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THE BIOTA AND PALEOECOLOGY OF THE UPPER PENNSYLVANIAN (MISSOURIAN) TINAJAS LOCALITY, SOCORRO COUNTY, NEW MEXICO

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Abstract—Upper Pennsylvanian (Missourian) strata of the Tinajas Member of the Atrasado Formation in the Cerros de Amado, Socorro County, include an unusual lacustrine deposit, the Tinajas locality. This locality yields a diverse fossil assemblage of plants, crustaceans, insects, a cnidarian, molluscs and fishes from laminar black shale that contains a prolific conchostracan assemblage. A lacustrine origin of the black shale is supported by the abundance of conchostracans; presence of darwinuloid (freshwater) ostracods, land plants and insect wings; lack of marine indicators; and the lithology and geometry of the deposit. Overlying gray shales are full of *Dunbarella*, which indicates the onset of nearshore, marginal marine conditions. Indeed, the stratigraphic succession at the Tinajas locality is analogous to a classical cyclothem. Thus, fluvial/deltaic deposits grade upward into a coastal lake that is then transgressively overlain by marginal marine and fully marine sediments. The preservation of the lacustrine sediments at the Tinajas locality was a local, unique event on the Late Pennsylvanian coastline in central New Mexico, as no other occurrence of a similar paleoenvironment is known.

INTRODUCTION

Pennsylvanian strata in New Mexico comprise interbedded marine and nonmarine clastic and carbonate sediments deposited in basins of the ancestral Rocky Mountain orogeny. These strata yield a diverse fossil biota dominated by characteristic late Paleozoic invertebrates, including brachiopods, crinoids and bryozoans. However, New Mexico's Pennsylvanian strata also contain a growing record of nonmarine fossils, especially of plants, arthropods and vertebrates. Particularly significant in this regard are two Late Pennsylvanian localities, the Kinney Brick quarry in the Manzanita Mountains (Zidek, 1992) and Carrizo Arroyo in the Lucero uplift (Lucas and Zeigler, 2004). The Tinajas locality (NMMNH locality 4667: Figs. 1-2) is a third significant Late Pennsylvanian site that yields a diverse fossil flora and fauna, including several taxa previously unknown from the Upper Pennsylvanian of New Mexico. Here, we provide an overview of the geology, sedimentology and the biota of the Tinajas locality, and discuss the paleoecology of the site. In this article, NMMNH refers to the New Mexico Museum of Natural History and Science, Albuquerque; and USNM refers to the National Museum of natural History, Smithsonian Institution, Washington, D. C.

HISTORY OF STUDY

In 2000 two students at New Mexico Tech, Ed Frye and Mike O'Keefe, showed one of us (SGL) a black shale bed in the Atrasado Formation in the Cerros de Amado (NMMNH locality 4629) that yielded numerous fossils of conchostracans and is overlain by a gray shale bed containing numerous bivalves, *Dunbarella*. This first site, NMMNH locality 4629, in sec. 25, T2S, R1E, is on a vegetation-covered slope and merited further excavation. However, by 2001, Mike Ripperger and one of us (AJL) discovered the same bed in the wall of a tributary of Tinajas Arroyo (Figs. 2-3). This locality, NMMNH locality 4667, also in sec. 25, T02S,

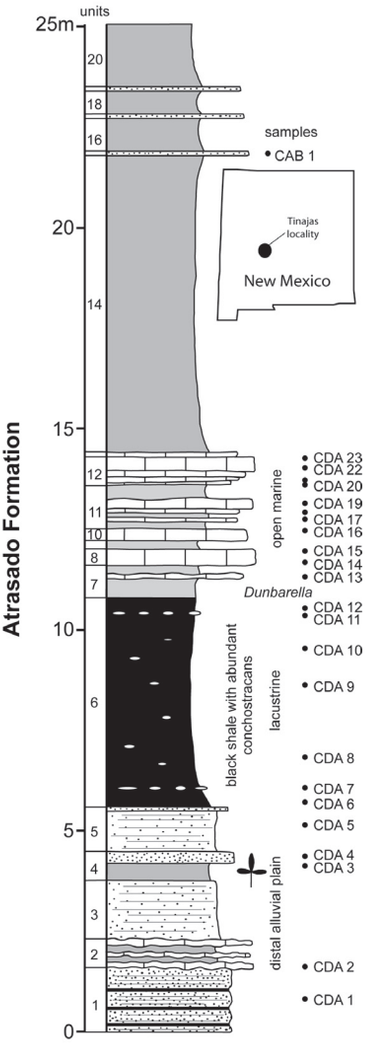


FIGURE 1. Measured stratigraphic section at the Tinajas locality. See text for description of lithographic units.

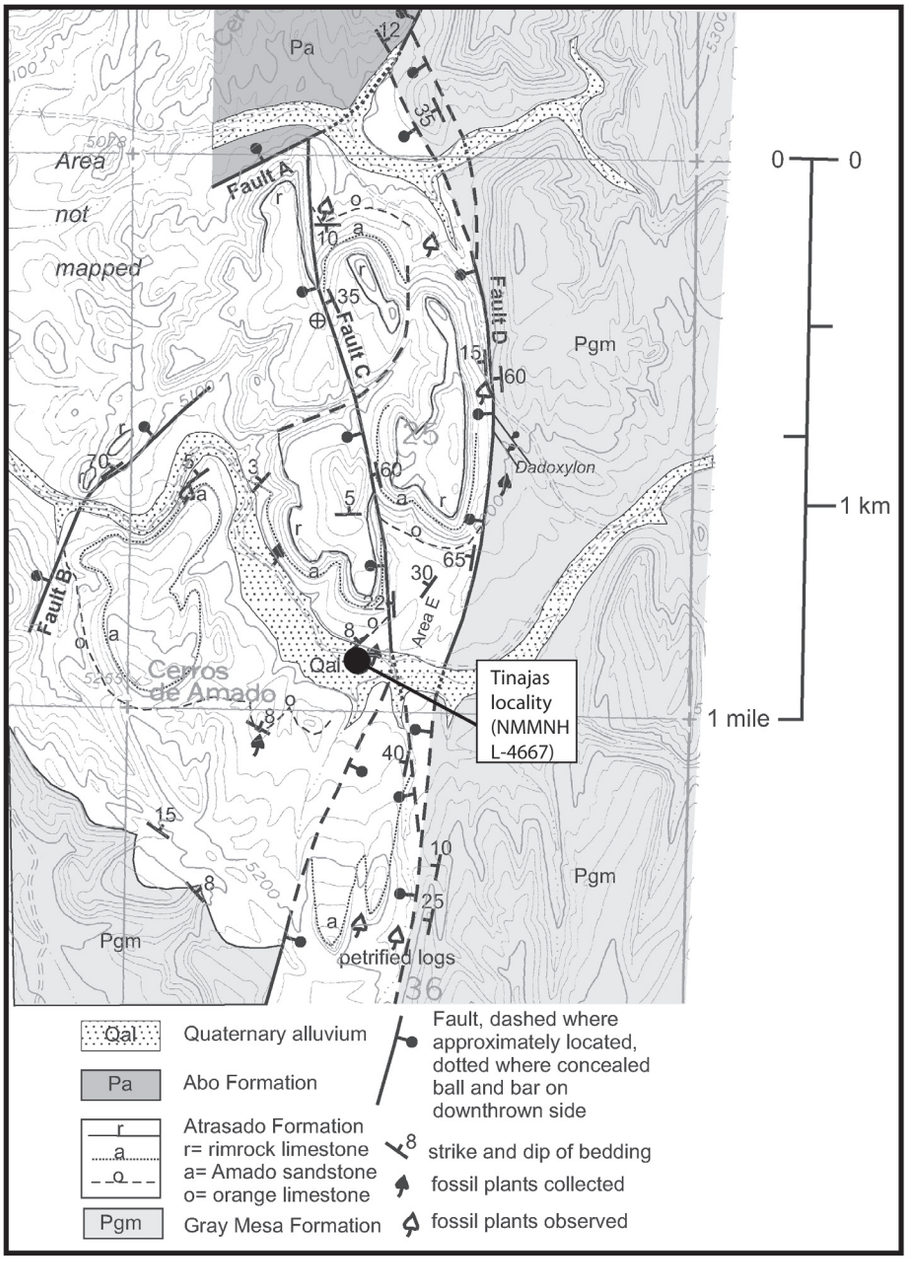


FIGURE 2. Geologic map of part of the Cerros de Amado area (sec. 25, T2S, R1E and adjacent area), Loma de las Cañas 7.5-minute quadrangle, Socorro County, with the Tinajas locality (NMMNH L-4667) highlighted.

