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Ichnology of the Lower Cretaceous (Albian) Mesilla Valley Formation, Cerro de Cristo Rey, southeastern New Mexico, USA

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Abstract

Invertebrate trace fossils from the Albian Mesilla Valley Formation (Washita Group) at Cerro de Cristo Rey, Sunland Park, NM represent the following ichnotaxa: *Ancorichnus* isp., *Arenicolites* isp., *Bergueria* isp., *Bichordites* sp., *Cardioichnus foradadensis*, *C. biloba*, *Chondrites intricatus*, *Cochlichnus anguineus*, *Coprulus oblongus*, *Gordia marina*, *Helicodromites* isp., *Lockeia* isp., *Ophiomorpha nodosa*, *Palaeophycus tubularis*, *P. striatus*, *P. heberti*, *Planolites* isp., *Protovirgularia dichotoma*, *Rhizocorallium commune* var. *irregulare* (with *Coprulus oblongus*), *Skolithos* isp., *Spongiomorpha* isp., *S. sublumbricoides*, *S. oraviense*, *Taenidium* isp., *Thalassinoides* isp., *T. paradoxicus*, *Treptichnus* isp., a chimney structure (*Chomatichnus*?), and the biofilm *Rugalichnus* (“*Kinneyia*”). This is the first study of the invertebrate ichnology of any of the shallow marine units at Cerro de Cristo Rey. The Mesilla Valley Formation contains a medium/high diversity ichnoassemblage, including fugichnia (i.e., *Skolithos*), fodichnia (i.e., *Chondrites*), domichnia (i.e., *Ophiomorpha*, *Thalassinoides*), repichnia (*Protovirgularia*), paschichnia (i.e., *Palaeophycus*), and cubichnia (i.e., *Bergueria*, *Cardioichnus*, *Lockeia*), as well as compound traces and composite traces. This ichnoassemblage was preserved in tempestites (storm deposits) from below wave base on the upper/middle continental shelf during Oceanic Anoxic Event 1d and contains ichnotaxa representative of the proximal *Cruziana* ichnofacies (with *Skolithos* influence).

Introduction

The Lower Cretaceous Mesilla Valley Formation has been described from several localities in southern New Mexico and far West Texas (Strain, 1976; Lucas et al., 1998, 2010a). The best exposures of this unit in the region are found on the flanks of Cerro de Cristo Rey, located at Sunland Park, Doña Ana County, New Mexico (Fig. 1A). Cerro de Cristo Rey is a prominent peak straddling the international border between Sunland Park, New Mexico, USA, and Juarez, Chihuahua, Mexico. Historically, this mountain was called Cerro de Muleros, but was renamed in honor of a 29 ft (8.8m) tall limestone statue of a crucifix constructed by Urbici Soler in 1939. It is also called “Sierra de Cristo Rey” and “Mount Cristo Rey” (Hook, 2008; Lucas et al., 2010a), both of which are misnomers because the hill is only 820 ft (250 m) above the surrounding pass to the north. It is a culturally and geologically important monument that sits on the Camino Real de Tierra Adentro National Historic Trail. Geologically, this hill is a trachy andesite dome, and, on its northeastern flanks, approximately 350 m of Cretaceous strata have been

exposed by uplift and erosion (Lovejoy, 1976). These strata represent the top of the Fredricksburg Group, and the entire Washita Group, with the Cenomanian Mancos Formation at the top (Fig. 1D). This sedimentary section represents the overall complex history of transgression and regression of the Cretaceous Interior Seaway during the late Albian and early Cenomanian, across the Early-Late Cretaceous boundary (Lucas et al., 2010a).

Part of the upper Albian succession is the Mesilla Valley Formation, a 65 m thick, dark gray to olive-colored, finely laminated marine shale with intercalated thin, calcareous and fossiliferous siltstone lenses, each ranging from 5 to 60 cm thick. In their revision of the stratigraphy of this unit, Lucas et al. (2010a) described the thinly-bedded siltstones as bioturbated storm deposits. They inferred that these strata represent quiet deposition on the outer continental shelf, with what appear to be sporadic interruptions by storm deposits (“tempestites”).

This unit was first described by Böse (1910) as “subdivision 6,” and he measured it at 20 m thickness, which was corrected to 64 m by Strain (1976), a thickness confirmed by Lucas et al. (2010a). Strain (1976) formally named this unit the “Mesilla Valley Shale” and divided it into two members. Lucas et al. (2010a) clarified and revised the biostratigraphy of this unit and divided it into three informal members, “A”, “B”, and “C” (Fig. 1B). The lowest member (member A) is a 13.7 m thick, gray shale with thin, sandy siltstone lenses (Lucas et al., 2010a). The middle member, which is 14.4 m thick, starts with a ledge-forming bioclastic packstone with abundant shells of the bivalve *Texigryphaea*. This olive-colored shale also has thin sandstone beds and three thick, ripple-laminated sandstone-siltstone intervals, each about 0.4 m thick (Lucas et al., 2010a). The upper member is a black shale, 36.5 m thick, and, as shown by Lucas et al. (2010a), grades up into the overlying Sarten Member of the Mojado Formation (“Anapra Sandstone” of Strain, 1976).

The depositional environment of the Mesilla Valley Formation was interpreted by Lucas et al. (2010a) as an outer continental shelf, below wave base. Shales were interpreted to have been deposited under quiet conditions, which were periodically interrupted by storm events (Kappus, 2016). The formation was deposited during Washita Group cycle #4 (WA4) of the late Albian during Cretaceous flooding of part of western North America (Scott et al., 2003), and records oceanic anoxic event (OAE) 1d (Scott et al., 2013), which has been dated at 100.6-100.2 Ma (Nuñez-Useche et al., 2014). The Mesilla Valley Formation has been loosely correlated using biostratigraphic data with the Weno and Pawpaw formations of the Washita Group of central Texas (LeMone, 1969; Scott et al., 2003; Lucas et al., 2010a).

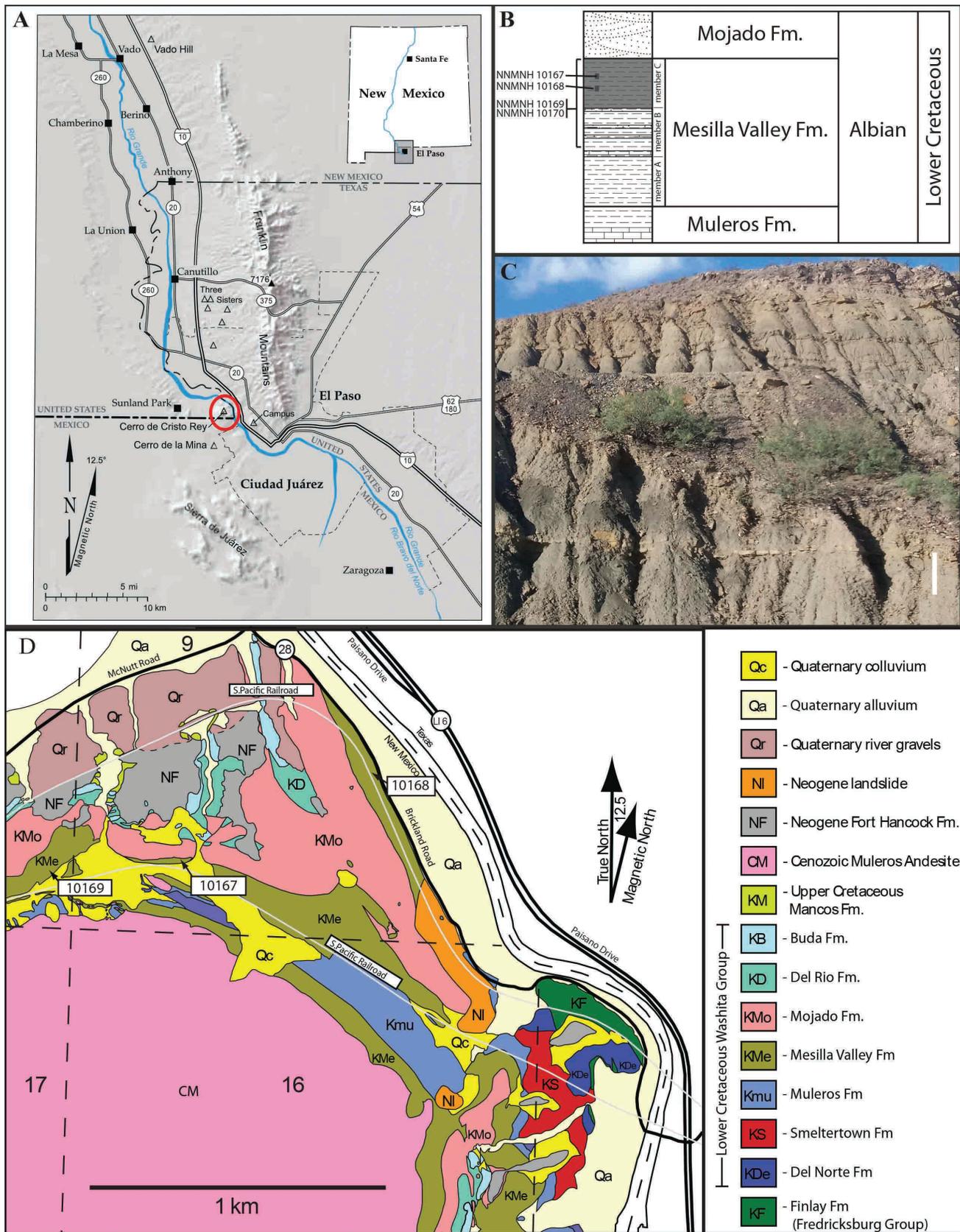


Figure 1A–D. A) Regional map showing location of the study area on the international border in southeastern New Mexico; B) General stratigraphy of the Mesilla Valley Formation, showing extent of collections from NMMNH localities 10167 and 10170 and stratigraphic position of localities 10167 and 10168; C) Outcrop photo looking west at member C of the Mesilla Valley Formation at NMMNH locality 10168. Scale bar is 1 meter; D) Generalized geologic map (from Lovejoy, 1976) of the north side of Cerro de Cristo Rey showing locations of NMMNH localities 10167, 10168, and 10169. Locality 10170 is 0.8 km west of the map area.

Invertebrate fossils of the Mesilla Valley Formation were first described by Böse (1910), who noted the presence of the oyster “*Ostrea quadriplicata* (renamed *Peilinia quadriplicata* by Kues, 1997) and a prolific assemblage of marine invertebrates, most notably the bivalve *Texigryphaea* sp. and the foraminiferan *Cribratina texana*, which are both common in the lower and middle member of this unit. Other fossils reported include echinoids (e. g., *Heteraster*), bivalves (e.g., *Neithea*), gastropods, ammonoids, brachiopods, dinoflagellates, serpulid worms, corals, algae, and terrestrial plant fragments (Böse, 1910; Strain, 1976; Cornell, 1982; Kues, 1989, 1997; Turnšek et al., 2003; Lucas et al., 2010a; Sealey et al., 2018).

Invertebrate trace fossils from the Mesilla Valley Formation were briefly mentioned by Lucas et al. (2010a) and have since been found in all styles of preservation in calcareous sandy-siltstone lenses in finely laminated shale. These trace fossils include the first records of invertebrate ichnogenera from the Washita Group of southern New Mexico, representing the *Cruziana* ichnofacies (Seilacher, 1967; Buatois and Mángano, 2011). Here, we document these trace fossils and interpret their paleoecological significance. In this paper, NMMNH refers to the New Mexico Museum of Natural History and Science, Albuquerque, NM, where all samples collected are housed. Locality numbers are NMMNH localities, where detailed locality data are on file and available to qualified investigators.

Provenance

Trace fossils documented here were collected over eight years at NMMNH localities 10167, 10168, 10169, and 10170, all located on the northern slopes of Cerro de Cristo Rey, southern Doña Ana County, NM (Fig. 1D, except locality 10170, which is 0.8 km west of the map area). Generalized stratigraphy of the Mesilla Valley Formation and the stratigraphic positions of 10169 and 10170, 10167 and 10168 are shown in Figure 1B. Trace fossils were revealed during the weathering of thinly bedded, calcareous sandstones/siltstones and bioclastic packstones. The Mesilla Valley Formation encompasses two ammonoid zones, the *Mortoniceras wintoni* and overlying *Drakeoceras drakei* (Lucas et al., 1998; Lucas et al., 2010a; Sealey et al., 2018), and is late Albian in age (Scott et al., 2013).

NMMNH locality 10167 is in beds steeply dipping to the north, stratigraphically below the type section of the “Anapra sandstone” (=Mojado Formation) of Strain (1976), which was re-measured by Lucas et al. (2010a, fig. 11). Several ichnofossil-bearing beds are found in member C at this location. One bed containing trace fossils was located and excavated, consisting of a bioclastic packstone with abundant bivalve bioclasts, including gryphaeids such as *Texigryphaea* sp. and other bivalves like *Neithea* sp. Trace fossils include *Cardioichnus* isp. and *Bichordites* isp. (Kappus and Lucas, 2019). Locally, this bed is red with gray fossils; it lies approximately 12 m below the Mesilla Valley/Mojado contact, which we place at the base of the first sandstone of typical Mojado lithology (Lucas et al., 2010a). Also, at this locality there is a small pile of bulldozed sandstone slabs from member B of the Mesilla Valley Formation (Lucas et al., 2010a). After several

decades of weathering, these slabs reveal details of ichnotaxa that were originally covered by shale.

NMMNH locality 10168 is preserved in beds of member C gently dipping west, stratigraphically below the Powerline Ridge dinosaur tracksite (Kappus et al., 2011). This locality is in a railroad cut and road cut on the western side of Brickland Road, at the same field location studied by Scott et al. (2013). Figure 1C (from NMMNH locality 10168) shows a view of the Mesilla Valley Formation at this locality. Ichnofossils are preserved in ripple-sculpted, planar and hummocky cross-stratified sandy siltstones at two stratigraphic levels. The first bed is ~12 m below the upper contact of the Mesilla Valley Formation. The second is ripple laminated, fractured, and has Liesegang banding. It is ~2 m below the upper contact of the Mesilla Valley Formation.

NMMNH locality 10169 is also in beds gently dipping west and includes members B and C of the Mesilla Valley Formation. Slabs of bioclastic sandy siltstone with hummocky cross-bedding and planar laminations were collected on this hillside, as they contain abundant invertebrate trace fossils revealed by long-term weathering, especially after shale weathers off the hypichnia/epichnia.

NMMNH locality 10170 is an arroyo and patio located at Ardivino’s Desert Crossing Restaurant and banquet facilities. The patio was laid by the senior author with sandstone slabs from members B and C of the Mesilla Valley Formation, collected from the arroyo on the property. Most of these slabs could not be removed, but were useful for identifying and photographing ichnotaxa.

Systematic Ichnology

Traces are described in alphabetical order, with *Problematica* at the end. Terminology for describing the morphology of individual traces mostly follows the recommendations of Basan (1978) and Gingras et al. (2009). Preliminary description of ichnoassemblages follows Taylor and Goldring (1993). See Appendix 1 for a glossary of descriptive/interpretive terms.

Ichnogenus *Ancorichnus* Heinberg, 1974

Ancorichnus isp.

Fig. 2A.

Referred specimen: NMMNH P-71998 from locality 10169 (Members B & C, Fig. 1).

Description: Small, horizontal, meandering, meniscate-filled tubular burrow with a thin mantle preserved in convex hyporelief. Each meniscus is a lined packet, which joins to others to make up the wall structure. The burrow is 1–1.5 mm wide, and 125 mm long, with small, tabular (uncurved) meniscae that are 0.5–0.8 mm thick, with a lining of similar thickness. Overall, the trace has a meandering pattern, and the distances between arcs in the meander are ~20 mm.

