STRATIGRAPHY, PALEONTOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE LOWER PERMIAN ROBLEDO MOUNTAINS FORMATION OF THE HUECO GROUP, ROBLEDO MOUNTAINS, NEW MEXICO

Authors
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Abstract

Early Permian fossil localities, including numerous tracksites, in the southern Robledo Mountains of Dona Ana County, New Mexico, cover an area of approximately 20 km2 . Lower Permian strata exposed here belong to four formations of the Hueco Group (ascend ing order): Shalem Colony, Community Pit, Robledo Mountains and Apache Da m Formations. With the exception of the Robledo Mountains Formation, the Hueco Group is dominated by shallow water ma rine facies. The Robledo Mountains Formation is as much as 125 m of ma rine carbona tes and shale, intercalated with siliciclastic red-beds that comprise about one-third of the uni t's thickness. At more than 30 localities, the red beds in the study area contain extensive invertebra te a nd vertebra te (tetrapod-footprint) trace fossils and a megafossil plant assemblage composed mainly of Wnlchin. Marine facies of the upper part of the Robledo Mountains Forma tion contain an extensive late Wolfcampian assemblage of megafossil invertebrates, dominated by brachiopods and bryozoans, with considerable numbers of molluscs (bivalves, gastropods, a few specimens of ammonites), and numerous indeterminate crinoids. on-fusulinid foraminifera ns and ostracods dominate the microfossil assemblages. Conodonts from the lower part of the Robledo Mountains Forma tion, found in stra ta that bracket most of the tracksites, indicate a late Wolfcampia n (= la te Artinskia n) age.

Carbonates of the Robledo Mow1tains Formation were deposi ted in relatively quiet shallow- water shelf environments below active wavebase. They show a trend from restricted circulation (brackish?) wa ters in the lower part of the forma tion to more open normal marine waters in the middle a nd u pper parts of the formation. Most of the 34 red-bed tracksites in the Robledo Mountai ns Formation occur a t one stratigraphic level and th us represent a mega tracksite tha t encompassed a t least 20 km2. Tracksites were formed on siliciclastic tidal flats during early stages of rising base level (transgression).

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STRATIGRAPHY, PALEONTOLOGY AND DEPOSITIONAL ENVIRONMENTS OF THE LOWER PERMIAN ROBLEDO MOUNTAINS FORMATION OF THE HUECO GROUP, ROBLEDO MOUNTAINS, NEW MEXICO

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ABSTRACT: Early Permian fossil localities, including numerous tracksites, in the southern Robledo Mountains of Dona Ana County, New Mexico, cover an area of approximately 20 km^2. Lower Permian strata exposed here belong to four formations of the Hueco Group (ascending order): Shalem Colony, Community Pit, Robledo Mountains and Apache Dam Formations. With the exception of the Robledo Mountains Formation, the Hueco Group is dominated by shallow water marine facies. The Robledo Mountains Formation is as much as 125 m of marine carbonates and shale, intercalated with siliciclastic red-beds that comprise about one-third of the unit's thickness. At more than 30 localities, the red beds in the study area contain extensive invertebrate and vertebrate (tetrapod-footprint) trace fossils and a megafossil plant assemblage composed mainly of *Walchia*. Marine facies of the upper part of the Robledo Mountains Formation contain an extensive late Wolfcampian assemblage of megafossil invertebrates, dominated by brachiopods and bryozoans, with considerable numbers of molluscs (bivalves, gastropods, a few specimens of ammonites), and numerous indeterminate crinoids. on-fusulinid foraminiferans and ostracods dominate the microfossil assemblages. Conodonts from the lower part of the Robledo Mountains Formation, found in strata that bracket most of the tracksites, indicate a late Wolfcampian (= late Artinskian) age.

Carbonates of the Robledo Mountains Formation were deposited in relatively quiet shallow-water shelf environments below active wavebase. They show a trend from restricted circulation (brackish?) waters in the lower part of the formation to more open normal marine waters in the middle and upper parts of the formation. Most of the 34 red-bed tracksites in the Robledo Mountains Formation occur at one stratigraphic level and thus represent a megatracksite that encompassed at least 20 km^2. Tracksites were formed on siliciclastic tidal flats during early stages of rising base level (transgression).

INTRODUCTION

The Robledo Mountains (Fig. 1) are a wedge-shaped horst of Paleozoic and Cenozoic rocks tilted southward 10° to 14° (Hawley et al., 1975). This horst lies along the western margin of the southern Rio Grande rift and exposes a 500+ m thick, carbonate-dominated section of Paleozoic strata overlain locally by eogene siliciclastics and cut locally by Cenozoic intrusives (Seager et al., 1987).

In the southern portion of the Robledo Mountains, numerous fossil-footprint localities (tracksites) are known from the southwestern quarter of T22S, R1E and the northeastern quarter of T22S R1W, Dona Ana County. Discovered and developed by Jerry P. MacDonald, these tracksites represent the most scientifically significant record of Permian tetrapod footprints in the world (Lucas et al., 1994b, 1995; Haubold et al., 1995a; Hunt et al., 1995b). The track-bearing strata are intercalated with marine sediments that contain an extensive invertebrate biota (e.g., Kietzke and Lucas, 1995; Kozur and LeMone, 1995; Kues, 1995). Our purpose here is to review the stratigraphic and depositional context of these tracksites. In this article, MMH refers to the New Mexico Museum of Natural History and Science, Albuquerque.

LOCATION AND METHODS

An area of about 20 km^2 (Fig. 2) is delimited by 43 known fossil localities in secs. 19-20, 29-30, T22S, R1E and secs 23-26, T22S, R1W (Lucas et al., 1995, table 1, figs. 2-3). Seager et al. (1987) and Lucas et al. (1995) recently mapped the geology of this area at scales of 1:250,000 and 1:24,000, respectively (Fig. 2).

Our stratigraphic conclusions are based on seven stratigraphic sections of the Robledo Mountains Formation (Fig. 3) described in detail and published by Lucas et al. (1995), as well as three other sections of the strata bracketing this formation published by Lucas et al. (1998).

PREVIOUS STUDIES

Regional Geology

Regional geologic maps have encompassed the Robledo Mountains (Kottlowski, 1960; Seager et al., 1987) as have broad regional studies of Permian stratigraphy in southern New Mexico (e.g., Kottlowski, 1963; Jordan, 1971, 1975). Sedimentological studies of the intertongued Abo-Hueco strata of the Robledo and Dona Ana Mountains were published by Mack and James (1986) and Mack et al. (1988, 1991). Seager et al. (1976) presented a stratigraphic section of Wolfcampian rocks in the Robledo Mountains. LeMone et al. (1967, 1971a, b, 1975) published brief paleontological and micro-facies analyses of the Robledo Mow1tains and Apache Dam Formations of the Hueco Group in the study area . Lucas et al. (1995) integrated much of this information into a detailed report on the stratigraphy and depositional history of the track-bearing interval.

Mack and associates studied the sedimentology of the track-bearing stra ta in general (Mack and James, 1986; Mack et al., 1988, 1991), and Lucas (1993) stud ied the sedimentology of NMMNH locality 846 in particular. Lucas (1993), Hunt et al. (1993, 1994a, b) and Lucas et al. (1994a,b) reported some initial results of scientific study of the tracksites, followed by the more detailed reports in Lucas and Heckert (1995).