R01E, is about 1.2 km due south of locality 4629. Hereafter, we refer to NMMNH locality 4667 as the Tinajas locality, named for nearby Tinajas Arroyo. In 2001, subsequent exploration discovered the same black shale cropping out another 0.2 km south-southeast of locality 4667, at NMMNH locality 4966. Thus, the black shale (and the lacustrine paleoenvironment it represents, see below) has a known lateral extent (strike) of at least 1.4 km.

STRATIGRAPHY AND SEDIMENTOLOGY

The strata at the Tinajas locality are in the Upper Pennsylvanian Atrasado Formation (Fig. 2). The site is in the strata that Rejas (1965) termed the "Adobe-Coane undifferentiated," a stratigraphic unit about 100-m-thick that consists mostly of slope-forming gray and olive-gray shale and siltstone. The Adobe and Coane units originally were named as formations in the northern Oscura Mountaisn of Socorro County by Thompson (1942), but are limestone-dominated stratigraphic units at their type sections, so use of Thompson's formation names, Adobe and Coane, in the Socorro area is problematic. Therefore, Lucas et al. (this guidebook) name this stratigraphic interval the Tinajas Member of the Atrasado Formation and assign it a late Missourian age based on conodont biostratigraphy.

At NMMNH locality 4667, the lower 5.6 m of the exposed Tinajas Member (Fig. 1, units 1-5 below the black shale) are composed of greenish, micaceous siltstone to fine-grained sandstone

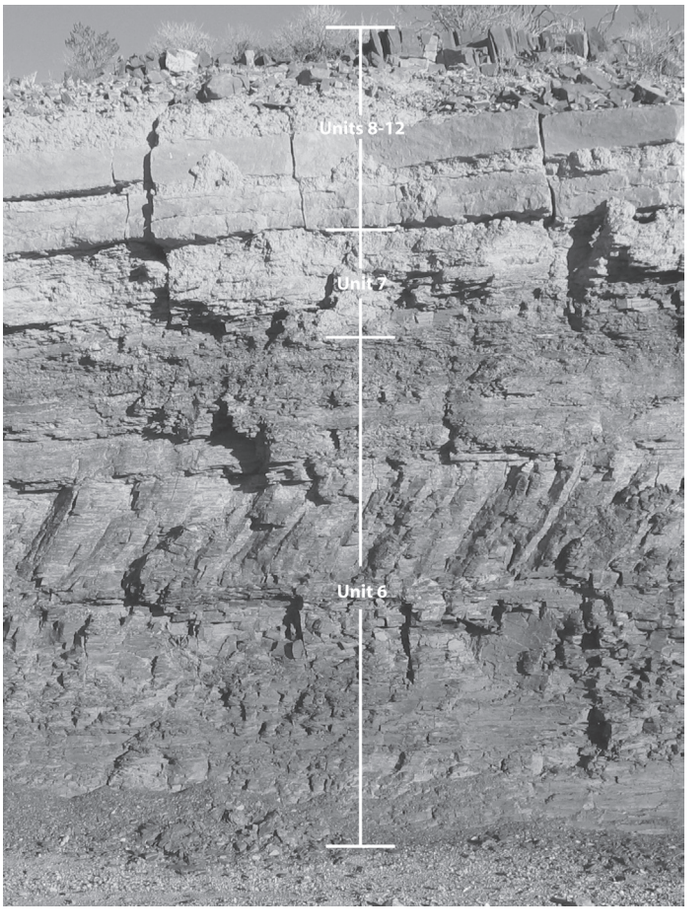


FIGURE 3. Photograph of the Tinajas locality. Numbers refers to units in the measured section in Figure 1.

with intercalated thin shale intervals, thinly laminated, coarse-grained siltstone to fine-grained sandstone beds, very micaceous, greenish silty shale containing fossil plants (seed ferns) and a 0.7-m-thick interval of three thin, nodular limestone beds intercalated with thin greenish shale. The limestone is a fine-grained conglomerate containing subangular to rounded, recrystallized, micritic intraclasts floating in a micritic matrix in which peloids may be observed. Locally, circumgranular shrinkage fissures are observed. Fossil ostracods are present but rare. The siltstone above the limestone contains small, reworked limestone clasts up to a few mm in diameter. Siltstone in the upper part of the succession contains plant debris on bedding planes.

The siltstone interval is overlain by a 5.2- to 7-m-thick black shale bed (Fig. 1, unit 6) that contains abundant conchostracans and a few small carbonate concretions. In the lower part, a bed with flat carbonate concretions composed of homogeneous micrite is present. A horizon with flat carbonate nodules (concretions) is also present near the top. The black shale is fissile in the lower part and laminated in the upper part.

A sample taken from the lowermost part of the black shale (Fig. 1, CDA 6) appears indistinctly laminated and dark brownish-gray to black under the microscope. The black shale is composed of calcite, quartz, kaolinite, ferroan phlogopite and chlinochlor (X-ray analysis). It contains abundant tubular structures in distinct horizons (Fig. 4A). These structures are approximately 0.5 mm in diameter, with a 0.05- to 0.1-mm-thick wall. The interior is mostly filled with calcite cement, rarely with mud (Fig. 4A). A few shell fragments (conchostracans) are present. In the upper part (Fig. 1, sample CDA 11), the shale is laminated and contains a few small black plant fragments (Fig. 4B). Individual laminae are less than 0.1 mm thick and lens out laterally. The laminae may also be slightly folded.

The black shale is overlain by brownish-gray shale grading upward to greenish shale that contains abundant fossil molluscs of the genus *Dunbarella*. The *Dunbarella* bed (Fig. 1, unit 7) is a fissile coquina largely composed of vast numbers of densely packed, decalcified, complete valves of the bivalve *Dunbarella*. A 3-5-cm-thick wavy limestone bed (Fig. 1, unit 7) is present above the *Dunbarella* shale. This thin limestone is composed of fine-grained, bioturbated bioclastic wackestone with a few large bioclasts. Brachiopod shell fragments and spines are common, whereas crinoid fragments, ostracods and a few smaller foraminifers are less common. A few bioclasts are encrusted by cyanobacteria (*Palaeonubecularia*).

Above this limestone are two limestone beds, 0.4 m [unit 8] and 0.3 m [unit 10] thick, separated by a thin shale interval (unit 9). The lower limestone bed (Fig. 1, unit 8) consists of bioclastic wackestone and locally of boundstone. The wackestone is partly bioturbated. Bioclasts include brachiopod shells and spines, crinoids, subordinate bryozoans, ostracods, rare smaller foraminifers (*Globivalvulina, Hemigordius* ex. gr. *harltoni* [Fig. 5D], *Planoendothyra* [Fig. 5G], *Syzrania* [Fig. 5F], *Tetrataxis* [Fig. 5E]) and trilobite fragments embedded in micritic matrix. Locally abundant encrusting organisms are present such as cyanobacteria and *Palaeonubecularia* transitional to *Tubiphytes* forming patches of boundstone (Fig. 5A-C).

The upper limestone bed (Fig. 1, unit 10) is a coarse-grained, crinoidal wackestone containing abundant crinoid stem fragments (mostly up to 2 mm, rarely up to 5 mm in diameter), subordinate brachiopod shells and spines and a few bryozoans, ostracods, rare trilobite fragments and very rare smaller foraminifers in micritic matrix (Fig. 4C). The limestone beds are overlain by a 1.1-m-thick shale interval with abundant thin limestone lenses in the lower part and a 0.2-m-thick limestone bed in the middle (Fig. 1, unit 11). The shale is brownish below the limestone bed, dark gray above and contains abundant brachiopods.

The limestone (Fig. 1, unit 11) is composed of bioclastic wackestone, partly bioturbated, coarse-grained and poorly sorted with large bioclasts floating in fine-bioclastic micritic matrix. Most abundant are crinoids, brachiopod fragments and bryozoans in varying amounts (Fig. 4D). Less abundant are small gastropods, ostracods, smaller foraminifers, bivalves and rare trilobite fragments. Bioclasts are dispersed in a non-homogeneous micritic matrix. A few bioclasts are encrusted by cyanobacteria (*Claracrusta* and *Palaeonubercularia*).

