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UPPERMOST PENNSYLVANIAN AND PERMIAN STRATIGRAPHY AND BIOSTRATIGRAPHY AT PLACITAS, NEW MEXICO

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Abstract—A well-exposed and locally representative section of uppermost Pennsylvanian and Permian strata is exposed at Placitas in the SW¼ sec. 14, T3N, R5E, Sandoval County, New Mexico. Upper Pennsylvanian strata belong to the Wild Cow Formation, and are overlain by the Permian Abo, Yeso, Glorieta, and San Andres formations. Strata of the uppermost Wild Cow Formation are a mixed marine-nonmarine interval 7–20 m thick. This interval consists of ledgy and nodular limestones, some with marine fossils, redbed mudstones, and siltstones, and intraformational limestone-cobble conglomerates that produce bones of fossil vertebrates, including sharks, lungfishes, amphibians, and pelycosaurs. Fusulinids, brachiopods, and bivalves indicate a middle to possibly late Virgilian age for the uppermost Wild Cow Formation at Placitas. The Abo Formation disconformably(?) overlies the Wild Cow Formation, is as much as 112 m thick and is mostly redbed mudstone, trough-crossbedded sandstone and limestone-pebble conglomerate. The Abo contains impressions of the conifer *Walchia* and other plants, tetrapod footprints of the ichnogenus *Dimetropus*, conchostracans, insects, and a thin crinoidal limestone conglomerate. However, these fossils are not diagnostic of a precise age, so it is not clear whether the Abo Formation at Placitas is entirely of Early Permian (Wolfcampian) age. The Yeso Formation (about 175 m thick) at Placitas consists of two members, Meseta Blanca and San Ysidro. The Meseta Blanca Member conformably overlies the Abo Formation (their contact is gradational over about 20 m of section), is up to 60 m thick and consists mostly of trough-crossbedded, yellow-to-tan, eolianite sandstone. The overlying San Ysidro Member is up to 115 m thick and mostly massive and ripple-laminated, thin-bedded, fine-grained sandstone, siltstone, and beds of gypsum. The overlying Glorieta Sandstone sharply overlies the Yeso Formation, is as much as 12 m thick and is mostly brown, trough-crossbedded quartzarenite/metaquartzite. Patchy and thin (up to 5 m thick), gray, dolomitic limestone of the San Andres Formation overlies the Glorieta and is disconformably overlain by fluvial red beds of the Middle Triassic Moenkopi Formation. The actual thickness of the Permian section at Placitas thus is 300–320 m, much less than previously published estimates. The Upper Pennsylvanian–Permian section at Placitas is significant for three reasons: (1) this is the singlemost complete, well-exposed Permian section around the Sandia uplift; (2) at Placitas, well-preserved and diverse marine invertebrate assemblages are present; and (3) the youngest Virgilian strata at Placitas include conglomerates that yield a diversity of fossil vertebrates. This is a rare case where a clear cross-correlation of vertebrate taxa to Upper Pennsylvanian marine biostratigraphy is possible.

INTRODUCTION

North of Placitas in Sandoval County, New Mexico, Permian strata are exposed between the Arroyo de San Francisco and Montezuma Ridge as an essentially homoclinal, northeast-dipping section about 320 m thick (Figs. 1–3). This is the singlemost complete and well-exposed Permian section around the Sandia uplift, yet it has been little described in the literature (e.g., Kelley and Northrop, 1975). Here, we describe the lithostratigraphy and biostratigraphy of the youngest Pennsylvanian and Permian strata exposed north of Placitas, expanding on our earlier, preliminary reports (Kues et al., 1997; Lucas et al., 1997; Rowland et al., 1997). NMMNH refers to the New Mexico Museum of Natural History, Albuquerque.

LITHOSTRATIGRAPHY

Upper Pennsylvanian

Wild Cow Formation

North of Placitas, a distinctive interval of strata 7–20 m thick marks the boundary between Upper Pennsylvanian carbonates characteristic of the Madera Group and red-bed siliclastics of the Abo Formation. These strata are a mixture of nodular limestone, fossiliferous marine limestone, limestone-pebble conglomerate, sandstone, and red-bed mudstone. Kelley and Northrop (1975, p. 49–50) alluded to this transitional interval, pointing out that it makes consistent placement of a Madera–Abo contact difficult.