Invertebrate Paleontology

Until 1995, there had been little previous study of the Wolfcampian ma rine faunas of the Hueco Group in the Robledo Moun tains, in spite of the highly fossiliferous na ture of these sh·a ta . Shumard (1859) noted the "Upper Carboniferous" stra tified na ture of Robledo Mountain, but reported no fossils from tha t range, although he did note la te Paleozoic taxa from several parts of the nearby San Andres, Caballo and Fra Cristobal Mountains. Shumard (1886, p. 106) repor ted *"Productus costatus, Athyris s 11btilita* and *Plwrotomaria, Chemnitizia,* and *S traparollus* of undescribed species" from the Robledo Mountains. Although Shumard (1886) identified the fossiliferous stra ta as Carboniferous, these taxa were almost certainly collected from the Permian Hueco Group. Not only is the Hueco most of the accessible marine stra ta in the Robledos, but taxa reported by Shumard (1886), including *Omphalotrochus ("Ple11rotomaria"), Wilkingia ("Cllemnitzia")* and *Euomphalus (S traparol/ 11s),* are abundant and conspicuous in the Hueco (Kues, 1995).

Intertonguing of uncommon nonma rine red-bed "Abo" and more typica l "Hueco" facies in the Robledos has been known for decades (e.g., Dunham, 1935; Thompson, 1942, 1954), bu t detailed studies of this section are considerably more recent (e.g., Jorda n, 1971; LeMone et al., 1975; Mack and Ja mes, 1986; Lucas et al., 1995). In spite of the extensive studies of Hueco faunas from cor rela tive sh·a ta to the east (e.g., Orogrande area, Hueco Mountains, Sierra Diablo area), the invertebra te fa una of the Hueco Group in the Robledos Mountains remained rela tively unstudied.

Thom pson (1954) repor ted a few Wolfca mpian fusulinids from the lower Hueco in the Robledo Mountains, and commented tha t most of the prolific fusulinid fa u na remained to be studied. LeMone et al. (1971 a,b) provided an abbrevia ted list of taxa and a lso published a brief study of the stra tigraphy and fa una! assemblages of the Robledo Mountains-Apache Dam sequence in this area (LeMone et al., 1975). Kozur and LeMone (1995)

This area(LeMone et al., 1975) Kozur and LeMone (1995)

presented additional informa tion on the conodonts of the Robledo Mountains Formation, and Kues (1995) was the f irst to document characteristic marine inver tebra te taxa from the Robledo Mou ntains Forma tion.

Mega-tracksite

The history of vertebra te fossi l collecting in the Robledo Mountains is limited to the history of tracksite collecting, and was documented in detail by MacDonald (1994, 1995). Although a few track specimens had been collected from the Robledo Mountains over many years, collecting increased with the opening of a public quarry (the Community Pit) in red beds of the Hueco Group. However, there was only one popular account of early collecting (Ratkevich, 1980), and only one specimen (of *Dimetropus)* ended up in a museum (Hunt et al., 1993). In 1987, MacDonald made a major find (NMMNH locality 846), and the next year he informed the BLM, who administer the area. MacDonald made extensive collections, and several popular articles were written about the Robledo tracks (e. g., Bowlds, 1989a, b; Garretson, 1989; MacDonald, 1990, 1992; Stewart, 1992). In 1990, the U.S. Senate passed a bill funding the study of these tracksites. Hun t et al. (1993) and Lucas et al. (1994b) published preliminary studies of the tracksites, and Lockley and Hunt (1995) illustrated several specimens.

Schult (1994) wrote his doctoral disser ta tion on the Robledo tracksites and authored three papers on this topic (Schult and Fa rlow, 1992; Schult, 1995a, b). Schult (1994, 1995b) listed the occmrence of 23 teh·apod ichnogenera in the Robledo Mountains Forma tion, bu t this purported ichnofa una includes some ichnotaxa known only from pre-Permian sh·ata (e.g., *A11thracop11s)* as well as forms only reported from eolia n dune facies (e.g., *Laoporus),* so we believe tha t this ichnotaxonomic evalua tion is largely incorrect.

Ichnofossils ha ve long been known from Lower Permian red beds of Europe, and their extensive history of study is well-documented (e.g., Haubold, 1971, 1984). Vertebrate and

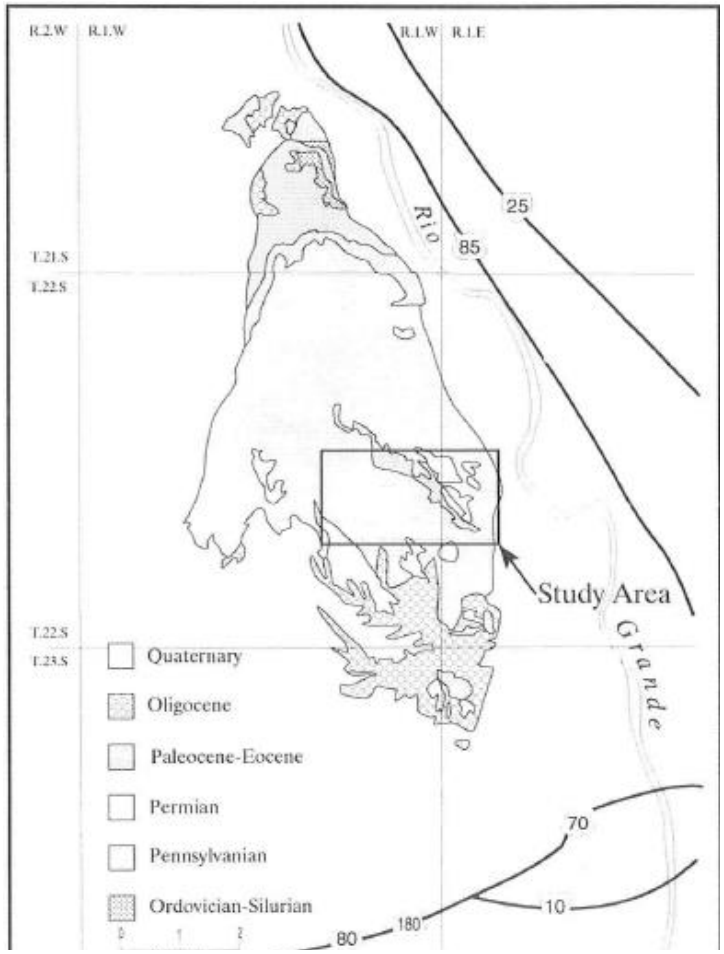

FIGURE I. Generalized geological ma p of the Robledo Mountains showing location of the study area in Figure 2 (based on Seager et al., 1987).

invertebrate trackways are also known from many localities in Lower Permian red beds of the American Southwest (e.g., Gilmore, 1926; Hunt et al., 1990; Lockley and Madsen, 1993; Hunt et al., 1995b). However, most localities yield only a few taxa, and few have been studied in detail. The Lower Permian localities in the Hueco Group of the southern Robledo Mountains surpass all others in quantity, quality, and diversity of ichnotaxa. Indeed, they represent the most scientifically important Early Permian terrestrial ichnofauna known (Lucas et al., 1994a).

STRATIGRAPHY

Three formations of the Hueco Group were mapped in the study area (in ascending order): Community Pit Formation, Robledo Mountains Formation, and Apache Dam Formation (Fig. 2). The lowest formation of the Hueco Group in the Robledo Mountains, termed the Shalem Colony Formation by Lucas et al. (1998), crops out well to the north of the mapped area. For purposes of this study we will concentrate on the Robledo Mountains Formation, with only minor attention to the bounding Community Pit (below) and Apache Dam (above) Formations.

Community Pit Formation

The Community Pit Formation of the Hueco Group crops out in the northeastern and north-central parts of the study area (Fig. 2). Brownish-gray and grayish-orange packstone and micritic limestone and shale/siltstone dominate the Community Pit Formation. No red-bed siliciclastics are present in the Community Pit Formation; the base of the overlying Robledo Mountains Formation is mapped at the base of the stratigraphically lowest red beds. The Community Pit Formation of the Hueco Group in the map area is about 85 m thick. Well-preserved permineralized logs of gymnospermous wood are present in gray calcareous shale about 3 m below the top of the Community Pit Formation at locality 3016 (Tidwell and Munzing, 1995). These logs clearly floated into and were buried in a shallow marine environment as driftwood.