Remarks: Only one specimen of *Ancorichnus* was observed in this study. This burrow meanders (Dam, 1990) and externally resembles *Cochlichnus* isp., which has also been observed in this study (Figs. 3C, D, F, 5B, 6D, 8C, 8E), but the specimen assigned to *Ancorichnus* has meniscate backfill and a structured mantle (see Keighley and Pickerill, 1994). Frey et al. (1984) state that *Ancorichnus coronus*

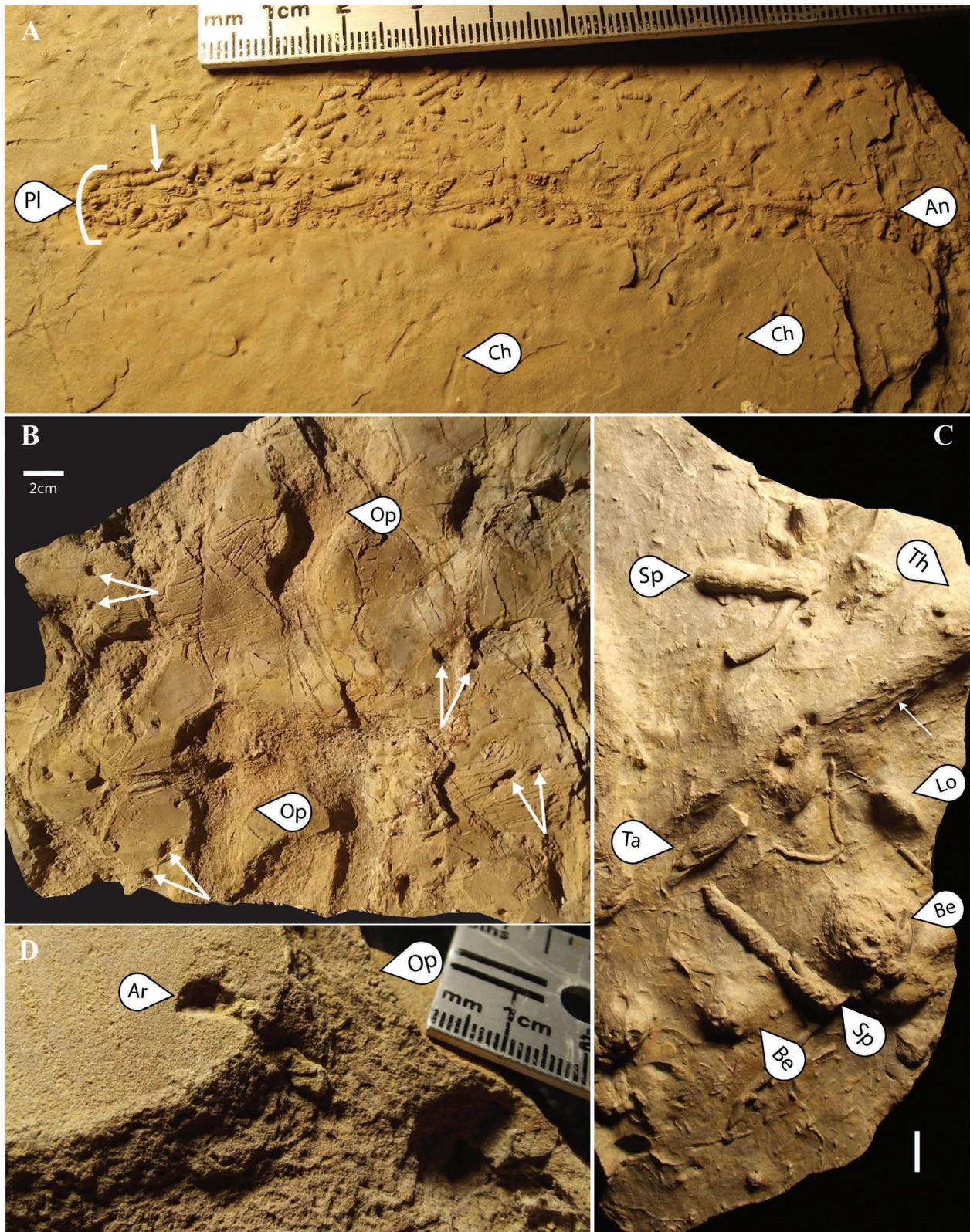


Figure 2A–D. A) Epichnial view showing *Ancorichmus* isp. (An) reworking *Planolites* isp. (Pl) with bioclastic fill of *Cribratina texana* (arrow denotes one specimen), as well as *Chondrites intricatus* (Ch). This sample (NMMNH P-71998) is a representative of the *Thalassinoides/Planolites-Chondrites* ichnoassemblage (#6) of this study; B) Field photo (epichnial view) showing the *Arenicolites* ichnocoenose of the *Skolithos* ichnofacies (ichnoassemblage #3 of this study; arrows = *Arenicolites* isp.; Op = *Ophiomorpha nodosa*), sample NMMNH P-72005 from NMMNH locality 10170; C) Hypichnial overview showing three specimens of *Bergaueria* isp. (Be), *Spongiomorpha* isp. (Sp), *Palaeophycus tubularis* (small and medium morphotypes), *Taenidium* isp. (Ta), *Thalassinoides* isp. (Th; arrow indicates passive fill) and *Lockeia* isp. (Lo). This sample (NMMNH P-71992) represents the *Palaeophycus-Spongiomorpha* ichnoassemblage (#5) of this study. Scale bar is 1cm; D) Close-up showing the bottom of a specimen of *Arenicolites* isp. (Ar) cross-cutting *Ophiomorpha nodosa* (Op, large morphotype), on sample NMMNH P-72005.

is only known from the type area, and we did not observe enough specimens to determine if these are *A. coronus* as described.

NMMNH P-71998 is an example of a composite trace, with *Ancorichnus* isp. reworking *Planolites* isp., which was filled with bioclastic debris, mainly consisting of the tests of the arenaceous uniserial foraminiferan *Cribratina texana*.

Ancorichnus isp. has been interpreted as the actively backfilled repichnia/domichnia of a deposit feeder (Frey and Howard, 1985b; Dam, 1990), with the concave side of the menisci indicating direction of movement (Frey et al., 1984). This trace has also been reported from the Upper Cretaceous of Utah (Frey and Howard, 1985b).

Ichnogenus *Arenicolites* Salter, 1857

Arenicolites isp. (aff. *A. sparsus* Salter, 1857)

Figs. 2B, 2D, 6D.

Referred specimens: NMMNH P-71984, P-71986, and P-72005; more than 10 specimens observed in the field at locality 10170 (Members B & C, Fig. 1).

Description: Epichnial/endichnial, vertical, U-shaped burrows with no spreiten. The limbs are vertical, closely spaced, circular to sub-circular in cross section, and are parallel to each other. Diameter of the limbs and width of the trace do not appear to change with depth. Burrow fills are a slightly different lithology than the host rock. Two size groups of *Arenicolites* isp. were identified in this study. The first group has a limb diameter of 5–6 mm and overall trace width of 20 mm; the second group has a limb diameter of 9 mm and an overall trace width of 46 mm, with two specimens reaching depths of up to 90 mm.

Remarks: These traces resemble “*Arenicolites carbonarius*” illustrated by Rajkonwar et al. (2013), but differ from the original description of *A. carbonarius* by Binney (1852). A more likely ichnospecific assignment may be *A. sparsus* Salter, 1857, based on their vertical limbs, simple morphology and lack of a thick lining (Rindsberg and Kopaska-Merkel, 2005). More specimens preserved in full relief are needed for a confident ichnospecific designation.

Arenicolites isp. has been interpreted as domichnia (Chamberlain, 1977; Fillion and Pickerill, 1990; Rindsberg and Kopaska-Merkel, 2005; Gingras et al., 2009) as well as fixichnia (Bromley and Asgaard, 1979; Fillion and Pickerill, 1990) and is typical of shallow-marine settings (Chamberlain, 1978; Rajkonwar et al., 2013; Buatois and Mángano, 2011). The most likely tracemaker is an annelid worm (Binney, 1852) such as a polychaete (Desai, 2012), although it is likely there are multiple tracemakers for this ichnogenus, including insects (Rindsberg and Kopaska-Merkel, 2005).

In the Mesilla Valley Formation, most of these traces are found associated with *Ophiomorpha* (large morphotype), *Skolithos*, *Protovirgularia*, and *Palaeophycus tubularis*. A piece of NMMNH P-72005 was sliced and stained to reveal internal structures, and this partially revealed one of these burrows. Horizontal laminae are interrupted, and the fill resembles host-rock, although it is not laminated and is sandier.

This ichnogenus has been reported from Cambrian to Recent and has been described from the Upper Cretaceous of Utah (Chamberlain, 1978; Howard and Frey, 1984; Frey and Howard, 1985a).

Ichnogenus *Bergaueria* Prantl, 1946

Bergaueria isp.

Figs. 2C, 5B.

Referred specimens: NMMNH P-71992, from locality 10169 (Members B & C, Fig. 1).

Description: Plug-shaped or conical protuberances preserved in convex hyporelief, with a height equal to or less than the diameter (see Alpert, 1973). Diameters range from 8 to 20 mm (Fig. 2C). Surfaces of the traces can be smooth or have an apical depression (Fig. 2C). The transverse section is mostly circular, and some specimens have a transverse constriction at the base.

Remarks: At least three specimens observed in the field resemble *Bergaueria* aff. *B. hemisphaerica* illustrated by Mángano et al. (2005) and Uchman (1998), but are larger than those they reported. Other specimens of *Bergaueria* isp. (i.e., NMMNH P-71992) have a central concavity at the bottom end of the trace, which *B. hemisphaerica* lacks (Mángano et al., 2005). *Bergaueria* isp. is almost always associated with *Lockeia* isp. in the Mesilla Valley Formation. We await collection of more specimens before we assign these samples to ichnospecies.

Crimes (1970) included *Bergaueria* as a representative member of the *Cruziana* or *Skolithos* ichnofacies (also see Buatois and Mángano, 2011). This trace most likely represents the domichnia/cubichnia of an anemone (Pemberton et al., 1988; Uchman, 1998; Mángano et al., 2005; Pfister and Keller, 2010; Lima and Netto, 2012), and is found in diverse settings from the late Precambrian to Recent (Uchman, 1998). *Bergaueria* isp. plugs have been found in mine tailings on the northern side of Cerro de Cristo Rey, having been replaced by hematite.

Ichnogenus *Bichordites* Plaziat and Mahmoudi, 1988

Bichordites isp.

Fig. 3E.

Referred specimen: NMMNH P-71976 from locality 10167 (Member C, Fig. 1).

Description: Simple, horizontal, twisting, and meandering burrows of variable width (10–30 mm) and length, preserved in convex epirelief. Several specimens show a clear, single drain tube 1–2 mm in diameter. Four specimens observed are compound fossils with *Cardioichnus biloba* Kappus and Lucas, 2019. Menseae were not observed in any of these specimens.

Remarks: We assign these burrows to the ichnogenus *Bichordites* because of their strong association with *Cardioichnus* isp. and the presence of at least one drain or sanitary tube (Nichols, 1959; Bromley and Asgaard, 1975; Uchman, 1995; Bernardi et al., 2010). This is in spite of a lack of menseae visible in the specimens (Kappus and Lucas, 2019). Two of these burrows have walls that were breached by the drain tube, possibly due to difficulty maneuvering through the gravel-sized clasts in the packstone. Also note that Uchman (1995) revised the classification, nomenclature, and spatial interpretation of echinoid burrows and included *Taphrhelminthopsis*, *Subphyllochorda*, *Taphrhelminthoidia* and *Laminites* in this ichnogenus. Uchman (1995) attributed these traces to burrowing echinoids.

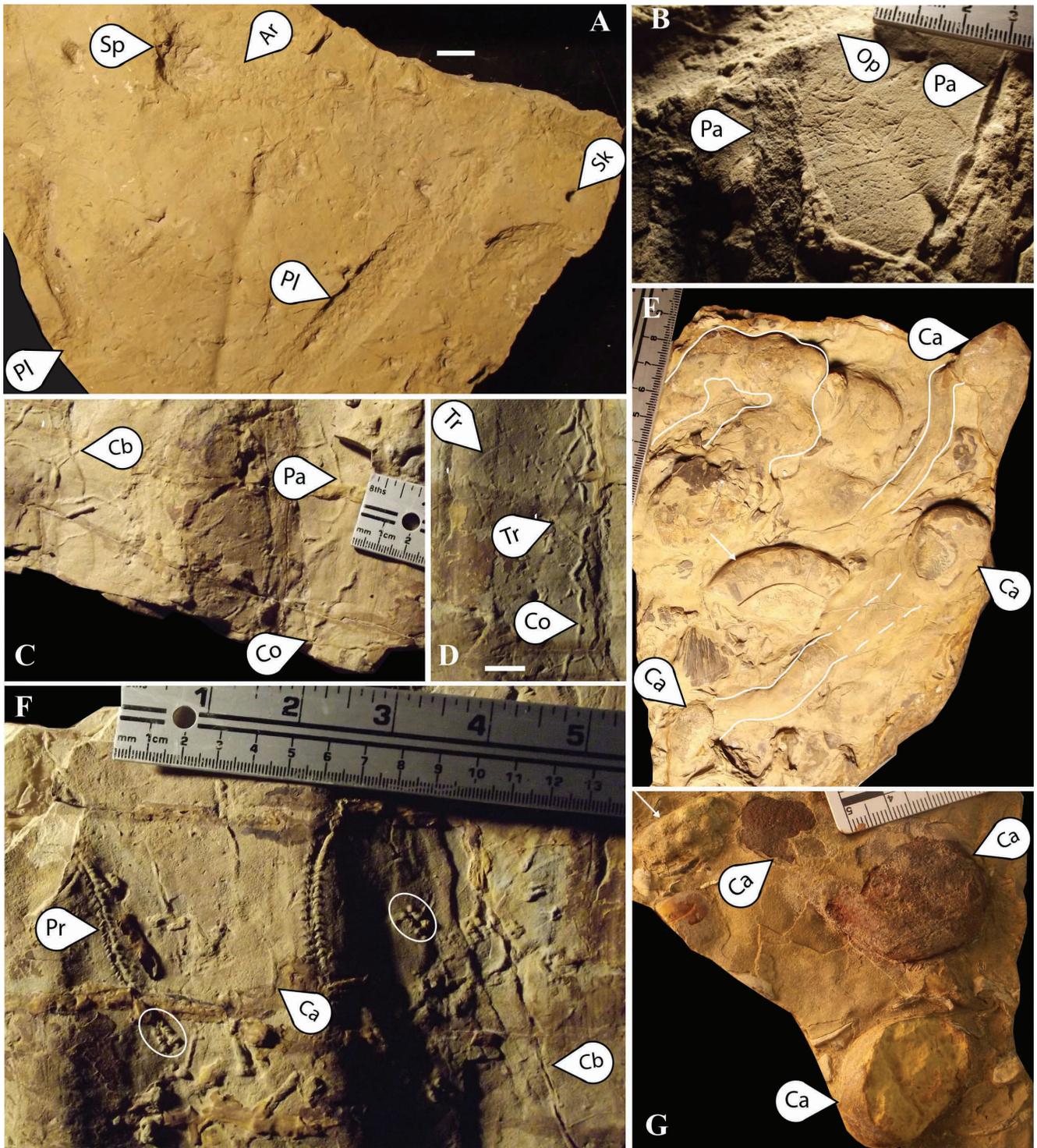


Figure 3A–G. A) Epichnial view showing *Chondrites intricatus* reworking two different specimens of *Planolites* isp. (Pl), *Skolithos* (Sk), and a possible arthropod trackway (Ar) as a compound trace with a *Spongiomorpha* isp. burrow (Sp). Sample P-71990. Scale bar is 1cm; B) Epichnial closeup showing a cluster of *Chondrites intricatus* (at center), together with *Palaeophycus tubularis* (Pa, large morphotype) and *Ophiomorpha* (Op) (medium morphotype). Sample NMMNH P-71988. A) and B) belong to the *Thalassanoides/Planolites-Chondrites* ichnoassemblage (#6) of this study; C) Epichnial view of convex *Cochlichnus anguineus* morphotype A (Co) on NMMNH P-71986, showing what appears to be a sharp, angular turn in the trace, *C. anguineus* morphotype B (Cb) and *Palaeophycus tubularis* (Pa, small morphotype; possibly *Gordia* sp?); D) Epichnial view showing a compound fossil of convex *Cochlichnus anguineus* morphotype A (Co) grading into *Treptichnus* isp., together with a convex specimen and two concave specimens of *Treptichnus* isp. (Tr) on sample NMMNH P-71986. Scale bar is 1cm; E) Epichnial view showing the holotype and paratypes of *Cardioichnus biloba* (Kappus and Lucas, 2019) on sample NMMNH P-71976. Three specimens (Ca) are compound traces with *Bichordites* isp. (outlined). Arrow indicates ammonoid fragment; F) Epichnial view showing concave *Cochlichnus anguineus* morphotype A (Ca) and convex morphotype B (Cb), together with two specimens of *Protovirgularia* isp. (Pr), and two *Problematica* (circled), one associated with *Protovirgularia* isp. on sample NMMNH P-71986; G) Photo of uncollected sample showing several specimens of *Cardioichnus foradadensis* (Ca). Arrow indicates ammonoid fragment (cast of possible mortonicerid). E) and G) represent the *Cardioichnus* ichnoassemblage (#7) of this study.