Applying a name to this transitional sequence in the Placitas area requires a brief review of how previous workers have treated it in central New Mexico. The presence of a thick sequence of strata, ranging from Missourian to early Wolfcampian in age, that becomes progressively less marine and includes fewer limestones and more siliclastic marine and nonmarine green, purple, and red shale and sandstone beds towards the top, until replaced by the nonmarine red-bed clastic strata of the Abo Formation, has long been recognized in central New Mexico (e.g., Read et al., 1944; Read and Wood, 1947; Armstrong et al., 1979). Early workers referred these strata in the Manzano, Sandia, and Nacimiento Mountains to the "upper arkosic member" of the Madera Formation, a practice followed by Kelley and Northrop (1975) in the Sandia Mountains. Farther south, the upper, predominantly nonmarine, mainly red-bed parts of this transitional sequence were separated as distinct named units, such as the Red Tanks Member of the Madera Formation in the Lucero uplift (Kelley and Wood, 1946). A little later, the Bursum Formation in Abo Pass, at the southern end of the Manzano Mountains and southward through the Los Pinos, Oscura, and Joyita uplifts, to the San Andres and Robledo Mountains, was established by Wilpolt et al. (1946; see also Bates et al., 1947, and Kottlowski et al., 1975, for a summary of "Bursum facies" distribution), for early Wolfcampian strata correlative with the Red Tanks Member to the west. Stark and Dapples (1946) named this interval the Aqua Torres Formation, an obvious synonym of Bursum (Lloyd, 1949), and later, the name Laborcita Formation was applied to early Wolfcampian transitional beds along the eastern side of the Orogrande basin in the Sacramento Mountains (Otté, 1959). Myers (1973) raised the Madera to group status in the Manzano Mountains, named the upper arkosic limestone member the Wild Cow Formation, and divided it into three members, in ascending order, the Sol se Mete, Pine Shadow, and the La Casa