Robledo Mountains Formation

Strata previously referred to as the Abo Tongue, Abo Formation, or Abo-Hueco Member in the Robledo and Dona Ana

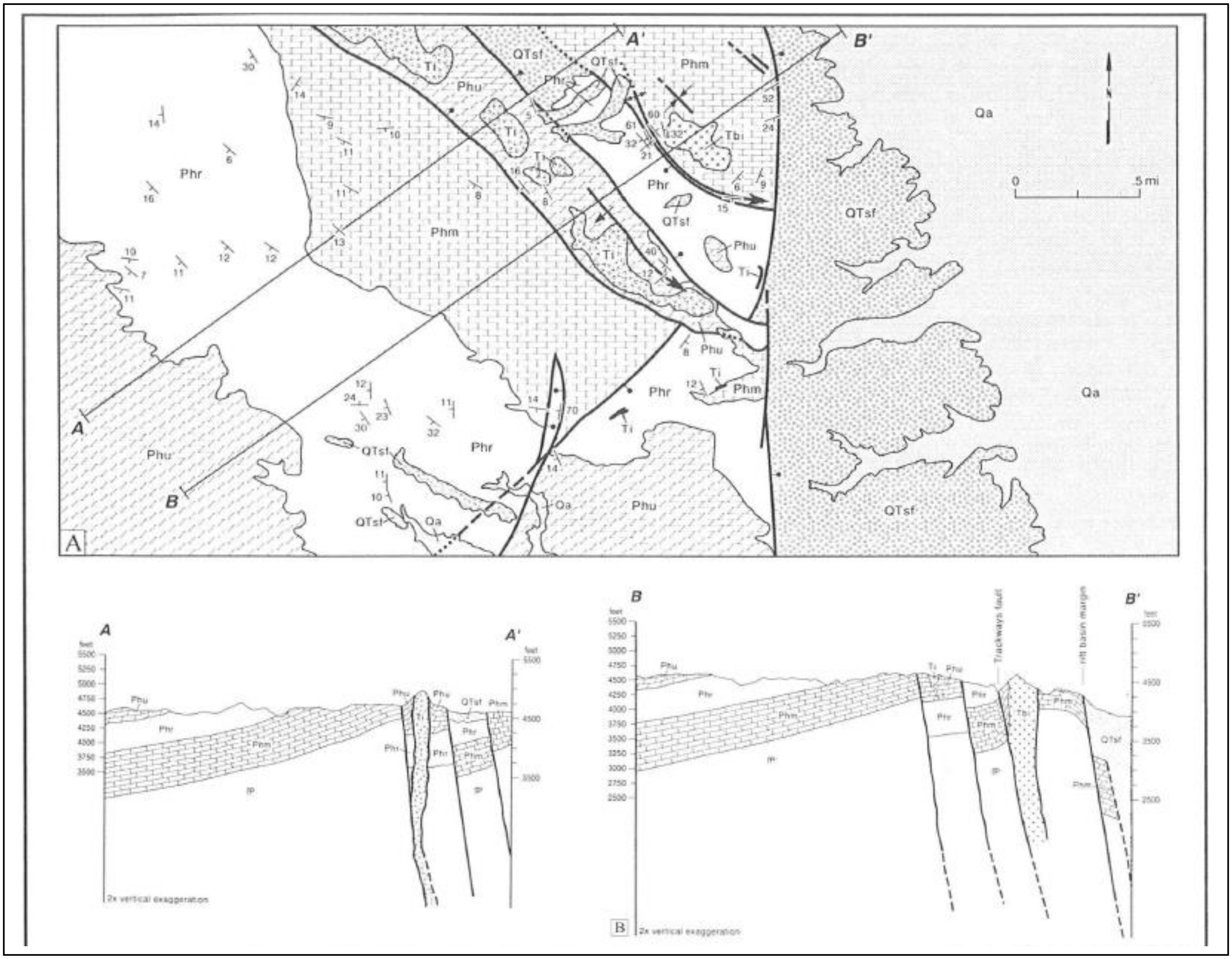

FIGURE 2. Geological map of the study area and structural cross sections in the southern Robledo Mountains (after Lucas et al., 1995). Map units are: Plun = Community Pit Formation; Phr = Robledo Mountains Formation; Phu = Apache Dam Formation; Qa = Quaternary alluvium; QTsf = Santa Fe Group; Ti = intrusive.

Mountains (Seager et al., 1976, 1987; Mack and James, 1986; Mack et al., 1988, 1991) were named the Robledo Mountains Member of the Hueco Formation by Lucas et al. (1995) and are raised in rank to the Robledo Mountians Formation of the Hueco Group by Lucas et al. (1998). The type section of the Robledo Mountains Formation is our section G (Fig. 3; Lucas et al., 1995, figs. 4,7), which was described previously by Jordan (1971) and Lucas et al. (1995). At its type section, the Robledo Mountains Formation is 125.4 m thick. Most of the section is interbedded marine shale and nodular limestone (34%) and nonmarine red-bed sandstone (33%). Ledgy marine limestones (12%) and shale (13%) make up most of the rest of the section; red-bed siltstones and mudstones are a very minor component.

Jordan (1971) and Krainer and Lucas (1995) provided detailed descriptions of the lithology of the Robledo Mountains Formation. Most Robledo Mountains Formation limestones are micritic and relatively unfossiliferous. Fossiliferous limestones are mostly bioclastic wackestones and packstones, some of which are dominated by shell material of tubular foraminiferans (especially *Tolypammina, Hypemmmina, Ammovertella, Globivalvulina, Hemigordius* and *Tuberitina)* (Krainer and Lucas, 1995) and ostracods (Kietzke and Lucas, 1995). Less common lithologies are bioclastic and foraminiferal grainstones. Calcareous shales, typically yellowish gray in color, are often interbedded with Robledo Mountains Formation limestones, and these strata yield most of the invertebrate macrofauna described by Kues (1995).

Red-bed strata of the Robledo Mountains Formation are dominated by grayish red to pale red, fine-grained, micaceous, litharenitic sandstone. Typical sedimentary structures include laminae and/or ripple laminae. A few sandstones are trough-crossbedded, hummocky bedded or have herringbone crossbeds. Raindrop impressions, mudcracks, leaf impressions and tetrapod footprints are common on bedding planes.

These characteristics suggest that most of the Robledo Mountains Formation is of marine origin and thus consists of characteristic Hueco Group lithologies-fossiliferous carbonates and calcareous shales. About one-third of the unit is red-bed siliciclastics that represent the intertonguing of facies typically associated with the Abo Formation to the north with facies of the marine Hueco Group. This is the basis of previous references to this interval as Abo Tongue, Abo Formation or Abo-Hueco Member, even though the bulk of the unit consists of typical Hueco Group marine facies. For this reason, we follow Lucas et al. (1995, 1998) and assign the Robledo Mountains Formation to the Hueco.

Lucas et al. (1995) reported seven measmed stratigraphic sections that encompassed all or part of the Robledo Mountains Formation in the study area (Fig. 3). These sections demonstrate that virtually all the red-bed tracksites in the Robledo Mountains are at the same stratigraphic level, just above a highly distinctive limestone bed. Correlation of the sections is based not just on this bed, but on an extremely fossiliferous marine calcareous shale/nodular limestone interval in the upper part of the Robledo Mountains Formation (Kues, 1995; Lucas et al., 1995) and on the base of the Apache Dam Formation of the Hueco Group (Lucas et al., 1995, 1998). Most of the h·acksites in the Robledo Mountains Formation thus constitute a rnegatracksite that covered at least 20 km^2.