Ichnogenus *Cardioichnus* Smith and Crimes, 1983

Cardioichnus biloba Kappus and Lucas, 2019

Fig. 3E.

Referred specimens: NMMNH P-71976 from locality 10167 (Member C, Fig. 1).

Description: Bilobate, heart-shaped cubichnia preserved in convex epirelief in a bioclastic packstone. Traces are 32 mm wide, with variable lengths. Three of the five traces in P-71976 are compound traces with *Bichordites* isp. burrows.

Remarks: Plaziat and Mahmoudi (1988) illustrated the named ichnospecies of this ichnogenus of echinoid resting traces, originally erected by Smith and Crimes (1983). Mayoral and Muñiz (2001) added the ichnospecies *C. reniformis*. The traces described here differ from other ichnospecies of *Cardioichnus* by having a bilobate terminus, preservation in convex epirelief in a bioclastic packstone, and a lack of a central protuberance or groove on the ventral side. For these reasons, we proposed a new ichnospecies for these specimens, *C. biloba* (Kappus and Lucas, 2019). One of the meandering burrows found in NMMNH P-71976 resembles figure 4A in Gibert and Goldring (2008), with twists and turns and repeated posterior impressions. One of these posterior impressions is associated with a fecal blowout through the burrow wall.

Cardioichnus foradadensis Plaziat and Mahmoudi, 1988

Fig. 3G.

Referred specimens: Field photo of three specimens (Fig. 3G), five others observed at locality 10167 (Member C, Fig. 1), and, tentatively, NMMNH P-71977 (also from locality 10167).

Description: Ovate, smooth, elongated, slightly heart-shaped cubichnia preserved in convex epirelief in a bioclastic packstone. Traces are ~20 mm wide, with variable length depending on degree of exposure by weathering. The sediment directly surrounding the traces is fine grained relative to the bioclastic debris of the host stratum.

Remarks: These traces were first described by Plaziat and Mahmoudi (1988), are found in the same bed as the above mentioned *Cardioichnus biloba*, and are commonly replaced by hematite or limonite. So far, none of the *C. foradadensis* specimens have been associated with *Bichordites* isp. (possibly NMMNH P-71977 is). These traces have been reported from the Cretaceous to the Pleistocene (Plaziat and Mahmoudi, 1988).

Ichnogenus *Chondrites* von Sternberg, 1833

Chondrites intricatus Brongniart, 1828

Figs. 2A, 3A, 3B, 5C, 6B, 6C, 8F.

Referred specimens: NMMNH P-71988, P-71990, P-71994, P-71997, P-71998, and two uncollected specimens, all at locality 10170 (Members B & C, Fig. 1).

Description: Small, straight, flattened, dichotomously branching tunnels radiating from a central point, preserved in bed junctions in low-angle cross-strata (Simpson, 1956). Commonly these burrows occur in clusters. Burrow fill erodes more quickly than the matrix (e. g., NMMNH P-71983, P-71987, P-71988, P-71998) or is darker than the matrix (e.g., Fig. 6B, P-71994). Individual burrow segments are often found penetrating bedding plane surfaces, are 1–1.5 mm wide, up to

20 mm long (per segment), and branch at an angle less than 45 degrees.

Remarks: Although the ichnotaxonomy of *Chondrites* has undergone significant revision (Fu, 1991; Uchman et al., 2012), the resemblance of these traces to *C. intricatus* (Simpson, 1956; El-Hedeny et al., 2012; Uchman et al., 2012) is sufficient to warrant ichnospecific designation of the Mesilla Valley specimens.

Chondrites is an ichnogenus found in many different paleoenvironments (Chamberlain, 1978), and has been attributed to several different tracemakers, such as annelids, sipunculoid worms, chemosymbiotic bivalves, nematodes, crustaceans, sea pens (El-Hedeny et al., 2012), and asymbiotic bivalves (Baucon et al., 2019). Simpson (1956) showed that the final form of this trace was preserved as the animal withdrew from a side branch and continued retreating toward the surface, putting to rest the dispute about whether or not this was a root trace. For a full review of the ethology of this trace see Baucon et al. (2019).

This ichnogenus can be an indicator of anoxic/dysoxic conditions (Bromley and Ekdale, 1984; Ekdale and Mason, 1988; Martin, 2004; Baucon et al., 2019), and this coincides with the documentation of Oceanic Anoxic Event 1d (OAE 1d) in the Mesilla Valley Formation (Scott et al., 2013). *Chondrites* isp. has also been reported from the Washita Group of central Texas (Scott et al., 2003), the Upper Cretaceous of Utah (Howard and Frey, 1984; Frey and Howard, 1985a), and the Albian of Alberta, Canada (Male, 1992).

Ichnogenus *Cochlichnus* Hitchcock, 1858

Cochlichnus anguineus Hitchcock, 1858

Figs. 3C, D, F, 5B, 6D, 8C, 8E.

Referred specimens: NMMNH P-71984, P-71986, P-71995, P-71997, locality 10170 (Members B & C, Fig. 1).

Description: Simple, unlined, sinusoidal, unbranched, horizontal burrows preserved in convex epirelief. Burrow-fill appears to be the same as the host rock. Two morphotypes of this meandering trace have comparable burrow diameters (1.2 mm), but the distance between arcs differs. Morphotype A has a repeating wavelength of 8 mm and is found on each of the specimens collected, while morphotype B has a longer wavelength of 36 mm and is only seen on NMMNH P-71986 and one uncollected specimen (Fig. 3F & 5B).

Specimens are associated with *Protovirgularia* isp., *Treptichnus* isp., *Thalassinoides* isp., and *Palaeophycus* isp. One specimen found on NMMNH P-71986 is a compound trace with *Treptichnus* isp. (Fig. 3D) and brings into question the relationship between these two traces. Lucas et al. (2010b) also noted a transitional form of this ichnogenus, from sinuous to less sinuous along the burrow. This variation within one burrow relates the two morphotypes of this ichnogenus found in this study, as they differ only in the wavelength of the meander.

Remarks: These traces are assigned to *Cochlichnus anguineus* Hitchcock, 1858, which is the type ichnospecies of this ichnogenus. This is based on a lack of wall markings or annulations, which are present in the other two ichnospecies of *Cochlichnus*, *C. antarcticus* and *C. annulatus* (Buatois and Mángano, 1993; Buatois et al., 1997a). For detailed ichnotaxonomy of this ichnogenus, the reader is referred to Buatois et al. (1997a) and Uchman et al. (2009).

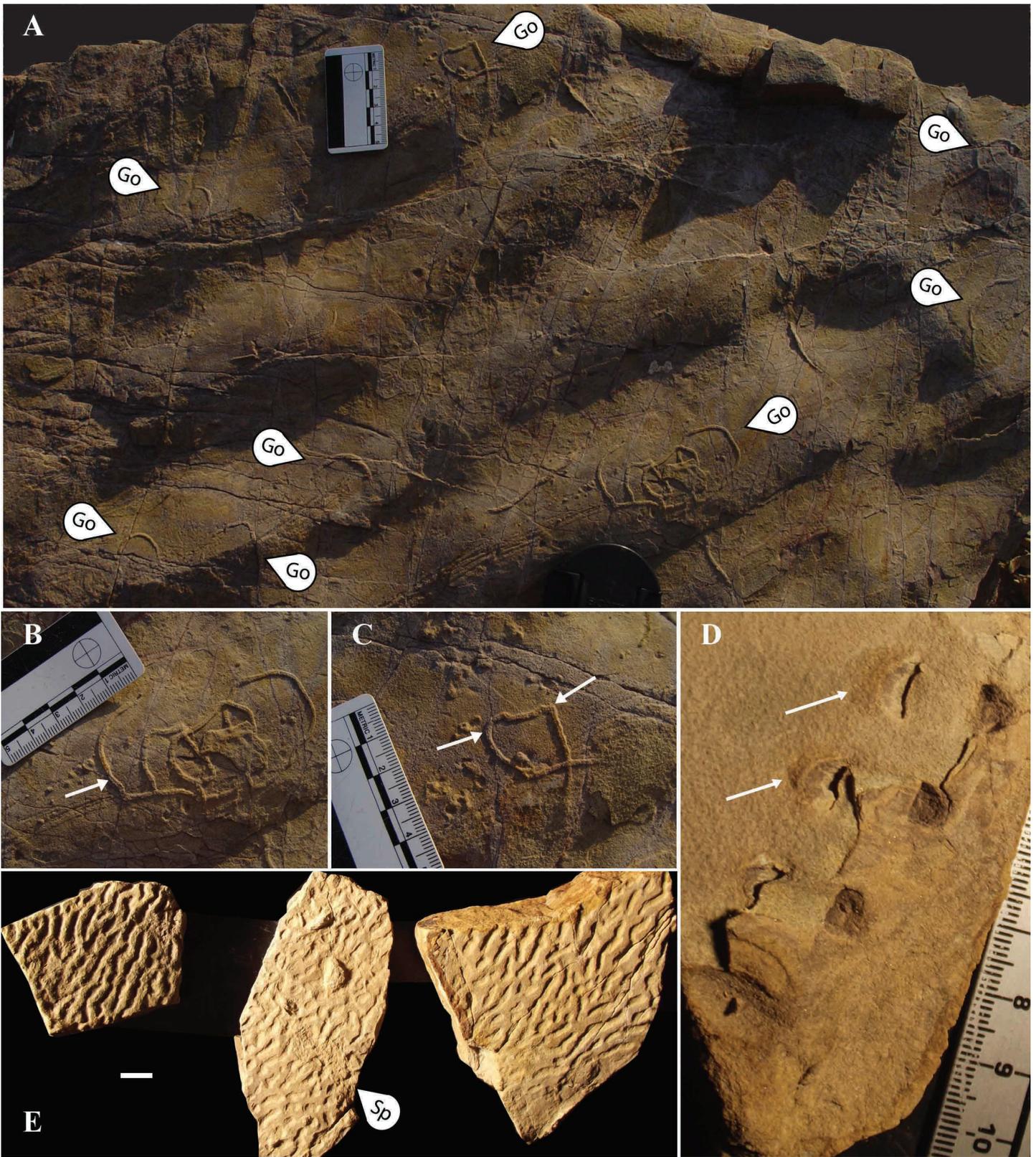


Figure 4A–E. A) Photo of uncollected, rippled sandstone slab with several epichnial specimens (8?) of *Gordia* isp. (Go); B) Close-up photo of epichnial *Gordia* isp. showing the axial furrow in the top of some segments of the burrow; C) Close-up photo of epichnial *Gordia* isp. with arrows showing a sharp turn and recurved burrow segments; D) Photo of endichnial *Helicodromites* isp. in a split piece of sandstone, sample NMMNH P-72001. Arrows point to semi-circular iron halos lateral to the semi-circular tunnel; E) Epichnial view of three samples of *Rugalichnus* (left to right, NMMNH P-71979, P-71980 and P-71978). Note the presence of *Spongeliomorpha sublumbricoides* (Sp) cross-cutting *Rugalichnus* on NMMNH P-71980. Scale bar is 1 cm.

In nonmarine settings this trace has been interpreted as feeding/grazing trails, possibly made by annelids, aquatic oligochaetes, nematodes, or insect larvae (Bordy et al., 2011). Sediment consistency had to be soft enough for the trackmaker to penetrate, yet firm enough to resist propulsion force (Elliot, 1985).

Cochlichnus anguineus has been described from the Cretaceous of England (Goldring et al., 2005), Spain (Rodríguez-Tovar and Uchman, 2008), and Korea (Kim et al., 2005). *Cochlichnus* ranges from the Ediacaran to Recent.

Ichnogenus *Gordia* Emmons, 1844

Gordia indianaensis Buatois et al., 1998

Fig. 4A, 4B, 4C.

Referred specimens: Seven specimens on an uncollected slab near the top of the Mesilla Valley Fm. (Member C, Fig. 1), at the site of the measured section depicted in Lucas et al. (2010a, fig.11).

Description: Smooth to bumpy, subcylindrical, unbranched, curving burrows that self-cross in a looping pattern. Some loop branches are at sharp angles instead of gently curving, and these angles are approximately 120 degrees. Sections of the burrow have a thin medial, shallow, discontinuous furrow that is not deep or continuous. Burrows are 2–3 mm wide and 1–2 mm in relief (convex epirelief) with a regular diameter. Burrows gently descend into the host bed at one or both ends. Burrows have the same fill as the host sediment.

Remarks: These traces were assigned to *Gordia indianaensis* because of the presence of sharp angles (Archer and Maples, 1984; Buatois et al., 1998). This trace was originally named *Haplotichnus indianaensis* Miller 1889, but was reassigned to *Gordia* by Buatois et al. (1998). Other accepted ichnospecies of *Gordia* are *G. marina* Emmons, 1844, *G. arcuata* Książkiewicz 1977, and *G. nodosa* Pickerill and Peel, 1991, and none of these display sharp, angled turns. All specimens of this trace were found on top of a rippled siltstone bed, and are almost all preserved on ripple crests. There are also other, unidentified traces on this surface (Fig. 4A).

Buatois et al. (1998) interpreted *Gordia indianaensis* as grazing trails (paschichnia) of surface-feeding creatures such as arthropods or nematodes. *Gordia* can be distinguished from similar traces, *Helminthopsis* and *Helminthoidichnites*, because it self-crosses, often multiple times (see Buatois and Mángano, 2003). *Gordia* is a facies-crossing trace with an age range from Early Cambrian (Crimes and Anderson, 1985) to Holocene (Ratcliffe and Fagerstrom, 1980, p. 625).

Ichnogenus *Helicodromites* Berger, 1957

Helicodromites isp.

Fig. 4D

Referred specimens: NMMNH P-72001, and two uncollected specimens, all from locality 10169 (Members B & C, Fig. 1).

Description: Simple, unlined, corkscrew-shaped burrows oriented horizontally and with a generally straight central axis, preserved only in full relief. These traces are preserved in sandy siltstones with hummocky crossbeds, and are revealed by the parting of laminae. Burrow-fill weathers more easily than the host rock, and the tunnel is semi-circular in cross section (Fig. 4D). A slight iron oxide halo is visible lateral to the tunnels. The burrow is 5 mm in diameter, with an

overall trace width of 18 mm. The distance between successive whorls is 16 mm.

Remarks: This trace is rare in the Mesilla Valley Formation and elsewhere (Poschmann, 2014). Due to a lack of specimens, we have not assigned these traces to an ichnospecies. *Helicodromites* isp. has been associated with *Cochlichnus* isp. (Moussa, 1968). This trace is interpreted as the feeding structure of a vermiform animal, is found in deep and shallow marine settings (Carmona et al., 2008), and ranges from Silurian to Recent (Poschmann, 2014).