On top of this shale interval (Fig. 1, unit 11) dark gray, brownish-weathered, micritic, bedded limestones are present (Fig. 1, units 12 and 13). On outcrop, solitary corals are observed. The limestones are composed of bioclastic and intraclast wackestone.

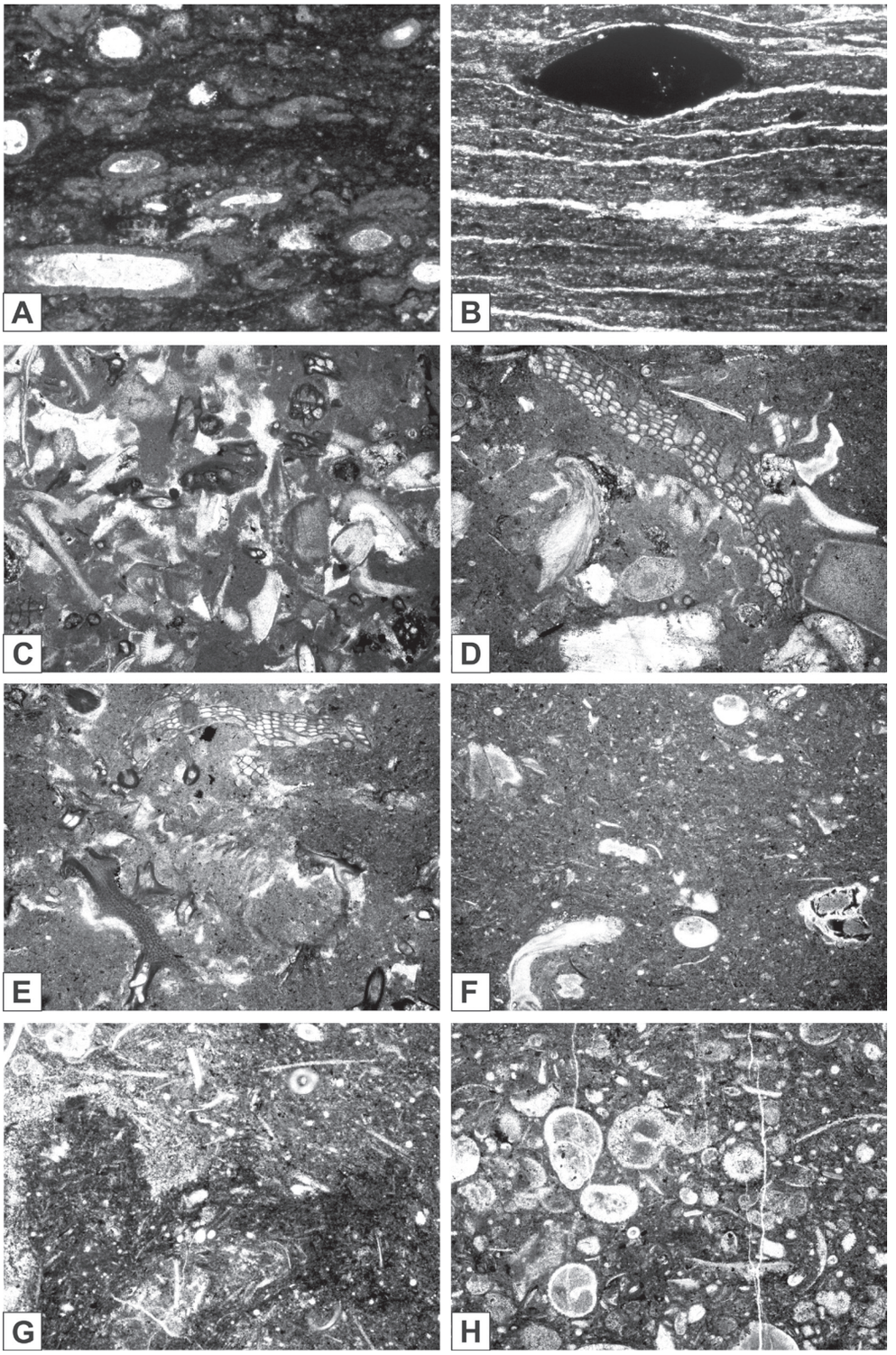


FIGURE 4. Thin section photographs of black shale and overlying limestone at the Tinajas locality. See Figure 1 for sample horizons. **A**, Black shale containing abundant tubular structures (sample CDA 6, width of photograph is 3.2 mm). **B**, Laminated black shale with a small plant fragment (sample CDA 11, width of photograph is 1.2 mm). **C**, Crinoidal wackestone, subordinately containing brachiopod, bryozoans and rare trilobite fragments (sample CDA 16). **D**, Coarse-grained bioclastic wackestone containing crinoid fragments, bryozoans, brachiopods and rare trilobite fragments (sample CDA 17). **E**, Bioclastic wackestone with abundant bryozoan fragments embedded in micritic matrix (sample CDA 18). **F**, Fine-grained bioclastic wackestone with few larger bioclasts such as bryozoans and shell debris, and very small bioclasts floating in micritic matrix (sample CDA 19). **G**, Fine-grained, bioturbated, bioclastic wackestone composed of spicules, echinoderm fragments, bryozoans, gastropods, brachiopods and other bioclasts embedded in micrite (CDA 20). **H**, Bioclastic wackestone/packstone containing abundant fragments of crinoids and gastropods, some other bioclasts and micrite (sample CDA 21). Width of photos **C-H** is 6.3 mm.

The bioclastic wackestone is similar to that of the shale interval below with a few large and abundant small skeletons dispersed in micritic matrix. Common fossils include crinoids, brachiopod shells and bryozoans (Fig. 4E-F). Less common are gastropods, ostracods, brachiopod spines, smaller foraminifers (*Calcitornella* [Fig. 5J], *Globivalvulina,* glomospiroid *Miliolata* [Fig. 5H-I], *Hemigordius* ex gr. *harltoni* [Fig. 5K-L, N, P, R-T], *Hemigordius* sp. 2 [Fig. 5M, Q], *Spireitlina* [Fig. 5O], *Syzrania*), corals and trilobite fragments. Locally, spicules are abundant. Encrustations are rare. The intraclast wackestone is coarse-grained and contains abundant recrystallized intraclasts up to 10 mm (mostly up to 1 mm) in diameter. Skeletons present include brachiopod shell debris, gastropods, ostracods, bryozoans, brachiopod spines and rare calcivertellid foraminifers. The matrix is recrystallized micrite (Fig. 4H).

The limestone (Fig. 1, units 12-13) is overlain by a 23.7-m-thick succession composed mainly of greenish (partly brownish) shale to fine-grained siltstone, partly sandy in the upper part with ripple laminations (Fig. 1, units 14-26 and strata above them). Intercalated are a few 0.1- to 0.2-m-thick, fine-grained sandstone beds. The sandstone beds may be massive, horizontally laminated, or ripple laminated (small-scale current ripples). The lowermost sandstone bed (Fig. 1, unit 15) contains fossil plants (*Calamites*). In the upper part, two 0.6-m-thick, fine-grained, ripple-laminated micaceous sandstones are present but are unfossiliferous.

BIOTA

Plants

Occurrence and Preservation

Three horizons of plant-bearing shales were identified in the vicinity of NMMNH locality 4667. One, Cerros de Amado #1 (USNM localities 41894 and 41913), is below the black shale horizon at the base of the arroyo adjacent to the main collecting site (NMMNH 4667), one is in the black shale (Cerros de Amado #2: USNM locality 41895), which is the focus of this report, and one is above the black shale, Cerros de Amado #3 (USNM locality 41911), at the top of the section (Fig. 1) described in this report. All three of these have substantially the same floristic composition, though the taphonomy differs considerably among the three localities. Here, we will discuss only the flora of the black, laminated shale (Fig. 1, unit 6).