Incomplete sections (top missing) of the Robledo Mountains Formation crop out in the Dof\a Ana Mountains northeast of the Robledo Mountains in T21S, RlE. Seager et al. (1976, p. 10-12, fig. 6, sheet 1) mapped the distribution and described a measured section of these rocks, which they referred to both as Abo Formation and as Abo Tongue. The preserved Robledo Mountains Formation in the Dof\a Ana Mountains is 81 m thick and consists of interbedded marine limestone/shales and red-bed siliciclastics similar to the strata exposed in the Robledo Mow1tains. We do not extend recognition of the Robledo Mountains Formation further to the east, into the San Andres Mountains, to encompass homotaxial rocks-upper Abo Tongue of Bachman and Myers (1969)-because these strata are wholly red beds and best referred to as Abo Formation.

Apache Dam Formation

Lucas et al. (1998) named the Apache Dam Formation of the Hueco Group for strata formerly termed the upper member of the Hueco Formation in the Robledo Mountains. This is the youngest Permian stratigraphic unit exposed in the study area. It is extensively faulted and intruded in the northern portion of the study area and caps escarpments to the south. Jordan (1971), LeMone et al. (197la, 1975), Simpson (1976) and Lucas et al. (1998) have studied the Apache Dam Formation in detail. These strata are mostly dark gray and brownish-gray algal-plate limestones, thin biostromes and interbedded siltstones. They contain a fossil biota dominated by phylloid algae, corals and gashopods (LeMone et al., 1971a, 1975). Total thickness of the Apache Dam Formation is about 122 m Gordan, 1971), though only about 62 m are exposed in the study area.

MICROFOSSILS

The Robledo Mountains Formation of the Hueco Group in the southern Robledo Mountains produces diverse and prolific microfossiJ assemblages dominated by non-fusulinid forarniniferans and ostracods (Kietzke and Lucas, 1995; Kozur and LeMone, 1995). Most of these microfossils are from a yellowish gray calcareous shale at the base of unit 30 of measured section C of Lucas et al. (1995; Kietzke and Lucas, 1995; Kues, 1995) in the upper part of the Robledo Mountains Formation (Fig. 3).

Kohn and Dewey (1990) described some ostracods from the Apache Darn Formation of the Hueco Group in the Robledo Mountains. They concluded that these ostracods, dominated by bairdeaceans, indicate shallow nearshore marine conditions of normal salinity. We believe a similar environment is indicated by the rnicrofossil assemblage described by Kietzke and Lucas (1995), which is slightly lower stratigraphically than the assemblage described by Kohn and Dewey (1990).

Most of the non-ostracods in the upper Robledo Mountains Formation assemblage suggest shallow marine conditions. For example, holothmioids and arnmodiscid foraminiferans indicate shallow marine waters of normal salinity (e.g., Lane, 1964). Spirorbids suggest very shallow waters, whereas tetrataxid forams indicate shallow to sublittoral waters (Lane, 1964; Stevens, 1966). Some of the ostracods in this assemblage are eurytopic, such as *Rectobairdia, Acmtia* and *Hollinella* (Melnyk and Maddocks, 1988a). Other species are characteristic of muddy, nearshore waters: *Healdia si111plex, Mo11ocemtina lewisi* and *Bairdia beedei* (Melnyk and Maddocks, 1988a). *Sansabella* is also characteristic of nearshore marine waters (Kaesler and Denver, 1988; Kaesler et al.,1990), but *Cavelli11a ed111istonae* is more typical of offshore waters, though it too can be found in neashore deposits (Melnyk and Maddocks, 1988a). Thus, most of the ostracods and other microfossils indicate a shallow, nearshore marine environment of normal salinity (Kietzke and Lucas, 1995).

Most of the Robledo Mountains Formation ostracods are long-ranging taxa found in Pennsylvanian and Lower Permian strata. The exception is *Cnvellinn edmistonne,* which first appears at or close to the base of the *Kindle/In* aff. *K. ftssi /obn* interval zone of latest Wolfcampian-Leonardian age in Texas (Melnyk and Maddocks, 1988b). On face value, this suggests a latest Wolfcampian-Leonardian age for the uppermost part of the Robledo Mountains Formation of the Hueco Group, an age assignment consistent with the latest Wolfcampian age determined by conodonts for strata lower in the Robledo Mountains Formation (Kietzke and Lucas, 1995; Kozur and LeMone, 1995; Lucas et al., 1995). Indeed, the Wolfcampian-Leonardian boundary may be close to the boundary between the Robledo Mountains and Apache Dam Formations of the Hueco Group in the Robledo Mountains.

MACROINVERTEBRATES

LeMone et al. (1971a,b, 1975) and Kues (1995) presented the most recent studies of the invertebrate macrofauna in the Hueco Group of the Robledo Mountains. The collections made by LeMone et al. (197la,b, 1975) were from a variety of localities, but the more than 70 marine invertebrate taxa reported by Kues (1995) were collected from near the top of the Robledo Mountains Formation, in an approximately 10-m-thick interval of gray to tan shale and limestone, just below the highest red sandstone bed (Kues, 1995, fig. 3). In general, this assemblage is dominated by brachiopods, bivalves, and gastropods, as well as rarer representatives of other stenohaline groups, such as bryozoans, echinoids, crinoids, corals, sponges, nautiloids, and sharks (Kues, 1995). Here, we summarize the analysis of Kues (1995) and its bearing on the age of the Robledo Mountains Formation.

In the Robledo Mountains, fusulinids have been documented only from the Shalem Colony Formation of the Hueco (Thompson, 1954), and only two, long-ranging species found there are also present in the type Hueco, preventing detailed correlation based on fusulinids (Kues, 1995). Furthermore, fusulinids are exceptionally rare in the Robledo Mountains and Apache Dam Formations of the Hueco Group (LeMone et al., 1975). LeMone et al. (1975) argued for a late Wolfcampian age for these units based on a suite of invertebrate taxa said to be indicative of that age, although many taxa they listed have long temporal ranges (Kues, 1995).

Among the macrofossil invertebrates, amrnonoids and brachiopods provide the best indicators of the age of the Robledo Mountains Formation (Kues, 1995). Kues (1995) reported two amrnonoids from the upper Robledo Mountains Formation of the Hueco Group: *Properrinites bosei* (Plummer and Scott) and *Metnlegocerns bnuloronx* (White). Of these, *Properrinites* was originally described from the late Wolfcampian Admiral Formation of Texas, and *Metnlegocerns* was first reported from the Leonardian Clyde Formation, which also yielded a more advanced species of *Properrinites*, *P. rnmminsi* (Kues, 1995). However, as Kues (1995) noted, Miller and Parizek (1948) reported specimens nearly identical to the Robledo Mountain Formation amrnonoids from the middle Hueco, of probable late Wolfcampian age, near Orogrande, New Mexico. Thus, the available amrnonoid evidence suggests that the Robledo Mountains Formation is of late Wolfcampian age, as Kues (1995) concluded.

The brachiopod fauna of the upper Robledo Mountains Formation consists of at least 16 genera and 19 species and includes numerous Wolfcampian species, and some species previously reported from strata no older than Leonardian. Kues (1995, p.64-65), however, noted that "the age significance of [Leonardian) species in the upper Hueco of the Robledo Mountains is somewhat equivocal, as Cooper and Grant (1972-1977) studied only a relatively small number of Hueco species and the possibility of longer stratigraphic ranges (into the Hueco) for some of their Leonardian species exists." This is perhaps especially true of the most abundant brachiopod in the Robledo Mountains Formation, which is closely related to or conspecific with *Squamnria moorei* Muir-Wood and Cooper, and was first described from the earliest Leonardian Clyde Formation. Otherwise, many of the taxa reported by Kues support a latest Wolfcampian age for the Hueco Formation.