Ichnogenus *Lockeia* James, 1879

Lockeia isp.

Figs. 2C, 5A, 5B.

Referred specimens: NMMNH P-71983 and P-71997 (terminal chambers), P-71992, and P-71995, from locality 10169 (Members B & C, Fig. 1).

Description: Convex, hypichnial, bilaterally symmetrical, almond-shaped cubichnia that stands out from the bedding plane. The exterior of the trace is smooth, and ends in a sharp termination. These traces vary in size and exposure, but the almond-shaped specimens are usually 8 mm wide and 15 mm long (e.g., Fig. 2C).

Remarks: Three ichnospecies have been described in this ichnogenus, *Lockeia siliquaria* James 1879, *L. serialis* Seilacher and Seilacher 1994, and *L. ornata* Mángano et al. 1998 (also see Paranjape et al., 2013). We did not observe enough specimens to justify ichnospecific designation of these traces. Some “terminal chambers” observed in this study (i.e., NMMNH P-71997) resemble bivalve traces, and are similar in shape to the bivalve *Protocardia* sp. observed/reported in these strata (Böse, 1910; Lucas et al., 2010a).

One specimen photographed in the field (Fig. 5B) resembles *Lockeia siliquaria* (Radley et al., 1998) and is a compound trace with a repichnia. This “locomotion trace” may be attributable to *Protovirgularia* (Ekdale and Bromley, 2001), which shows a wide variety of preservation styles (Carmona et al., 2008, 2010). However, without visible internal structures we hesitate to assign this locomotion trace to the ichnogenus *Protovirgularia* (Fernández et al., 2010). This locomotion trace and *Lockeia* were both reworked by *Cochlichnus* isp. in convex hyporelief (Fig. 5B). This trace also shows a preferred orientation parallel to current direction before sand deposition, as indicated by hypichnial flute casts and prod marks. This phenomenon was also reported by Masakazu (2003).

The name *Lockeia* is a senior synonym of *Pelecypodichnus* (Maples and West, 1989), and the ichnogenus ranges from Ordovician to Recent (Ekdale, 1988). *Lockeia* was reported from the Lower Cretaceous of England by Radley et al. (1998) and Goldring et al. (2005), and the Upper Cretaceous of Wyoming by Clark (2010).

Ichnogenus *Ophiomorpha* Lundgren, 1891

Ophiomorpha nodosa Lundgren, 1891

Figs. 2B, 2D, 5C, 5D.

Referred specimens: NMMNH P-71988 and P-72005 from locality 10169 (Members B & C, Fig. 1).

Description: Simple, cylindrical tunnels with knobby, pelted walls. Overall trace width ranges from 8 to 30 mm, and

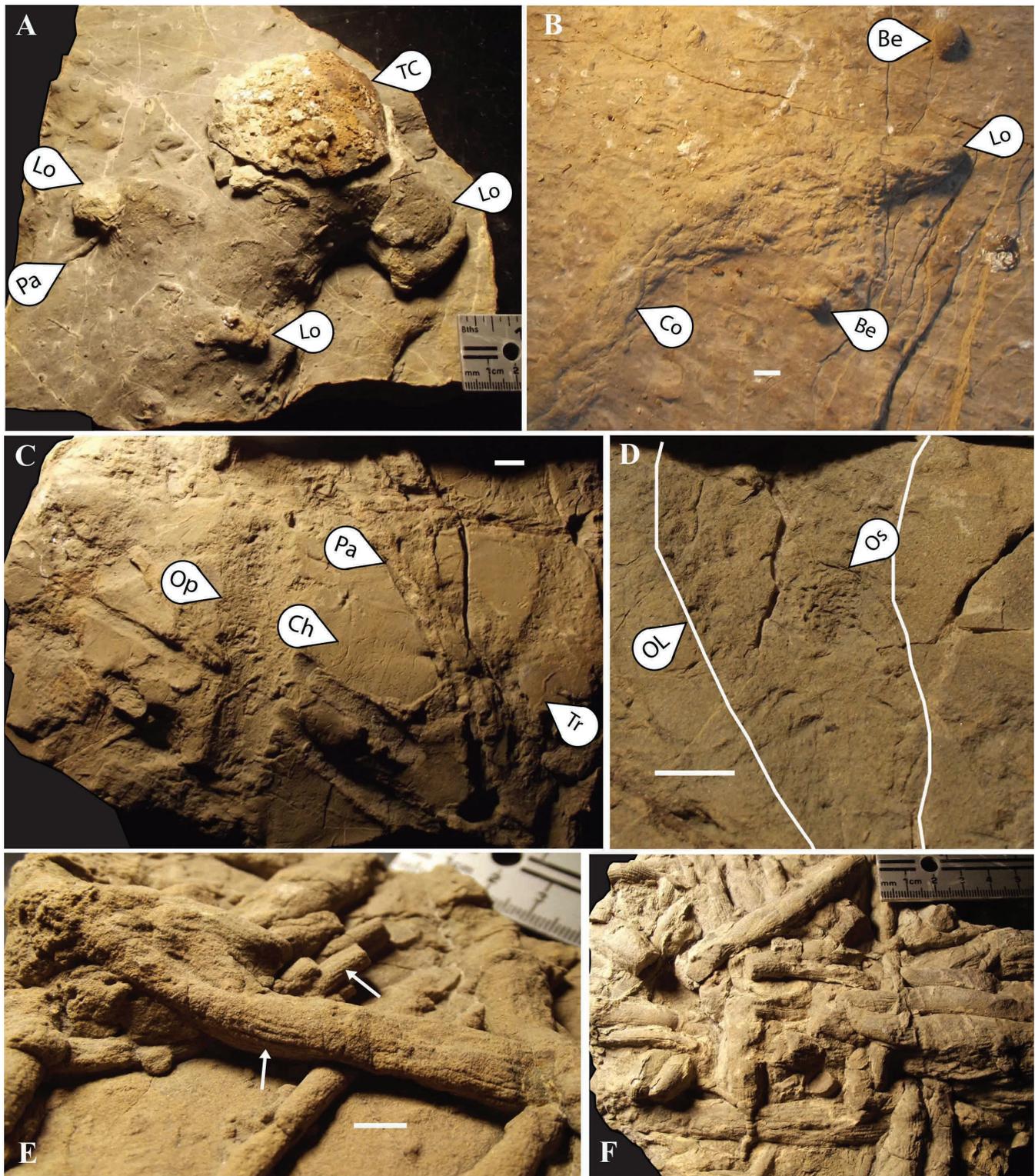


Figure 5A–F. A) Photo showing *Lockeia* sp. (Lo), together with *Palaeophycus tubularis* (Pa, medium morphotype) and a burrow we attribute to *Thalassinoides* isp. with mineralized terminal chamber (TC) on sample NMMNH P-71997. This sample represents the *Thalassinoides/Planolites-Chondrites* ichnoassemblage (#6) of this study; B) Field photo showing *Lockeia* isp. (Lo) as a compound trace with a burrow, both reworked by *Cochlichnus anguineus* (Co, morphotype B). This sample most likely represents the *Palaeophycus-Spongeliomorpha* ichnoassemblage (#5) of this study, because of the presence of a repichnia associated with *Lockeia* isp. and *Bergaueria* isp. (Be); C) Epichnial overview of NMMNH P-71988 showing concave *Ophiomorpha nodosa* (Op), *Chondrites* (Ch), endichnial *Palaeophycus tubularis* (Pa, large morphotype), and convex *Treptichnus* isp. (Tr); D) Photo showing concave, epichnial *O. nodosa* (Os), small morphotype) reworking *O. nodosa* large morphotype (OL) on sample P-71988. This sample belongs to the *Palaeophycus-Chondrites-Ophiomorpha* ichnoassemblage (#1) of this study; E) Close-up of NMMNH P-71993 showing a monospecific assemblage of *Palaeophycus striatus*. Arrows indicate striations; F) Overview of NMMNH P-72000 also showing a monospecific assemblage of *P. striatus*. These samples belong to the *Palaeophycus striatus* ichnoassemblage (#4) of this study. All scale bars are 1 cm.

lengths vary from 30 to 80 mm. Irregular polygonal pellets range in size from 1 to 2 mm and weather out of the walls. The larger specimens have more poorly preserved walls and pellet morphology. These larger traces commonly span the slab on which they are preserved (Fig. 2B).

Remarks: Three ichnospecies have been described from this ichnogenus, including *Ophiomorpha annulata* Książkiewicz 1977, *O. irregulaire* Frey, Howard & Pryor 1978, and *O. nodosa* Lundgren 1891. Based on the morphology of the pelleted walls, we assign these traces to *Ophiomorpha nodosa*. Two morphotypes of *O. nodosa* were identified in this study. Morphotype 1 is small and rare, and is found reworking another *Ophiomorpha* (i.e., Fig. 5D; NMMNH P-72005). Morphotype 2 is larger (25–30 mm wide) and is preserved in concave epirelief (Fig. 5C; NMMNH P-71988).

Ophiomorpha has been reported from the Lower Cretaceous Vectis Formation (Stewart et al., 1991), and its morphology overlaps with *Gyrolithes* and *Ardelia* (Frey et al., 1978; Bromley and Frey, 1974), but has been taxonomically differentiated from taxa such as *Thalassinoides* and *Spongiomorpha* (Fürsich, 1973; Yanin and Baraboshkin, 2013). *Ophiomorpha* is considered an indicator of shallow marine conditions (i.e., Pollard et al., 1993) until the mid-Cretaceous, when it also migrated to the deep-sea (Tchoumatchenco and Uchman, 2001). *Ophiomorpha* is also considered to be a member of the *Skolithos* ichnofacies (Buatois and Mángano, 2011) and is commonly associated with tempestites (Pemberton and MacEachern, 1997). This ichnospecies has also been reported from the Upper Cretaceous of Wyoming (Clark, 2010), Utah (Howard and Frey, 1984; Frey and Howard, 1985b), Texas (Henk et al., 2002), and New Mexico (Pillmore and Maberry, 1976; Lucas, 2019). The most likely tracemaker was a callianassid shrimp (Frey et al., 1978).

Ichnogenus *Palaeophycus* Hall, 1847

Palaeophycus tubularis Hall, 1847

Figs. 2C, 3B, 3C, 3F, 5A, 5C, 6A, 6F, 7A, 7B, 7C, 7D, 7E, 8E, 8F.

Referred specimens: NMMNH P-71981, P-71977, P-71983 (also another reworked by smaller size *P. tubularis*), P-71985, P-71986, P-71987, P-71991? (possibly collapsed), P-71992, P-71993, P-71996, P-71997 (both morphotypes also lining visible in one photo), P-71999, P-72000, P-72002, P-72003, P-72004 from localities 10167 and 10168 (Member C, Fig. 1), 10169 and 10170 (Members B & C, Fig. 1).

Description: Simple, predominantly unbranched, distinctly lined burrows that are cylindrical or elliptical in cross section. They are either inclined or horizontal, and the sediment fill of the burrow is the same as the host lithology. Three morphotypes have been identified in this study. The first is a small morphotype with a burrow diameter of 1–2 mm (i.e., NMMNH P-71997, Fig. 5A). The second is a medium-sized morphotype with burrow diameters of 4–6 mm (i.e., NMMNH P-71997, Fig. 5A). After weathering, it is difficult to see the burrow lining of these two morphotypes. The third morphotype is larger (~10 mm diameter) and has thicker walls, but not as thick as *Palaeophycus heberti* (compare *P. heberti* Fig. 2A, NMMNH P-71998 with specimen shown in Fig. 5C, NMMNH P-71988).

Remarks: Some specimens of the medium morphotype

are partially collapsed (i.e., NMMNH P-72004, Fig. 6F), probably due to incomplete filling by host sediment. The taxonomy of *Palaeophycus* has been well established and reviewed by Pemberton and Frey (1982), Fillion and Pickerill (1990), Keighley and Pickerill (1994) and Buckman (1995). This ubiquitous, facies-crossing ichnotaxon ranges from the Precambrian to Recent (Fillion and Pickerill, 1990). It is interpreted as a domichnia or fodichnia, possibly of predaceous polychaetes (Gingras et al., 1999).

Palaeophycus heberti Saporta, 1872

Fig. 6A.

Referred specimens: NMMNH P-71995, and two specimens observed in the field at locality 10169 (Members B & C, Fig. 1).

Description: Simple, isolated, inclined to vertical *Palaeophycus* with smooth walls and a very thick burrow lining. Burrow diameter is 8 mm, with a lumen that is 3 mm wide. The burrow lining makes up for at least half of the diameter of the trace (NMMNH P-71995, Fig. 6A). Wall filling is darker than the host rock, and the central tube appears to be the same lithology as the host rock.

Remarks: This burrow was only identified where it intersected the upper bedding plane. The burrow lining is darker than the host rock or burrow lumen, which is the opposite of the description by Frey and Howard (1985a). Only one size grouping of this trace was recognized. *Palaeophycus heberti* has been described from shallow and deep marine environments in the Upper Cretaceous of Utah (Howard and Frey, 1984; Frey and Howard, 1985b) and from the Lower Cretaceous of Bulgaria (Tchoumatchenco and Uchman, 2001).

Palaeophycus striatus Hall, 1852

Figs. 5E, 5F, 7A, 7C.

Referred specimens: NMMNH P-71992, P-71993, P-71995, P-71996, and many specimens observed in the field at localities 10169 and 10167 (Members B & C, Fig. 1).

Description: Hypichnial, horizontal or inclined, straight or slightly curved, longitudinally striated but unlined burrows with massive fill similar to the host rock. These traces are found isolated, but can also form dense, monospecific assemblages (i.e., Fig. 5F, NMMNH P-72000). Burrows are 8–12 mm wide, and individual striations are continuous, and generally 0.6–1 mm in width.