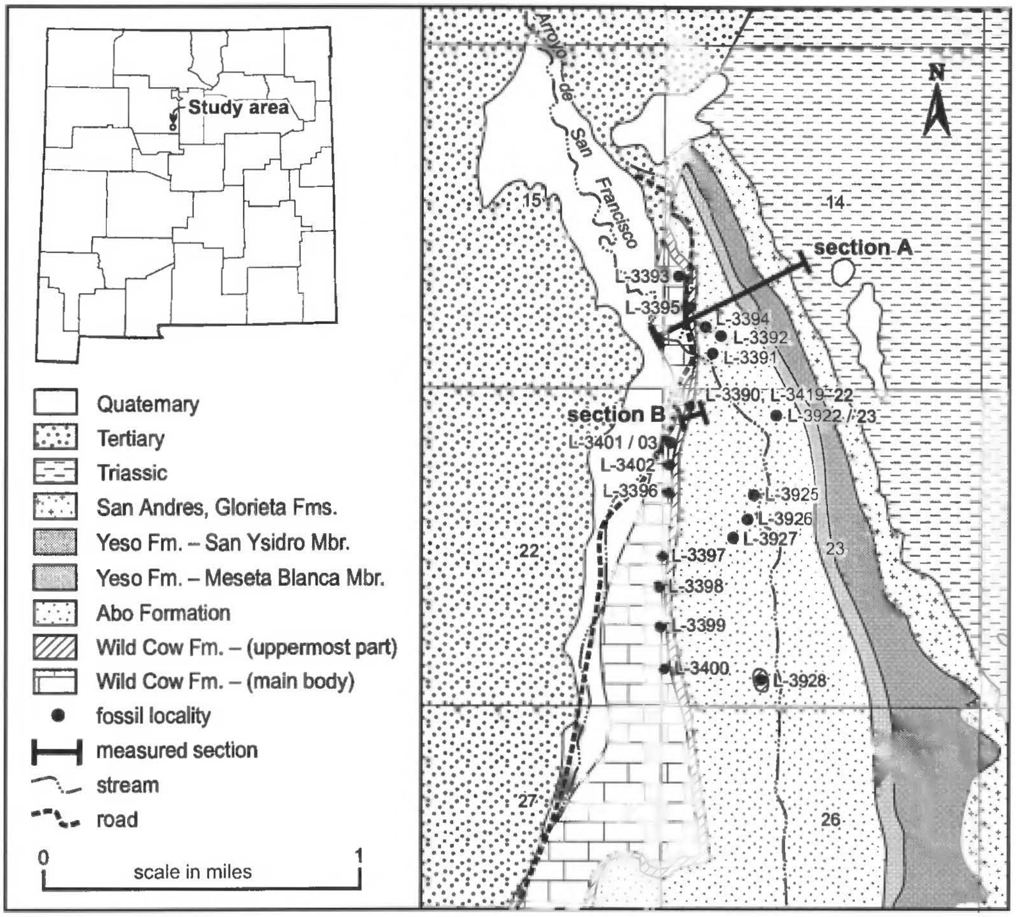

FIGURE 1. Geologic map of the Upper Pennsylvanian–Permian outcrops north of Placitas (geology after Kelley and Northrop, 1975) showing locations of measured sections and fossil sites.

members. The Wolfcampian Bursum Formation was considered the uppermost formation of the Madera Group, but was not recognized north of the southern Manzanos. In the northern Manzano and Manzanita Mountains, the La Casa Member of the Wild Cow Formation includes strata equivalent to the lower Bursum farther south (Myers, 1973; Myers and McKay, 1976).

Applying an appropriate stratigraphic nomenclature to these transitional beds in areas where they have not previously been intensively studied, like the northern Sandia Mountains (Placitas), requires study on a regional scale, as Bates et al. (1947) indicated more than 50 years ago. In addition, because the Bursum Formation at its type section was described only briefly and with a very generalized stratigraphic section, this unit warrants further study in order to define it better stratigraphically and lithologically. This will serve to separate it better from the underlying transitional units of the upper Madera Formation (or Group), establish its age more precisely, and describe in detail its lateral relationships with the coeval Red Tanks and La Casa members. In the Placitas area, the relative thinness of the exposed transitional beds precludes definite assignment to a particular named unit. Lithologically, these beds could be reasonably accommodated in the Bursum Formation (Madera Group), the Red Tanks Member (or Formation) of the Madera Formation (or Group), or in the La Casa Member of the Wild Cow Formation (Madera Group). The closest reported exposures of the Bursum and Red Tanks are 80 km from Placitas, to the south and southwest, respectively, and they are both entirely or largely Wolfcampian in age. The closest reported La Casa Member exposure is about 25 km to the south and it is largely Virgilian in age (Myers, 1973; Myers and McKay, 1976). Therefore, we tentatively regard the Virgilian transitional sequence near Placitas as belonging to the uppermost Wild Cow Formation, possibly the La Casa Member (though we do not make a definite assignment) pending more extensive regional studies of this interval planned for the future.

North of Placitas, the uppermost Wild Cow Formation forms a ledgy slope between the prominent Wild Cow limestone cuesta and the rolling topography developed in Abo red beds. Most of the uppermost Wild Cow Formation is reddish-brown and greenish-gray mudstone, shale, and micaceous litharenite sandstone (Fig. 2). Fossiliferous marine limestones and nodular limestones are a subordinate lithotype. A distinctive lithotype is limestone-pebble conglomerate, which at Placitas contains fossil bones and teeth of vertebrates. North of Placitas, we identify the base of the uppermost Wild Cow as the first clastic beds above bioclastic packstone at the top of the main body of the Wild Cow Formation; and, we place the top of the Wild Cow at the stratigraphically highest marine limestone (Fig. 2).

Permian

Abo Formation

Siliclastic red beds of the Abo Formation rest disconformably(?) on the Wild Cow Formation north of Placitas. Here, the Abo section is about 112 m thick and consists mostly of ridge- and cuesta-forming arkosic sandstone and valley- and slope-forming mudstone. The sandstones are typically pale red, grayish red, or pinkish gray and trough crossbedded. They are sometimes associated with pale brown, limestone-pebble conglomerates. Abo mudstones are the same color as the sandstones, so the entire formation appears to be a grayish-red or reddish-brown succession of mudstone slopes and sandstone ledges or cuestas.

