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GEOLOGY OF EARLY PERMIAN TRACKSITES, ROBLEDO MOUNTAINS, SOUTH-CENTRAL NEW MEXICO

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ABSTRACT: Early Permian fossil localities, including numerous tracksites, in the southern Robledo Mountains of Doña Ana County, New Mexico cover an area of approximately 20 km². Detailed mapping and measurement of seven stratigraphic sections shows that Lower Permian strata exposed here belong to three members of the Hueco Formation. In ascending order they are the middle, Robledo Mountains and upper members. We introduce the term Robledo Mountains Member of Hueco Formation to refer to strata previously termed Abo Tongue, Abo Formation, or Abo-Hueco Member. The Robledo Mountains Member 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. The red beds in the study area contain extensive invertebrate and vertebrate (tetrapod-footprint) trace fossils and a large, megafossil plant assemblage composed mainly of *Walchia* from more than 30 localities. Marine facies of the upper part of the Robledo Mountains Member contain an extensive late Wolfcampian assemblage of megafossil invertebrates, dominated by brachiopods and bryozoans, with considerable numbers of molluscs—bivalves, gastropods and a few specimens of ammonites. Non-fusulinid foraminiferans and ostracods dominate the microfossil assemblages. Conodonts from the middle part of the Robledo Mountains Member, found in strata that bracket most of the tracksites, indicate a late Wolfcampian (= late Artinskian) age. Quaternary alluvia overlie and Tertiary intrusive igneous rocks cut Hueco Formation strata in the southern Robledo Mountains.

Most of the 34 red-bed tracksites in the Robledo Mountains Member occur at one stratigraphic level and thus represent a megatracksite that encompassed at least 20 km². Carbonates of the Robledo Mountains Member 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 member to more open normal marine waters in the middle and upper parts of the member. Tracksites were formed on siliciclastic tidal flats during early stages of rising base level (transgression). Our data suggest deposition of the red beds of the Robledo Mountains Member that encompass the megatracksite during a transgressive episode, rather than a cycle of regression-transgression as previously suggested.

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 Rio Grande rift and exposes a thick, carbonate-dominated section of Paleozoic strata overlain by Tertiary-Quaternary siliciclastics and cut locally by Tertiary 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, Doña Ana County. Discovered and developed by Jerry P. MacDonald, these tracksites represent one of the most significant records of Permian tetrapod footprints in the world (Lucas et al., 1994b). The track-bearing strata are intercalated with marine sediments that contain an extensive invertebrate biota (see Kues, Kietzke and Lucas, and Kozur and Lemone, this volume). Our purpose here is to establish the geological, especially the stratigraphic and depositional, context of these fossil localities. In this article, NMMNH refers to the New Mexico Museum of Natural History and Science, Albuquerque.

LOCATION AND METHODS

This study focused on an area of about 20 km² that encompasses 43 known fossil localities: secs. 19–20, 29–30, T22S, R1E and secs 23–26, T22S, R1W (Table 1; Figs. 2–3). Fossil localities discovered by Jerry MacDonald, as well as some we collected, all of Early Permian (Wolfcampian) age (Table 1), delimited the study area. We mapped the geology of this area at a scale of 1:24,000 (Fig. 2). Low altitude oblique aerial photographs taken by Paul L. Sealey aided the mapping; some of these photographs are published here (Figs. 7–9).

Seven stratigraphic sections (Fig. 4) of Permian strata were measured in the study area. All sections were measured with a Brunton compass and 1.5-m-long staff. They are described in Appendix 1 of this paper.

PREVIOUS STUDIES

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 Doña 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, 1971, 1975) published brief paleontological and microfacies analyses of the upper member of the Hueco Formation in the study area.

Ichnofossils have long been known from Lower Permian red beds of Europe and have been studied extensively (e.g., Haubold, 1971, 1984). Vertebrate and 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). However, most localities yield only a few taxa, and few have been studied in detail. The Lower Permian localities in the Hueco Formation of the southern Robledo Mountains surpass all others in quantity, quality, and diversity of ichnotaxa. In fact, we suggest that they represent the most scientifically important Early Permian terrestrial ichnofauna known (Lucas et al., 1994a).

Geologists long knew that Permian vertebrate tracks occur in the Robledo Mountains (e.g., LeMone et al., 1971; Mack and James, 1986), as did amateur collectors and local stone-quarry operators (MacDonald, 1989, 1990). One specimen of a *Dimetropus* trackway was donated to NMMNH years ago, and others are in private collections or are visible in walls and rock floors around the city of Las Cruces (MacDonald, 1990).

However, it was not until 1986 that Las Cruces resident Jerry MacDonald prospected exposures of the Hueco Formation in the Robledo Mountains and located an outcrop which contains 25 superposed bedding planes covered with laterally extensive trackways of vertebrates and invertebrates. Plant fossils are also present on other bedding planes. This locality (NMMNH locality 846) is only one of several in the area, but it has been the most extensively excavated and has yielded the vast majority of collected specimens of tracks (MacDonald, 1989, 1990, 1992, 1994).

Several popular articles and booklets have been written about the Robledo trackways (Bowlds, 1989a,b; Garrettson, 1989; MacDonald, 1989, 1990, 1992, 1994; Mimms, 1992; Stewart, 1992), but little has been published in detail or in the scientific literature. Mack and associates studied the sedimentology of the track-bearing strata in general (Mack and James, 1986; Mack et al., 1988, 1991), and Lucas (1993) studied 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.

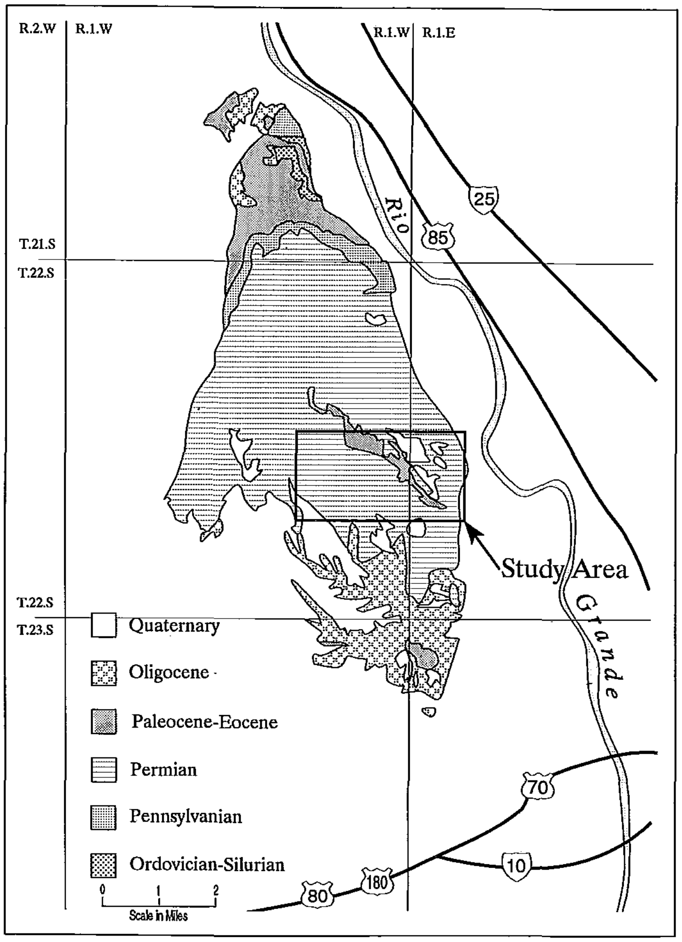


FIGURE 1. Generalized geological map of the Robledo Mountains (based on Seager, et al., 1987).

TABLE 1. Fossil localities in the Robledos Mountains Member of the Hueco Formation in the Robledo Mountains. I = invertebrate tracks, IM = invertebrate macrofossils, P = fossil leaves, V = vertebrate tracks, W = fossil wood. Note that all UTM coordinates are in zone 13.

LOCALITY NO.	UTM		FOSSILS
NMMNH 846	323070E	3584120N	I,P,V
NMMNH 2811	323094E	3583881N	V
NMMNH 2812	323128E	3583894N	V
NMMNH 2813	323405E	3583698N	V
NMMNH 2814	323508E	3583694N	V
NMMNH 2815	323595E	3583655N	P,V
NMMNH 2816	323690E	3583644N	V
NMMNH 2817	323253E	3583790N	I,V
NMMNH 2818	323251E	3582613N	P,V
NMMNH 2819	323188E	3582589N	I,P,V
NMMNH 2820	323114E	3582533N	V
NMMNH 2821	323059E	3582550N	V
NMMNH 2822	323369E	3582524N	V
NMMNH 2823	322430E	3582572N	P,V
NMMNH 2824	323360E	3584750N	V
NMMNH 2825	322422E	3580691N	P,V
NMMNH 2826	321177E	3582413N	I,V
NMMNH 2827	321170E	3582372N	I,V
NMMNH 2828	321105E	3582498N	I,P,V
NMMNH 2829	321132E	3582596N	P,V
NMMNH 2830	321132E	3582480N	P,V
NMMNH 2831	321155E	3582288N	V
NMMNH 2832	321040E	3582315N	V
NMMNH 2833	319199E	3583811N	I,V
NMMNH 2834	319551E	3584157N	V
NMMNH 2835	319218E	3584116N	I,V
NMMNH 2836	319382E	3584145N	V
NMMNH 2837	319218E	3584116N	V
NMMNH 2838	319269E	3584116N	V
NMMNH 2839	319416E	3584208N	V
NMMNH 2849	323287E	3584236N	V
NMMNH 2850	323378E	3582696N	V
NMMNH 2851	321215E	3582400N	I,P,V
NMMNH 2852	321420E	3585740N	V
NMMNH 3010	322975E	3584082N	IM
NMMNH 3011	323512E	3583210N	IM
NMMNH 3012	323240E	3582480N	IM
NMMNH 3013	323120E	3582260N	IM
NMMNH 3014	320757E	3583456N	IM
NMMNH 3015	322880E	3582684N	IM
NMMNH 3016	320906E	3584365N	W
NMMNH 3017	323360E	3583280N	I
NMMNH 3018	323320E	3583050N	I

STRATIGRAPHY

Rocks of Early Permian, Tertiary and Quaternary age are exposed in the mapped area (Figs. 2–9). The Permian rocks belong to the Hueco Formation, whereas the Tertiary-Quaternary rocks are intrusive igneous rocks and sedimentary rocks of the Santa Fe Group and younger Quaternary alluvia.

Hueco Formation

Three members of the Hueco Formation were mapped in the study area (in ascending order): middle member, Robledo Mountains Member, and upper member. The lower member of the Hueco Formation crops out well to the north of the study area.

Middle Member

The middle member of the Hueco Formation crops out in the northeastern and north-central parts of the study area (Fig. 2). Tan and gray dolostone and dolomitic limestones dominate the middle member. Stromatolitic lamination and fenestral fabric are common. A few packstone beds, dominantly composed of bryozoans and brachiopods or of ostracods, also are present. No red-bed siliciclastics are present in the middle member; the base of the overlying Robledo Mountains Member is mapped at the stratigraphically lowest red beds. The middle member of the Hueco Formation 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 middle member at locality 3016 (Fig. 6D). These logs clearly floated into and were buried in a shallow marine environment as driftwood.

Robledo Mountains Member

Strata previously referred to as the Abo Tongue, Abo Formation, or Abo-Hueco Member in the Robledo and Doña Ana Mountains (Seager et al., 1976, 1987; Mack and James, 1986; Mack et al., 1988, 1991) are here named the Robledo Mountains Member of the Hueco Formation. The type section of the Robledo Mountains Member is our section G (Figs. 4,7), which was described previously by Jordan (1971, 1975). At its type section, the Robledo Mountains Member is 125.4 m thick. Most of the section is 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 are a minor component.