Complementing the collections made by the New Mexico Museum of Natural History at the Tinajas locality, NMMNH locality 4667, the National Museum of Natural History (USNM) made collections from the same black shale unit, 500 m to the SW at Cerros de Amado #2 (USNM locality number 41895). At the USNM collecting site, the black shale is exposed in an area of low breaks. Two people spent 3 ½, 8-hour days collecting from this site. All specimens from this collection are housed in the Paleobotanical Collections of the National Museum of Natural History. Mapping in the area of the USNM collecting site (Fig. 2) reveals that the black shale bed is widespread throughout the area and thicker than exposed in the arroyo itself, reaching a maximum thickness of 6 m.

Both in the main arroyo (NMMNH 4667) and in the subsidiary location (USNM 41895), plant fossils are extremely uncommon in the black shale bed. They are most often found in several very thin horizons, each only a few mm thick, but also occur scattered throughout the black shale matrix. In the zones of concentration, plant fossils are significantly more common than in the matrix on average, yet they are still quite rare. The lateral extent of these thin layers could not be ascertained. They seemed to disappear laterally, but this may partly reflect the fact that this shale is fissile only where it is weathered.

Also found in the course of excavating the black shale for plants, were small, elongate coprolites (probably from fish, though no fish macrofossil debris was observed), linguloid inarticulate brachiopods, and rare conchostracans. Locally, on some bedding planes, what appeared to be invertebrate feeding trails were found, but these did not disrupt sediment laminae, and no evidence of sediment burrowing was recorded.

Plant fossils are mainly small- to medium-sized fragments, including isolated pinnules, pinnae (of leaves that were compound) and branches (Fig. 6). The best preserved and most recognizable fossils are iron-oxide coated or possibly impregnated, giving them a reddish to orange color against the black shale. Others are preserved as organic compressions. Preservation can be quite exquisite.

The fossil flora includes the following elements:

Seed plants:
- *Neuropteris* cf. *N. subauriculata* (Fig. 6A)
- *Odontopteris* cf. *O. lingulata*
- ?*Alethopteris* sp. (Fig. 6B)
- *Cordaites* sp.
- *Walchia* sp. (Fig. 6E)
- *Walchia* cone scales (Fig. 6F)
- *Dicranophyllum* sp. (Fig. 6G)
- *Charliea manzanitana*

Sphenopsids:
- Calamite stems
- *Asterophyllites equisetiformis*
- *Annularia sphenophylloides*
- *Sphenophyllum emarginatum*
- *Sphenophyllum oblongifolium*

Lycopsids:
- Unidentified lycopsid stem
- cf. *Sigillaria bra*

Ferns or Incertae Sedis
- *Pecopteris* sp. (Fig. 6C-D)
- *Sphenopteris* spp.

Invertebrates

Conchostracans

Conchostracans are bivalved branchiopod crustaceans that are considered reliable indicators of freshwater depositional environments. Their valves are highly abundant at the Tinajas locality

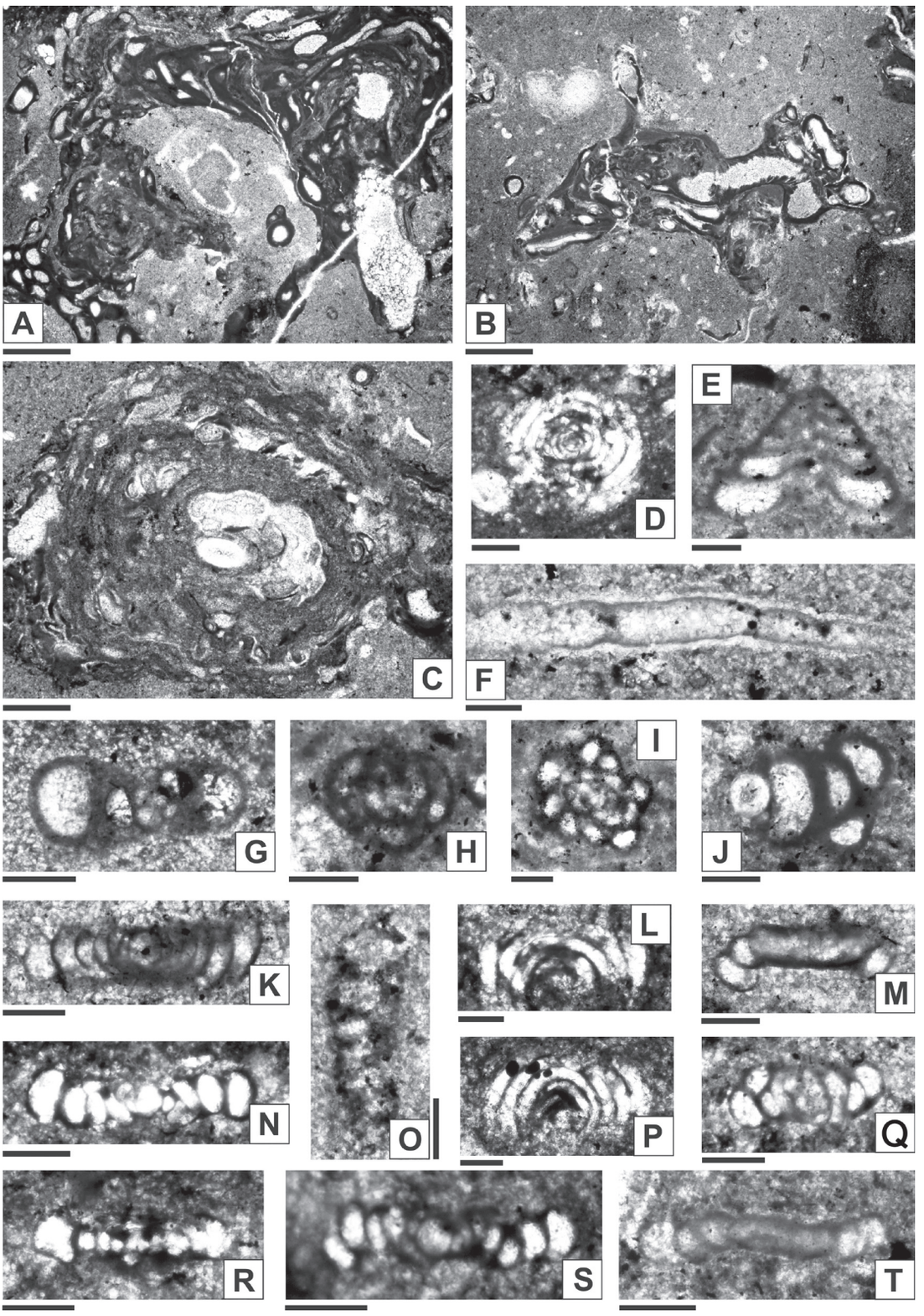


FIGURE 5. Thin section photographs of fossils from limestones above the black shale horizon at the Tinajas locality. See Figure 1 for sample horizons. Scale bar of **A-C** is 1 mm, of **D-U** is 0.1 mm. **A-C**, *Palaeonubecularia* transitional to *Tubiphytes*, forming bindstone (**A**, sample CDA 14) and oncoid-like structures (**B-C**, sample CDA 15). **D**, *Hemigordius* ex gr. *H. harltoni* (sample CDA 13). **E**, *Tetrataxis* sp. (sample CDA 14). **F**, *Syzranella* sp. (sample CDA 14). **G**, *Planoendothyra* sp. (sample CDA 13). **H-I**, glomospiroid *Miliolata* = "*Glomospira*" or *Hemigordiellina* (H sample CDA 21, I sample CDA 20). **J**, *Calcitornella* sp. (sample CDA 22). **K-L, N**, **P**, **R-T**, *Hemigordius* ex gr. *H. harltoni* (various sections; **K**, **T** sample CDA 22, **L**, **N**, **P**, **R-S**, sample CDA 23). **M**, **Q**, *Hemigordius* sp. 2 (sample CDA 22). **O**, *Spireitlina* sp. (sample CDA 14).