Two unusual, very thin and localized rock types are present in the Abo Formation north of Placitas. One is a thin (0.2-m-thick), lenticular conglomerate composed completely of crinoid columnals (unit 22 in Figure 2). The other is a 0.2-m-thick lens of black shale that contains

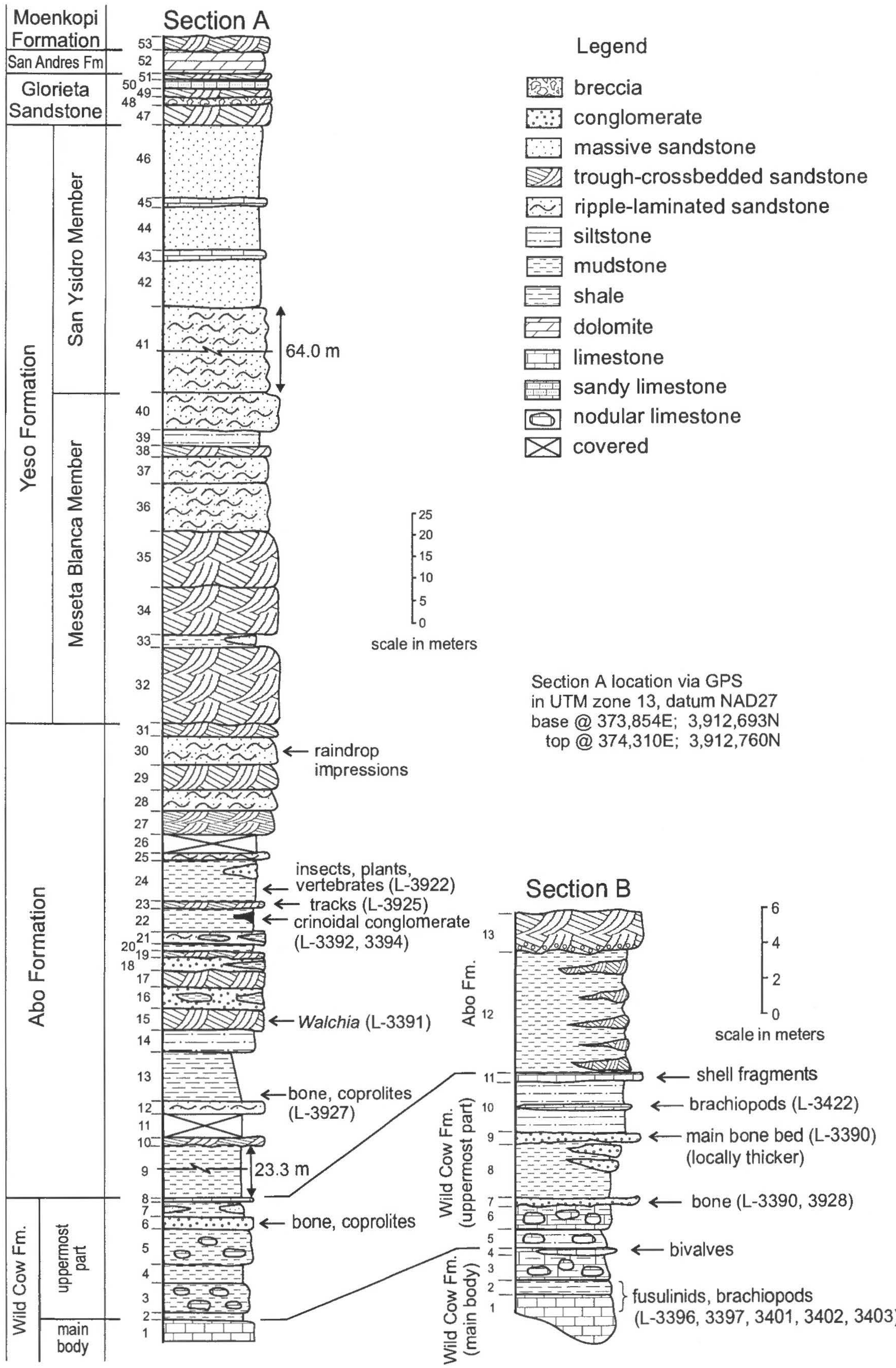

FIGURE 2. Measured sections of Permian strata exposed at Placitas. See Figure 1 for locations of sections and Appendix 1 for descriptions of numbered stratigraphic units.