Remarks: *Palaeophycus striatus* is described and illustrated by Goldring et al. (2005) and Mángano et al. (2005) as well as by Paranjape et al. (2013). These authors show specimens in isolation and in monospecific assemblages. The Mesilla Valley specimens are isolated (Fig. 7A, NMMNH P-71995), in groups, or as monospecific assemblages (Fig. 5F, NMMNH P-72000), which is evidence of opportunistic behavior (Pemberton and MacEachern, 1997). Goldring et al. (2005) noted that some of these burrows superficially resemble the nonmarine trace *Scoyenia*, and we also noted this in one

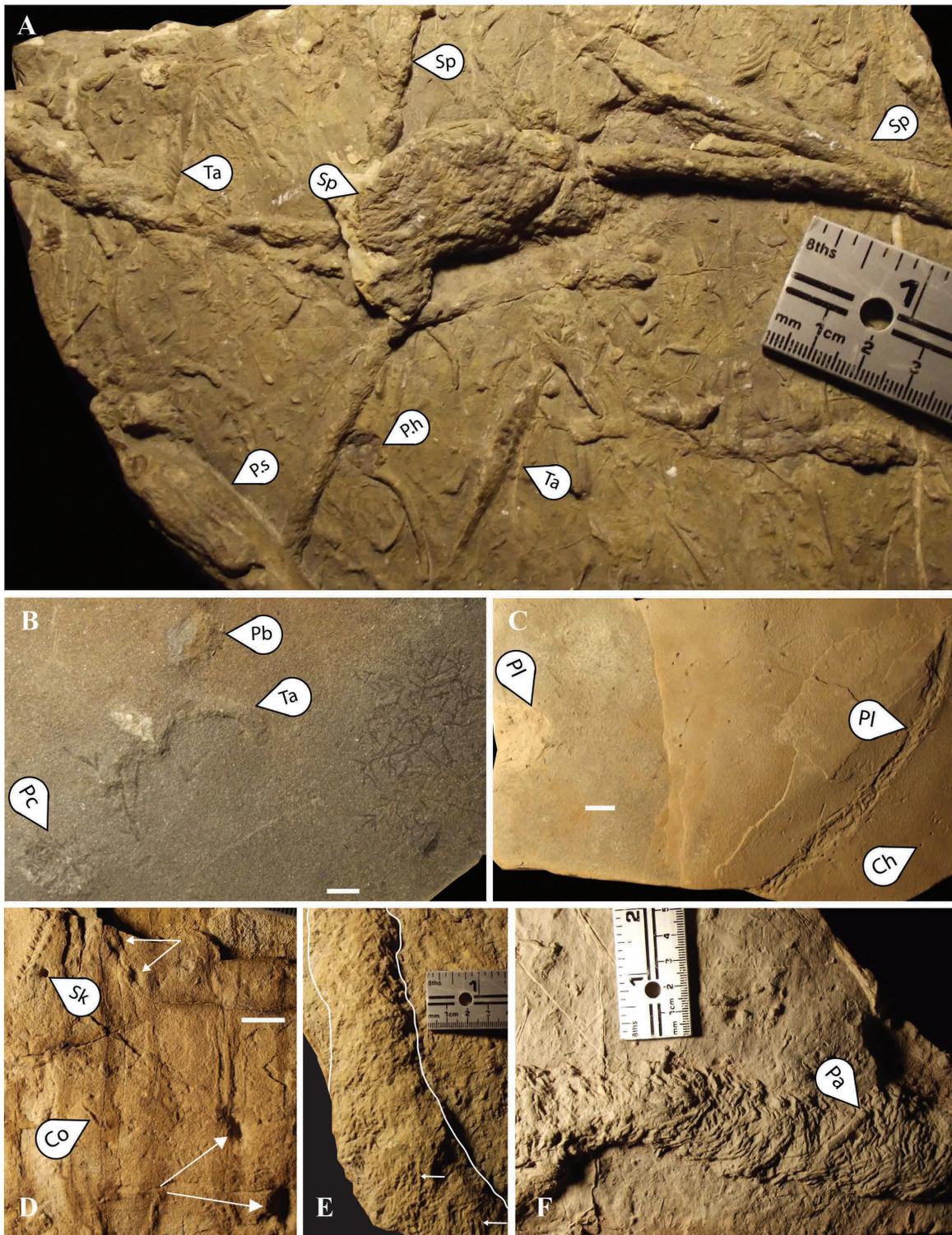


Figure 6A–F. A) Photo overview showing *Spongiomorpha* isp. (Sp), small *Palaeophycus tubularis*, *P. heberti* (Ph), *P. striatus* (Ps), and *Taenidium* isp. (Ta) on sample NMMNH P-71995. This sample belongs to the *Palaeophycus-Spongiomorpha* ichnoassemblage (#5) of this study; B) Hypichnial view showing endichnial traces *Taenidium* isp. (Ta), bedding plane *Chondrites intricatus* (fill darker than host rock), *Planolites* isp. with bioclastic fill (Pb), and *Chondrites intricatus* reworking a shaft of *Planolites* isp. (Pc) on sample NMMNH P-71994. This sample represents the *Thalassinoides/Planolites-Chondrites* ichnoassemblage (#6) of this study; C) Epichnial view of endichnial traces showing a tunnel (horizontal) and shaft (vertical) of *Planolites* isp. (Pl, note lighter color of burrow fill) being reworked by *Chondrites intricatus* (Ch) on sample NMMNH P-71983; D) Photo close-up showing *Skolithos* (Sk), *Arenicolites* isp. (arrows), *Protovirgularia* isp. (top-left), and poorly preserved example of *Cochlichnus anguineus* (Co) morphotype A on sample NMMNH P-71984. This sample belongs to the *Protovirgularia-Arenicolites-Skolithos* ichnoassemblage (#2) of this study; E) Hypichnial view showing *Spongiomorpha oraviense* preserved in convex hyporelief on sample NMMNH P-72003; F) Hypichnial view of *Spongiomorpha oraviense* and the medium morphotype of *Palaeophycus tubularis* (Pa) on sample NMMNH P-72004. E) and F) belong to the *Spongiomorpha-Palaeophycus* ichnoassemblage (#8) of this study. All scale bars are 1 cm.

sample (Fig. 7A, NMMNH P-71995). The Mesilla Valley *P. striatus* were not attributed to *Scoyenia* because of the continuous, longitudinal scratch marks, and as Goldring et al. (2005) also noted, the absence of meniscate backfill.

This wide-ranging burrow has been interpreted as a domichnia/fodichnia (Lucas and Lerner, 2004) and has also been recognized in the Smelertown Formation at Cerro de Cristo Rey (Lucas et al., 2010a), the Upper Cretaceous of Alberta, Canada (Pemberton and Frey, 1984) and the Lower Cretaceous of England (Goldring et al., 2005).

Ichnogenus *Planolites* Nicholson, 1873

Planolites isp.

Figs. 2A, 3A, 6B, 6C.

Referred specimens: NMMNH P-71983, P-71990, P-71994, P-71998, from localities 10168 (Member C, Fig. 1) and 10169 (Members B & C, Fig. 1).

Description: Cylindrical, horizontal or inclined, unlined, smooth-walled burrows with fill that differs from the host rock. Several specimens observed have a meandering pattern. Burrow diameter is 10 to 13 mm.

Remarks: *Planolites* is distinguished from *Palaeophycus* by the absence of a lining and the presence of fill differing from the host lithology (Pemberton and Frey, 1982). Several specimens we have identified as *Palaeophycus* isp. herein resemble hypofaunal *Planolites* isp. previously described, but the Mesilla Valley burrows are filled with the same lithology as the siltstone to which they are still attached, and in many cases are found to be lined. *Planolites* is an actively filled paschichnia, as opposed to *Palaeophycus*, which is interpreted as a passively filled domichnia (Pemberton and Frey, 1982). We generally reserved the designation “*Planolites*” for burrows preserved as endichnia, or partial endichnia. Four ichnospecies of *Planolites* have been designated, *P. montanus*, *P. beverleyensis*, *P. annularis*, and *P. constrictannulatus* (Christopher et al., 1994). The traces recorded here most closely resemble *P. beverleyensis* because they are larger than *P. montanus* and unornamented.

NMMNH P-71983 contains *Planolites* isp. that are reworked by *Chondrites* isp. in hummocky crossbedded siltstone/sandstone (Fig. 6C). P-71998 shows *Planolites* isp. reworked by *Ancorichnus* isp. (Fig. 2A). P-71990 does not have smooth walls, but resembles *Planolites* isp. from the western portion of the study area (i. e., P-71998, locality 10169) has coarser grained, bioclastic fill. This kind of difference in fill has been reported elsewhere (Buatois and Mángano, 2002).

This ichnogenus has also been recognized from the Washita Group of Texas (Scott et al., 2003), the Upper Cretaceous of Utah (Frey and Howard, 1985b), and the Albian Bluesky Formation (Male, 1992). *Planolites* is interpreted as a fodichnia (Pfister and Keller, 2010) and a paschichnia (Dam, 1990) and has been described from the Precambrian to Recent (Alpert, 1973). This ichnotaxon has been described from the Upper Cretaceous of Texas (Henk et al., 2002), New Mexico (Pillmore and Maberry, 1976) and Wyoming (Clark, 2010).

Ichnogenus *Protovirgularia* McCoy, 1850

Protovirgularia isp.

Figs. 3F, 6D, 8C, 8E.

Referred specimens: P-71984, P-71985, P-71986, locality 10168 (Member C, Fig. 1).

Description: Curved, unbranched, epichnial trace consisting of two parallel rows of linear or teardrop-shaped imprints oriented oblique or perpendicular to a medial groove. The lateral imprints are somewhat disorganized and vary in shape and size, commonly within one specimen (Fig. 3F). On some specimens, the lateral imprints are anastomosing and join the medial groove, and on others they are clearly separated from it. The lateral impressions are almost always associated with a sediment bulge. Overall width of the trackways is 5–6 mm, with lateral linear imprints extending 2–3 mm away from the medial groove, which is 0.1–1mm wide and continuous. Internal widths vary from zero to 1.5 mm (Fig. 8C, 8E). All specimens of this trace are short.

Two specimens (on NMMNH P-71986; Fig. 3F) contain portions at the end of the trace without a medial groove, showing that the lateral impressions are deeper into the substrate. Also, two specimens from P-71986 are associated with *Problematica* (Fig. 3F). These traces are described below. P-71985 contains two traces that appear to converge (Fig. 8D).

Remarks: These traces resemble “chevronate-” and “feather-stitch trails” shown by Buta et al. (2013), as well as *Protovirgularia* sp. shown by Ekdale and Bromley (2001), Nara and Ikari (2011), Kim et al. (2000), and Carmona et al. (2010). Several species of *Protovirgularia* have been described, including *P. bidirectionalis* Mángano et al. 2002, *P. rugosa* Miller and Dyer 1878, *P. triangularis* MacSotay 1967, *P. longespicata* de Stefani 1885, *P. tuberculata* Williamson 1887, and *P. dichotomata* McCoy 1850. Our specimens superficially resemble *P. dichotoma*, but they also resemble arthropod trackways such as *Dendroidichnites* sp., a kind of resemblance that has also been noted by Carmona et al. (2010). Unlike the *Protovirgularia* sp. of Carmona et al. (2010), our specimens are not associated with *Lockeia* isp. Poor preservation, small number of specimens, and resemblance to arthropod trackways deterred us from assigning these traces to an ichnospecies.

Seilacher and Seilacher (1994) and Fernández et al. (2010) attributed this trace to the feeding activity of photo-branch bivalves, using their split foot to tunnel through the sediment (Carmona et al., 2010). This trace ranges from the Ordovician to the Holocene (Lucas and Lerner, 2004).

Ichnogenus *Rhizocorallium* Zenker, 1836

Rhizocorallium commune var. *irregularare* Knaust 2013

Fig. 8G, 8H, 8I.

Referred specimens: NMMNH P-596097 from locality 10169 (Members B & C, Fig. 1), and two uncollected field specimens.

Description: Horizontal, unbranched, short and straight or longer and winding U-shaped tubes with protrusive spreite. The spreite are either symmetrical/semicircular, or asymmetrical/J-shaped in hypichnial view. Overall burrow size ranges

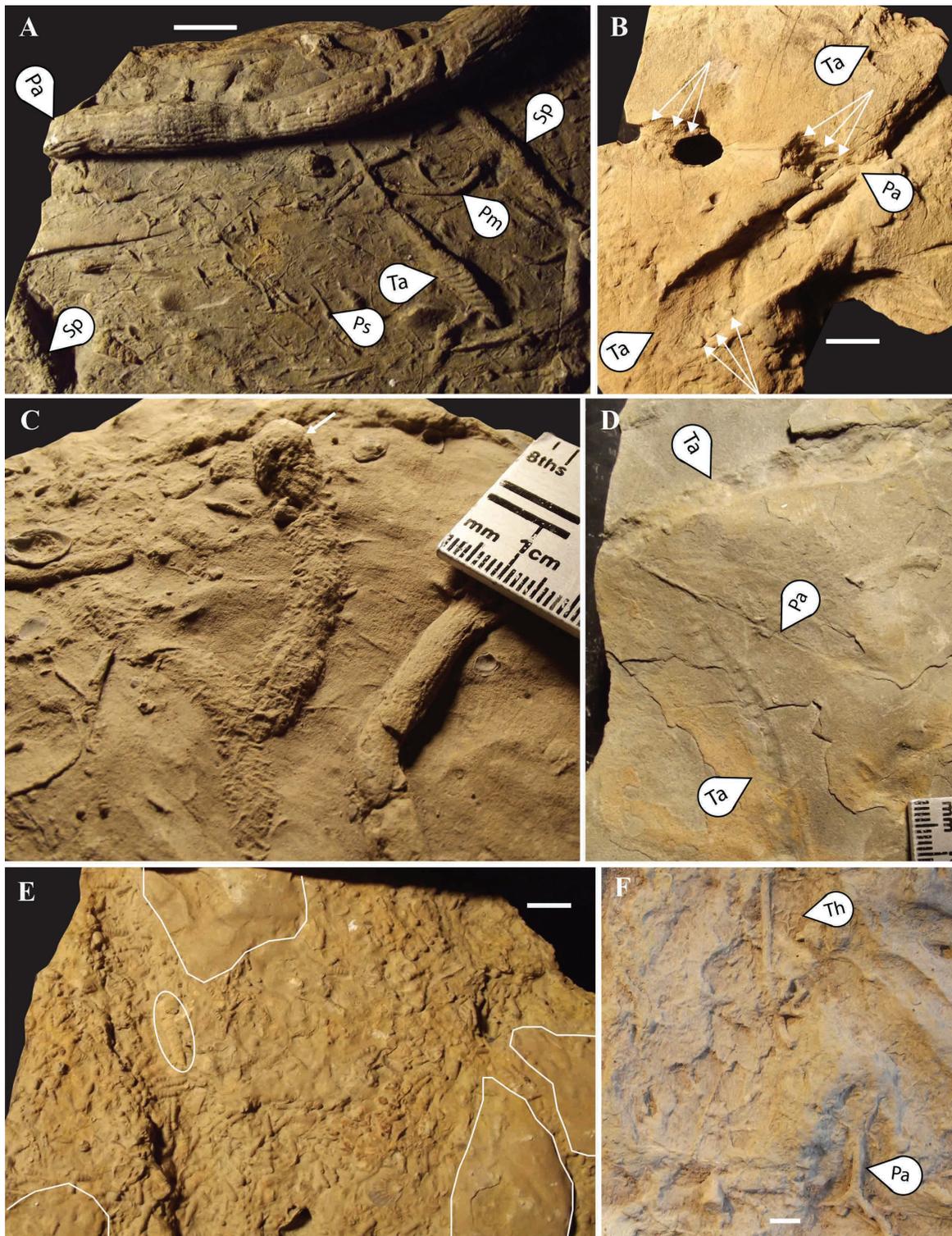


Figure 7A–F. A) Hypichnial view showing *Spongeliomorpha sublumbroides* (Sp), *Palaeophycus striatus* (Pa), *Taenidium* isp. (Ta), and *Palaeophycus tubularis* (Ps and Pm represent small and medium morphotypes, respectively) on sample NMMNH P-71995; B) Epichnial view of *Taenidium* isp. (Ta) being reworked by the medium-sized morphotype of *Palaeophycus tubularis* (Pa) on sample NMMNH P-71981. Arrows indicate meniscae; C) Close-up of P-71996, showing branched *S. sublumbroides* with knobby burrow termination (indicated by arrow), *Palaeophycus striatus*, and the medium morphotype of *Palaeophycus tubularis* (left), all preserved in convex hyporelief. This sample belongs to the *Palaeophycus-Spongeliomorpha* ichnoassemblage (#5) of this study; D) Epichnial view of P-71992 showing horizontal, poorly preserved, endichnial *Taenidium* isp. (Ta), apparently cross-cut by convex/concave small morphotype of (Pa). Sample belongs to the *Palaeophycus-Spongeliomorpha* ichnoassemblage (#5) of this study; E) Epichnial view showing *Thalassinoides* sp., filled with bioclastic debris (dominated by *Cribratina texana*, with *Turritela* sp. (oval outline) on sample NMMNH P-71989. Burrow system is outlined in white; F) Field photo from locality #10170 of tiny convex burrows we attribute to *Thalassinoides* isp. (Th) together with a specimen of the medium-sized morphotype of *Palaeophycus tubularis* (Pa). This sample belongs to the *Thalassinoides/Planolites-Chondrites* ichnoassemblage (#6) of this study. All scale bars are 1 cm.

from 40 to 95 mm wide and 150 to 180 mm in length, with the U-tube arms between 10 and 20 mm in diameter, and the spreite ranging from 5 to 20 mm at the widest point. The U-tubes are passively filled and contain very few groups of parallel and oblique scratch marks (Fig. 8I). The arcuate spreite were actively filled with no visible scratch marks, are imbricated, and are often truncated by one arm of the U-tube (called the “truncating arm” by Basan and Scott, 1979). The fill of the U-shaped tube of these traces is not preserved, probably because it was weathered away due to higher mud content than the surrounding siltstone matrix. Spreite and overall burrow width are narrower toward the distal end of the trace, and one specimen (P-597097) has spreite with abundant fecal pellets that we identify as *Coprulus oblongus* Mayer 1952 (Fig. 8H) based on their morphology, size and association with *Rhizocorallium*. These fecal pellets are also shown in *Rhizocorallium* by Knaust (2013, fig. 8). All specimens are preserved in positive hyporelief, and the fill of the U-shaped tube has been weathered out.