Jordan (1971) and Krainer and Lucas (this volume) provide detailed descriptions of the lithology of the Robledo Mountains Member. Most Robledo Mountains Member limestones are micritic. Fossiliferous limestones are mostly bioclastic wackestones and packstones (Fig. 6E), some of which are dominated by shell material of tubular foraminiferans (especially *Tolypammina*, *Hyperammina*, *Ammovertella*, *Globivalvulina*, *Hemigordius* and *Tuberitina*) and ostracods. Less common lithologies are bioclastic and foraminiferal grainstones. Calcareous shales, mostly yellowish gray in color, are usually associated with Robledo Mountains Member limestones. Red-bed strata of the Robledo Mountains Member are dominated by grayish red to pale red, fine-grained micaceous, litharenitic sandstone. Typical sedimentary structures include lamination and/or ripple lamination (Fig. 5E). A few sandstones are trough-crossbedded, hummocky bedded or have herringbone crossbeds (Fig. 5D). Raindrop impressions (Fig. 6A), mudcracks (Fig. 6B), leaf impressions (Fig. 6C) and tetrapod footprints (Fig. 6F) are common on bedding planes. Red-bed mudstones and siltstones are a very minor component of the Robledo Mountains Member.

These characteristics suggest that most of the Robledo Mountains Member is of marine origin and thus consists of characteristic Hueco Formation lithologies—fossiliferous carbonates and calcareous shales. About one-third of the unit is red-bed siliciclastics that represent the intertonguing of Abo Formation facies with the Hueco Formation. This is the basis of previous references to this interval as Abo Tongue, Abo Formation or Abo-Hueco Member, even though it is much more Hueco Formation than Abo lithologically. For this reason, we assign the Robledo Mountains Member to the Hueco Formation.

We measured seven stratigraphic sections to encompass all or part of the Robledo Mountains Member in the study area (Fig. 4). 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 (Figs. 4, 5C). 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 Member and on the base of the upper member of the Hueco Formation (Fig. 4).

Most of the tracksites in the Robledo Mountains Member thus constitute a megatracksite that covered at least 20 km². Our data (Fig. 4) do not support Schult's (1994, fig. 6) conclusion that NMMNH localities 846 and 2819 are separated by a stratigraphic thickness of approximately 500 m.

Incomplete sections (top missing) of the Robledo Mountains Member crop out in the Doña Ana Mountains northeast of the Robledo Mountains in T21S, R1E. 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 Member in the Doña 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 Mountains. We do not extend recognition of the Robledo Mountains Member 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.

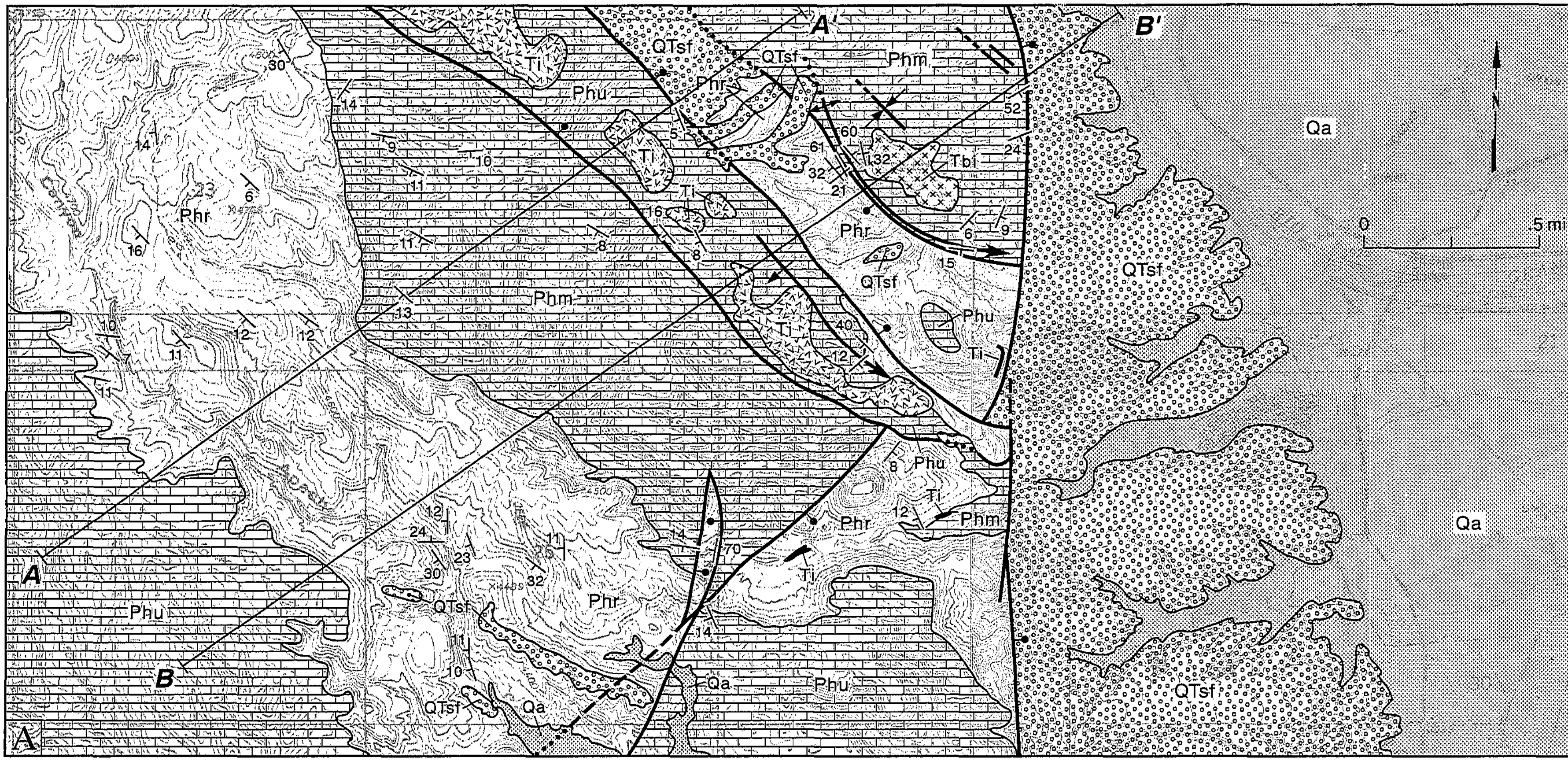
The age of the Robledo Mountains Member is late Wolfcampian (Kues, this volume). According to B. Wardlaw (written commun., 1995), conodonts from the middle part of the member (units 2, 6, and 8 of section A: Fig. 4) include *Sweetognathus expansus* (Perlmutter), *Hindeodus excavatus* (Behnken) and *Neostreptognathodos clarki* (Kozur) of latest Artinskian (= late Wolfcampian) age (Kozur, 1991). The ammonoid *Properrinites bosei* (Plummer and Scott) from the upper part of the Robledo Mountains Member also indicates a late Wolfcampian age (Kues, this volume).

Upper Member

The upper member of the Hueco Formation 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 (Figs. 2, 7). No effort was made by us to study this unit in detail, and much information about it can be found in Jordan (1971), LeMone et al. (1971, 1975) and Simpson (1976). These strata are gray algal-plate limestones, thin biostromes and interbedded siltstones. They produce a fossil biota dominated by phylloid algae, corals and gastropods (LeMone et al., 1971, 1975). Total thickness of the upper member is about 122 m.

Cenozoic Sedimentary Rocks

Sedimentary rocks of Cenozoic age in the map area are assigned to the Camp Rice Formation (Santa Fe Group) and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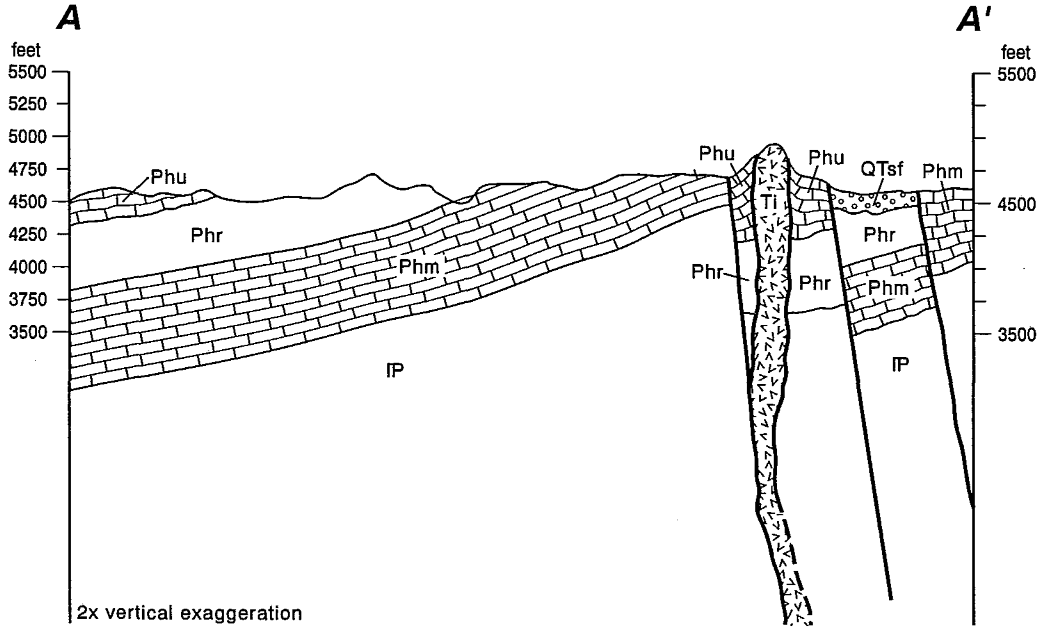
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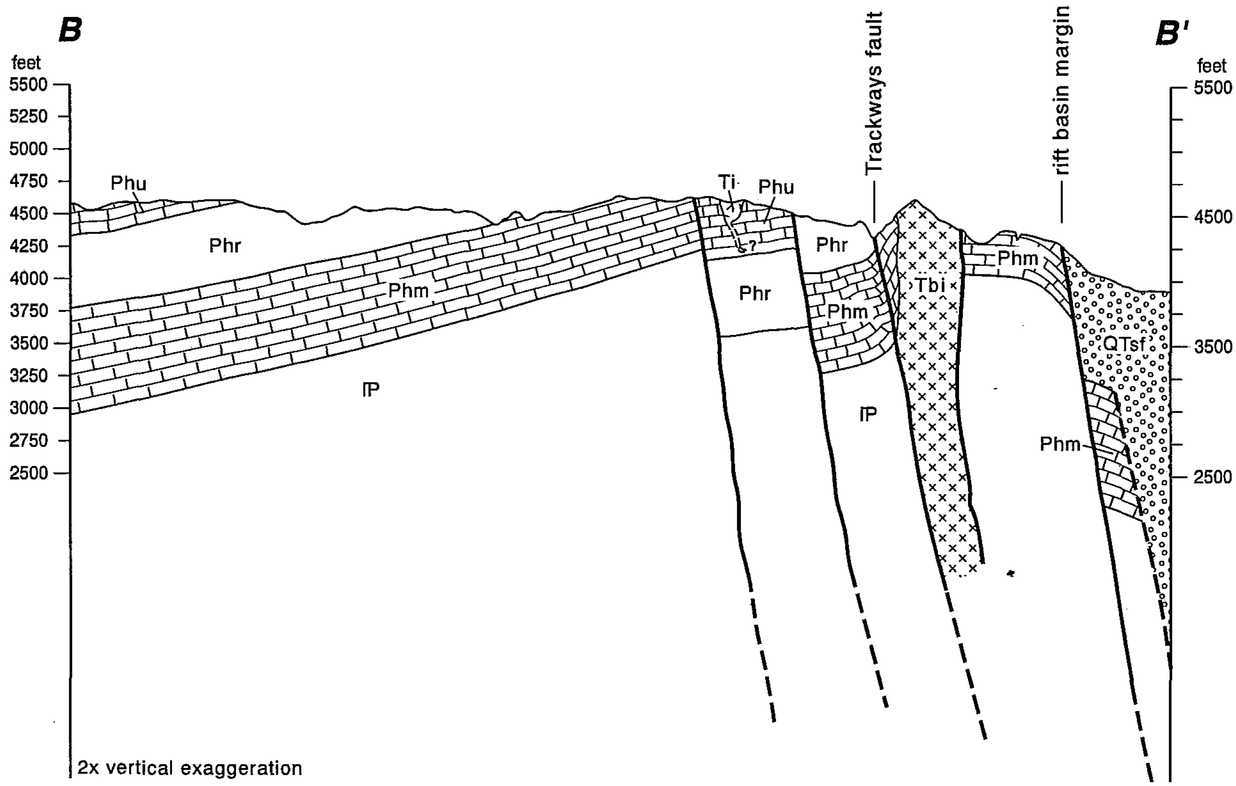
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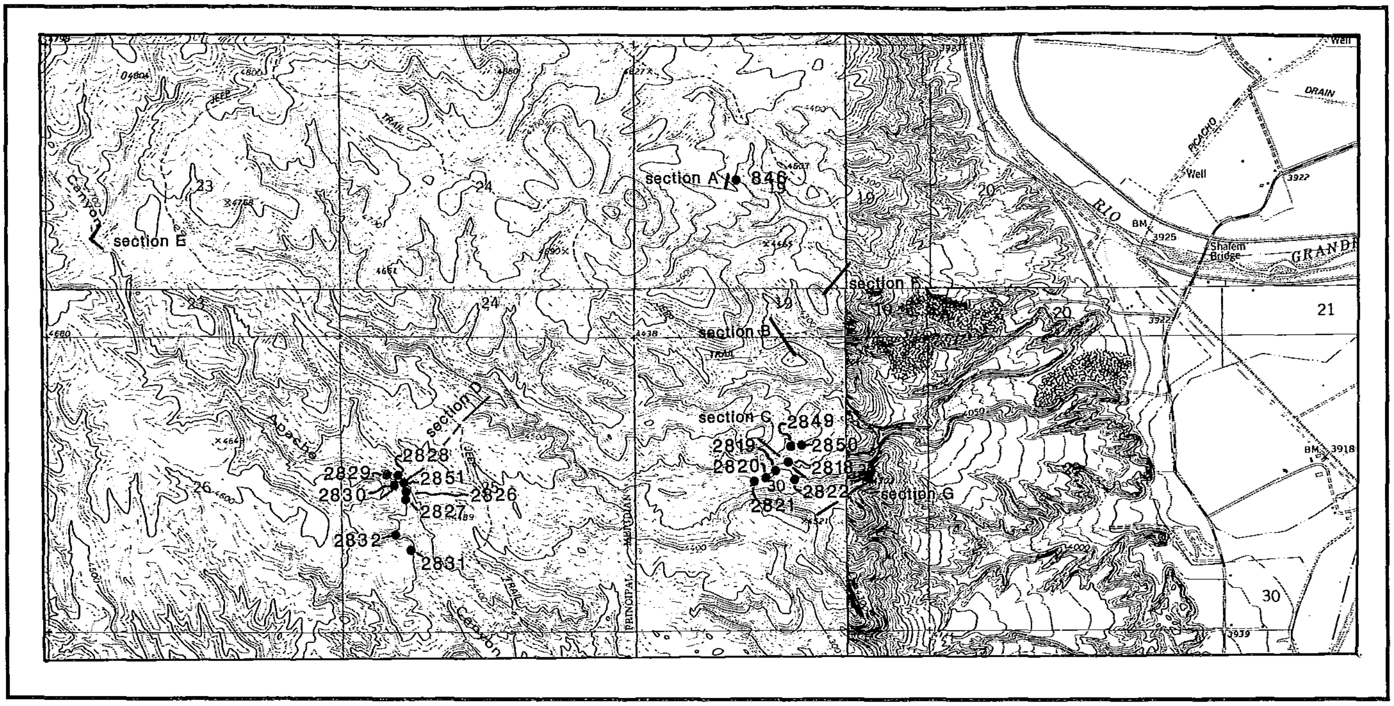