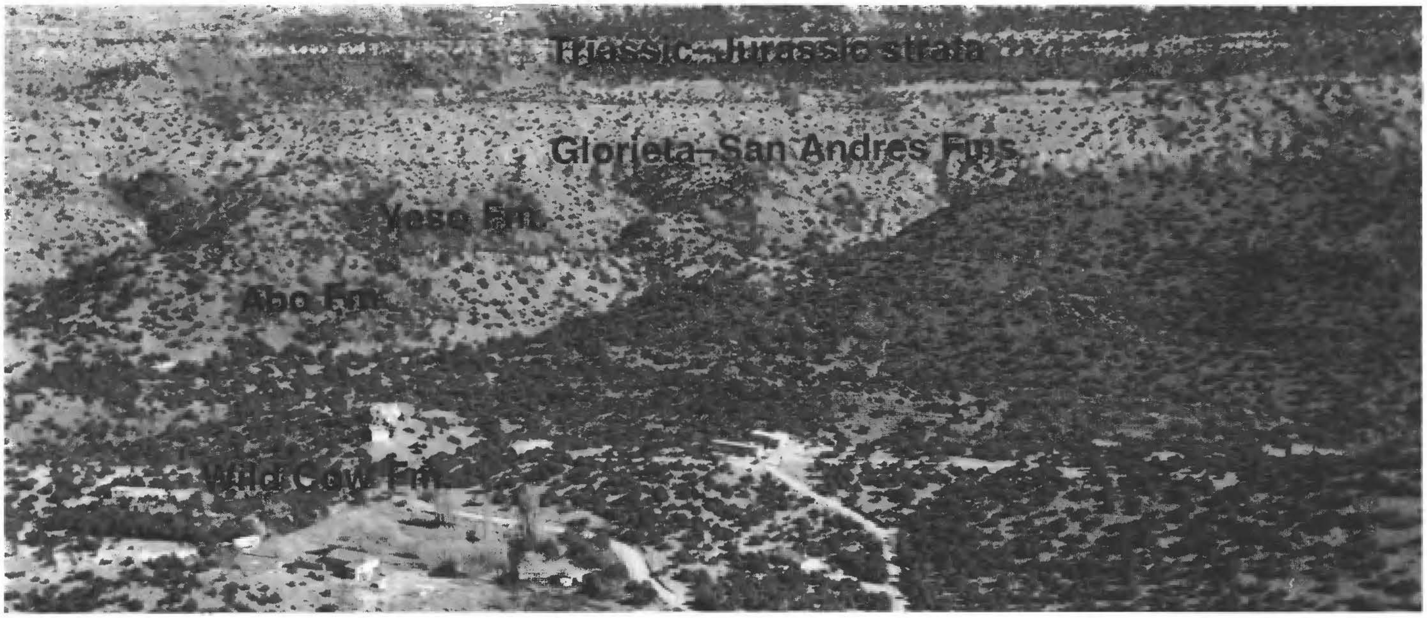

FIGURE 3. Low-angle aerial photograph of the Permian section north of Placitas.

leaves, conchostracans, and insect fossils at NMMNH locality 3922 (unit 24 in Fig. 2). The crinoidal conglomerate is evidence of marine facies very close to the characteristically nonmarine depositional system of the Abo Formation, whereas we interpret the black shale as a pond deposit.

North of Placitas, we can divide the Abo Formation into two informal units. The lower part of the formation (units 9–14 of section A in Fig. 2) is mudstone dominated (about 40–50 m thick). The upper part of the formation (units 15–31 of section A in Fig. 2, about 60–70 m thick) is sandstone dominated. This type of two-fold subdivision of the Abo is also present to the south, in the Manzano Mountains (e.g., Myers, 1977).