Remarks: *Rhizocorallium commune* is a common trace found in the *Cruziana* (and *Glossifungites*) ichnofacies (Seilacher, 1967; Buatois and Mángano, 2011; Knaust, 2013) and ranges from the early Cambrian to the Holocene (Knaust, 2013, and references therein). This trace was first described by Zenker (1836) from Germany and was later reviewed by Fürsich (1974), who regarded three ichnospecies as valid. Later, Schlirf (2011) introduced a new classification scheme for U-shaped spreite burrows, including abandonment of *R. commune* Schmid, 1876. The most current, comprehensive review of this ichnogenus was by Knaust (2013), who suggested there are only two valid ichnospecies of *Rhizocorallium*—*R. jenense* Zenker, 1936 and *R. commune* Schmid, 1876. Knaust (2013) also designated several varieties (ichnosubspecies) of *R. commune*, and this classification scheme is followed here.

Paleoenvironmental interpretation of this trace varies. It has been found in positive hyporelief overprinting a similar softground suite of traces that partially matches those found in the Mesilla Valley Formation, including *Planolites*, *Protovirgularia*, and *Lockeia* (Knaust, 2007). Basan and Scott (1979) state it is a lower/upper shoreface indicator, and this is consistent with a lower shoreface/shallow marine interpretation for the depositional environment of the Mesilla Valley Formation. Knaust (2013) states that the presence of *Coprulus oblongus* indicates deposition in an intertidal or deeper environment.

The relative absence of scratch marks is consistent with the traces being constructed in relatively soft sediment, as opposed to a firmground and is not uncommon for *Rhizocorallium commune* (Knaust, 2013).

We assign these traces to *Rhizocorallium commune* var. *irregulare* based on the following characteristics: isolated traces, subhorizontal, U- to tongue-shaped, abundant fecal pellets, active spreite with a passive marginal tube, association with traces from the *Cruziana* ichnofacies, and a subtidal paleoenvironment (see Knaust, 2013, fig. 11, table 1). These same traces have also been described from an Upper Cretaceous estuarine deposit in Alabama (Savrda et al., 2016).

Rhizocorallium was reported from the Albian of eastern-central NM by Gage and Asquith (1977, fig 8) and Kues

et al. (1985) and in Colorado (Basan and Scott, 1979). Worsley and Mørk (2001) report *Rhizocorallium* from Triassic tempestites, including bioclastic and fine-clastic sediments.

The tracemaker of *Rhizocorallium* is not known, but given that the ichnogenus is heterogeneous, this implies the likelihood of several different tracemakers, including terrestrial and marine organisms. Likely marine tracemakers are annelids and decapod crustaceans, which were probably deposit feeders (Basan and Scott, 1979; Knaust, 2013).

Rugalichnus Stimson et al., 2017

Rugalichnus matthewii Stimson et al., 2017

Fig. 4E.

Referred specimens: NMMNH P-71978, P-71979, P-71980 from locality 10169 (Members B & C, Fig. 1).

Description: Closely spaced, fairly regular, steep-walled wrinkles found on the upper bedding plane of horizontally laminated sandy siltstone. Wrinkle crests are sharp, symmetrical, and flat-topped, and sometimes branched. Flat troughs separate these wrinkles, forming subparallel sets. Crests are usually 2–3 mm wide, with troughs of similar width. Lengths of troughs and ridges vary but do not exceed 30 mm.

Remarks: This trace is a microbially induced sedimentary structure (MISS; Noffke, 2009) and has been traditionally called “*Kimneyia*” as described by Walcott (1914), but Walcott’s holotype was a cross-sectional feature, not a bedding plane feature as the term was subsequently used (Stimson et al., 2017). These traces have also been described as “wrinkle structures” (i.e., Porada and Bouougri, 2007). The specimens described here occur exclusively at the tops of bedding planes in fine-grained sandstones with horizontal/low angle cross bedding, like others described in the literature (Mata and Bottjer, 2009; Porada et al., 2008; Stimson et al., 2017). These traces are not restricted to shallow/tidal environments (Stimson et al., 2017), and can be found in relatively deep-water shelf environments (Tanoli and Pickerill, 1989). An absence of ripples or hummocky cross strata may also indicate a more distal tempestite (deeper water) origin for these samples. Thomas et al. (2013) experimentally reproduced a *Rugalichnus*-like geometry in siliciclastics in a wave pool using visco-elastic films as an analogue. *Rugalichnus* has been reported from the Archean to Recent (Porada et al., 2008; Noffke, 2009).

Skolithos Haldeman, 1840

Skolithos isp.

Figs. 6D, 8E.

Referred specimens: NMMNH P-71984, P-71985, P-71986?, P-71987? (described here as *Chomatichnus*), and P-71990 from localities 10168 and 10167 (Member C, Fig. 1).

Description: Vertical, cylindrical, unlined/unornamented shafts, preserved in concave epirelief or as endichnia. Openings are typically 5–6 mm in diameter, and depths are generally unobserved in cross section. Sediment fill always weathers faster than host rock, so it is probably finer grained.

Remarks: Although an indicator of high energy conditions, this burrow is commonly associated with storm deposits in typical *Cruziana* assemblages (Gibert and Martinell, 1999; Zonneveld, 2004). This may be because the *Skolithos*

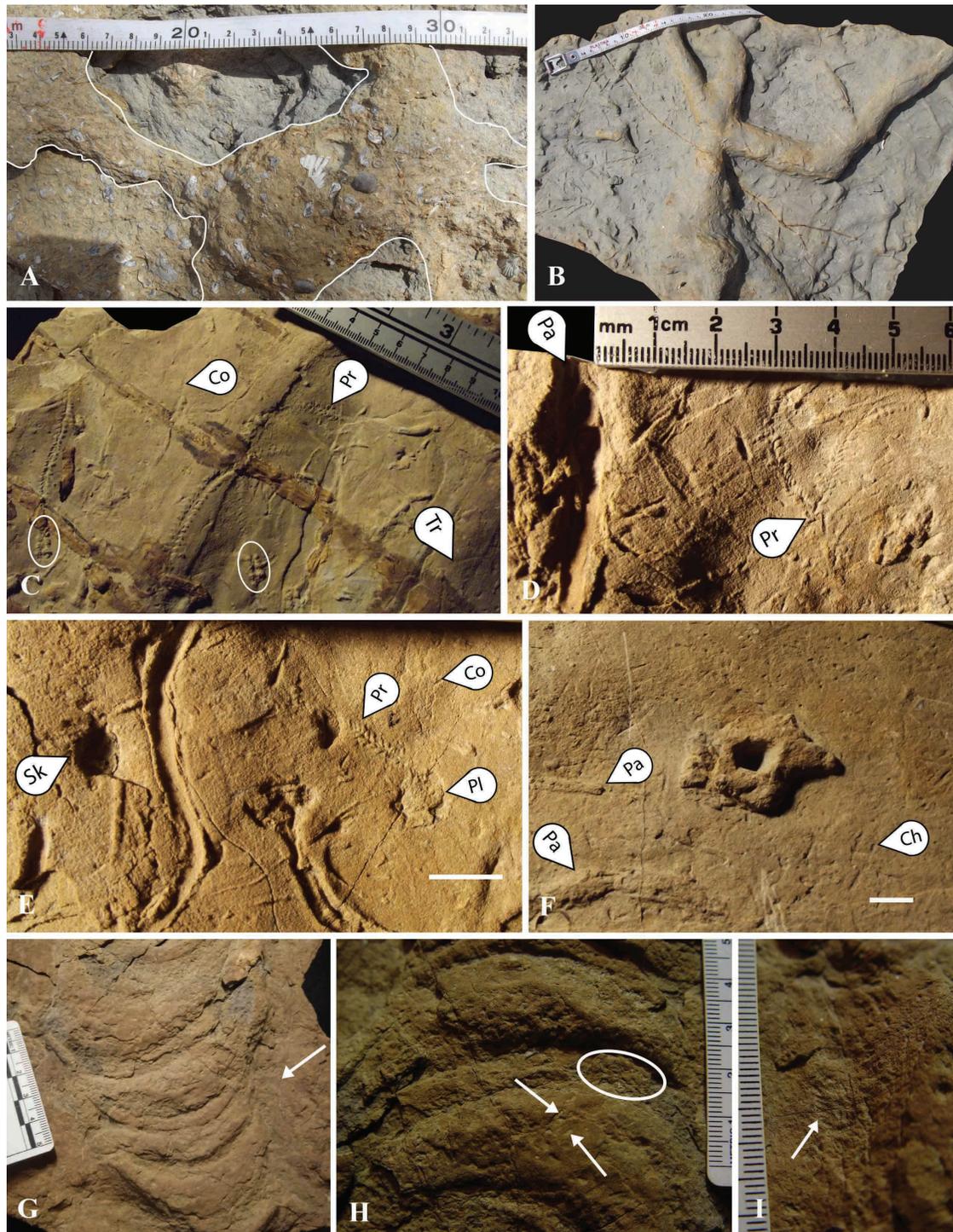


Figure 8A–H. A) Uncollected sample of *Thalassinoides paradoxicus* from NMMNH locality #10170, showing bioclastic fill (burrow system outlined in white; note *Neithea* sp.); B) the largest specimen of *T. paradoxicus* (also uncollected) found in this study. This sample is from NMMNH locality #10168 (note the lack of bioclastic fill, and the X-shaped branching). Both A) and B) belong to the *Thalassinoides/Planolites-Chondrites* ichnoassemblage (#6) of this study; C) Epichnial view showing three specimens of *Protovirgularia* isp. (Pr), two of which are associated with *Problematica* (circled), poorly preserved *Cochlichnus anguineus* (Co), and concave *Treptichnus* isp. (Tr), all on sample of NMMNH P-71986; D) Close-up showing *Palaeophycus tubularis* (Pa, medium morphotype) and two, apparently converging *Protovirgularia* (Pr), on sample NMMNH P-71985; E) Close-up showing *Protovirgularia* (Pr), possibly a compound trace, with steeply inclined *Planolites* isp. (Pl), *Palaeophycus tubularis* (small and medium morphotypes), *Cochlichnus* isp. (Co, Morphotype A) and *Skolithos* isp. (Sk) on sample NMMNH P-71985. C), D), and E) belong to the *Protovirgularia-Arenicolites-Skolithos* ichnoassemblage (#2) of this study; F) Epichnial view of NMMNH P-71987, showing a chimney structure, possibly *Chomatichnus* isp., and the medium-sized morphotype of *Palaeophycus tubularis* (Pa). Both appear to be cross-cut by *Chondrites intricatus* (Ch). This sample belongs to the *Palaeophycus-Chondrites-Ophiomorpha* ichnoassemblage (#1) of this study; G) Overview of NMMNH P-596097 showing *Rhizocorallium commune* var. *irregular* (arrow indicates truncating arm of the U-tube); H) Close-up photo showing *Coprulus oblongus* (indicated by arrows) on sample P-596097. A spreite with a larger concentration of coprolites is circled; I) Close-up photo of the U-tube of P-596097 showing grouped, lateral scratch marks (arrow). Scale bars in E and F are 1 cm.

tracemaker was escaping upward during deposition of the tempestites, or because the tracemaker simply excavated a domichia after deposition. The latter makes more sense because there is no evidence of *Skolithos* isp. as part of an equilibrium community of traces in shale before/after deposition of tempestites. An equilibrium community (or equilibrium fauna) is the resident community found in strata representing stable environmental conditions between storm deposits (Pemberton and MacEachern, 1997).

Skolithos has been described often in the literature, and ranges from Precambrian to Recent (Howard and Frey, 1975; Carmona et al., 2008). It is also a very common ichnogenus in coastal settings (MacEachern et al., 2012). Simpson (1975) interpreted these burrows as fugichnia, but they could also be domichnia or even fodichnia (Vossler and Pemberton, 1988).

Ichnogenus *Spongeliomorpha* Saporta, 1887

Spongeliomorpha isp.

Figs. 2C, 6A, 7A.

Referred specimens: P-71995 (two different morphotypes), P-71996, and P-71999 from locality 10169 (Members B & C, Fig. 1).

Description: Isolated, convex, hypichnial, inclined burrows in half-relief with abundant linear scratch marks (“bioglyphs” of Gibert and Ekdale, 2010) covering the burrow walls and floor. Scratch marks are incise and stand out as a pattern of ridges forming the outer surface of the trace. Burrows are simple and oval in cross section (Fürsich, 1973). The trace width varies, but is 10 to 60 mm wide and is at least 60 mm long. Individual scratch marks vary in width from 0.5 to 1.5 mm, and are up to 15 mm long.

Remarks: There are six ichnospecies of *Spongeliomorpha*, *S. iberica* Saporta 1887, *S. sudolica* Zareczny 1878, *S. sicula* D’Alessandro and Bromley, 1995, *S. sinuostriata* and *S. chevronensis* Muñiz and Mayoral, 2001, *S. oraviense* Książkiewicz 1977, and, finally, *S. carlsbergii* Melchor et al., 2010, based on ichnotaxobases outlined by Fürsich (1973), which were amended by Melchor et al. (2010). This ichnotaxon is restricted to the horizons marking a lithologic change, and the traces are considered to have formed in mud firmground before the deposition of shallow marine carbonates (Gibert and Ekdale, 2010), but *Spongeliomorpha* has also been reported from the *Cruziana* ichnofacies (Fürsich, 1973; Ekdale, 1992; Schlirf and Uchman, 2005). We do not see any other evidence of dewatering or firmground, but the presence of *Rugalicchnus* in the Mesilla Valley Formation does hint at very shallow water conditions, and it is possible that firmground colonizers of the *Glossifungites* ichnofacies are present in this unit. We reserve this interpretation until more evidence of an erosional surface (Gibert and Ekdale, 2010) is found, or until more firmground ichnotaxa are described from the Mesilla Valley Formation.

It has been shown that the morphology of this trace overlaps considerably with *Ophiomorpha*, *Thalassinoides*, *Gyrolithes*, and *Ardelia* (Frey et al., 1978; Schlirf and Uchman, 2005) to the extent that Bromley and Frey (1974) even recommended abandoning this ichnogenus. However, Melchor et al. (2010) demonstrated that the ichnotaxobases for *Spongeliomorpha* produced by Fürsich (1973) can be used to differentiate between this ichnogenus.

Spongeliomorpha has been reported from the Permian to Recent (Carmona et al., 2008). The tracemaker was most likely a decapod crustacean (Asgard et al., 1997), or at least an animal capable of scratching the firm mud (Gibert and Ekdale, 2010).

Spongeliomorpha oraviense Książkiewicz, 1977

Fig. 6E, 6F.

Referred specimens: NMMNH P-72003 and P-72004 from locality 10169 (Members B & C, Fig. 1).

Description: Large, unbranched *Spongeliomorpha* isp. with thick, irregular scratch marks oriented transverse to the burrow axis. Burrows vary in width from 40 to 60 mm, with coarse scratch marks of variable width.

Remarks: These two specimens are tentatively assigned to *Spongeliomorpha oraviense* based on the absence of branching, and the large, irregular scratch marks oriented oblique to transverse to the burrow axis (Uchman, 1998; Muñiz and Mayoral, 2001). These traces are found in isolation and are always hypichnial, and are included in the *Glossifungites* ichnofaces (Buatois and Mángano, 2011). We did not find any other evidence of firmground ichnogenus. It is possible that the tracemaker stamped the ridges we interpret to be “scratchmarks.” *Spongeliomorpha* ranges from Permian to Recent (Carmona et al., 2008). Asgard et al. (1997) attribute this trace to suspension-feeding decapod crustaceans.