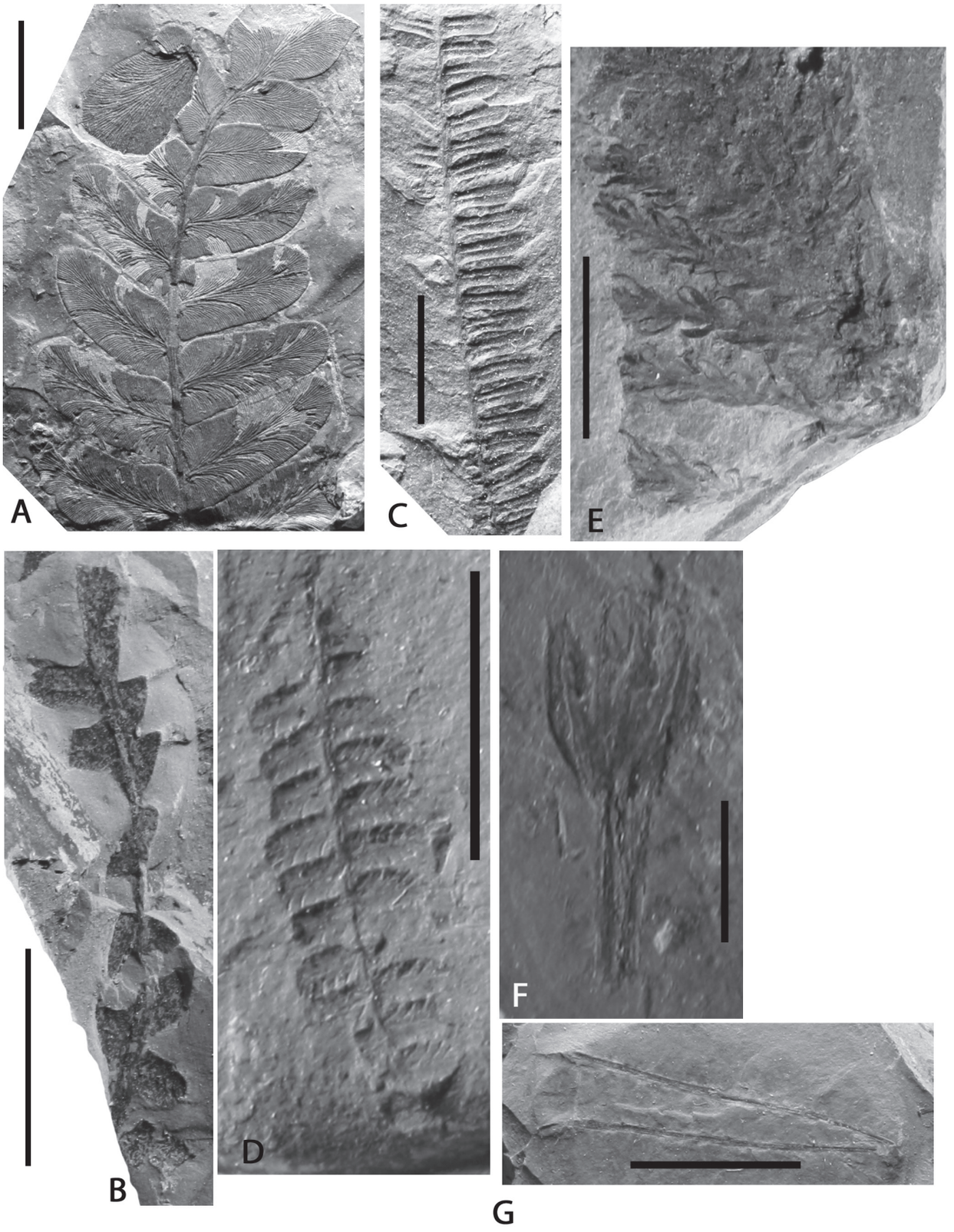


FIGURE 6. Selected fossil plants from the Tinajas locality (NMMNH L-4667). **A**, *Neuropteris* cf. *N. subauriculata*, NMMNH P-40166. **B**, ?*Alethopteris* sp., NMMNH P-37638. **C**, *Pecopteris* sp., NMMNH P-40167. **D**, *Pecopteris* sp., NMMNH P-43151. **E**, *Walchia* sp., NMMNH P-40172. **F**, Walchian cone scale, NMMNH P-42199. **G**, *Dicranophyllum* sp., NMMNH P-37646. Scale bars = 1 cm.

black shale (Fig. 1, unit 6) and they are undoubtedly autochthonous elements. The valves are primarily found flattened along bedding plane surfaces, which is typical of conchostracan preservation in other Carboniferous localities. A small number of Tinajas locality valves show minimal effects from compaction and retain their original curvature.

Martens and Lucas (2005) provided a detailed study of the Tinajas locality conchostracan assemblage. They determined that certain characteristic features of the larval shell warranted the naming of a new species, *Lioestheria carinacurvata*. *Lioestheria* is a cosmopolitan genus that ranges from the latest Carboniferous (Stephanian) to the Early (?Middle) Permian (Martens and Lucas, 2005). *L. carinacurvata* is presently known only from the Tinajas locality.

?Pygocephalomorph

Late Paleozoic pygocephalomorph crustaceans are found in nearshore marine and freshwater settings (Taylor et al., 1998). They are thought to have been low level carnivores and scavengers (Schram, 1976). A fragmentary specimen (P-40205) from the Tinajas locality black shale (Fig. 1, unit 6) is thought to be a pygocephalomorph crustacean carapace (Fig. 7C). It is probably a molt, which makes assignment difficult. Schram (1976) noted a characteristic pygocephalomorph-syncarid association within Upper Carboniferous fresh to brackish water faunas of Europe and North America. Thus, the finding of a possible pygocephalomorph is not surprising considering that syncarids are relatively common in the Tinajas locality assemblage. Pygocephalomorphs ranged in age from Mississippian to Permian (Brooks, 1969). There are no prior reports of pygocephalomorphs from New Mexico.

Syncarida

New Mexico's fossil record contains two endemic occurrences of syncarid crustaceans. *Uronectes kinniensis* Schram and Schram, 1979, is known from the Virgilian Kinney Brick quarry, and *Erythrogaulos carrizoensis* Schram, 1984, is known from the upper Virgilian Carrizo Arroyo section. There are eleven known specimens of *U. kinniensis* and three of *E. carrizoensis*. An addition to this important New Mexico syncarid record comes from the Tinajas locality black shale (Fig. 1, unit 6). Twenty-one specimens (e.g., Fig. 7E-F) have been found, which makes the Tinajas locality highly productive of syncarids when compared to the other localities.

Characteristic features of the Tinajas syncarids include a much reduced first thoracomere, second and third raptorial thoracopods, a small rostrum, spinescent pleomeres, a spinescent spatulate telson and distally rounded uropods bearing strong median ribs and spines. Transversely striate segment decoration is not apparent. Lerner and Lucas (2002), in a preliminary examination of the Tinajas syncarids, mistakenly interpreted two long spines along the terminus of the telson as furcae. This led them to consider a possible placement of the specimens within the Anaspidacea. It is now clear that the Tinajas syncarids belong within the Palaeocaridacea and that they may represent a new species of *Palaeosyncaris*. They are relatively small, although distinct from *Palaeosyncaris micra*, which is known from Mazon Creek.

Ostracoda

There is an abundant ostracod fauna in the Tinajas locality black shale (Fig. 1, unit 6), which has received only preliminary study. Two groups of ostracods can be recognized. The first group is most numerous and consists of elongate valves of differing sizes. Most of these are oriented parallel to the bedding plane, with their external valve surfaces exposed. A few valves are seen on edge, which exposes a thin profile. The valve surfaces appear smooth, and conspicuous muscle scars are not detected. We tentatively identify this form as ?*Carbonita* sp., although they could be *Darwinula*, in which the characteristic muscle scars did not preserve. The second form is known from only a few specimens, which we refer to *Geisina* sp. (Fig. 8C). These specimens have smooth carapaces and display a conspicuous median sulcus. The presence of *Geisina* may indicate periods of increased brackishness to mesohaline levels compared to beds where ?*Carbonita* dominates (H. Kozur, pers. commun., 2009).