Yeso Formation

The Yeso Formation conformably overlies the Abo Formation north of Placitas and is about 175 m thick. As is characteristic of the Abo-Yeso contact elsewhere (for example, at the Abo Formation type section in the southern Manzano Mountains: Hatchell et al., 1982), there is a transitional interval in which a formation contact can only be picked arbitrarily. North of Placitas, this Abo-Yeso transition interval encompasses units 28 through 31 of our measured section A (Fig. 2). Here, we have chosen the contact at the top of the stratigraphically highest sandstone of characteristic Abo lithotype—arkosic and trough crossbedded.

North of Placitas, the Yeso Formation can be divided into two units—the Meseta Blanca and San Ysidro members (Kelley and Northrop, 1975). The Meseta Blanca Member is about 60 m thick and consists mostly of light brown, pale red, and pinkish-gray trough-crossbedded and ripple-laminated sandstone. The overlying San Ysidro Member is about 115 m thick and is mostly very fine-grained, light brown, silty, gypsiferous sandstone. It forms a long slope between the Meseta Blanca and Glorieta cuestas.

Glorieta Sandstone

A very prominent, 11- to 12-m-thick interval of sandstone and metaquartzite overlies the San Ysidro Member of the Yeso Formation north of Placitas. We assign these strata to the Glorieta Sandstone. They do contain one bed of sandy limestone like the overlying San Andres Formation, but this is just evidence of the intertonguing and conformable relationship of the Glorieta and San Andres formations well documented regionally (e.g., Kelley, 1972). Like other Glorieta outcrops, those north of Placitas are dominated by yellowish gray and orange quartzarenite.

San Andres Formation

We assign the stratigraphically highest Permian strata north of Placitas to the San Andres Formation. This is an interval of grayish-orange, sandy limestone about 5 m thick. San Andres strata are patchy, probably largely as a result of erosion prior to the deposition of overlying Triassic strata. Red-bed sandstones of the Middle Triassic Moenkopi Formation disconformably overlie the San Andres Formation north of Placitas (Lucas, 1991; Lucas and Heckert, 1995b).

PALEONTOLOGY AND BIOSTRATIGRAPHY

Upper Pennsylvanian

Wild Cow Formation, main body: invertebrates

The upper limestone and shale of the main body of the Wild Cow Formation (unit 1, section B, Fig. 2) contain a diverse marine invertebrate assemblage of abundant brachiopods (especially *Composita subtilita* (Hall) and *Derbyia* sp.), fenestrate and rhomboporoid bryozoans, crinoid skeletal debris, and fusulinids, with lesser numbers of other brachiopods (*Juresania*, *Neochonetes*, *Crurithyris*), bivalves (*Aviculopecten*), and gastropods (*Amphiscapha*). The fusulinids belong to three species: *Triticites coronadoensis* Ross and Tyrrell, *T. whetstonensis* Ross and Tyrrell, and *T.* cf. *T. bensonensis* Ross and Tyrrell. These fusulinids indicate a middle Virgilian age (Ross and Tyrrell, 1965).

The overlying unit (unit 2, section B, Fig. 2) is a greenish-gray mudstone that grades into a dark gray, splintery, calcareous shale. It contains a diverse, mixed brachiopod-bivalve-fenestrate bryozoan assemblage composed of typically well-preserved, often unfragmented specimens indicative of a quiet marine environment. Of the nearly 500 specimens collected (excluding bryozoan remains), brachiopods account for about 82%, bivalves for about 15%, and rare trilobites, gastropods, conulariids, and crinoids for the remaining 3% of the assemblage (Table 1).

Brachiopods are represented by at least 16 species (Table 1). *Composita subtilita* (Fig. 4A) and *Phricodothyris perplexa* (Fig. 4B), together with numerous fragments of fenestrate bryozoan colonies, comprise the majority of the fossil specimens from the unit 2 assemblage. In general, the brachiopods are similar to those reported from the mid-Virgilian Jemez Springs Shale Member of the Madera Formation near Jemez Springs, about 60 km northwest of the Placitas section (Sutherland and Harlow, 1967; Kues, 1996), The specimens of *P. perplexa* collected from unit 2 are the same taxon as *Phricodothyris* sp. from the Jemez Springs Shale. Dunbar and Condra (1932) noted that

TABLE 1. Invertebrate taxa, number of specimens, and percentage of total (excluding bryozoans and crinoid fragments) in unit 2 of uppermost Wild Cow Formation north of Placitas.