Spongeliomorpha sublumbricoides Azpeitia Moros, 1933

Figs. 7C.

Referred specimens: NMMNH P-71985, P-71980, P-71995 (beneath *P. striatus* at edge), and P-71996 (next to *P. striatus*) from locality 10169 (Members B & C, Fig. 1).

Description: A small, inclined, branched *Spongeliomorpha* with short, very fine scratch marks oriented oblique to the burrow axis (Uchman, 1998). This burrow is always preserved in partial hyporelief, and is slightly inclined, so the scratchmarks are revealed as it enters hyporelief. Some specimens terminate in a smooth, rounded chamber that is unlined and unscratched. Burrow width is 7–9 mm, but is variable, as are the lengths.

Remarks: These traces are smaller than other *Spongeliomorpha* burrows identified in this study, and burrow terminations are “knobby,” as shown by Uchman (1998). Figure 7C (NMMNH P-71996) shows one of these scratchless, rounded terminations.

Ichnogenus *Taenidium* Heer, 1877

Taenidium isp.

Figs. 2C, 6A, 6B, 7A, 7B, 7D.

Referred specimens: NMMNH P-71981, P-71992, and P-71995 from locality 10169 (Members B & C, Fig. 1).

Description: Unwalled, winding, curved, basically cylindrical, meniscate-filled burrow with a horizontal to inclined orientation. Overall trace width is 6–10 mm. Meniscae are heterogeneous, not deeply arcuate, segmented or packeted, and vary in thickness from 2–4 mm. In all specimens, meniscae are always thicker towards the center of the burrow. Two specimens were found to be cross-cut/reworked by *Palaeophycus tubularis* (NMMNH P-71981; P-71992).

Remarks: Four ichnospecies of *Taenidium* have been established. The ichnospecies *T. serpentinum* Heer, 1877, *T. satanassi* D'Allesandro and Bromley 1995 and *T. cameronsensis* Pickerill et al. 1993 were reviewed and revised by D'Alessandro and Bromley (1987), who also added a fourth ichnospecies, *T. barretti*. Keighley and Pickerill (1994) also revised the taxonomy of *Taenidium*, in relation to *Beaconites* and *Ancorichnus*, which are both meniscate as well. Specimens NMMNH P-71981 and P-71995 described here resemble *T. satanassi* illustrated by D'Alessandro and Bromley (1987) and shown by Rotnicka (2010), and sample P-71992 resembles *T. serpentinum* illustrated by D'Alessandro and Bromley (1987). However, we did not assign specimens to ichnospecies because of an insufficient number of specimens and poor preservation of those encountered. Vertical examples of this burrow were not found, as in some other studies (i.e., Keighley and Pickerill, 1994; Good, 2013).

Taenidium is generally regarded as a nonmarine trace (Keighley and Pickerill, 1994) of a deposit feeder (Kulkarni et al., 2008) and is a member of the nonmarine *Scoyenia* ichnofacies, although it has also been found in shallow marine settings (Buatois and Mángano, 2011). Keighley and Pickerill (1994) suggested an arthropod for the tracemaker based on association with other arthropod traces such as *Cruziana* and *Hexapodichnus*. *Taenidium* ranges from Cambrian to Recent (Crimes et al., 1992; Carmona et al., 2008), and has been reported from the Upper Cretaceous of Utah ("*Muensteria*" of Howard and Frey, 1984; Bracken and Picard, 1984; Frey and Howard, 1985b) and Wyoming (Clark, 2010), and the Cretaceous of Alabama (Savrdá et al., 2016).

Ichnogenus *Thalassinoides* Ehrenberg, 1944

Thalassinoides isp.

Figs. 2C, 5A, 7F, 8A, 8B.

Referred specimens: NMMNH P-71983, P-71989, P-71990, P-71992, P-71997, and P-72002 from (localities 10168, 10169, and 10170, Members B & C, Fig. 1).

Description: Mostly horizontal, regularly branched tunnel that is subcircular in cross section and has passive fill. These burrows are preserved as epichnia, hypichnia, and endichnia, but most commonly as hypichnia. Burrow width varies highly, but is usually 15 mm. Burrow segments between branches range from 60 to 80 mm in length, and the burrow does not widen noticeably at the junctions.

Remarks: Many ichnospecies of *Thalassinoides* have been reported, and their taxonomy and validity is in need of review (Yanin and Baraboshkin, 2013). For this reason, we did not assign many of these burrows to ichnospecies. Specimens preserved in finer sediments (siltstones) contain isolated scratch marks and trample fill (see Frey and Howard, 1985a), or show bedding of passive fill.

One very small specimen (Fig. 7F) observed at locality 10170 appears to be *Thalassinoides* isp. based on its morphology and preservation, but is extremely small, with a burrow diameter of 1 mm, and segments 2–3 mm long with no swelling at the Y-shaped branches. The smallest burrow diameter we could find in the literature is 7 mm (El-Hedeny et al., 2012).

Thalassinoides is reported from Cambrian to Recent

(Yanin and Baraboshkin, 2013), and is usually attributed to decapod crustaceans (Carmona et al., 2008). Crayfish fossils have also been discovered in these burrows (Yanin and Baraboshkin, 2013). This ichnogenus has been reported throughout the Washita Group of Texas (Scott et al., 2003), in the Albian of Alberta, Canada (Male, 1992), the Upper Cretaceous of Texas (Henk et al., 2002), New Mexico (Pillmore and Maberry, 1976; Lucas, 2019), Wyoming (Clark, 2010), and Utah (Howard and Frey, 1984).

Thalassinoides paradoxicus Woodward, 1830

Fig. 7E.

Referred specimens: NMMNH P-71983, P-71989, P-71997, and several uncollected samples, from localities 10168 (Member C, Fig. 1), 10169 and 10170 (Members B & C, Fig. 1).

Description: Large, hypichnial, irregularly branched *Thalassinoides* with short, blind tunnels or terminal chambers and distorted X-shaped, or trident-shaped branching, not T- or Y-shaped. Burrows are commonly 30 mm in diameter (up to 100 mm) and have been observed to be more than 400 mm long (Fig. 8B).

Remarks: Several specimens of *Thalassinoides* observed in this study are distinctive, with an irregular branching pattern, smaller terminal chambers, and commonly with bioclastic fill. On outcrop, the amount of bioclastic fill in these tunnels decreases towards the east. This could mean that the western outcrops were more shoreward during the late Albian, and the burrow infill was therefore coarser grained. Figure 8A and 8B compare two photos of specimens from localities 10170 and 10168 to demonstrate this.

One sample collected (NMMNH P-71997) has its own large, rounded terminal chamber that has been mineralized with limonite and gypsum (Fig. 5A). This sample also contains two smaller, lateral terminal chambers. One of these looks like a resting trace of the local bivalve *Protocardia* sp., first described in the area by Böse (1910). The other is less distinctive. *Thalassinoides* has been reported from every continent, ranges from Cambrian to Recent, and has been attributed to the burrowing activity of decapod crustaceans (Carmona et al., 2008).

Ichnogenus *Treptichnus* Jensen and Grant, 1992

Treptichnus isp.

Figs. 3D, 8C.

Referred specimens: NMMNH P-71986 and P-71988 from localities 10168 (Member C, Fig. 1) and 10169 (Members B & C, Fig. 1).

Description: Simple, unlined, smooth, zigzag trace with straight segments between joints that meet at an obtuse angle. No vertical tubes, pits, or twig-like projections were noted in these specimens. Specimens preserved in convex and concave epirelief. Burrow width is 1 to 2 mm and lengths vary from 20 to 40 mm. Lengths of burrow segments are between 15 and 18 mm.

Remarks: The taxonomy of *Treptichnus* was revised by Buatois and Mángano (1993) and is discussed in Buatois et al. (1998). This ichnogenus contains several ichnospecies (*T. bifurcus* Miller, 1889; *T. triplex* Palić, 1976; *T. lublinensis*

Paczeńska, 1986; and *T. pollardi* Buatois and Mángano, 1993), and our specimens most closely resemble *T. pollardi*, proposed by Buatois and Mángano (1993). However, the absence of pits or nodes on these traces causes us to hesitate with ichnospecific designation. Similar traces have been reported from the Upper Cretaceous of Kansas (Buatois et al., 1997b). One specimen we collected (Fig. 3D; NMMHH P-71986) is a compound ichnofossil with *Cochlichnus anguineus*. The morphology of these two traces overlaps (Buatois et al., 1998). *Treptichnus* has been interpreted as a feeding trace (fodichnia) and ranges from earliest Cambrian to Eocene (Buatois and Mángano, 1993, 2011). These burrows have been attributed to deposit feeders (Rindsberg and Kopaska-Merkel, 2005).

Problematica

Protovirgularia? McCoy, 1850

Figs. 3F, 8C.

Referred specimens: NMMNH P-71986 from locality 10168 (Member C, Fig. 1).

Description: Bilaterally symmetrical, elongate resting trace (?) with two parallel rows of 3 to 4 teardrop-shaped impressions preserved in convex epirelief. These impressions are paired and symmetrical as well. Traces are 1.8 mm long and taper from 5 mm down to 3 mm wide.

Remarks: These traces resemble the *Protovirgularia* traces they are associated with, as well as arthropod resting traces such as *Tonganoxichnus* isp. illustrated by Buatois et al. (1998, fig. 12), Buatois and Mángano (2011), Mángano et al. (2002), and Getty et al. (2013). We have compared these with early Permian specimens from the Robledo Mountains, New Mexico, housed in the New Mexico Museum of Natural History, and although there is resemblance between the thoracic appendage imprints, the Cristo Rey specimens are not preserved well enough to warrant assignment to an ichnogenus. Both specimens are associated with traces we assign to *Protovirgularia* isp., and both are found at the end of the *Protovirgularia* traces, with chevrons opening in the direction of the *Problematica*. It is likely these traces are from the same bivalves that formed the *Protovirgularia*. Nonetheless, we note the similarity between these and those reported from the late Carboniferous of Kansas (Buatois et al., 1997b).

Chomatichnus (chimney structures) Donaldson and Simpson, 1962
Fig. 8F.

Referred specimens: NMMNH P-71987, locality 10169 (Members B & C, Fig. 1).

Description: Lobed, epichnial sediment mounds surrounding a burrow entrance on the upper bedding plane of a massive sandy siltstone. Sediment mounds are the same lithology as the host rock, but the burrow fill is different than the host rock and weathers more quickly. Burrow width is 6 to 7 mm, and internal structures are not visible, but, due to the presence of sediment mounds, we can ascertain that this is not an escape structure. It is most likely the domichnia of a marine arthropod.

Remarks: These resemble the ruptured sediment

mounds at the top of bubbler crab burrows illustrated by Chakrabarti et al. (2006, fig 3). Yanin and Baraboshkin (2013) show a schematic structure of callianassid burrows and illustrated a “waste bank” pile that also resembles this structure. Hasiotis and Dubiel (1993) associated chimney structures with the burrow *Camborygma*, but these are much larger than the specimen discussed here, and the *Camborygma* association is questionable (Tanner and Lucas, 2007). Desai (2012) classified epichnial mounds present on the bedding plane as *Chomatichnus* isp. Additional specimens from the Mesilla Valley Formation may aid in the further classification of this epichnial sediment mound.

Ichnoassemblages

Analysis of ichnoassemblages aids in environmental reconstruction and interpretation (Frey and Howard, 1985a). Most of the bioturbated deposits of the Mesilla Valley Formation show repetitive patterns and associations of trace fossils. We group these into eight ichnoassemblages, but it is important to note that the same strata vary laterally in grain size, bedding, and bioturbation intensity. In general, at Cerro de Cristo Rey, outcrops to the east have higher ichnodiversity, which may also be an effect of better exposure of units. Outcrops to the west also consistently have more bioclastic debris than outcrops to the east, which coincides with a N-S shoreline in the area and a clastic source to the west, as suggested by Kappus (2007) because of an E-W bimodal orientation of trough cross-strata in the overlying Mojado Formation. More study of these relationships is needed before drawing conclusions about depositional processes across such a short distance (~2 km). Several of the bioturbated units we observed/collected did not adequately fit the description of any of the ichnoassemblages described below, but all samples contain members of the *Cruziana* ichnofacies as described by Buatois and Mángano (2011).

1. *Palaeophycus-Chondrites-Ophiomorpha* ichnoassemblage—Figs. 3B, 5C, 8F, locality 10169 (Members B & C, Fig. 1).

The first ichnoassemblage is represented by epichnial *Palaeophycus tubularis* (all three morphotypes described herein), *Ophiomorpha* (small morphotype), and *Chondrites intricatus*. It is found in siltstones with horizontal laminations and hummocky cross-strata at the tops of beds. *O. nodosa* is cut by *P. tubularis*, which is cross-cut by *C. intricatus*. NMMNH P-71987 contains an epichnial chimney structure, which appears to be cross-cut by *C. intricatus* (Fig. 8F). This is evidence for a post-tempestite, equilibrium ichnofauna in the shale consisting of *C. intricatus*. NMMNH P-71987 and P-71988 (and many others observed in the field) are included in this ichnoassemblage. It is possible that P-71987 (containing *Chomatichnus*, *Palaeophycus* isp., and *C. intricatus*) also belongs to this ichnoassemblage.

2. *Protovirgularia-Arenicolites-Skolithos* ichnoassemblage—Fig. 3F, 6D, 8E, locality 10168, (Member C, Fig. 1).

The second ichnoassemblage is on the ripple-sculpted tops of horizontally laminated, silty sandstones. Ripples are symmetrical and sinuous, showing current in one direction. All samples contain *Protovirgularia* isp., *Arenicolites* isp. and *Skolithos* isp., with secondary *Palaeophycus tubularis* (small and medium morphotypes), *Cochlichnus* isp. and

Treptichnus isp. This ichnoassemblage appears to be one group of beds approximately 2 m below the contact with the overlying Sarten Member of the Mojado Formation, but more detailed stratigraphy is needed. All examples were collected at NMMNH locality 10168. It appears that *Cochlichnus* isp. is a compound trace with *Treptichnus* isp. (NMMNH P-71986), but this is tentative. We include samples P-71984, P-71985, and P-71986 in this ichnoassemblage.

3. *Arenicolites* ichnoassemblage of *Skolithos* Ichnofacies—Figure 2B, Locality 10168 (Member C, Fig. 1).

The third ichnoassemblage is simple, it contains *Arenicolites* isp., *Ophiomorpha nodosa* (large morphotype), and *Skolithos* and is preserved in massive to hummocky cross-stratified sandstones with ripple-sculpted upper bedding planes (Fig. 2B). This ichnoassemblage strongly resembles the *Arenicolites* ichnoassemblage described by Bromley and Asgaard (1979; 1991) and MacEachern et al. (2012). This ichnoassemblage is known for its low ichnodiversity (MacEachern et al., 2012), dominated by *Arenicolites* and *Ophiomorpha*, with hummocky cross-strata in the upper portion of the bed. It has been reported from numerous units, including the Triassic of Greenland (Bromley and Asgaard, 1979), the Devonian of Antarctica (Bradshaw et al., 2002), and the Cambro–Ordovician of Wales (Droser et al., 1994). At Cerro de Cristo Rey, *Arenicolites* isp. cross-cuts *Ophiomorpha nodosa* in this ichnoassemblage. This assemblage was observed at locality 10168. Sample NMMNH P-72005 (+ field photo “ophiomorpha and arenicolites”) is included in this ichnoassemblage.

4. *Palaeophycus striatus* ichnoassemblage—Fig. 5E, 5F, Locality 10169 (Members B & C, Fig. 1)

The fourth ichnoassemblage is mostly monospecific and hypichnial, with either isolated or densely clustered, semi-parallel *Palaeophycus striatus* burrows, and secondary *P. tubularis* (this could simply be weathered *P. striatus*). It is not uncommon to find densely populated, monospecific assemblages in the *Cruziana* ichnofacies, and this probably records an opportunistic fauna exploiting organic-rich material after a storm event. *P. striatus* cross-cuts itself, but a relationship with *P. tubularis* could not be established. Three samples fit the description of this ichnoassemblage, but only NMMNH P-71993 and P-72000 represent monospecific assemblages.