FIGURE 3. Fossil localities (see Table 1) and locations of measured stratigraphic sections (see Figure 4).

younger Quaternary alluvia. Santa Fe Group strata are exposed only to the east of the rift-bounding fault (Fig. 2). They are poorly lithified boulder conglomerates, yellow sandstones and gravelly conglomerates. These rocks belong to the Plio-Pleistocene Camp Rice Formation (Mack et al., 1993) but as mapped here may include some Quaternary gravels mapped by Seager et al. (1987) as "Qvo." Strata mapped by us as "Qa" are non-indurated sand, gravel and clayey deposits that are relatively recent terrace, fan and arroyo-fill facies.

Cenozoic igneous rocks

Igneous rocks in the map area (Fig. 2) consist of shallow intrusives of early Oligocene to Miocene age. They occur as non-foliated rhyolites in the form of sills or plugs, non-porphyritic to slightly porphyritic dikes, and one dike of more intermediate composition. The latter dike is coincident with the middle fault, which apparently is a very high angle normal fault that trends northwest just south of the trackways fault. Rhyolite sills and plugs in the Robledo Mountains and vicinity have been K-Ar dated at about 35 Ma (Seager et al., 1987).

Another type of intrusive rock occurs immediately east of the main trackway site (locality 846) (Fig. 2). It consists of a basalt plug which displays columnar jointing on its south face. This rock is a black-dark gray, alkali-olivine basalt containing xenocrysts of hornblende and plagioclase that contain small peridotite xenoliths (Seager et al., 1987). This rock type regionally yields radiometric age dates of 7 to 15 Ma (Seager et al., 1987). It is obvious from the map pattern and the accompanying cross sections that the extensive high angle faulting in the area has controlled the development of magma conduits for all the intrusive rock types present (Fig. 2).

FIGURE 2. (previous two pages) Geological map and structural cross sections in the southern Robledo Mountains.

STRUCTURAL GEOLOGY

The Robledo Mountains are a wedge-shaped horst block of Paleozoic and Cenozoic rocks tilted southward approximately 10° to 14° (Hawley et al., 1975), at the western margin of the Rio Grande rift basin and are the dominant structural feature locally. The western margin of the Robledo horst is defined by a shallow basin outside of our map area.

Within the 20 km^2 area mapped in this study, the structure is moderately complex (Fig. 2). It is defined and characterized by at least five, high-angle normal faults of diverse strikes. The first, alluded to above, is the north-striking (trending) fault forming the western margin of the rift basin and consequently the eastern margin of the Robledo Mountains. This fault zone, so called because it likely consists of multiple strands, is evident in several arroyos which drain into the rift basin. Here Hueco Formation rocks flex abruptly down to the east where they become buried under the basin fill of the Camp Rice Formation. Dips of up to 52° were recorded in this flexure, which represents drag folding into the fault on the footwall. Not all dip directions are normal to the strike of the fault, but this is not unusual in such a moderate to high displacement fault zone. Variable dip direction is probably due to local variation in stratigraphic throw along the strike of the fault. At no place is a fault plane visible, so no slickensides were observed. These are rarely preserved in carbonate rocks.

Three northwest-striking faults are present in the map area, all of which are truncated eastward by the north-trending rift margin fault (Figs. 2,7,8,9). The southernmost one, called the south fault, is the master fault, whereas the other two of lesser displacement are antithetic to the master fault and are interpreted to have fault planes that dip to the southwest. These faults have controlled the location of magma conduits and hence the emplacement of intrusive rocks in the area. With the oldest rhyolitic intrusive rocks being 35 Ma or older (pre 1976 K-Ar dates tend to be anomalously young), this strongly indicates that the faults

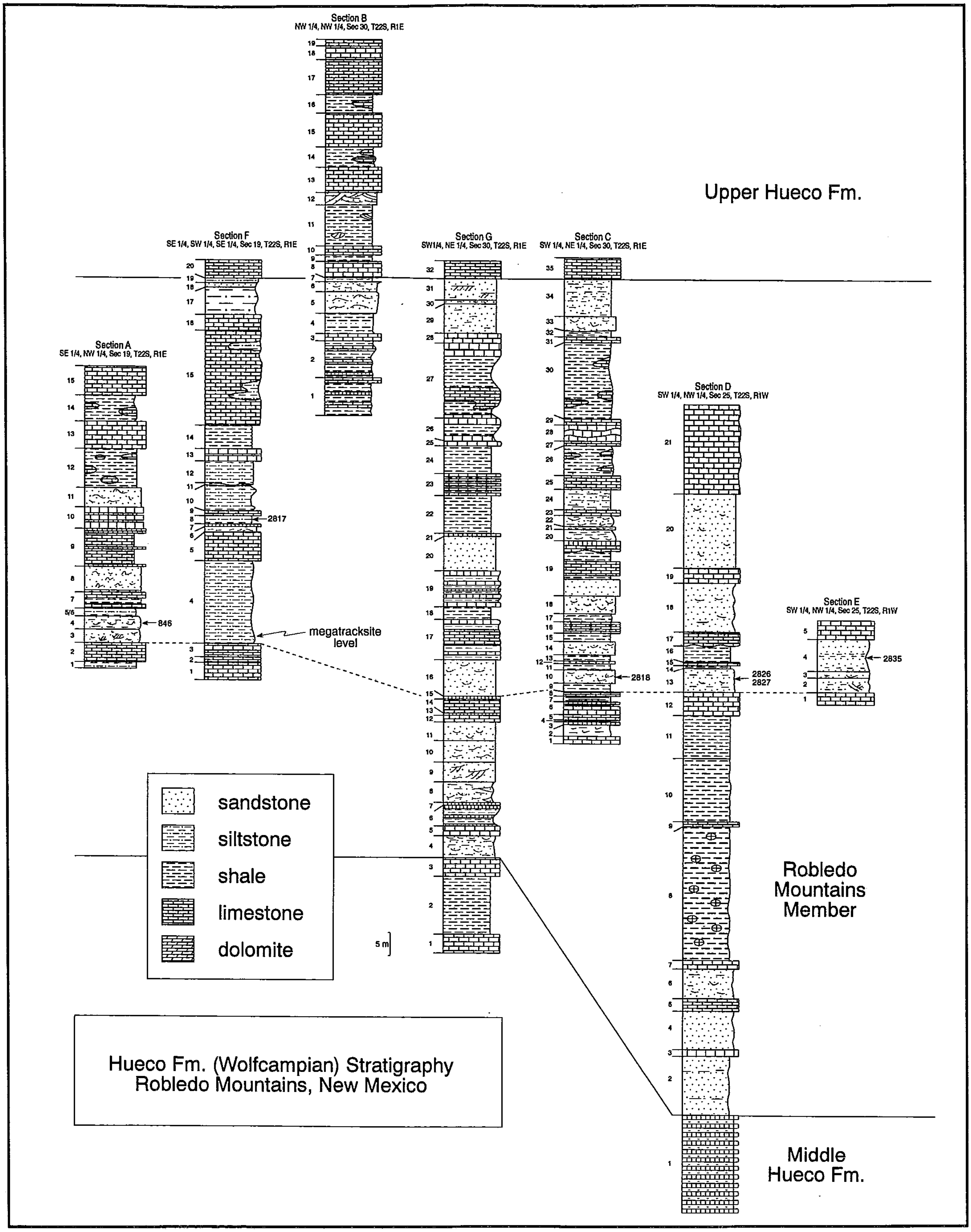

FIGURE 4. Measured stratigraphic sections of the Robledo Mountains Member of the Hueco Formation and some associated Lower Permian strata. See Figure 3 for map locations of sections and Appendix for descriptions of lithologic units.