Insecta

Six insect fossils, all cockroaches (Blattida), have been collected from the Tinajas locality black shale (Fig. 1, unit 6). Five of the six specimens belong to the mylacrid genus *Neorthroblattina*. One of these is a nearly complete forewing, approximately 12 mm long (Fig. 7D). An isolated, ~7 mm wide, head shield (Fig. 7A) is identified as *Neorthroblattina* because of its radial color strips, which are typical of the taxon; in addition, one isolated analfield and two other wing fragments likely pertain to this genus. *Neorthroblattina* occurs in some Late Carboniferous (Pennsylvanian or Stephanian, respectively) and Early Permian faunas of Europe and North America, but is generally rare. Thus, it is found in the Sharp Mountain, Westphalian C of Pennsylvania, the Stephanian Lawrence Shale of Kansas, the Wettin subformation in Germany, the Early Permian (Asselian) Fairplay locality in Colorado and the Goldlauter Formation of equivalent age in Germany (Schneider, 1980, 1983). Overall, *Neorthroblattina* is found in semihumid to semiarid paleoenvironments.

A single spiloblattinid forewing fragment of *Sysciophlebia* cf. *S. grata* (Fig. 7B) is the most biostratigraphically informative specimen from Tinajas. The directed development of color patterns in the wings of spiloblattinids allows for a high-resolution biozonation of nonmarine deposits (e.g. Schneider, 1982; Schneider and Werneburg, 2006). The wing venation in NMMNH P-40189 is framed by medium wide dark bands, which is characteristic of *S. grata*, a typical early to middle Stephanian species.

Mollusca

The Tinajas locality black shale yielded a single specimen of a bivalve (Fig. 8A), which consists of a left valve compressed along the bedding plane. The valve is ornamented, with numer-

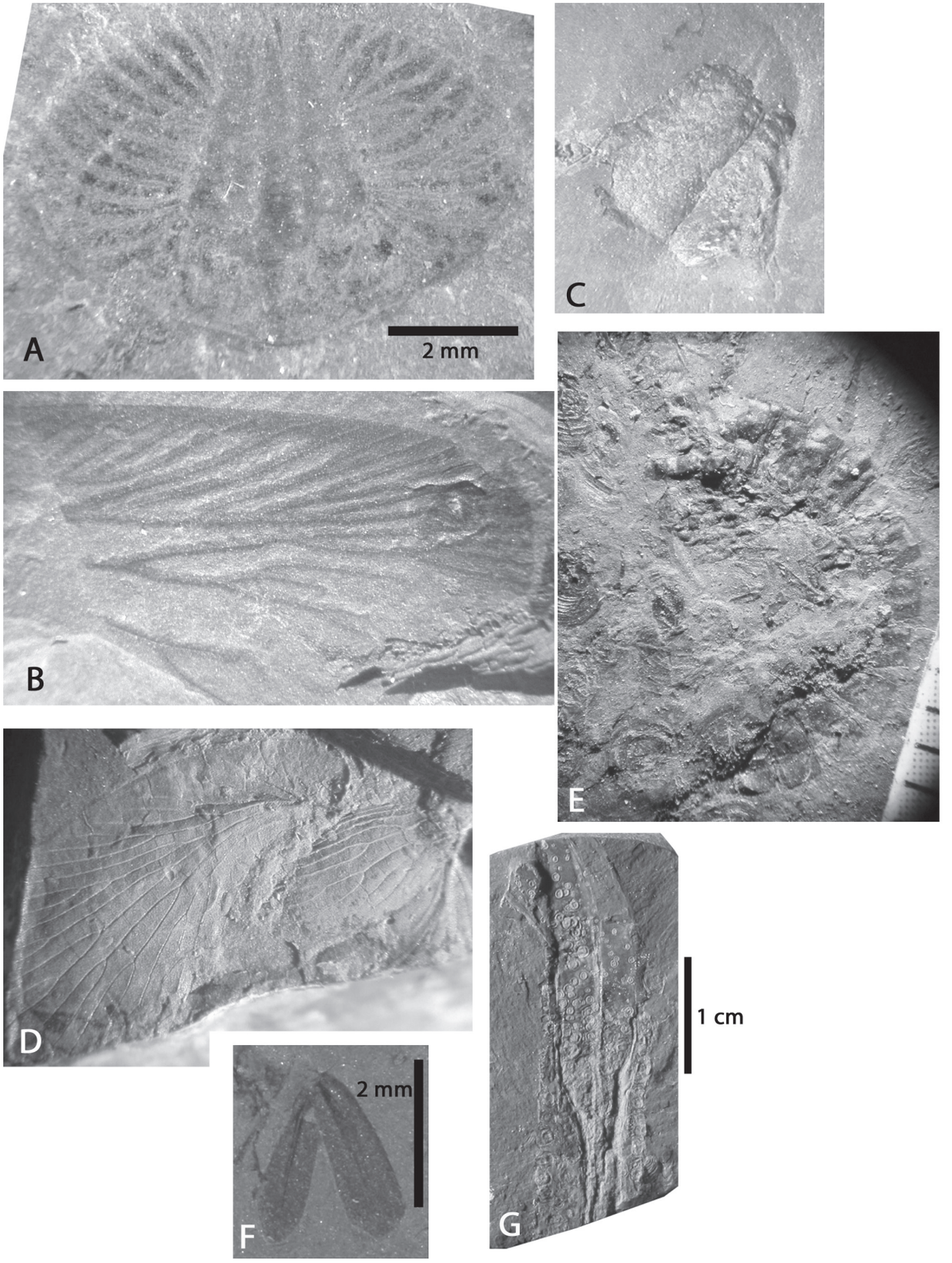


FIGURE 7. Invertebrates from Tinajas Arroyo (NMMNH L-4667). **A**, *Neorthroblattina*, NMMNH P-33747, head shield (pronotum). **B**, *Sysciophlebia* cf. *S. grata*, NMMNH P-40189, forewing. **C**, ?Pygocephalomorph, NMMNH P-40205. **D**, *Neorthroblattina*, NMMNH P-40190, two forewings. **E-F**, cf. *Palaeosyncaris* sp., **E**, NMMNH P-40158, incomplete specimen in lateral view, **F**, NMMNH P-40156, isolated uropods. **G,** *Sphenothallus* sp., NMMNH P-37916.

ous growth lines and is obliquely oval in outline. Several small ostracods are preserved along the valve surface. Shell dimension measurements (after Vasey and Bowes, 1985) are as follows: length measured parallel to the dorsal margin = 7.5 mm; height measured perpendicular to the length = 4.0 mm; length of the dorsal margin = 2.5 mm; width = 4.5 mm; length from the anterior point of the shell to the lowest point on the ventral margin = 3 mm; and anterior length = 1.5 mm.

We provisionally refer this specimen to *Anthraconauta phillipsi* based on its similarity to the revised description of the species provided by Rogers (1965). *A. phillipsi* has been recorded from northwestern Europe, Spain, and several North American localities in eastern Canada, the Appalachians and the Illinois Basin (Vasey, 1994; Bailey and Sroka, 1997). *Anthraconauta* is thought to have inhabited fresh to brackish water environments (Calver, 1968), so it is likely an autochthonous element in the primarily nonmarine Tinajas locality assemblage. *Anthraconauta phillipsi* ranges in age from the middle of Westphalian C into the Stephanian (Vasey, 1994). This is the first record of *Anthraconauta* from New Mexico.

The pectinoid bivalve *Dunbarella* (Fig. 8B) was first reported from the Tinajas locality by Kues et al. (2002) as part of their study of the invertebrate fossils from the strata immediately above the black shale. They noted that the *Dunbarella* occurs in a thin bed of fissile shale near the top of the nonmarine shale and that overlying beds mark a transition from a nonmarine brackish environment into a marginal marine community. *Dunbarella* has also been recorded in central New Mexico from the Upper Pennsylvanian Kinney Brick Quarry (Kues, 1992) and the Pennsylvanian-Permian transition at Carrizo Arroyo (Kues, 2004). This relative of modern scallops is abundant at many horizons in the Pennsylvanian of the Illinois Basin and is generally considered an indicator of brackish water, as in bays and lagoons.

Cnidaria

NMMNH P-37916 from the Tinajas locality black shale consists of an incomplete, crushed sphenothallid tube preserved along the bedding plane as part and counterpart (Fig. 7G). It is 35 mm long and 10 mm at its maximum width. It lacks a basal attachment structure or an apertural opening. One end of the tube gently tapers, so it is considered the proximal end. Near this end a small segment of the tube is displaced that retains a thickened lateral margin. The tube lacks annulations and is covered in places by carbon. Numerous (~200) irregularly circular holdfasts are attached to the tube surface. Holdfast diameters range from 0.25 mm to 1 mm. None of the holdfasts retain their own tubes.