	Specimens	Percentage
BRACHIOPODS		
Composita subtilita (Hall)	124	26.3
Phricodothyris perplexa (McChesney)	105	22.3
Neospirifer dunbari (King)	38	8.1
Hystriculina wabashensis (Norwood and Pratten)	32	6.8
Cancrinella boonensis (Swallow)	22	4.7
Juresania aff. *J. nebrascensis* (Owen)	19	4.0
Neochonetes granulifer (Owen)	11	2.3
Reticulatia sp.	9	1.9
Derbyia sp.	7	1.5
Neospirifer sp.	6	1.3
Linoproductus sp.	4	0.8
Punctospirifer kentuckyensis (Shumard)	3	0.6
Crurithyris sp.	3	0.6
Derbyia texana (Dunbar and Condra)	2	0.4
Orbiculoidea sp.	2	0.4
Echinaria sp.	1	0.2
Wellerella sp.	1	0.2
BIVALVES		
Paleolima retifera (Shumard)	37	7.9
Acanthopecten carboniferus (Stevens)	20	4.2
unidentified pectinids	9	1.9
unidentified myalinids	2	0.4
Streblochondria hertzeri (Meek)	1	0.2
Aviculopecten sp.	1	0.2
Leptodesma (Leptodesma) longa (Geinitz)	1	0.2
Parallelodon sp.	1	0.2
Edmondia sp.	1	0.2
GASTROPODS		
Amphiscapha muricata (Knight)	1	0.2
TRILOBITES		
Ditomopyge sp.	5	1.1
CONULARIIDA	4	0.8

early to middle Virgilian specimens of *P. perplexa* from the Midcontinent region were larger than earlier Pennsylvanian representatives, and might be a separate species, but we retain them in *P. perplexa*. The specimens of *Juresania* from Placitas differ in minor features of ornamentation and are somewhat larger than specimens referred to *J. nebrascensis* from the Jemez Springs Shale; hence we refer them to *J.* aff. *J. nebrascensis* (Figs. 4K–L).

Three common Jemez Springs Shale brachiopods are replaced by closely related species in the Placitas assemblage of unit 2. The small productoids identified as *Hystriculina wabashensis* from Placitas are analogous to *H. armata* (Dunbar and Condra) from the Jemez Springs Shale, and *Neospirifer dunbari* (Fig. 4C) occurs in the Placitas fauna in place of *N. pattersoni* (Sutherland and Harlow) from the Jemez Springs Shale. Specimens of *Neochonetes* in the Jemez Springs Shale were referred by Sutherland and Harlow (1967) to *N. transversalis* (Dunbar and Condra), a wider morph of *N. granulifer*. In Placitas unit 2, specimens are more quadrate and are better assigned to *N. granulifer*; both morphs occur higher in the Placitas section (unit 10). Most of the Placitas brachiopods of unit 2 are wide ranging stratigraphically in the Pennsylvanian to Early Permian of the Midcontinent, but *P. perplexa* is not known above the middle Virgilian there (Dunbar and Condra, 1932). The occurrence of *P. perplexa* in unit 2 supports the fusulinid-based mid-Virgilian age of these Wild Cow strata.

Bivalves are also conspicuous in unit 2. Two species, *Paleolima retifera* (Fig. 4D) and *Acanthopecten carboniferus*, comprise nearly 80% of the bivalve specimens, with other pectinids comprising most of the remainder of the bivalve fauna. Trilobites are represented by a few fragments of *Ditomopyge* sp., the most common Pennsylvanian genus in New Mexico. Of special interest are a few flattened, incomplete specimens of the pyramidal, phosphatic skeletons of conulariids (Fig. 4E), assigned by most workers to scyphozoan cnidarians (jellyfish).