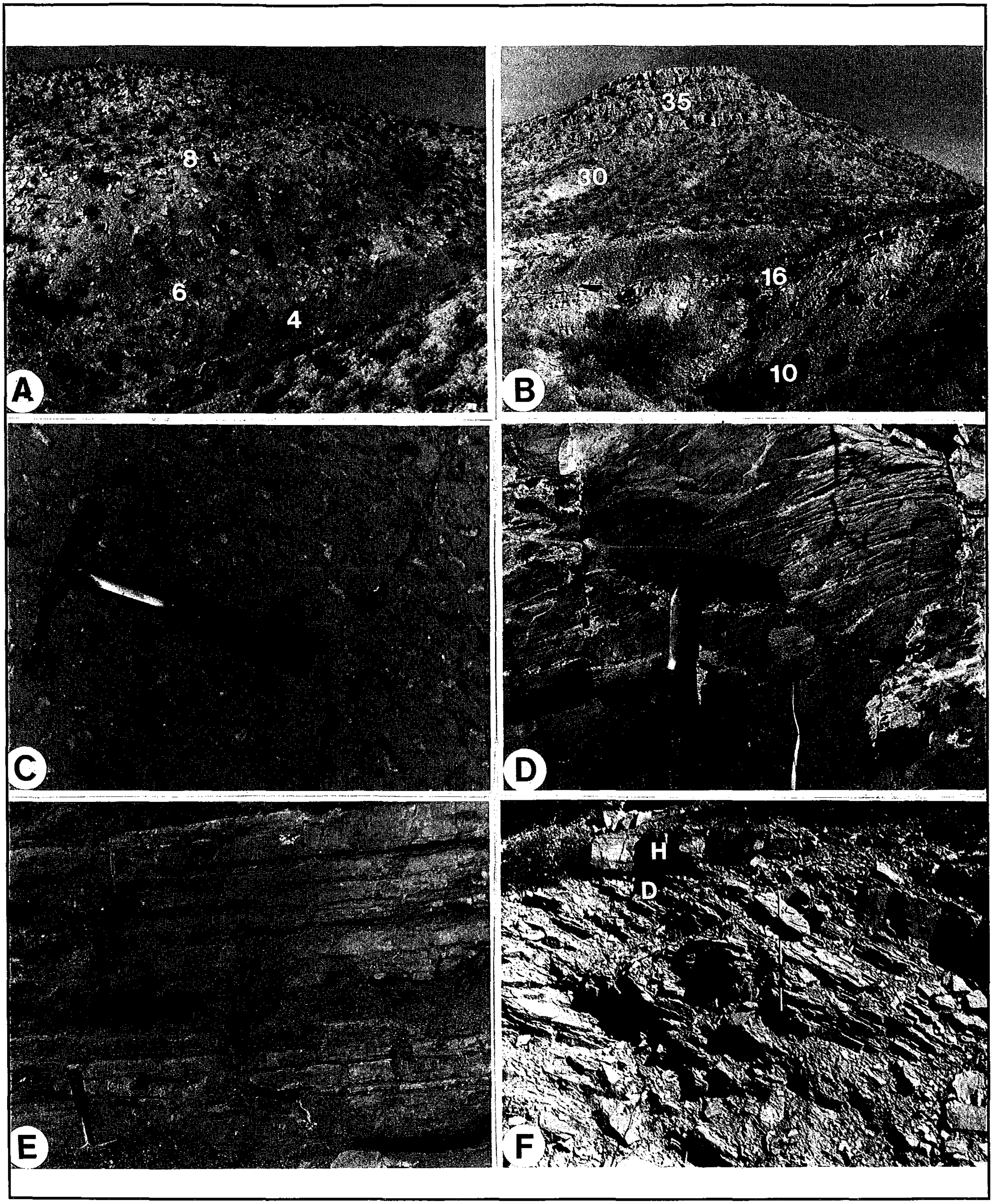

FIGURE 5. Selected fossil localities and outcrops of the Robledo Mountains Member. A, View of measured section A (Fig. 4); numbered units correspond to description in Appendix; note large excavation in unit 4 is NMMNH locality 846. B, Overview of middle–upper part of measured section C (Fig. 4); numbered units (35 = upper member of Hueco) correspond to description in Appendix. C, Top surface of unit 8 of section C, the marker bed of limestone below the megatracksite. D, Shoreface sandstone, unit 3 of section A. E, Excavated high wall at NMMNH locality 846 (unit 4 of section A). F, NMMNH locality 2851, showing steeply dipping delta cliniforms (D) overlain by horizontal (H) strata.

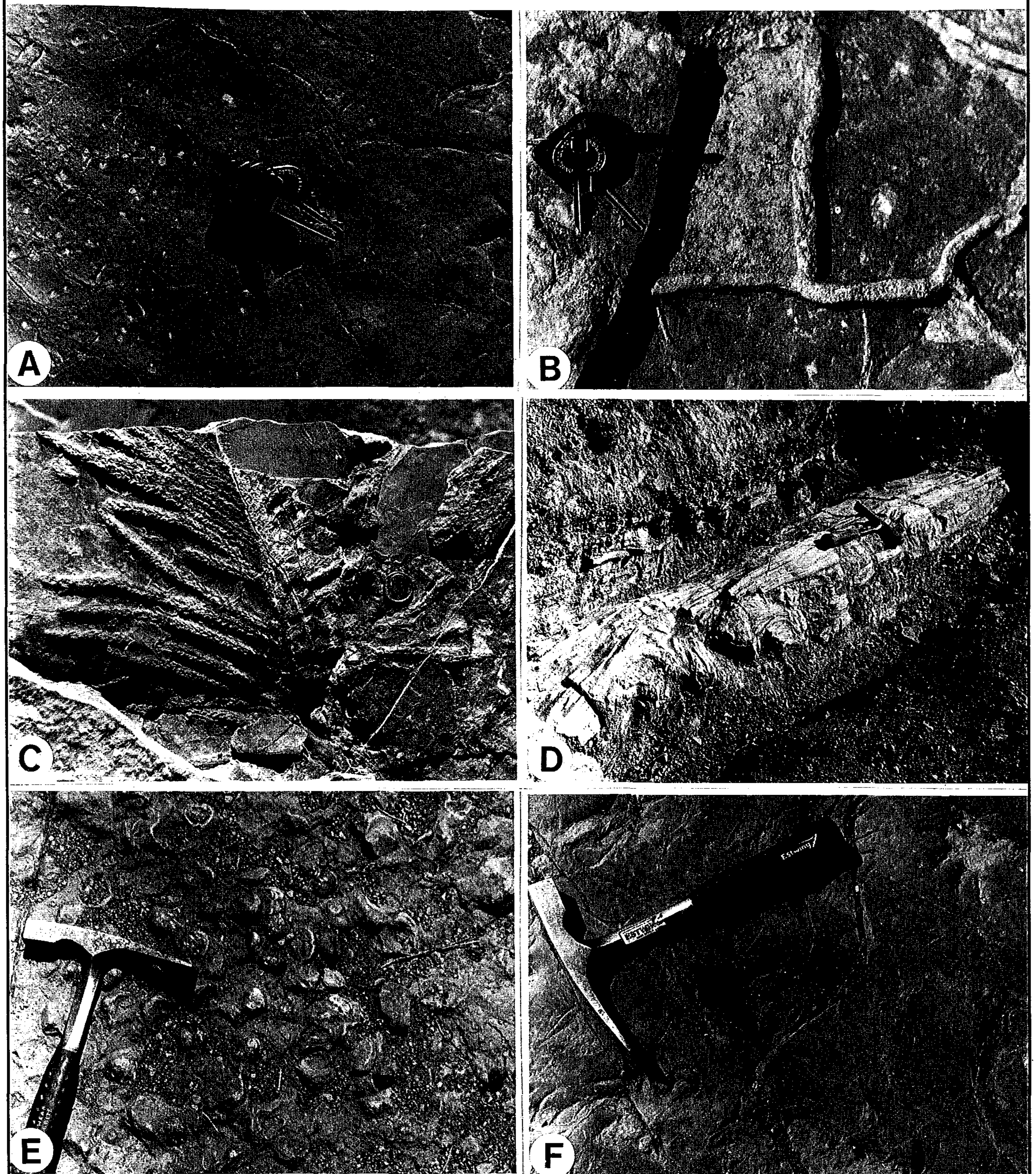

FIGURE 6. Selected sedimentary structures and fossils in the middle and Robledo Mountains Members of the Hueco Formation. A, Raindrop impressions at locality 846. B, Mudcrack filing at locality 846. C, Impression of the conifer *Walchia pinniformis* at locality 2828. D, Conifer log in the middle member of the Hueco Formation at locality 3016. E, Brachiopod coquina near locality 3011. F, *Dimetropus* tracks at locality 846.

originated as Laramide structures, or at least the master fault is this old. Indeed, the master fault may well represent part of a conjugate shear set associated with generally northward-directed regional compression, which gave definition to this small uplift during the Laramide orogeny. The eastward margin of the original uplift did not necessarily correspond to the present rift basin margin.

Middle and later Tertiary crustal extension associated with the formation of the Basin and Range Province in the southwestern U.S. has vastly modified Laramide structures and perhaps even resulted in the reversal of movement on some of the original faults. Certainly the antithetic faulting was associated with this later episode of deformation. The presence of much younger intrusive rocks associated with the antithetic faults is consistent with this interpretation; the basaltic intrusive in sec. 19 is a rock type that has been dated at 7 to 15 Ma locally (Seager et al., 1987). During this time interval, the dominant tectonic process was one of crustal extension, and rift development was well underway.

The implications of the above are that the south fault is much older than the rift- basin-margin fault. Both, however, have seen movement during the middle and late Tertiary episodes of crustal extension. It is important to note, however, that the onset of crustal extension is generally not considered to be synonymous with the onset of rifting; the rift developed somewhat later. Although crustal extension may have begun as early as immediate post-Laramide time (36 Ma: Cather, 1989), the onset of rifting in the middle and southern segments of the rift is thought to have occurred at about 27-28 Ma (Chapin, 1988). A recent study in the southern segment of the rift, just north of the Robledo Mountains, has suggested that the onset of rifting may have been 2 to 7 million years earlier than previous estimates, and hence could be as old as 35 Ma (Mack et al., 1994). This is based on the presence of an eastward tilted half-graben containing ash flow tuffs as old as 34.8 Ma. Nonetheless, the south fault has its origins in a crustal event that predates rift development.

The south fault repeats the Permian section in the map area, dropping the upper member of the Hueco Formation with an apparent displacement of as much as 340 m (Fig. 2). Here again the fault plane is not exposed, but the geometry of the adjacent blocks (similar structural dip) and the relatively straight trace suggest that it is a deep-seated, high-angle

FIGURE 7. Low-angle aerial photograph looking to the southwest over the study area. Photograph by Paul L. Sealey.

normal fault. The fact that all three faults become more easterly trending as they approach the rift basin margin may be a feature inherited from their Laramide origin. The two antithetic faults are merely mimicking the change in strike of the master (south) fault.

The northernmost of the three faults is called the trackways fault (Figs. 2,9). It drops in the block of Robledo Mountains Member that contains the principal tracksite (locality 846). Structural dips in the area of this locality are somewhat variable due to the proximity to the fault. An interesting structural feature is visible from up the hill immediately east of locality 846. Looking northward from this vantage point, a tight anticlinal fold, of probable Laramide origin, can be seen. The left (west) limb of this fold is truncated by the trackways fault, which is antithetic to the south fault, and which drops in and thus preserves locality 846 (Fig. 9).

The last fault to be discussed is present in secs. 25 and 30 in the south-central part of the map area (Fig. 2). This fault, called the Apache Canyon fault, is the only northeast-trending structural element on the map; the strike of its trace is N46-47°E. It is a normal fault, down to the southeast, and locally drops the upper member of the Hueco against the middle member (Fig. 6). Displacement is thus similar to that of the south fault. The intersection of the Apache Canyon fault and the south fault forms a slightly acute to near-right angle, depending on whether the overall trend or the local trend of the south fault is used. The relationship of these two faults suggests that they belong to the same set of conjugate shears, probably developed in a north-south-directed stress field during Laramide compressional deformation. This interpretation is admittedly somewhat conjectural because of the lack of kinematic indicators (slickensides), but can be used as a working hypothesis until more analytical work can be done.