TRACKSITES

There are 33 localities that yield tehapod hacks in the Robledo Mountains (NMMNH localities 846, 2811-2839, 2849-2852). The localities are scattered over an area of about 20 km^2 in a structurally complex area, but they have been correlated by careful mapping and stratigraphic analysis (Lucas et al.,1995). By far the most important of these is NMMNH locality 846, which has been extensively quarried by J. P. MacDonald and has yielded most of the recovered specimens. This locality produced h·acks from multiple stratigraphic levels (25) and preserved multiple layers of undertracks of some layers.

Popular accounts of the Robledo Mountains ichnofauna have suggested that it contains an unprecedented level of diversity (e.g., MacDonald, 1994). This is also suggested by Schult (1994, 1995a, b). However, we agree with Haubold et al. (1995a) and believe that the ichnodiversity has been greatly overestimated. This is in part due to the extraordinary wide range of gait- and substratum-influenced variations of track morphology exhibited by this ichnofauna (Haubold et al., 1995a), termed extramophological variation by Peabody (1948). This is partly the result of varying substratum conditions (e.g., moisture). In addition, there are large numbers of undertracks (which can often be associated with original tracks). Fmthermore, iclrnotaxonomic inflation of the Robledo ichnofaunas was caused in part by a confusing ichnotaxonomic literature and a lack of intercontinental studies of Permian tracks, but the latter is beginning to change (e.g., Haubold et al., 1995a, b; McKeever and Haubold, 1996; Haubold, 1996). The ichnotaxonomy utilized here follows Haubold et al. (1995a), who described and illustrated many Robledo specimens.

Bntrnchichnus and *Limnopus* are tracks of small and large temnospondyl amphibians, respectively (Haubold, 1971). The most common track is *Dromopus* (Fig. 4), the track of an araeoscelid. *Hyloidichnus* is the track of a ?diadectid, *Dimetropus* is the track of a large sphenacodontid pelycosaur, and *Gilmoreichnus* probably represents a smaller pelycosaur (Haubold, 1971). Bones of these trackmakers are generally not known from the Abo Formation in southern New Mexico (Vaughn, 1969; Berman, 1993; Lucas et al., 1995).

The Robledo tracksites provide abundant information for paleoecological studies. Schult (1994, 1995a) compared ichnotaxa between different layers at tracksites and related them to substratum differences. However, as noted above, his iclrnotaxonomy, which forms the basis of his paleoecology, is at odds with ours, so we cannot easily evaluate his results.

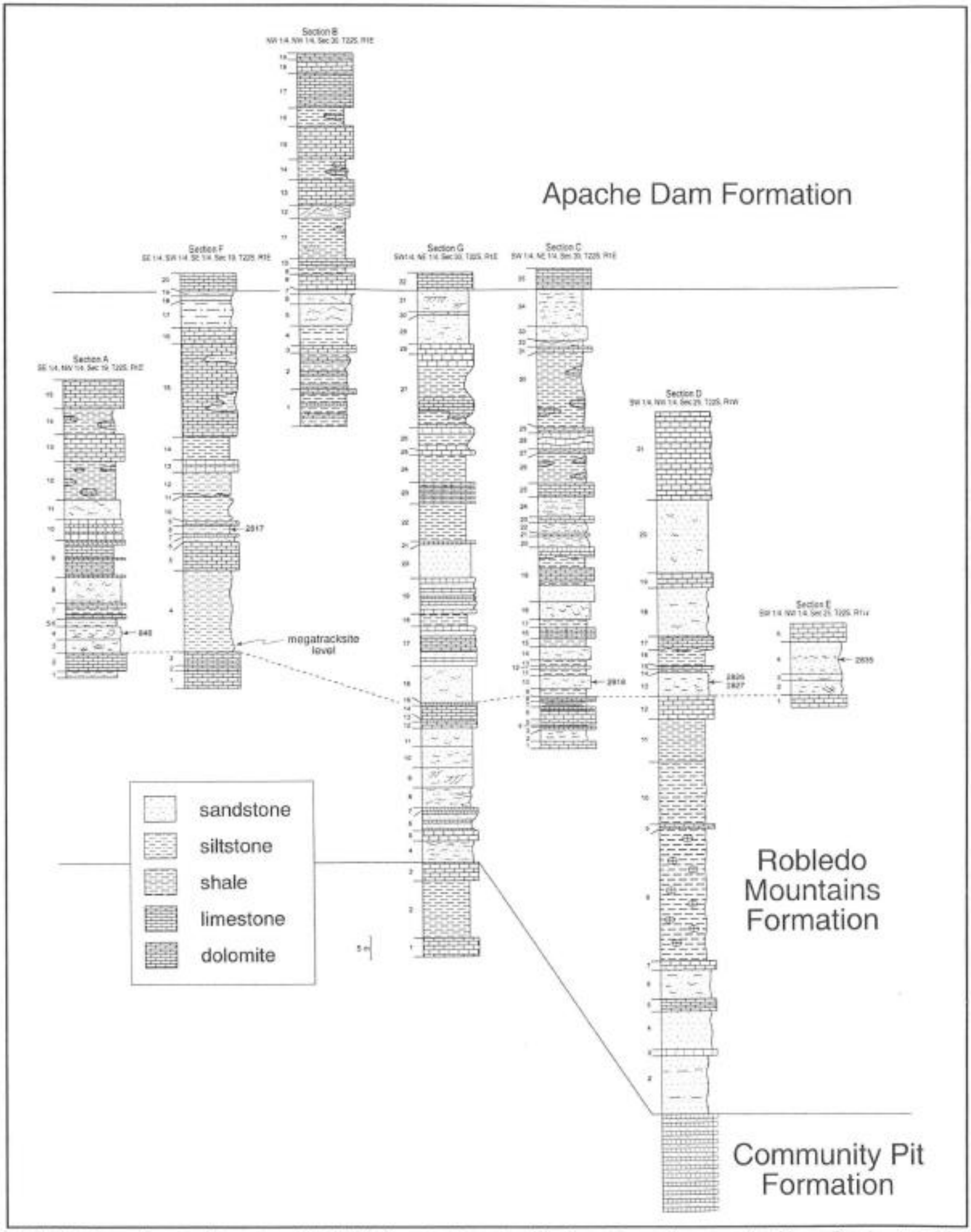

FIGURE 3. Measured stratigraphic sections of the Robledo Mountains Formation of the Hueco Group and some associated Lower Permian strata (after Lucas et al., 1995).

It is clear that there are differences in ichnotaxonomic composition between layers at NMMNH locality 846. MacDonald's layer 16 consists almost entirely of tracks of *Dromopus agilis*, whereas tracks on layers 4, 5 and 6 are almost exclusively *Batrachichnus delicatulus*. Many of the *Batraclzichnus* specimens on layers 4-6 exhibit a tridactyl morphology. Other layers (e.g., layer 10) have numerous specimens of both *Batrachichnus* and *Dromopus*. Several layers (e.g., layers 10, 21) contain abundant trackways of *Dimetropus nicolasi*. There seems to be some evidence for a separation of *Dromopus* and *Batrachichnus* on different surfaces, which might have ecological significance.

The Robledo h·ackways have important potential for the study of locomotor evolution in the Paleozoic. The trackways of *Dimetropus* are particularly interesting in that they suggest that traditional skeletal mounts of sphenacodontids need to be modified. These restorations suggest a wide gait, and that trackways should preserve a tail drag. Robledo samples of *Dimetropus* indicate a relatively narrow gait and no tail drag (Hunt et al., 1993; MacDonald, 1994). Interestingly, Small (1993) found, in mow1ting a *Dimetrodon* skeleton for the Denver Museum of Natural History, that he could not articulate the limbs to achieve the traditional sprawled posture of this animal.

