D) P84545, multiple small specimens.

DISCUSSION

Zoophycos comprises a diverse group of spreiten structures known from both the fossil record and modern deep-sea sediment cores. It has a stratigraphic record extending from Cambrian to Recent (e.g., Miller, 1991; Ekdale, 1992), although Seilacher (2007, p. 108) considered pre-Ordovician occurrences to be questionable. *Zoophycos* is generally thought to be a deposit-feeding structure produced by worms or various worm-like animals (e.g., Osgood and Szmuc, 1972; Miller and Johnson, 1981; Löwemark et al., 2004; Olivero and Gaillard, 2007). There are, however, alternative ethological explanations for *Zoophycos* in an extensive literature (e.g., Bromley, 1991). Although *Zoophycos* is known from present day deep-sea cores, the trace producing animal has not been captured (Seilacher, 2007), and its exact identity remains elusive.

Zoophycos gives its name to an archetypal ichnofacies traditionally associated with deep, poorly-oxygenated sea bottoms (Seilacher, 1967), although the paleoenvironments in which the namesake ichnotaxon occurs have shifted through time (Ekdale, 1988). Thus, *Zoophycos* commonly occurs in shallow-water facies during the Paleozoic, but it became primarily a deep-sea trace from the Mesozoic onward (e.g., Miller, 1991; Zhang et al., 2015). The conditions prevalent at the time of trace formation within the low-diversity *Zoophycos* ichnofacies were summarized by McIlroy (2008) as representing dysaerobic, mud-rich environments where the poor quality of food resources often required intensive, spreiten-producing feeding patterns, and sediments containing *Zoophycos* are commonly completely bioturbated (Bromley, 1990). *Zoophycos* is known from different depositional environments ranging from the shelf (sublittoral) to the deep sea (bathyal), so it is present in different lithofacies.

The Guadalupe Box *Zoophycos* bed was clearly deposited in a shallow marine setting, as are most other Paleozoic records of the ichnogenus. Given that these Paleozoic records are not in deep marine, dysaerobic, or anaerobic deposits, the use of the *Zoophycos* ichnofacies for Paleozoic records of the ichnogenus has been questioned (Miller, 1991). We also question this. If the *Zoophycos* ichnofacies is to be a useful concept, identifying deep-marine, low-oxygen sea bottoms, its use should be restricted to the Mesozoic-Cenozoic.

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Looking northwestward up the valley of the Guadalupe River above Guadalupe Box. The drab, tan beds in the foreground to the right are Middle Pennsylvanian Sandia Formation. The thick, greenish slope beyond is Middle-Upper Pennsylvanian Guadalupe Box Formation. The mesa is capped by Pleistocene Bandelier Tuff. *Photo by Spencer G. Lucas*