TRACKSITE GEOLOGY

Ichnofossils of invertebrates and vertebrates have been collected from 34 localities in the Robledo Mountains Member (Fig. 3, Table 1). Most of these tracksites are from one stratigraphic interval, and thus constitute a megatracksite as discussed below. The depositional environments and cyclicity of the tracksite strata also merit some discussion.

FIGURE 8. Low-angle aerial photograph looking to the northeast over part of the study area. Area shown is principally in sec. 19, T22S, R1E. Photograph by Paul L. Sealey.

Megatracksite

Lockley (1991, p. 153), in a book on dinosaur footprints, described megatracksites as "footprint-bearing layers of strata that cover large geographic areas on the order of hundreds, even thousands, of square kilometers." He contrasted them with tracksites "which are known to extend for only a few tens or hundreds of square meters." Obviously, Lockley's (1991) distinction between tracksites and megatracksites fails to cover the Robledos tracksites, most of which occur at one stratigraphic level over a 20 km^2 area. We expand the use of the term megatracksite to cover the Robledo occurrence because a 20 km^2 area of (mostly) very small Early Permian footprints is comparable in scale to a hundreds-of-square-kilometer area covered by much larger dinosaur footprints. The Robledo Mountains megatracksite is much older than the oldest known dinosaur megatracksite, which is from the Middle Jurassic Entrada Sandstone in the Four Corners area. The presence of the megatracksite in the Robledo Mountains Member indicates that conditions favorable to track preservation were especially widespread in this area during one short time interval of the late Wolfcampian.

Depositional Environment and Cyclicity

Jordan (1971, 1975), Mack and James (1986) and Mack et al. (1988, 1991) have carried out sedimentological studies of the Robledo Mountains Member and adjacent Lower Permian strata. They concluded that the middle member of the Hueco represent shallow, marine shelf environments, whereas the upper member of the Hueco consists of shallow marine shelf limestone and siltstone with a diverse biota that allowed Jordan (1971, 1975) and LeMone et al. (1971, 1975) to recognize a variety of biofacies. The Robledo Mountains Member 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 Member. The dominance of micritic limestones in the marine facies of the Robledo Mountains Member indicate deposition in a quiet environment on a shallow shelf. Some limestones, dominated by small foraminiferans and ostracods, suggest restricted

FIGURE 9. Low-angle aerial photograph looking to the southeast along the trackways fault. Area shown is principally in the SE1/4 sec. 19, T22S, R1E. Photograph by Paul L. Sealey.

(brackish?) depositional environments, whereas bioclastic wackestones and packstones with diverse, brachiopod- and bryozoan-dominated megafaunas suggest normal marine conditions.

The distribution of limestone facies in the Robledo Mountains Member indicates a "deepening" upward or transgressive upward trend within the member. Thus, ostracod- and foraminiferan-rich limestones are most abundant in the lower part of the Robledo Mountains Member whereas megafauna-rich wackestones and packstones dominate limestones of the upper part of the member. We interpret this as a trend from restricted circulation marine environments low in the Robledo Mountains Member to more open shelf marine environments in the middle to upper part of the member. The transition occurs above the megatracksite level.

Mack and James (1986) interpreted red-bed siliciclastics of the Robledo Mountains Member 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 Mack and James (1986) interpretation that the red-bed siliciclastics of the Robledo Mountains Member 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. 10). 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 Member 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. 10). Like Mack and associates, we agree that limestones bounding red-bed packages in the Robledo Mountains Member represent maximum transgression, or, more accurately stated, local sea-level highstand. 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) created an unconformity surface on top of the transgressive 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. 4, section A, unit 3; Fig. 5D), thick shoreface sandstone (Fig. 4, section G, unit 16), tidal flat sandstone/siltstone (Fig. 4, section C, unit 4) and very localized delta cliniforms (Fig. 5F, at locality 2851) provide strong evidence of the infilling of an irregular, incised landscape developed on top of a highstand marine limestone. Vuggy recrystallization of the top of the transgressive limestone underlying the megatracksite level (Fig. 5C) suggests subaerial exposure.

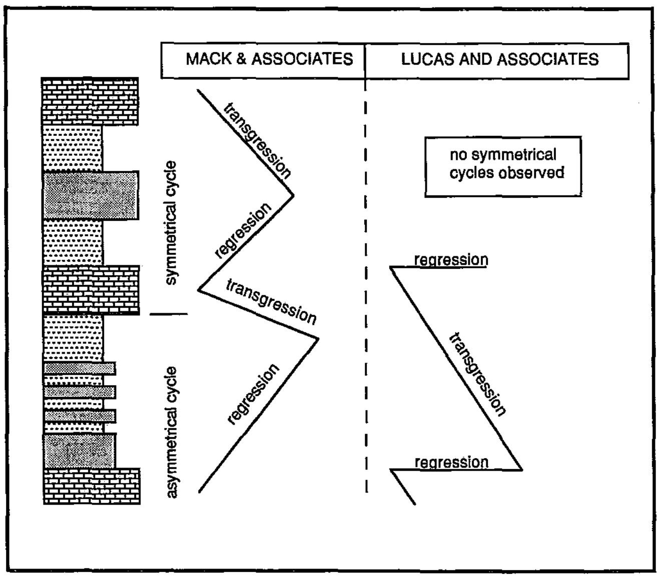

FIGURE 10. Depositional cycles of the Robledo Mountains Member as interpreted by Mack and associates compared with our interpretation.

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 tidal-flat 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 Member (Fig. 4).

The differences between our interpretations of depositional cyclicity in the Robledo Mountains Member 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 clastic sediments above that unconformity and the next marine limestone above the clastics form a fining upward sequence (Fig. 4, 10). 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 Member as largely those that accumulated during transgression (Fig. 10). We thus view the tracksites as having formed on intertidal flats during transgression (Fig. 11).

Schult (1994) concluded that because of the tidal flat origin of the Robledo Mountains tracksites, 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. 11). 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. 10).

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 arthropods that are not salinity tolerant are common at most of the Robledo tracksites.

4. The conifer *Walchia*, commonly preserved as complete leaf impressions at the Robledo tracksites, 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 *Walchia* shrouded the landscape. To what extent tidal cyclicity (e.g. Feldman et al., 1993) controlled trackway preservation is a subject we are now studying and will be discussed in detail in a subsequent paper.

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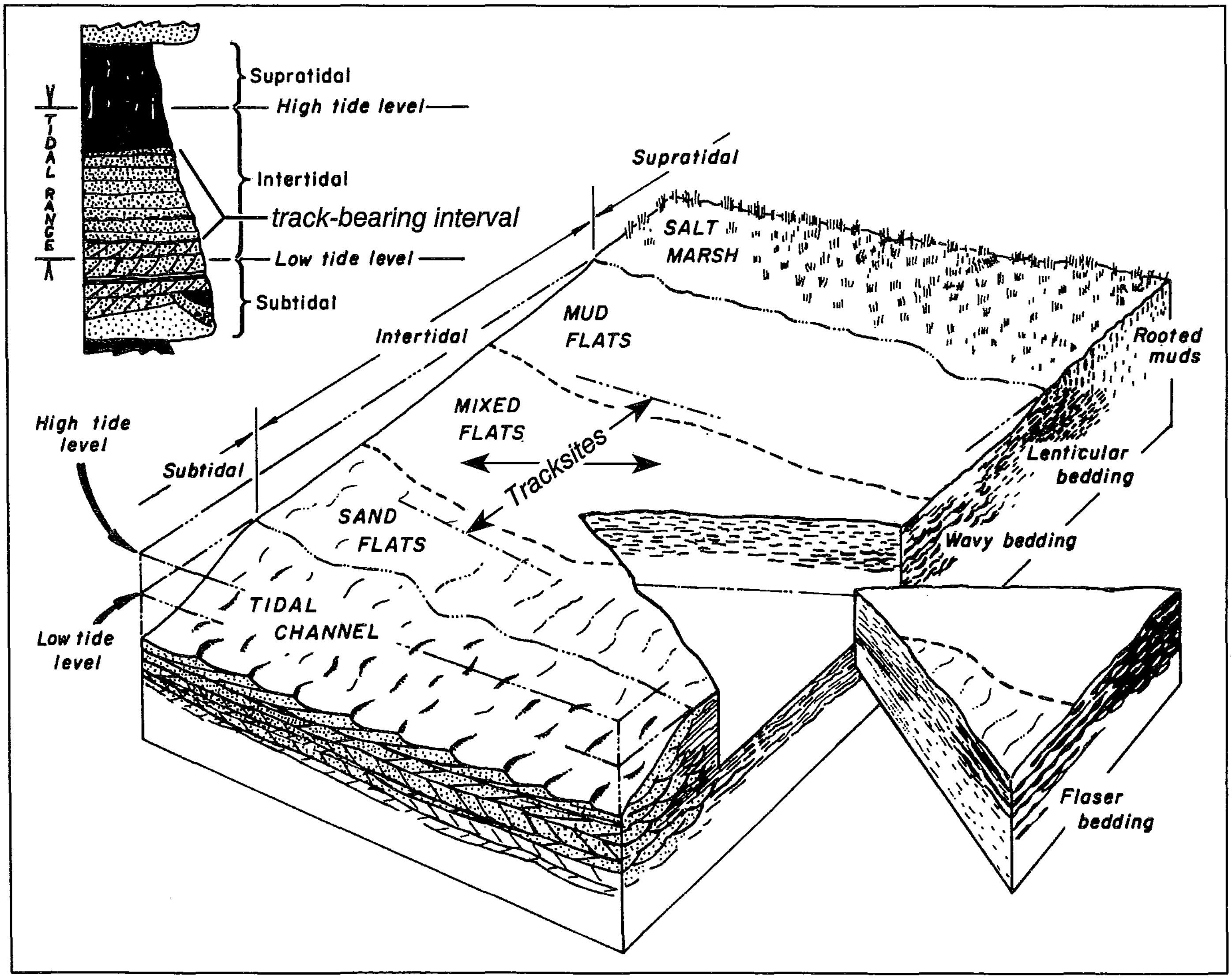

FIGURE 11. Block diagram showing inferred depositional environment of Robledo Mountains megatracksite (based, in part, on a diagram in Dalrymple, 1992).

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REFERENCES

Bachman, G.O. and Myers, D.A., 1969, Geology of the Bear Peak area, Doña Ana County, New Mexico: U.S. Geological Survey, Bulletin 1271-C, 46 p.

Bowlds, L.S., 1989a, Tracking down the Early Permian: Geotimes 1989 (May issue), p. 12–14.

Bowlds, L.S., 1989b, Tracking the Early Permian: Earth Science, v. 42, p. 16–19.

Cather, S.M 1989, Post-Laramide tectonic and volcanic transition in west-central New Mexico: New Mexico Geological Society, Guidebook 40, p. 91–97.

Chapin, C.E., 1988, Axial basins of the northern and central Rio Grande rift: Geological Society of America DNAG volume D-2, Sedimentary cover-North American craton, p. 165–170.

Dalrymple, R.W., 1992, Tidal depositional systems; in Walker, R.G. and James, N.P., eds., Facies models response to sea level change: Ontario, Geological Association of Canada, p. 195–218.

Dalrymple, R.W., Knight, R.J., Zaitlin, B.A. and Middleton, G.V., 1990, Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay-Salmon River Estuary (Bay of Fundy): Sedimentology, v. 37, p. 577–612.

Feldman, H.R., Archer, A.W., Kvale, E.P., Cunningham, C.R., Maples, C.G. and West, R.R., 1993, A tidal model of Carboniferous Konservat-Lagerstätten formation: Palaios, v.8, p. 485–498.