Schult (1994) and MacDonald (1994) considered the abundance of amphibian trackways in the Robledo tracksites to be a problem because they believed that these ichnofaunas formed on a saline tidal flat. Schult (1994) went to great lengths to discuss the very limited salinity tolerances of modern amphibians. Lucas et al. (1995) noted that: (1) Robledo tracksites were made on tidal flats, but were not right at the shoreface and were not necessarily subject to saline waters when the tracks were made: (2) the salinity tolerances of modern amphibians are irrelevant as lissamphibians are very distantly related to Early Permian amphibians; and (3) tracks of spiders and other terresh·ial invertebrates not tolerant of high salinity are common at the Robledo tracksites (Braddy, 1995). We add other features that are relevant to this discussion: (1) the primitive (and xerophytic?) conifer *Wa/chia* is common at tracksites (Hunt, 1983; Hunt et al., 1993); (2) despite claims to the contrary (e. g., Hunt, 1993), the only amphibian family ever to have documented high-salinity tolerance is the Triassic Trematosauridae; (3) vertebrate tracks are rare on saline tidal flats, whereas infauna! invertebrate traces are abundant (Frey and Pemberton, 1986, 1987)-the latter are absent at Robledo tracksites; and (4) there are no differences between the ichnotaxonomy of the Robledo sites and those of other redbed sites in unequivocally freshwater settings (Haubold et al., 1995a; Hunt et al., 1995a, b, c). Therefore, we conclude that there is no evidence that the Robledo tracks were formed on a saline tidal flat.

Several vertebrate tracksites contain an abundance of invertebrate trails (notably NMMNH localities 846, 2851) or plant fossils (notably NMMNH locality 2828) (Braddy, 1995). The invertebrate trails are mostly of arachnids and arthropods, although eurypterid and limulid tracks also are present (Braddy, 1995). The plaeoflora is almost monospecific and consists principally of *Walchia piniformis*. This primitive conifer is the dominant plant in Early Permian floras in New Mexico (Hunt, 1983). Large fronds are preserved at several localities, notably NMMNH 2828. The abundance of this plant may reflect its true abundance or it may be a taphonomic artifact. *Walchia* is usually considered to be xerophytic because of its needle-like leaves and is taken to indicate at least a seasonally dry climate, although the fossil logs reported by Tidwell and Munzing (1995) from the underlying Community Pit Formation lack well-defined growth rings, indicating a less seasonal climate. Studies of paleosols and oxygen isotopes confirm a seasonally dry climate in southern New Mexico during the Early Permian (Mack et al., 1991).

Lucas et al. (1995) demonstrated that the majority of the Robledo tracksites occur at one stratigraphic level over an area of 20 km^2 and thus constitute a megatracksite *(sensu* Lockley, 1991). The Robledo Mountains megatracksite is unique for a number of reasons: (1) it is the only pre-Middle Jurassic megatracksite; (2) it is the only megah·acksite to include abundant invertebrate trails; (3) it has a much more diverse tetrapod ichnofauna than any other megatracksite; (4) it is the only megatracksite to be dominated by small (< 20 cm pes impression length) tetrapod tracks; (5) it is the only megatracksite to occur in red beds; and (6) it is the only megatracksite not to include dinosaur footprints.

The Robledo Mountains tracksites are the only Permian tracksites that can be correlated without question to the global standard marine biochronology. Most of the Robledo ichnotaxa are identical with, or have close relatives in, European teh·apod tracks (Haubold et al., 1995a), which have been used as the basis of local biostratigraphies (e.g., Boy and Fichter, 1988). The presence of *Batrachichnus* (similar to *Anthichnium), Gilmoreichnus, Hyloidichnus* and *Dimetropus /eisnerianus* in the Robledo ichnofauna suggests affinities with the late Autunian ichnofauna of Europe (e.g., Gand and Haubold, 1988, figs. 1-2). Late Autwuan is consistent with a late Artinskian age for the Robledo ichnofauna.

The Robledo Mountains tetrapod ichnofauna is broadly similar to those found in other Early Permian h·acksites in western North America (Hunt et al., 1995a, b, c). It differs from fluvial-facies ichnofaunas from the Abo Formation in central New Mexico (e.g., Hunt et al., 1995c) by including greater numbers of *Batrachichnus* and *Dimetropus* and in having fewer specimens of *Limnopus*. The Robledos ichnofauna differs from that of the Hermit Shale of Arizona and Sangre de Cristo Formation of northeastern New Mexico in lacking *Parabaropus* and *lchniotherium,* which seem only to have been present in more inland ichnofaunas (Hunt et al., 1995c).

Wolfcampian ichnofaunas of the American Southwest are taxonomically very similar to those in the Rotliegend of Europe, and many ichnospecies from both regions appear to be conspecific (Haubold, 1996). One iclmotaxon wluch is conspicuously absent from the Robledo ichnofauna, and from other U.S. tracksites, is *Amphisauropus*. The apparent absence of this iclmotaxon in North America may be due to biogeographic or paleoecological (intermontane vs. lowland deposition) factors.

DEPOSITIONAL ENVIRONMENT AND CYCLIPTY

Jordan (1971, 1975), Mack and James (1986) and Mack et al. (1988, 1991) have carried out sedimentological studies of the Robledo Mountains Formation and adjacent Lower Permian strata. More recently, Krainer and Lucas (1995) evaluated the microfacies of Robledo Mountain Formation limestones and Lucas et al. (1995) described the stratigraphy and sedimentology of the Robledo Mountains Formation. These workers concluded that the Community Pit Formation of the Hueco represent shallow, marine shelf environments, whereas the Apache Dam Formation of the Hueco consists of shallow marine shelf limestone and siltstone, including a diverse biota that allowed Jordan (1971, 1975) and LeMone et al. (197la, b, 1975) to recognize a variety of biofacies. The Robledo Mountains Formation represents a complex intercalation of siliciclastic tidal flat (red beds) and shallow marine shelf (limestones and calcareous shales) deposits. All of the Robledo tracksites are in the tidal flat deposits.

Our observations support in a general way the conclusions of Mack and associates regarding the depositional environments of the Robledo Mountains Formation. The dominance of micritic limestones in the marine facies of the Robledo Mountains Formation indicate deposition in a quiet environment on a shallow shelf. Some limestones, dominated by small foraminiferans and ostracods, suggest restricted (brackish?) depositional environments, whereas bioclastic wackestones and packstones with diverse, brachiopod- and bryozoan-dominated megafaunas suggest normal marine conditions (Krainer and Lucas, 1995).

The distribution of limestone fades in the Robledo Mountains Formation indicates a "deepening" upward or transgressive upward trend within the member (Lucas et al., 1995). Thus, ostracod- and foraminiferan-rich limestones are most abundant in the lower part of the Robledo Mountains Formation, whereas megafauna-rich wackestones and packstones dominate limestones of the upper part of the member. We interpret this as a trend from resh·icted circulation marine environments low in the Roblec!o Mountains Formation to more open shelf marine environments in the middle to upper part of the unit. The transition occurs above the megatracksite level.

The predominance of micritic facies types within the fossiliferous limestone horizons of the Robledo Mountains Formation indicates deposition in a quiet water environment of a shallow shelf, below active wave base (also see Mack and James 1986; Krainer and Lucas, 1995). LeMone et al. (197la, b) suggested water depths of less than 10 m.