Both the tube and holdfast morphology are characteristic of the genus *Sphenothallus*, which is a widely-distributed marine invertebrate taxon that ranges in age from Early Cambrian to Permian. Its phylogenetic affinities have historically been uncertain, but it is now considered by most to be a cnidarian. P-37916 is the first record of *Sphenothallus* from New Mexico (Lerner and Lucas, 2005). There is insufficient material preserved in this specimen to make a specific assignment. *Sphenothallus* typically occurs in low-energy marine environments (Van Iten et al., 1992), so we consider it to be an allochthonous element within the mostly nonmarine Tinajas locality assemblage.

Vertebrates

Acanthodes

Acanthodian fish remains (Fig. 8E) are relatively scarce in the Tinajas locality black shale. This may be a result of taphonomic processes rather than reflecting their actual abundance. Acanthodians tend to be poorly fossilized due to a weakly ossified internal skeleton. They are often found in fossil assemblages as isolated elements, which is how they occur at the Tinajas locality. Acanthodian spines and bones have also been found in coprolites at the Tinajas locality, which indicates that they were probable prey items. The acanthodian specimens from the Tinajas locality are referable to *Acanthodes*, which was one of the last members of the acanthodian fishes. Acanthodians ranged from Silurian to Early Permian

Orthacanthus

Often trace fossils provide the only record of certain animals ever having been present in ancient environments. In rare instances trace fossils may be predictive of finding body fossils. Spiral coprolites (Fig. 8D), which are associated with freshwater elasmobranch producers, indicated the presence of xenacanths in the Tinajas locality black shale before NMMNH P-51220, a single tooth of *Orthacanthus*, was found.

This single xenacanthid tooth (NMMNH P-51220: Fig. 8F) is referred to *Orthacanthus* based on the serrated lateral cutting edges, the otherwise smooth labial surface of the tooth cusps and the prominent basal tubercle (Schneider, 1996). These 2.5-m-long sharks were the top predators in the Late Carboniferous through Middle Permian lakes of Europe and North America. Because of their dominant position in the food chain, they were much less numerous than their prey, which consisted of fishes and amphibians (Kriwet et al., 2008).

Palaeonisciforms

Palaeonisciform skeletal elements (e.g., Fig. 8H-I) are the most abundant fish remains in the Tinajas locality assemblage. These elements include disarticulated scales and boney plates belonging to the families Elonichthyidae, Haplolepidae and cf. Platysomidae.

NMMNH P-40162 is a distinctive, large flank scale that probably came from a deep-bodied form (cf. Platysomidae). Deep-bodied forms are considered indicative of low energy environments. NMMNH P-40186 (Fig. 8I) is a partially preserved caudal fin with squamation and fin rays. Most palaeonisciform caudal fins are heterocercal, although the distal end is not preserved in this specimen. NMMNH P-40182 (Fig. 7H) is an isolated scale with a denticulate posterior edge that probably belongs to the genus *Elonichthys*.

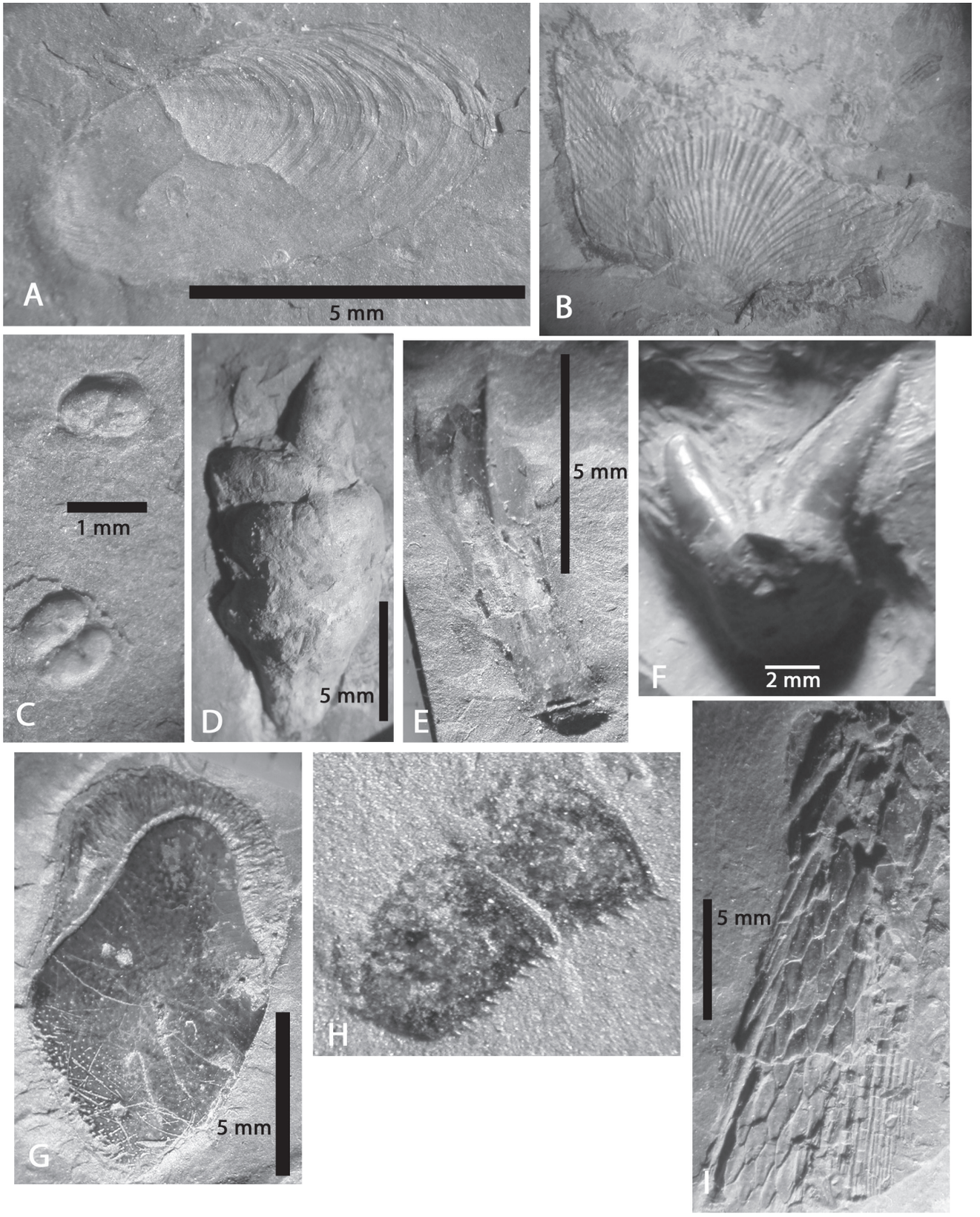


FIGURE 8. Selected invertebrate and vertebrate fossils from the Tinajas locality (NMMNH L-4667). **A**, *Anthraconauta*, NMMNH P-37917, valve. **B**, *Dunbarella*, NMMNH P-37683, valve. **C**, *Geisina*, NMMNH P-40163, valves. **D**, Heteropolar coprolite, NMMNH P-37674. **E**, *Acanthodes*, NMMNH P-37651, incomplete isolated scapula. **F**, *Orthacanthus*, NMMNH P-51220, incomplete tooth. **G**, Osteolepiform, NMMNH P-40181, isolated scale possibly from a megalichthyid. **H**, *Elonichthys*?, NMMNH P-40182, isolated scale. **I**, Paleonisciform, NMMNH P-40186, complete caudal fin.

Sarcopterygians

Sarcopterygian remains are of relatively low abundance when compared to the actinopterygian remains within the Tinajas locality assemblage. This low abundance may be reflective of their role as top predators within the ancient ecosystem. The Tinajas sarcopterygian fauna consists of osteolepiform scales and rhizodontiform scales, teeth and skull bones.

The osteolepiform scales (Fig. 8G) found at the Tinajas locality are probably referable to *Greiserolepis* or *Megalichthyes*. The rhizodontid material is likely referable to the genus *Strepsodus*.

Vertebrate coprolites

In addition to the spiral shark coprolites mentioned above, abundant ovoid coprolites and less common spiral coprolites of probable fish origin occur at the Tinajas locality. Flat ground masses that contain scales and bones are also found. Coprolites are generally considered to be trace fossils. Other trace fossils are absent at the Tinajas locality, which is likely due to anoxic bottom conditions during deposition.