Garrettson, D., 1989, Marvelous mystery uncovered in Las Cruces District: Adviser (BLM, Santa Fe), April, 1989, cover and 2 unnumbered pages.

Gilmore, C.W., 1926, Fossil footprints from the Grand Canyon: Smithsonian Miscellaneous Contributions, v. 77, 41 p.

Haubold, H., 1971, Ichnia amphibiorium et reptiliorum fossilium: Handbuch der Paläoherpetologie, Teil 18. Stuttgart, Gustav Fischer Verlag, 124 p.

Haubold, H., 1984, Saurierfährten. Wittenberg Lutherstadt, A. Ziemesen Verlag, 231 p.

Hawley, J.W., Seager, W.R. and Clemons, R.E., 1975, Third day road log from Las Cruces to north Mesilla Valley, Cedar Hills, San Diego Mountain, and Rincon area: New Mexico Geological Society, Guidebook 26, p. 35–53.

Hunt, A.P., Lucas, S.G., and Huber, P., 1990, Early Permian footprint fauna from the Sangre de Cristo Formation of northeastern New Mexico: New Mexico Geological Society, Guidebook 41, p. 291–303.

Hunt, A.P., Lucas, S.G. and Lockley, M.G., 1994[a], The world's oldest megatracksite: Early Permian of southern New Mexico: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A–124.

Hunt, A.P., Lucas, S.G., Lockley, M.G., MacDonald, J.P. and Hotton, N. III, 1994[b], Early Permian tracksites in southern New Mexico: Journal of Vertebrate Paleontology, v. 14, supplement to no. 3, p. 30A.

Hunt, A.P., Lockley, M.G., Lucas, S.G., MacDonald, J., Hotton, N. III and Kramer, J., 1993, Early Permian tracksites in the Robledo Mountains, south-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, p. 23–31.

Jordan, C.F. Jr., 1971, Lower Permian stratigraphy of southern New Mexico and West Texas [Ph. D. dissertation]: Houston, Rice University, 136 p.

Jordan, C.F. Jr., 1975, Lower Permian (Wolfcampian) sedimentation in the Orogrande basin, New Mexico: New Mexico Geological Society, Guidebook 26, p. 109–117.

Kottlowski, F.E., 1960, Reconnaissance geologic map of Las Cruces thirty-minute quadrangle: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 14.

Kottlowski, F.E., 1963, Paleozoic and Mesozoic strata of southwestern and central New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 79, 100 p.

Kozur, H., 1991, Boundaries and subdivision of the Permian system: Occasional Publication, Earth Sciences and Resources Institute, University of South Carolina, new series, v. 9B, p. 139–154.

LeMone, D.V., Klement, K.W. and King, W.E., 1967, Permian (Wolfcampian) hylloid algal mound in the southern Robledo Mountains, Doña Ana County, New Mexico: New Mexico Journal of Science, v. 8, p. 24–25.

LeMone, D.V., Klement, K.W. and King, W.E., 1971, Abo-Hueco facies of the upper Wolfcampian Hueco Formation of the southeastern Robledo Mountains, Doña Ana County, New Mexico: Permian Basin Section of SEPM annual field seminar, basin to shelf facies transition of the Wolfcampian stratigraphy of the Orogrande basin, p. 137–174.

LeMone, D.V., Simpson, R.D. and Klement, K.W., 1975, Wolfcampian upper Hueco Formation of the Robledo Mountains, Doña Ana County, New Mexico: New Mexico Geological Society, Guidebook 26, p. 119–151.

Lockley, M.G., 1991, Tracking dinosaurs. Cambridge, Cambridge University Press, 238 p.

Lockley, M.G., and Madsen, J.H. Jr, 1993, Early Permian vertebrate trackways from the Cedar Mesa Sandstone of eastern Utah: evidence of predator-prey interaction: Ichnos, v. 2, p. 147–153.

Lucas, S.G., 1993, Geological context of Permian tracksite, Robledo Mountains, Doña Ana County, New Mexico: New Mexico Geology, v. 24, p. 56.

Lucas, S.G., Hunt, A.P. and Hotton, N. III, 1994[a], The Paleozoic trackways scientific study report: Unpublished report to U.S. Bureau of Land Management, Las Cruces, New Mexico, 58 p.

Lucas, S.G., Hunt, A.P. and Lockley, M.G., 1994[b], Preliminary report on Permian tracksite, Robledo Mountains, Doña Ana County, New Mexico: Geological Society of America, Abstracts with Programs, v. 26, no. 4, p. A27.

MacDonald, J.P., 1989, Finding footprints: tracking New Mexico's pre-dinosaurs. Las Cruces, Paleozoic Trackways Project, 78 p.

MacDonald, J.P., 1990, Finding footprints: tracking the path of scientific discovery. Las Cruces, Paleozoic Trackways Project, 64 p.

MacDonald, J.P., 1992 Footprints from the dawn of time: Science Probe, v. 2, p. 32–47.

MacDonald, J.P., 1994, Earth's first steps. Boulder, Johnson Books, 290 p.

Mack, G.H. and James, W.C., 1986, Cyclic sedimentation in the mixed siliclastic-carbonate Abo-Hueco transitional zone (Lower Permian, southwestern New Mexico): Journal of Sedimentary Petrology, v. 56, p. 365–647.

Mack, G.H., James, W.C. and Seager, W.R., 1988, Wolfcampian (Early Permian) stratigraphy and depositional environments in the Doña Ana and Robledo Mountains, south-central New Mexico: Permian Basin Section of SEPM Annual field seminar, basin to shelf facies transition of the Wolfcampian stratigraphy of the Orogrande basin, p. 97–106.

Mack, G.H., Salyards, S.L. and James, W.C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formation in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49–77.

Mack, G.H., Seager, W.R. and Kieling, J., 1994, Late Oligocene and Miocene faulting and sedimentation, and evolution of the southern Rio Grande rift, New Mexico, USA: Sedimentary Geology, v. 92, p. 79–96.

Mack, G.H., Cole D.R., Giordano, T.H., Schaal, W.C. and Barcelos, J.H., 1991, Paleoclimate controls on stable isotope oxygen and carbon isotopes in caliche of the Abo Formation (Permian), south-central New Mexico, U.S.A.: Journal of Sedimentary Petrology, v. 61, p. 458–472.

Mimms, F.M. III, 1992, Jerry MacDonald and his magnificent fossils: Science Probe, v. 2, p. 3.

Schult, M.F., 1994, Paleoecology and paleoenvironment of an Early Permian vertebrate trace fossil fauna, Las Cruces, New Mexico [Ph. D. dissertation]: Bloomington, Indiana University, 191 p.

Seager, W.R., Kottlowski, F.E. and Hawley, J.W., 1976, Geology of Doña Ana Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 147, 36 p.

Seager, W.R., Hawley, J.W., Kottlowski, F.E. and Kelley, S.A., 1987, Geology of east half of Las Cruces and northeast El Paso 1 by 2 sheets, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 57.

Simpson, R.D., 1976, Systematic paleontology and paleoenvironmental analysis of the upper Hueco Formation, Robledo and Doña Ana Mountains, Doña Ana County, New Mexico [M.S. thesis]: El Paso, University of Texas at El Paso, 256 p.

Stewart, D., 1992, Petrified footprints: a puzzling parade of Permian beasts: Smithsonian, v. 23, p. 70–79.

Wilson, J.L. and Jordan, C.F., Jr., 1988, Late Paleozoic-early Mesozoic rifting in southern New Mexico and northern Mexico: controls on subsequent platform development: Permian Basin Section of SEPM annual field seminar, basin to shelf facies transition of the Wolfcampian stratigraphy of the Orogrande basin, p. 79–88.

APPENDIX: DESCRIPTIONS OF MEASURED SECTIONS

Section A

Measured 11 May 1994 by S.G. Lucas, O.J. Anderson, and A.P. Hunt at UTM 3584120N, 323070E, zone 13 in the SE 1/4 NW1/4 sec. 19, T22S, R1E. Strata dip 18° to S75E. This includes and supersedes the section published by Hunt et al. (1993).

unit	lithology	thickness (m)
Hueco Formation:		
Robledo Mountains Member:		
15	Limestone; upper and lower units are medium light gray (N6) and light brownish gray (5YR6/1) fresh and light brownish gray (5YR6/1) to yellowish gray (5Y8/1) weathered; middle limestone is medium gray (N5) to brownish gray (5YR4/1) fresh, weathers to light brownish gray (5YR6/1); top forms a hogback.	5.8
14	Mostly covered interval (shale?) with some thin limestone ledges; rocks are brownish gray (5YR4/1) fresh, yellowish gray (5Y8/1) weathered; unit forms a slope break.	5.2
13	Limestone; basal 0.9 m is brownish gray (5YR4/1) fresh, weathers to light brownish gray (5YR6/1); upper 4.6 m is medium gray (N5) to light brownish gray (5YR6/1) fresh, weathers to light gray (N7); forms a massive ledge on ridge crest.	5.5
12	Much covered slope with some shale and nodular limestone ledges; shales are moderate brown (5YR4/4); limestone is mottled medium light gray (N6) and grayish orange (10YR7/4), weathers to yellowish gray (5Y8/1) and light olive gray (5Y6/1).	7.8
11	Sandstone; pale red (5R6/2 and 10R6/2); ripple laminated and hummocky-bedded; ledgy; much covered.	3.9
10	Limestone; light olive gray (5Y6/1) with brownish black (5YR4/1) flecks of shell debris; packstone; forms a ribbed cliff that caps the ridge above the tracksite.	4.5
9	Limestone; interbedded packstones and micrites; basal packstone is light brownish gray (5YR6/1) to light olive gray (5Y6/1); 30 cm thick; lower micrite is pinkish gray (5YR8/1) and yellowish gray (5Y8/1); middle packstone is medium dark gray (N4) fresh, weathers to medium light gray (N6) and light brownish gray (5YR6/1); 30 cm thick; upper micrite is light yellowish gray (5Y7/2) and light brownish gray (5YR6/1); uppermost packstone is light gray (N7) to light brownish gray (5YR6/1); 1.0 m thick; forms a ledge.	7.6
8	Interbedded silty sandstone, sandy siltstone and silty shale; grayish red (10R4/2) with some light olive-gray (5Y6/1) reduction spots; sandstones; basal 20 cm is the same color and lithology as unit 3; upper 5.1 m is light brownish gray (5YR7/1) fresh, weathers to pale red (5R6/2); very calcareous; the silty sandstone is a very fine-grained, subrounded, well-sorted micaceous litharenite; ripple laminated ledges of silty sandstone and sandy siltstone are split by thinner, recessed beds of silty shale; some soft-sediment deformation is present in the silty sandstones; ripple laminated in trough crossbeds; very lensy; some overturned beds; mudstone interbeds of unit 5 lithology; forms a slope, upper half of which is covered by colluvium.	5.3
7	Limestone and shale; basal 1.25 m is yellowish gray (5Y7/2) micrite; next 1.0 m is grayish orange (10YR7/4) to grayish yellow (5Y8/4) shale with pale yellowish brown (10YR6/2) and very pale orange (10YR8/2) nodular limestone; next 0.60 m is light brownish gray (5YR6/1) to light gray (N7) limestone; next 0.25 m is light gray (N7) limestone bed; top of unit is 0.40 m light gray (N7) to light brownish gray (5YR6/1) limestone.	3.5
6	Silty mudstone; moderate brown (5YR3/4) to grayish red (5R4/2); very calcareous; some dark yellowish-orange (10YR6/6) mottling; smectitic; contains root casts, calcareous nodules and slickensides; forms a recessed slope under the ledge formed by unit 6.	1.3
5	Siltstone and mudstone; siltstone is grayish red (10R4/2) to dark reddish brown (10R3/4); mudstone is grayish red (10R4/2) and light brown (5YR5/6); blocky.	1.5
4	Sandstone and silty sandstone; pale red (5R6/2) to grayish red (10R4/2); very fine-grained, subrounded, well-sorted micaceous litharenite; very calcareous; laminar and ripple laminar; bedding planes in lower 5+ m of the unit are covered with invertebrate and vertebrate trackways (NMMNH locality 846); some bedding planes have clay drapes, mudcracks, raindrop impressions and/or plant debris (the conifer *Walchia*); forms a slope; ripple laminated with siltstone partings; minor mudstone; upper portion is pale red (5R6/2) with mottles of yellowish gray (5Y7/2) and grayish yellow (5Y8/4); pedogenically modified; paleosol.	3.25
3	Sandstone; moderate orange pink (5YR8/4) to light brown (5YR6/4); very fine-grained, subrounded,	

unit	lithology	thickness (m)
	well-sorted litharenite; hematitic and calcareous; hummocky; herringbone and ripple laminae in trough crossbeds; forms a ledge.	1.5
middle member:		
2	Limestone; olive gray (5Y4/1) to light olive gray (5Y6/1) with brownish-black (5YR4/1) flecks of miscellaneous shell debris; packstone; forms a prominent ledge.	4.0
1	Siltstone and silty limestone; grayish red (5R4/2); very calcareous; forms a ledge.	not measured

Section B

Section measured in the NW 1/4 NW1/4 sec. 30, T22S, R1E, 12 May 1994 by S.G. Lucas and A.P. Hunt. Strata dip 15° to S 50° E.