5. *Palaeophycus-Spongiomorpha* ichnoassemblage—Figs. 2C, 6A, 7A, 7B, Locality 10169 (Members B & C, Fig. 1).

The fifth ichnoassemblage has a higher diversity than the others, with dominant hypichnial *Palaeophycus striatus*, *P. tubularis* (small and medium morphotypes), *P. heberti*, and *Spongiomorpha* isp., also with epichnial and hypichnial *P. tubularis* and *Taenidium*. Several specimens of *Lockeia* isp. and *Bergaueria* isp. are found with this ichnoassemblage. *Bergaueria* isp. represents part of an equilibrium community found before/after tempestite deposition and possibly so does *Spongiomorpha* isp. NMMNH P-71981, P-71991, P-71992, P-71995, and P-71996, and others observed in the field, are included in this ichnoassemblage.

6. *Thalassinoides/Planolites-Chondrites* ichnoassemblage—Figs. 2A, 3A, 8A, 8B, Localities 10168, 10169, and 10170 (Members B & C, Fig. 1).

This ichnoassemblage is found in massive and finely laminated sandy siltstones. Traces are dominated by large *Thalassinoides* isp. and *T. paradoxicus*, as well as epichnial/endichnial *Chondrites* isp. and *Planolites* isp. In the western portion of the study area, the *Thalassinoides* isp. and *Planolites* isp. burrows are filled with bioclastic debris (dominated by *Cribratina texana*, Fig. 7E), but in the eastern portion there is little to no bioclastic debris in these same ichnofossils (Fig. 8B). Two specimens show *Planolites* isp. reworked by *Chondrites* isp. (NMMNH P-71983, P-71990) or *Ancorichnus* isp. (Fig. 2A, P-71998). This is the second piece of evidence in this study for a *Chondrites* isp. equilibrium fauna in the shales, which would have penetrated into deeper tiers, namely the tempestites below (or in other cases was infilled by the tempestite sediments). Samples included in this assemblage are NMMNH P-71983, P-71989, P-71990, P-71994, P-71997, P-71998, P-72002, and others observed in the field (Fig. 8A). One sample observed at locality 10168 contains the largest *Thalassinoides* burrow found in this study (Fig. 8B).

Similar ichnoassemblages were described by Pemberton and Frey (1984) from the Upper Cretaceous of Alberta, Canada, by Bayet-Goll et al. (2015) from the Upper Cretaceous of Iran, and from the Jurassic of Norway by McIlroy (2004) with *Thalassinoides* and *Planolites* associated with *Chondrites*.

7. *Cardioichnus* ichnoassemblage—Figs. 3E, 3G, Locality 10167 (Member C, Fig. 1).

The seventh ichnoassemblage is found in bioclastic packstones at locality 10167, and consists of *Cardioichnus* isp. and *Bichordites* isp. Bioclastic fragments are large, and *Bichordites* burrows meander as the echnoids worked their way through the bioclastic debris, evidently seeking out the top of the bed, because this is where all resting traces in this ichnoassemblage were found. NMMNH P-71976, P-71977, and an uncollected field specimen are all grouped within this ichnoassemblage.

8. *Spongiomorpha-Palaeophycus* ichnoassemblage—Figs. 6E & F, 7A & D, Locality 10169 (Members B & C, Fig. 1).

This ichnoassemblage contains hypichnial *Spongiomorpha* isp. and *Palaeophycus tubularis* (medium and large morphotypes). No other traces have been observed in this ichnoassemblage. *Palaeophycus tubularis* cross-cuts the *Spongiomorpha* isp. Samples included in this ichnoassemblage are NMMNH P-71999, P-72003, and P-72004.

Discussion

We interpret each of the ichnoassemblages described here as belonging to the *Cruziana* ichnofacies, with ichnoassemblages 1 and 2 containing ichnotaxa from the *Skolithos* ichnofacies. Tempestites (discussed below) in shales like those in the Mesilla Valley Formation have been associated with the *Cruziana* ichnofacies (e.g., Pemberton et al., 1992; Pemberton and

MacEachern, 1997; Mángano et al., 2005). Like our samples, they show a dominance of paschichnia and repichnia (i.e., Figs. 6A), opportunistic forms actively seeking food sources (i.e., Fig. 7A) or deposit feeders exploiting the nutrient-rich shales below (i.e., Fig. 5F).

Ichnoassemblages 1, 5, and 6 seem to contain ichnotaxa representative of a different ichnocoenose from equilibrium communities that were present either after or before the deposition of the coarser grained bed. Ichnoassemblage 1 contains *Chondrites intricatus* which originates from shales above. Ichnoassemblage 5 has hypichnial *Bergaueria* isp., which was preserved by infilling during deposition of the coarser grained bed. This ichnoassemblage also contains hypichnial *Spongeliomorpha* isp., with abundant scratchmarks from a tracemaker (crustacean?) that was possibly part of the equilibrium community before deposition of the coarser grained bed. Finally, ichnoassemblage 6 contains hypichnial *Thalassinoides* and *Chondrites*, which may also be from an earlier equilibrium community. No definitive traces were seen in the shales.

Ongoing field work at the contact between the Mesilla Valley Formation and the overlying Sarten Member of the Mojado Formation shows a vertical change in *Cruziana* ichnotaxa and ichnoassemblages, and a vertically increasing influence of the *Skolithos* ichnofacies, coinciding with progradation of the delta into the area (Lucas et al., 2010a). Preliminary observation of ichnoassemblages in the lowermost Mojado Formation indicates that ichnoassemblages change with the first bed of typical Mojado lithology.

Proximal *Cruziana* Ichnofacies

Overall, the diverse ichnoassemblages of the Mesilla Valley Formation contain a variety of ethological categories including repichnia, fodichnia and paschichnia, fixichnia and cubichnia, as well as domichnia. Horizontal structures dominate, with a secondary influence of vertical or inclined elements, which represents the *Cruziana* ichnofacies (Pemberton and Frey, 1984). Ichnotaxa of the Mesilla Valley Formation are representative of the proximal *Cruziana* ichnofacies (Seilacher, 1967; Buatois and Mángano, 2011; MacEachern et al., 2012), with secondary elements of the *Skolithos* ichnofacies. Both ichnofacies intergrade and are well-represented by modern analogues (MacEachern et al., 2012).

The *Cruziana* ichnofacies was first described by Seilacher (1967) and refined by others (Frey and Seilacher, 1980; Pemberton and Frey, 1984). It is characterized by a dominance of simple, superficial/shallow trace fossils combining locomotion, grazing, and dwelling structures, with very few escape structures. This trace fossil association suggests the activities of mobile carnivores and deposit feeders exploiting nutrient-rich, fine-grained sediments (Pemberton and Frey, 1984; Pemberton and MacEachern, 1997). The *Cruziana* ichnofacies is a high-diversity, high individual-density ichnofacies (Pemberton and MacEachern, 1997). Ichnoassemblages similar to those in the Mesilla Valley Formation showing *Skolithos* influence in *Cruziana* ichnoassemblages have been described from the Cretaceous of Utah (Frey and Howard, 1985b), Alberta, Canada (Pemberton and Frey, 1984; Raychaudhuri et al., 1992),

eastern New Mexico (Kues et al., 1985), Iran (Bayet-Goll et al., 2015), the Jurassic of Western India (Fürsich, 1998; Desai, 2012), and the Ordovician of Argentina (Aceñolaza and Aceñolaza, 2002).

Overall, the Mesilla Valley Formation at Cerro de Cristo Rey contains a background ichnoassemblage (in the shales) of *Thalassinoides* isp., *Bergaueria* isp., and *Chondrites intricatus* (and *Spongeliomorpha*?), and an opportunistic ichnoassemblage (in siltstones/sandstones) dominated by *Paleophycus tubularis*, *P. striatus* and *Planolites* isp., together with subordinately common occurrences of *Skolithos* isp., *Ophiomorpha nodosa*, *Cardioichnus* isp., and *Arenicolites* isp.

Importance of Tempestites

Study of the trace fossils and their host lithology within the Mesilla Valley Formation has revealed details about the paleoenvironment and paleoecology of the area during late Albian time. Dark gray to olive-colored, anoxic, organic-rich, marine shales make up the majority of the Mesilla Valley Formation (Scott et al., 2013), punctuated by storm deposits of siltstones/sandstones that are commonly bioclastic and/or bioturbated with angular sand grains (Lucas et al., 2010a). The storm deposits are massive, horizontally laminated, or contain hummocky cross strata (c.f. Gluszek, 1998). Individual bed thickness varies, but is usually between 5 and 30 cm. Beds closer to the upper contact of the formation are found in bundles. These sandy siltstones have sharp, often fluted bottoms (where unbioturbated) indicating erosive bases (Aigner, 1985; Pemberton and MacEachern, 1997). All these are characteristics of storm deposits (Howard, 1978; Dott and Bourgeois, 1982; Pemberton and MacEachern, 1997), termed “tempestites” by Seilacher (1982).

Tempestites represent fluctuations in depositional energy and sedimentation rate (Gluszek, 1998) and often have distinct proximal and distal signatures (Pemberton and MacEachern, 1997). They show the onset, culmination, and waning of water turbulence during an event, and they change the ecological situation for benthic organisms by redistributing sediment and organic material (Seilacher, 1982). Dott (1983) argued that much of the sedimentary record represents episodic deposition such as this.

Trace fossils in the Mesilla Valley Formation are mostly hypichnial, with the tops of beds heavily bioturbated and intermixed with muds, as conditions and sedimentation returned to normal (Pemberton et al., 1992). Our observations show that most of these tempestites in the Mesilla Valley Formation are bioclastic and coarse-grained to the west, and finer grained with higher ichnodiversity to the east. In addition, several of the passively filled trace fossils in the west also contain bioclastic fill, but these same traces contain finer-grained fill to the east (i.e., *Thalassinoides* isp., compare Fig. 8A and Fig. 8B). These differences across a 2 km west-to-east transect in lithology and trace-fossil assemblage warrant further investigation.

Most trace fossils are only found in the sand/silt tempestite beds, with the exception of *Thalassinoides paradoxicus*, *Planolites* isp., *Bergaueria* isp., and *Chondrites intricatus*

(and possibly *Spongeliomorpha* isp.). This preservation bias has been described from the Cretaceous of Utah (Frey and Howard, 1985b) and the Triassic of Spitsbergen (Worsley and Mørk, 2001). It shows that not only did the storm events transport sediment into the area, but they also supplied oxygen to a dysoxic system. The opposite has also been described, with relatively unbioturbated tempestites in the presence of a diverse equilibrium fauna in the shales (Gingras et al., 2009). Traces restricted to the tempestites likely represent an opportunistic (“r-selected” of Pemberton and MacEachern, 1997) fauna that was introduced during storm-related deposition (Ekdale, 1988; Taylor and Goldring, 1993; MacEachern et al., 2007). Traces in the shales would represent a fair-weather, or equilibrium fauna (“K-selected” of Pemberton and MacEachern, 1997). The shales of the Mesilla Valley Formation are finely laminated, so evidence of bioturbation should be obvious. The only evidence of an equilibrium fauna in the shales are multiple examples of *Chondrites* traces on upper bedding planes at localities 71987 and 71988, *Chondrites* reworking other forms such as *Planolites* isp. and *Palaeophycus* isp., and also the presence of *Bergaueria* isp. and *Spongeliomorpha* isp. in convex hyporelief on a few samples (Figs. 2C, 6F).

Benthic Dysoxia

The low number of equilibrium fauna (*Chondrites* isp., *Bergaueria* isp., *Thalassinoides* isp., and *Planolites* isp.) in the Mesilla Valley Formation might be the result of dysoxic conditions at the sea floor (Ekdale and Mason, 1988; MacEachern et al., 2007), specifically from Oceanic Anoxic Event (OAE) 1d, which was recently identified in the upper Mesilla Valley at Cerro de Cristo Rey by Scott et al. (2013) and may coincide with another event at the Albian-Cenomanian boundary in Alberta, Canada (Leckie et al., 1992). Scott et al. (2003) also correlated the east Texas Albian Pawpaw Formation with the latest Albian Breistroffer Interval, a time of organic-rich sedimentation and probably part of OAE1d. As mentioned above, and often in the literature, *Chondrites* is associated with anoxia/dysoxia in sediments, and the ichnoassemblages from the Mesilla Valley Formation supports this. Thus, the shales of the Mesilla Valley Formation preserve a dysoxic assemblage that is linked to independent geochemical evidence for benthic oxygen conditions (Scott et al., 2013). This is important for understanding the relationship between dysoxic conditions and its effect on the ichnotaxa present (Martin, 2004). In fact, the identification of OAE1d in this unit was the first step in a multidisciplinary approach to reconstructing paleoenvironmental conditions in the area during latest Albian time. Interestingly, Scott et al. (2013) show that OAE1d was not a simple event, but instead had a dysoxic precursor. Detailed stratigraphic placement of ichnoassemblages may confirm this.

A few other examples of impoverished ichnofauna in the literature include the Lower Cretaceous Wilrich Member (Spirit River Formation) of Alberta, Canada (Bann and Ross, 2014), the Plio-Pleistocene Choshi Group, Japan (Katsura et al., 1984), and the Middle Jurassic Jaisalmer Formation,

India (Kulkarni et al., 2008). In contrast, and interestingly, one study of ichnofauna of the lower Toarcian (Jurassic) OAE showed little evidence for anoxia in the ichnofauna (Rodríguez-Tovar and Uchman, 2008).

Future Work

Detailed stratigraphic sections and correlation of tempestites (storm deposits) within the Mesilla Valley Formation would aid in the interpretation of ichnofossils at Cerro de Cristo Rey. Some excavation and rock slabbing is sure to reveal additional ichnotaxa, particularly those that weather away quickly after exposure or are yet undiscovered within certain units.

Also, the upper contact of the Mesilla Valley Formation was arbitrarily placed at a particular 30-cm-thick bed by Strain (1976), and later redefined by Lucas et al. (2010a) at the “first traceable sandstone of typical Mojado lithology.” Current fieldwork and analysis may provide a more precise stratigraphic horizon for the contact with the overlying Mojado Formation. Designation of other stratigraphic boundaries using ichnology has been advocated by some (Taylor and Goldring, 1993; Pemberton and MacEachern, 1997). It is possible that this stratigraphic boundary can be designated based not only on the first appearance of typical Mojado lithology, but also by a change in ichnotaxa.

Finally, the recognition of an OAE in the Mesilla Valley Formation also warrants further detailed study of this unit comparing geochemistry and detailed biostratigraphy (and ichnoassemblage analysis). This has important implications for understanding the dysoxic shelf during late Albian time. It also can aid in characterizing the Mesilla Valley Formation as a hydrocarbon source rock (see Arthur and Schlanger, 1979), particularly for petroleum plays in the Chihuahua trough sediments of northern Mexico.

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Appendix 1: Glossary of Ichnological Terms

Ichnology of the Lower Cretaceous (Albian) Mesilla Valley Formation, Cerro de Cristo Rey, southeastern New Mexico, USA

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- Hypichnia: traces on the soles of strata.
- Epichnia: traces on the tops of strata.
- Hyporelief: traces exposed on the soles of strata.
- Endichnia: traces found wholly within strata.
- Repichnia: a trace from locomotion.
- Domichnia: a dwelling structure.
- Fixichnia: a trace from organisms anchored in the substrate.
- Epirelief: traces exposed on the tops of strata.
- Cubichnia: a resting or stopping trace.
- Paschichnia: a surface-grazing trace.
- Fodichnia: feeding traces.
- Hypofaunal: referring to traces on the bottoms of strata.
- Fugichnia: escape traces.