PALEOECOLOGY

Sedimentology

At the Tinajas locality, we interpret the fine-grained clastic interval below the black shale (Fig. 1, units 1-5) as nonmarine distal alluvial plain deposits (floodplain deposits with intercalated distal sheetflood deposits). The overlying nodular limestone (Fig. 1, unit 2) is a pedogenic carbonate bed. This interpretation is supported by the characteristic features seen in the solid carbonate nodules – the presence of caliche peloids and circumgranular fissures. Additionally, there are no marine fossils, though this is not conclusive support of a nonmarine formation of the carbonate nodules.

At the base of the black shale (Fig. 1, unit 6) overlying the floodplain sediments is a sharp disconformity. The black shale that contains abundant conchostracans throughout is interpreted to have been deposited in a poorly oxygenated lacustrine environment.

The greenish shale with abundant *Dunbarella* on top of the black shale (Fig. 1, unit 7) formed during a marine transgression. The transition to a marine environment is marked by the thin overlying bed of gray shale and profuse, irregular, encrusting algal growths with a fauna dominated by the brachiopods *Derbyia* and *Crurithyris*, representing a pioneering marginal marine community.

This phase of marine deposition ended with deposition of a thin, sparsely fossiliferous gray limestone unit (Fig. 1, unit 7) bearing a fauna essentially limited to solitary rugose corals, *Crurithyris* and crinoid debris, possibly representing a slightly hypersaline lagoon. Overlying limestones and shales (Fig. 1, units 8-12) represent microfacies and have fossils indicative of shallow, fully marine deposition.

Limestone deposition was stopped by a regression accompanied by fine-grained siliciclastic influx and deposition of shale and siltstone on an alluvial floodplain or coastal plain (Fig. 1, units 14-20). Thin, intercalated, fine-grained sandstone beds indicate some variability in flow rate.

Indeed, the stratigraphic succession at the Tinajas locality is analogous to a classical cyclothem. Thus, fluvial/deltaic deposits grade upward into a coastal lake that is then transgressively overlain by marginal marine and fully marine sediments.

Plant Paleoecology

In the Tinajas locality black shale, the sparseness of the plant fossils, their small size, and their rare zones of concentration, suggest transport, possibly considerable, some distance from the site of growth. Fossil concentration may have resulted from occasional storms of sufficient magnitude to wash large concentrations of plant material into the depositional environment, possibly in water plumes (which might account for the lateral impersistence of zones of plant concentration). The interpretation of the black shale as a fresh-to-brackish water lake, with generally slow, gentle deposition is consistent with the excellent detail preserved in the fossil plants. This environment of deposition is also consistent with the mixed composition of the plant assemblage, as if the flora were drawn from a drainage basin or shoreline, rather than a point source.

The fossil flora of the Tinajas black shale is allochthonous, accumulated over an extended period of time through transport of plant material into a lake with anoxic-dysoxic bottom waters, favoring organic preservation. At times, plant debris was considerably more concentrated, though still sparse. This concentration possibly was due to storms, which would flush large amounts of organic debris into the system or, conceivably, to periods of reduced, but non-zero, rates of sedimentation, concentrating a background rain of plant debris.

It is possible, even likely, that the flora represents the original taxonomic composition of the source vegetation. The small size of fragments and their distribution in the rock body suggest a gradual accumulation over an extended period. The long sampling window makes it likely that many elements of the flora, at least of the larger trees and shrubs, would eventually be represented in the flora. Our collections captured a large number of plant taxa that probably grew close to the lake and floated offshore to be fossilized. However, a number of unknown biases may have operated, preventing the collections from being fully representative.

The composition of the Tinajas locality flora is somewhat unusual compared to the Late Pennsylvanian (Missourian/Kasimovian) wetlands paleofloras known from most of Europe and eastern North America. Many elements, such as the pecopterids, calamiteans, *Sphenophyllum*, and pteridosperms are, indeed, elements of wetland floras, at least at the clade level. Some of these species and genera, however, have very broad paleoenvironmental ranges. And, medullosans such a *Odontopteris lingulata* and *Neuropteris subariculata* are among the more extreme

members of the medullosan pteridosperm clade, occurring in somewhat more water-stressed habitats than others. The most telling elements of the Tinajas locality flora are the rare, but unusual, components – *Walchian* conifers, the putative conifer *Dicranophyllum*, the putative cycad *Charliea*, and cordaitalean foliage, all of which are known from other sites in which moisture appears to be seasonally distributed.

The Tinajas deposit is similar to others reported from the Pennsylvanian of the United States, such as the floras from the 7-11 locality of Ohio, the Garnett and Hamilton quarries of Kansas and the Kinney Quarry of New Mexico. These and other floras contain elements that appear later in both Europe and North America in the Early Permian, representing the more mesic end of the tropical Permian floristic spectrum.

Invertebrate Paleoecology

At the Tinajas locality, the thinly laminated, laterally continuous black shale (Fig. 1, unit 6) with abundant conchostracans and some other fossils of a nonmarine and terrestrial biota is readily identified as of lacustrine origin. Although modern conchostracans occur exclusively in fresh water, some extinct species apparently inhabited marine waters during the Devonian-Pennsylvanian. Most of the extinct conchostracans, however, lived in fresh water.

Syncarid crustaceans, a significant component of the Tinajas invertebrate fauna, are often associated with Carboniferous freshwater to minimally brackish environments such as within the Braidwood association of the Mazon Creek biofacies (Baird et al., 1985). Modern syncarids inhabit a variety of freshwater environments. The presence of a few marine/euryhaline invertebrate taxa in the black shale, such as *Sphenothallus*, indicate this lake must have had occasional influxes of, or contact with, marine waters.

Fish Paleoecology

The Tinajas Arroyo fish assemblage consists of acanthodians, palaeoniscoids, rhizodontids, osteolepids, a xenacanthid and another chondrichthyan. Rhizodontids are typically associated with river and lake environments. Acanthodians and palaeoniscoids are typically associated with a wide spectrum of environments ranging from shallow marine to lacustrine, channel and fluvial settings. Osteolepids are primarily associated with marine settings. Late Paleozoic xenacanthid fossils are primarily found in freshwater settings. As such, the Tinajas Arroyo fishes represent a moderately diverse, predominantly freshwater to brackish assemblage.

The Tinajas locality fish remains are generally preserved as small groups of scales and isolated bones and teeth. This indicates that they probably came from carcasses that decomposed while drifting in the water column. Some of these carcasses might have been transported from other settings such as inflowing rivers or bordering marine environments. However, fish coprolites are associated with fish body remains within the same beds at the Tinajas locality. Coprolites, by their nature, are thought to have not been transported, which indicates that some fishes also lived within the depositional setting. The fossil fish biota from the Tinajas locality thus indicates a minimally brackish, coastal lacustrine environment that had some intermittent access to lagoonal/shallow marine conditions. This was a large enough body of water to support a complete food chain of tiny crustaceans, numerous small fishes, and a few large predators.

SUMMARY

The Tinajas locality is in strata that encompass three paleoenvironments – a terrestrial lakeside community, a minimally brackish coastal lake and a lagoonal/shallow coastal marine environment. The Tinajas locality black shale contains a diverse, primarily freshwater to brackish fauna that includes bivalves, crustaceans, and fishes. Terrestrial plants and insects from a lakeside community also are present. The Tinajas locality coastal lake paleoenvironment had some limited marine contact during its deposition along New Mexico's Late Pennsylvanian seacoast.

The sedimentology and paleontology of the black shale bed at the Tinajas locality thus supports the following paleoecological conclusions:

1. The thinly-laminated black shale formed in a large (at least 1.4 km diameter) lake with an anoxic bottom.
2. Biota that lived in the lake include conchostracans, ostracods, syncarids and some fishes.
3. Terrestrial plant material was episodically washed into the lake.
4. The lake had intermittent connection to marine waters, as a few elements of the fossil assemblage in the black shale (a cnidarian and some of the fishes) are taxa that normally inhabit saline waters. This also indicates that the lake formed in a coastal setting.
5. A marine transgression first marked by a *Dunbarella* shale ended lacustrine deposition at the Tinajas locality.

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