Hueco Formation

upper member:

unit	lithology	thickness (m)
19	Same color and lithology as unit 17.	1.3
18	Same color and lithology as unit 13.	2.9
17	Limestone; medium light gray (N6) to light brownish gray (5YR6/1); micritic.	7.5
16	Mostly covered slope; similar lithologies and colors as unit 14.	3.7
15	Limestone; light gray (N7) to pinkish gray (5YR8/1) fresh, weathers to grayish orange (10YR7/4); cherty "birds eyes"; bottom 2/3 ledgy, upper third is massive; micrite.	7.3
14	Shale and limestone; very light gray (N8) to pinkish gray (5YR8/1) fresh; weathers from pinkish gray (5YR8/1) to grayish orange pink (5YR7/2); primarily a slope with micritic ledges.	4.3
13	Limestone; yellowish gray (5Y8/1); micrite; cliff/bench.	5.5
12	Calcarenite; light gray (N7) with speckles of medium light gray (N6) to very light gray (N8); lithology as in unit 11; trough crossbedded; bench-forming.	2.4
11	Calcareous shale and sandstone; shale is grayish orange (10YR7/4) fresh, weathering to very pale orange (10YR8/2); sandstone is medium light gray (N6); fine-grained, angular, micaceous calcarenite; unit is predominantly a slope with thin (.03–.15 m) lenses of sandstones.	9.0
10	Limestone overlain by mudstone/muddy micrite; limestone is medium gray (N5) fresh, weathering to light gray (N7); mudstone is medium light gray (N6).	1.8
9	Calcareous shale; very pale orange (10YR8/2) to grayish orange (10YR7/4); forms a much-covered slope.	1.4
8	Limestone:	
	C: Packstone; medium light gray (N6).	2.5
	B: Calcareous shale	0.5
	A: Packstone; light gray (N7)	0.5

Robledo Mountains Member:

unit	lithology	thickness (m)
7	Silty mudstone; light brown (5YR6/4) to pale red (10R6/2).	0.7
6	Sandstone; same color and lithology as unit 5 but with smaller ripples; ledgy; bleaches yellow.	2.3
5	Sandstone; pale red (5R6/2); micaceous, very fine-grained; subangular; ripple laminated to laminar; hummocky bedding.	4.5
4	Siltstone covered by mudstone and thin ripple sandstones; siltstone is grayish red (5R4/2) to pale red (5R6/2); mudstone is pale yellowish born (10YR6/2) to yellowish gray (5Y7/2); unit forms a slope.	4.3
3	Limestones: micrite; light brownish gray (5YR6/1); packstone; medium gray (N5) to light brownish gray (5YR6/1); and packstone; medium light gray (N6) to light brownish gray (5YR6/1). In this unit dip changes to 10° to S 35° E.	1.5
2	Same lithology as unit 1; colors range from yellowish gray (5Y7/2) and grayish orange pink (5YR7/2) to moderate brown (5YR4/4); biofacies of scaphopods, bivalves, and larger shells.	7.5
1	Interbedded thin (0.15–0.3) limestones and calcareous shales; limestones are yellowish gray (5Y7/2); mudstones are pale yellowish brown (10YR6/2).	8.1

Section C

Measured in the SW 1/4 NE 1/4 sec. 30, T22S, R1E, 13 May 1994 by S.G. Lucas, A.P. Hunt, and J. Estep. Section begins at 358264N, 13323082 E, strata dip 15° to S25°W.

Hueco Formation:

upper member:

unit	lithology	thickness (m)
36	Calcareous shale; much covered; slope-former.	not measured
35	Limestone; brownish gray (5YR4/1) and light brownish gray (5YR6/1) with calcite seam of dark yellowish orange (10YR6/6).	4.5

Robledo Mountains Member:

unit	lithology	thickness (m)
34	Interbedded sandstones and shales; grayish orange (10YR7/4) to light brown (5YR6/4); slope-former.	10.1
33	Sandstone; pale red (5R6/2); ripple laminated; thin ledges.	3.0
32	Mudstone; green to red.	1.5
31	Limestone; medium gray (N5) to light olive gray (5Y6/1) with swirls of grayish orange (10YR7/4); packstone; ledge-former.	1.3
30	Shale with thin ledges of nodular limestone; shale is yellowish gray (5Y7/2) to grayish orange (10YR7/4); limestone is light gray (N7). This is equivalent to the basal interval of section B. Fossil collection 30a is 7.5 m above base; 30 b is 12.5 m above base; 30 c is 14.6 m above base.	15.6
29	Limestone; medium gray (N5) to brownish gray (5YR4/1) fresh, weathers to very pale orange (10YR8/2) and grayish orange (10YR7/4); nodular; ledge.	1.4
28	Limestone; light gray (N7) to light olive gray (5Y6/1) fresh, weathering to very pale orange (10YR8/2) and grayish orange (10YR7/4); slope-forming unit; 28a is 2.0 m above base; lithologies are very similar to unit 26.	3.5
27	Limestone; ledge-forming.	0.8
26	Calcareous shale and nodular limestone; medium light gray (N6) to light olive gray (5Y6/1); upper 2 m contains brachiopod fauna similar to that above locality 846 in section A.	6.25
25	Limestone; light brownish gray (5YR6/1); forms several tightly spaced ledges.	2.8

unit	lithology	thickness (m)
24	Calcareous shale with very minor sandstone interbeds; light brownish gray (5YR6/1); sandstones are ripple laminated.	4.3
23	Limestone; yellowish gray (5Y8/1) to light olive gray (5Y6/1) fresh, weathers to pale yellowish brown (10YR6/2); bioturbated.	1.0
22	Same color and lithology as unit 20.	2.9
21	Sandstone; pale red (5R6/2) fresh, weathers from grayish brown (5YR3/2) to dusky brown (5YR2/2); massive; ripple laminated.	0.5
20	Calcareous shale with thin platey red bed sandstones; pale red (10R6/2) fresh with streaks of pale red purple (5RP6/2) to grayish red purple (5RP4/2) and weathering to light brown (5YR6/4) to yellowish gray (5Y7/2); mostly covered interval.	2.6
19	Multiple units:	
	F: Limestone; light olive gray (5Y6/1) to medium gray (N5) with specks of medium dark gray (N4).	0.8
	E: Limestone; grayish orange (10YR7/4) to pale yellowish brown (10YR6/2).	1.3
	D: Calcareous shale; covered.	2.3
	C: Sandstone; brownish gray (5YR4/1) to light brownish gray (5YR6/1) fresh; weathers to yellowish gray (5Y8/1).	2.8
	B: Sandstone; yellowish gray (5Y7/2) to light gray (N7); weathers to very pale orange (10YR8/2) to grayish orange (10YR7/1).	0.6
	A: Sandstone; light brownish gray (5YR6/1) fresh, weathers to yellowish gray (5Y7/2).	3.8
18	Sandstone; pale red (5R6/2) to grayish red (5R4/2); ripple laminated; ledgy; 0.3 m beds. Stratigraphic level of locality 2820.	3.8
17	Claystone and thin sandstones; pale yellowish brown (10YR6/2); sandstone is ripple laminated.	1.8
16	Limestone; expressed as four distinct ledges of equal thickness:	
	D: Variegated brownish gray (5YR4/1) and yellowish gray (5Y8/1).	
	C: Light olive gray (5Y6/1) fresh, weathers to yellowish gray (5Y7/2).	
	B: Olive gray (5Y4/1) mottled with yellowish gray (5Y7/2).	
	A: Light olive gray (5Y6/1) to brownish gray (5YR4/1).	
	Total thickness:	2.5
15	Calcareous shale and siltstone; yellowish gray (5Y7/2 to 5Y7/1); slope-former.	1.7
14	Sandstone; pale yellowish brown (10YR6/2); ripple laminar to laminar; ledgy.	3.0
13	Shale; same color and lithology as unit 13.	1.2
12	Sandstone; pale brown (5YR5/2) to grayish orange pink (5YR7/2), weathers to light brown 5YR6/4.	0.4
11	Shale; grayish red (104/2); pedoturbated.	2.5
10	Sandstone; light brown (5YR6/4) to pale brown (5YR5/2); ripple laminated; this is the horizon for 2818 and equals the horizon of 846 and defines the Robledo Mountains megatracksite.	2.8
9	Sandy claystone overlain by yellow shale with thin (0.15 m) sandstone at base; claystone is pale yellowish orange (10YR8/6) to grayish orange (10YR7/4); shale and sandstone is pale yellowish brown (10YR6/2) to pale brown (5YR5/2); sandstone is ripple laminated.	1.8
8	Limestone; light gray (N7) and very light gray (N8) fresh, weathers to moderate brown (5YR4/4).	0.8
7	Shale; grayish orange (10YR7/4); slope forming, expressed as notch in base of unit 8; contains carbonized plant debris.	1.2
6	Limestone ledges much like units 3 and 5 with shale partings like unit 4:	
	C: Very pale orange (10YR8/2) fresh, weathers to pale yellowish brown (10YR6/2).	
	B: Yellowish gray (5Y8/1) fresh, weathers to pale yellowish brown (10YR6/2) and dark yellowish brown (10YR4/2).	
	A: Very pale orange (10YR8/2) fresh, weathers grayish orange (10YR7/4).	
	Total thickness:	2.8
5	Limestone, same lithology as unit 3; yellowish gray (5GY8/1) fresh; weathers to grayish orange (10YR7/4); ledge.	1.0
4	Calcareous shale; medium dark gray (N4) to light gray (N7) fresh; weathers to yellowish gray (5Y8/1) and grayish orange (10YR7/4).	0.4
3	Limestone; grayish orange (10YR7/4); ledge.	0.8
2	Sandstone and shale; sandstone is pale brown (5YR5/2) fresh, weathers to pale red (10R6/2); shale is moderate brown (5YR3/4); sandstone is ripple laminated; shale is laminar.	2.5
1	Limestone; light gray (N7) fresh, weathers to medium gray (N5) with dark yellowish orange (10YR8/6) mottling.	not measured

Section D

Section measured in two parts. Units 28–37 measured by S.G. Lucas and A.P. Hunt, 22 September 1994 in the SW 1/4 NW 1/4 sec. 25, T22S, R1W. Units 1–28 measured by S.G. Lucas and O.J. Anderson, 10 October 1994.