Limestones containing a restricted fauna composed mostly of ostracods and /or small foraminiferans point to a restricted (?brackish) depositional environment (Krainer and Lucas, 1995). The bioclastic wackestones/ packstones with a diverse fauna indicate normal marine conditions and deposition in a quiet water depositional environment below the active wave base. Limestone

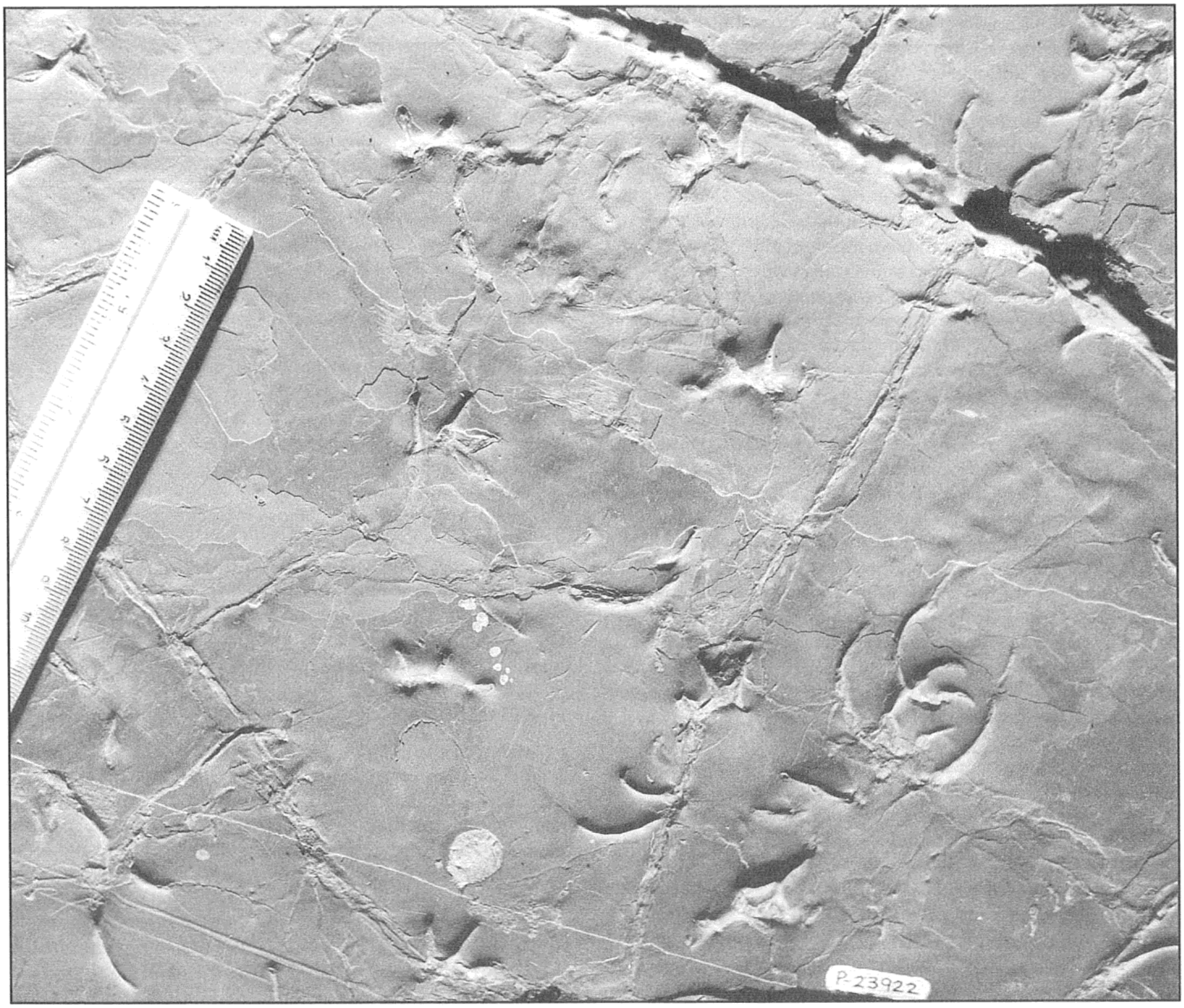

FIGURE 4. Tracks of the ichnogenus *Dro111op11s* from NMMNH locality 846. Scale in cm.

horizons are frequently under- and overlain by ostracod-rich shales of a brackish environment.

Within the Robledo Mountains Formation, ostracod- and foraminiferan-rich limestones are more abundant in the lower part, whereas bioclastic wackestones dominate in the upper part. Thicker limestone horizons are composed of ostracod mudstones at the base, grading upward into ostracod wackestones, which in turn grade into foraminiferal wackestones and grainstones and finally into bioclastic wackestones (Lucas et al., 1995). The bioclastic wackestones frequently are overlain by ostracod- and foraminiferan-rich wackestones and mudstones. This reflects gradation from a restricted environment at the base to an open shelf environment in the central part or on top ("deepening upward" or transgressive trend), and gradation to a restricted environment ("shallowing upward" or regressive trend) to the top of thicker limestone horizons.

Mack and James (1986) interpreted red-bed siliciclastics of the Robledo Mountains Formation as representing three tidal-flat facies: (1) ripple-laminated sandstones deposited on intertidal sandflats near mean low tide; (2) "mixed sandstone-shale" deposited landward of the ripple-laminated sandstones, on an intertidal flat; and (3) nodular (pedogenic calcrete) shale deposited in a supratidal setting. We agree with the interpretation of Mack and James (1986) that the red-bed siliciclastics of the Robledo Mountains Formation represent tidal-flat facies, but differ in our interpretation of specific facies. This difference reflects our view of depositional cyclicity (transgression-regression) in the Robledo Mountains, which is essentially diametrically opposed to that of Mack and associates (Fig. 5). Our interpretation, however, is restricted to the megatracksite level, which we have studied in great detail.

Mack and associates viewed limestones immediately below and above packages of red beds in the Robledo Mountains Formation as maximum points of transgression. Overlying red beds were interpreted as largely regressive, with the next transgression beginning in the middle (symmetrical cycle) or upper (asymmetrical cycle) portion of the red-bed package (Fig. 5). Like Mack and associates, we agree that limestones bounding

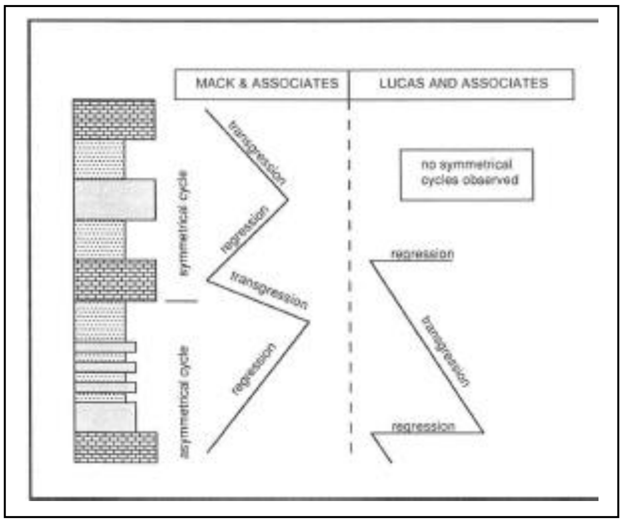

FIGURE 5. Depositional cycles of the Robledo Mountains Formation as interpreted by Mack and associates compared with our interpretation.

red-bed packages in the Robledo Mountains Formation represent maximum hansgression, or, more accurately stated, local sea-level highstand (Lucas et al., 1995). However, we view the subsequent regression as an event that did not lead to accumulation of sediment. Instead, the lowering of local base level produced by the regression (lowstand) resulted in the development of an unconformity surface on top of the high-stand limestone. During the subsequent transgression, sediment began to accumulate as base level began to rise. In the case of the megatracksite level, the patchy distribution of thin shoreface sandstone (Fig. 3, section A, unit 3), thick shoreface sandstone (Fig. 3, section G, unit 16), tidal flat sandstone and siltstone (Fig. 3, section C, unit 4) and very localized delta foresets (at locality 2851) provide strong evidence of the infilling of an irregular, incised landscape (paleotopography) developed on top of a highstand marine limestone (Lucas et al., 1995). Vuggy recrystallization of the top of the hansgressive limestone underlying the megatracksite level also suggests subaerial exposure (Lucas et al., 1995).