Hueco Formation:

upper member:

21	Limestone; medium light gray (N4) fresh, weathers to light browns (5YR5/6 and 5YR6/4); slightly recrystallized; encrinitic; gastropods; ledgyin 0.5–1.5 m ledges; forms crest of ridge to south of localities 3827 and 2826 and 2827.	19+

Robledo Mountains Member:

20	Red bed slope; same color and lithology as unit 34; much covered	15.9
19	Limestone ledges and gray shales; numerous brachiopods.	3.0
18	Much-covered red-bed slope; much ripple laminated sandstones; platey to ledgy.	10.5
17	Dolomitized limestone; grayish orange pink (5YR7/2) to moderate reddish orange (10R6/6) with light red (5R6/6) streaks; hummocky base with bedding breaks every 0.5 m; ostracodal in places; ledge.	2.9
16	Mudstone; pale red (10R6/2); slope-former.	3.5
15	Limestone; moderate pink (10R7/4); micritic; dolomitic ledge.	0.8
14	Mudstone; pale olive (10Y6/2); slightly calcareous.	0.5
13	Sandstone and siltstone; moderate reddish brown (10R4/6); very fine-grained, subrounded, well-sorted litharenite; massive; siltstone is same colors with ripple laminae, mud cracks, and many *Walchia*; sandstone is calcareous; siltstone is not. This horizon is the stratigraphic interval of localities 2826 and 2827.	5.0

unit	lithology	thickness (m)
12	Limestone; grayish orange pink (5YR7/2) weathers to pale red (5R6/2) and grayish red (5R4/2); much "floating" fossil hash; ostracodal.	5.0
11	Calcareous shale; yellow.	9.1
10	Shaley; same colors and lithologies as unit 6.	13.5
9	Limestone; ledge; gastropod rich.	1.0

Above here dip changes to 19°

unit	lithology	thickness (m)
8	Calcareous shale with nodular limestone; abundant brachiopods and other invertebrates as uppermost shale of Robledo Mountains Member.	28.0
7	Limestone; same color and lithology as unit 5.	2.0
6	Same colors and lithology as unit 2 but thinner bedded with some shale partings.	6.3
5	Gray ostracodal limestone ledge; echinoid hash on top surface.	2.6
4	Same color and lithology as unit 2.	8.3
3	Yellow ripple-bedded calcarenite limestone ledge.	1.4
2	Red-bed slope of siltstone? and fine sandstone; much covered.	12.8

middle member:

unit	lithology	thickness (m)
1	Ostracodal limestone ledges with interbeds of thin pink calcareous shale; limestones are 0.5 m thick, interbeds are usually 0.1–0.2 m thick but are occasionally 0.5 m thick.	20.6

Section E: Cattle Tank

Section measured in the SW1/4 NW1/4 sec. 25, T22S, R1W 10 October 1994 by S.G. Lucas and O.J. Anderson.

Hueco Formation:

Robledo Mountains Member:

unit	lithology	thickness (m)
5	Limestone; gray to yellow; ostracodal; ledge-former.	not measured
4	Interbedded shales and sandstone; red beds; sandstones are ripple laminated; cattle tank track localities in lower 3.1 m of this unit.	6.9
3	Sandstone; massive cliff; laminated to hummocky bedding.	2.4
2	Interbedded sandstones and siltstones; tidal channel; 0.5 m interbeds with small-scale trough crossbedding.	3.1
1	Limestone; vuggy, recrystallized top.	not measured

Section F: Community Pit Section

Measured in the SE1/4 SW1/4 SE1/4, sec. 19, T22S, R1E on 9 December 1994 by A.P. Hunt, P.K. Reser, and J. Li. Strata dip 22° to N 140° W.

Hueco Formation:

upper member:

unit	lithology	thickness (m)
20	Limestone; cliff-forming, irregular beds 0.3–0.5 m thick; crinkly with much organic debris; undulatory.	not measured

Robledo Mountains Member:

unit	lithology	thickness (m)
19	Siltstone and sandstone; similar to unit 10; pale red (10R6/2) to moderate reddish orange (10R6/6); calcareous; slabby; sandstone is very fine-grained, subrounded, moderately well-sorted sublitharenite; slightly micaceous.	0.75
18	Sandstone; pale reddish brown (10R5/4); very fine-grained, subangular, well-sorted sublitharenite; ledge-forming; laminated; not calcareous.	1.0
17	Siltstone; moderate reddish orange (10R6/6); micaceous; laminar; calcareous.	6.0
16	Limestone; pale red (5R6/2) and grayish orange (10YR7/4); very fossiliferous, including brachiopods and gastropods; biopackstone.	3.2
15	Limestone with minor siltstone debris; limestone is pale brown (5YR5/2); biopackstone; intact brachiopods; also bryozoans, echinoid fragments; siltstone is pale reddish brown (10R5/4); entire unit is much covered.	22.0
14	Mudstone; grayish red (10R4/2); slightly calcareous; mostly covered.	5.0
13	Limestone; medium gray (N5) to light gray (N7); massive beds with 0.3 m of less massive limestone separating them; biopackstone; ledge-forming; offset at top of this unit to main hill above pit.	2.6
12	Slightly sandy siltstone; grayish red (10R4/2); micaceous; laminar; calcareous.	5.3
11	Silty mudstone; light olive gray (5Y6/1); calcareous.	0.2
10	Mudstone and calcareous siltstone interbedded; mudstones are grayish red (10R4/2); calcareous; calcareous siltstone is pale red (10R6/2) to light olive gray (5Y6/1); siltstones crop out as 0.25- and 1.8-m-thick ledges 0.5 and 3.75 m above base of the unit.	5.6
9	Limestone; grayish yellow (5Y8/4); minor shell hash; separated by 0.3 m of pale red (10R6/2) limy mudstone.	1.0
8	Silty mudstone; grayish red (5R4/2); calcareous. AF-9 layer.	2.1
7	Limestone; dark greenish gray (5GY4/1); packstone.	0.3
6	Siltstone with gypsum stringers; grayish yellow green (5GY7/2); crossbeds up to 1 cm high; gypsum is plates 2–3 mm thick that are yellowish gray (5Y8/1) with green mottles.	1.1
5	Limestone; medium light gray (N6) and light gray (N7); micritic with minor shell fragments; thinly bedded; much covered; offset into main pit.	6.0
4	Interbedded mudstone and sandy siltstone; mudstone is grayish red (10R4/2) and light olive gray (5Y5/2); slightly silty; calcareous; sandstone is pale red (10R6/2); calcareous; much covered.	18.0
3	Limestone; pale olive (10Y6/2); bedding thickens upward; ledge.	3.0
2	Limestone interbedded with limy mudstone; limestone is mottled greenish gray (5G6/1) and pale green (5G7/2); micritic; ledgy; mudstone is medium light gray (N6) with dark yellowish orange (10YR6/6) mottles.	1.0
1	Limestone; grayish yellow green (5GY7/2) to pale greenish yellow (10Y8/2); micritic; heavily fractured; undulating top.	not measured

Section G: Jordan

Section measured 9 December 1994 by S.G. Lucas and O.J. Anderson. Strata dip 13° to S 50° W. Measured in the SW1/4 NE1/4 sec. 20, T22S, R1E; this is the type section of the Robledo Mountains Member of the Huedo Formation.

unit	lithology	thickness (m)
	Hueco Formation:	
	upper member:	
32	Limestone; light brownish gray (5YR6/1) fresh, weathering to dark yellowish orange (10YR6/6) in places; biopackstone; ledge-former.	4.0+
	Robledo Mountains Member (type section):	
31	Sandstone; grayish orange (10YR7/4) and pale reddish brown (10R5/4); very fine-grained, subrounded, well-sorted sublitharenite; micaceous; shale partings; platey; planar crossbeds; not calcareous.	4.5
30	Sandstone; pale reddish brown (10R5/4); very fine- to fine-grained, subrounded, moderately well-sorted quartzarenite; hummocky bedded; calcareous.	0.6
29	Silty sandstone; moderate reddish orange (10R6/6); very fine-grained, subrounded to subangular, moderately well-sorted quartzarenite; calcareous; laminated; ripples; very platey; last red bed.	6.5
28	Limestone; medium gray (N5); minor shell hash; packstone.	2.0
27	Limestone and shale; same colors and lithologies as unit 26 but more ledge-forming; abundant brachiopods.	16.2
26	Limestone and calcareous shale; yellowish gray (5Y7/2) to greenish gray (5GY6/1); nodular; much shell debris; abundant brachiopods.	5.5
25	Limestone; medium gray (N5) to medium dark gray (N4); much biogenic debris, especially crinoid columnals; packstone; ledge.	0.8
24	Calcareous shale; same color and lithology as unit 22; much covered.	6.1
23	Limestone; greenish gray (5G6/1); fine-grained biopackstone; alternating ledges of limestone 0.3–0.6 m thick with calcareous shale between.	4.5
22	Calcareous mudstone and shale; yellowish gray (5Y7/2); slightly silty; very calcareous.	8.3
21	Limestone; greenish gray (5GY6/1); ledge.	0.3
20	Sandstone; pale reddish brown (10R5/4) to pale red (10R6/2) and grayish red (10R4/2); may weather as dark as very dusky red (10R2/2); very fine- to fine-grained, subrounded, moderately well-sorted sublitharenite; ripple laminated; platey; forms a red-brown slope; invertebrate trails and vertebrate tracks.	7.6
19	Limestone and calcareous shale; limestone is medium gray (N5), weathering to grayish orange (10YR7/4); some minor recrystallization; shale is moderate brown (5YR4/4) to light brown (5YR6/6); very calcareous; limestone forms 0.3–1.0 m thick ledges with shale slopes in between.	7.5
18	Covered interval; primarily calcareous shales.	2.5
17	Limestone interbedded with calcareous shale; grayish orange (10YR7/4) to grayish yellow green (5GY7/2); fine shell debris; forms numerous 0.1–0.2 m thick ledges.	8.5
16	Sandstone; grayish red (5R4/2); fine-grained, subangular, well-sorted litharenite; laminar to ripple-laminated; some tracks; correlates approximately with level of locality 2818.	8.0
15	Limestone; light olive gray (5Y6/1) and yellowish gray (5Y7/2); somewhat recrystallized.	0.3
14	Limestone; same color and lithology as unit 12.	3.0
13	Limestone; light olive gray (5Y6/1); biopackstone; many crinoid stems.	0.3
12	Limestone; grayish orange (10YR7/4); minor fossil hash; some calcareous shales; nodular.	1.5
11	Sandstone; moderate reddish brown (10R4/6) and grayish red (5R4/2); very fine- to fine-grained, subrounded, poorly sorted sublitharenite; rippled; not calcareous.	4.0
10	Sandstone; grayish orange pink (5YR7/2) fresh, weathers to pale red (10R6/2); very fine- to fine-grained, subrounded, moderately well-sorted sublitharenite; ripples and hummocks; similar to unit 9 but much less massive/more flaggy.	4.5
9	Sandstone; pinkish gray (5YR8/1) fresh; weathers to pale reddish brown (10R5/4) and moderate reddish orange (10R6/6); very fine- to fine-grained, subrounded, well-sorted quartzarenite; trough crossbedded; hummocky; forms a ledge.	5.2
8	Muddy siltstone; pale reddish brown (10R5/4); slightly sandy; ripple laminated; some sandstone interbeds.	4.5
7	Limestone; yellowish gray (5Y7/2); shell hash packstone.	0.4
6	Calcareous shale with limestone ledges; limestone is medium gray (N5) and yellowish gray (5Y7/2); limestone forms 0.2–0.3 m ledges.	5.5
5	Limestone; yellowish gray (5Y7/2); muddy to micritic; ledge.	2.3
4	Siltstone and very fine sandstone; moderate reddish brown (10R4/6); sandstones are very fine-grained, rounded quartzarenites; laminar to ripple laminated; slope.	4.5
	middle member:	
3	Limestone; grayish orange (10YR7/4); muddy with minor shell hash and crinoid stems; thickly bedded ledge.	4.2
2	Silty calcareous mudstone; brownish gray (5YR4/1) and pale yellowish brown (10YR6/2); much cover.	12.5
1	Limestone; yellowish gray (5Y7/2); muddy; ledge.	not measured