Using the megatracksite as the best studied example (it is an asymmetrical cycle in the terminology of Mack and associates), continued base-level rise formed extensive tidal flat environments leading to deposits covered with a wide range of invertebrate and vertebrate tracks. Continued rising base level caused paleosols to form on top of the tidal flats until they were flooded over by marine waters that deposited the next highstand carbonate. The existence and interpretation of symmetrical cycles identified by Mack and associates is problematic; none are present in our detailed measured sections of the Robledo Mountains Formation (Fig. 3).

The differences between our interpretations of depositional cyclicity in the Robledo Mountains Formation and those of Mack and others are both observational and conceptual. The principal difference between our observations and those of Mack and associates is that we did not observe calcareous marine shales overlying transgressive limestones. Instead, relatively coarse-grained sediments directly overlie the limestones and fine upward into siltstones and shales. If, as we argue, the top of the marine limestone is an unconformity and/or lowstand, then the elastic sediments above that unconformity and the next marine limestone above the elastics form a fining upward sequence (Fig. 5). This fining upward sequence cannot readily be interpreted as regressive, because regression usually produces a coarsening-upward sequence (Dalrymple, 1992).

This highlights the conceptual differences between our interpretation and that of Mack and associates. As Dalrymple (1992, p. 212) observed "no modern examples of regressive, prograding tidal systems are sufficiently well documented to serve as a model" and "there are also surprisingly few ancient examples [of regressive prograding tidal systems]." Regression in these environments is characterized by erosion and sediment bypassing as base level falls. Although regressive progradation may backfill some estuaries (e.g., Dalrymple et al., 1990), it seems unlikely that much sediment accumulates or is preserved in a tidal flat system during regression. For this reason, it makes much more sense to interpret sediments in the Robledo Mountains Formation as largely those that accumulated during hansgression (Fig. 5). We thus *view* the hacksites as having formed on intertidal flats during transgression (Fig. 6).

Schult (1994) concluded that because of the tidal flat origin of the Robledo Mountains hacksites, the amphibians who made many of the tracks were tolerant of high salinities. To support this conclusion, he reviewed the literature on salinity-tolerance in living amphibians, pointing out that a few salamander and frog taxa can tolerate a salinity of 40% seawater for extended periods of time.

The following evidence, however, runs contrary to Schult's (1994) conclusion that salinity-tolerant amphibians made many of the tracks at the Robledo Mountain sites:

1. Although the Robledo tracksites were made on tidal flats they were not right at the shoreface and therefore not permanently subjected to saline waters (Fig. 6). Particularly significant is the lack of deposit-feeder bioturbation-indicative of the shoreface-at any Robledo tracksite. Instead, the Robledo deposits appear to have been in the intertidal zone and thus subaerial during low tides when the tracks were impressed (Fig. 6).

2. A few living lissamphibians capable of tolerating high salinity is irrelevant to the salinity tolerances of Paleozoic temnospondyls. Lissamphibians are distant relatives of temnospondyls; they are distinct subclasses of the class Amphibia. Furthermore, a few salinity-tolerant lissamphibians are hardly representative of the Lissamphibia, almost all of which can only tolerate freshwater. There is essentially no direct evidence of salinity tolerance by temnospondyls, except for the Triassic trematosaurs.

3. Trackways of spiders *(Octopodichnus)* and other invertebrates that are not salinity tolerant are common at most of the Robledo hacksites.

4. The conifer *Wnlchin,* commonly preserved as complete leaf impressions at the Robledo h·acksites, must have lived very close to the tidal flats and was probably not salinity tolerant.

We therefore conclude that the Robledo Mountain tracksites formed on tidal flats during rising base level due to transgression. The flats were in the intertidal zone and subjected to frequent subaerial exposure. Small temnospondyl amphibians and araeoscelid reptiles were the dominant tetrapod trackmakers. Scorpions and spiders were the most common invertebrate trackmakers. An extensive forest dominated by the conifer *Wnlchin* shrouded the landscape.

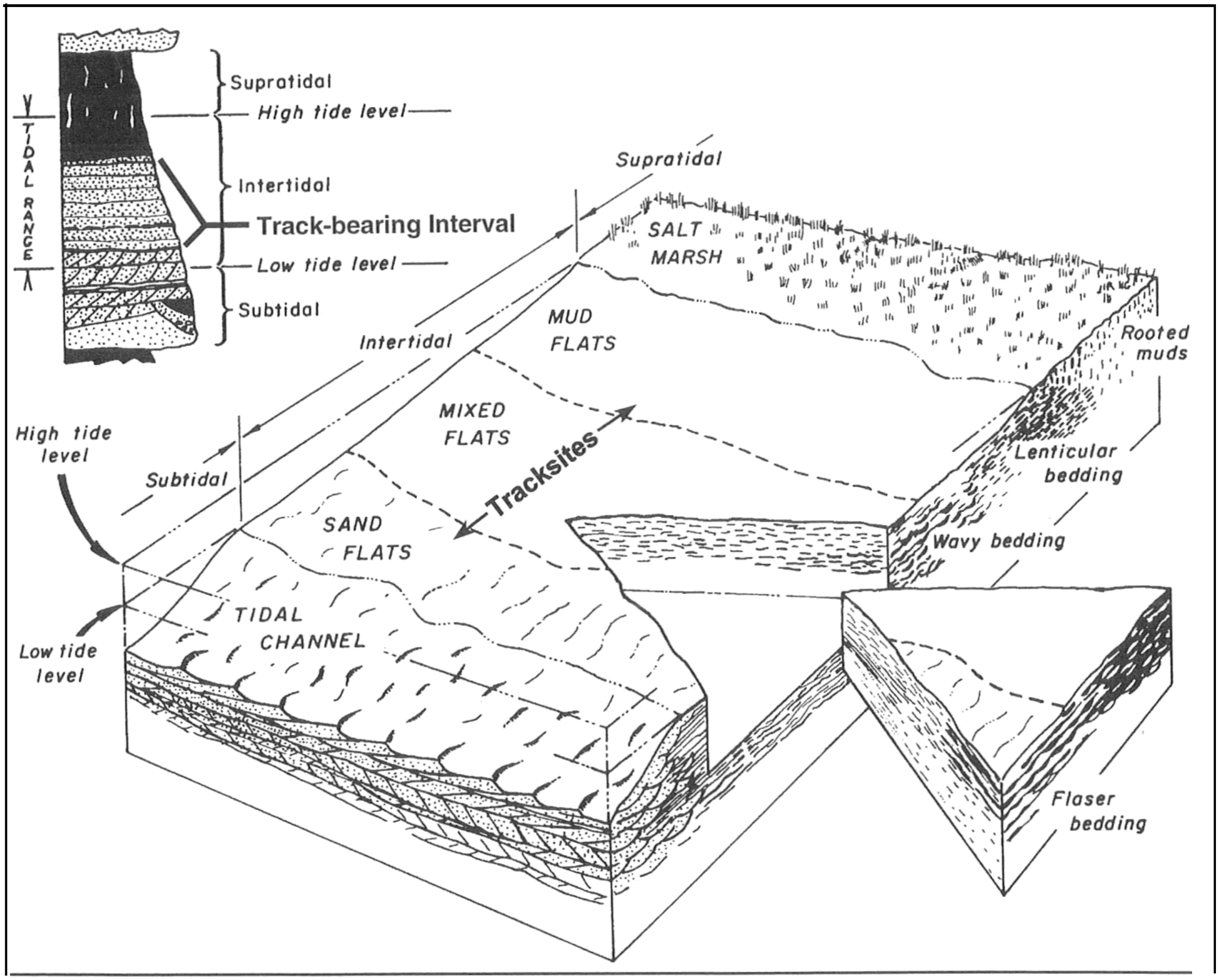

FIGURE 6. Block diagram showing inferred depositional environment of Robledo Mow1tains megatracksite (based, in part, on a diagram in Dalrymple, 1992).

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