About 1.6 m above unit 2 is a thin interval of hard, medium gray, ledge-forming, locally bioclastic limestones, interbedded with micaceous siltstone (unit 4, section B, Fig. 2). This unit contains *Neochonetes granulifer*, *Derbyia*, *Composita*, fragmentary productoids, fusulinids, ostracods, the gastropod *Amphiscapha*, bryozoan fragments, crinoid and echinoid debris, pectinid bivalves, and complete shells of the large myalinid bivalve *Myalina* (*Orthomyalina*) *slocombi* (Sayre). The latter species has a well-documented range that extends no higher than middle Virgilian in the Midcontinent region (Newell, 1942), and it is a common species in the lower and middle Virgilian of the Jemez Springs area (Kues, 1996).

Wild Cow Formation, Uppermost Interval: Invertebrates

The thin, uppermost interval of the Wild Cow Formation contains both marine and nonmarine fossiliferous strata north of Placitas. At locality 3928, the stratigraphically highest fusulinids in the Placitas section are present. These are the Virgilian taxa *Triticites bensonensis* (Ross and Tyrrell) and *T. coronadoensis* (Ross and Tyrrell). However, they occur as loose specimens weathering from the bone-producing conglomerate of unit 7 in section B (Fig. 2), so these fusulinids probably are reworked from a slightly lower stratigraphic level.

The highest fossiliferous marine unit is a thin gray bioclastic limestone near the top of this interval (unit 10, section B, Fig. 2), about 3 m above the main vertebrate-bone-bearing horizon (unit 9). The diverse invertebrate assemblage from unit 10 (Table 2) is quite different in composition from the assemblages of units 1 and 2. The unit 10 limestone lacks fusulinids, the five most abundant brachiopod species, and one of the two dominant bivalve species present in the unit 2 assemblage. The taxonomic differences between the two assemblages are not temporal (see below), but rather are a consequence of environmental differences. The upper limestone was deposited on a very shallow marine carbonate shelf and bears a fragmented, transported assemblage, whereas the unit 2 assemblage lived, and was buried with little to no transportation, in quiet marine conditions dominated by siliclastic deposition.

In unit 10, molluscs (bivalves and gastropods) are much more abundant (48% of 1100+ specimens, excluding bryozoans and echinoderm fragments) relative to brachiopods (50%) than in unit 2, and both mollusc groups are considerably more diverse, whereas brachiopods are less diverse, than in unit 2. The abundance of molluscs (especially the common bellerophontid gastropods), and, among the brachiopods, the dominance of *Neochonetes*, which could tolerate slightly euryhaline conditions, suggests that unit 10 was deposited near the shoreline (e.g., West, 1972; Yancey and Stevens, 1981).

In unit 10, *Neochonetes granulifer* (Figs. 4G–H) and *N. "transversalis"* (Figs. 4I–J), *Juresania* aff. *J. nebrascensis* (Figs. 4K–L), *Linoproductus prattenianus* (Fig. 4M) and *Derbyia* spp. comprise 93% of the brachiopod fauna, with *N. granulifer* predominating. *Composita subtilita*, nearly ubiquitous in a wide range of lithologies in the Upper Pennsylvanian of New Mexico, is conspicuous by its absence. The brachiopod fauna resembles that of the Jemez Springs Shale but is missing several species that are abundant in that unit, notably *C. subtilita*, and species of Neospirifer and Antiquatonia. A few specimens of the large productoid *Echinaria semipunctata* (Figs. 4O–P), which measures up to 70 mm long, are present in unit 10, instead of the smaller *B. moorei* (Dunbar and Condra), which occurs in the Jemez Springs Shale. The largest Placitas specimen of *B. semipunctata* is nearly identical in size, shape, and proportions to a specimen of this species illustrated by Muir-Wood and Cooper (1960, pl. 86, fig. 3) from the Wayland Shale in Texas, which is middle Virgilian in age (Kier et al., 1979). In the Midcontinent region, *B. semipunctata* does not occur above middle Virgilian strata, and the same is true of *Derbyia texana* (Fig. 4F) in Texas. These species suggest that unit 10, like unit 2, is no younger than middle Virgilian in age.

Preservation of most bivalve and gastropod species is poor; most are

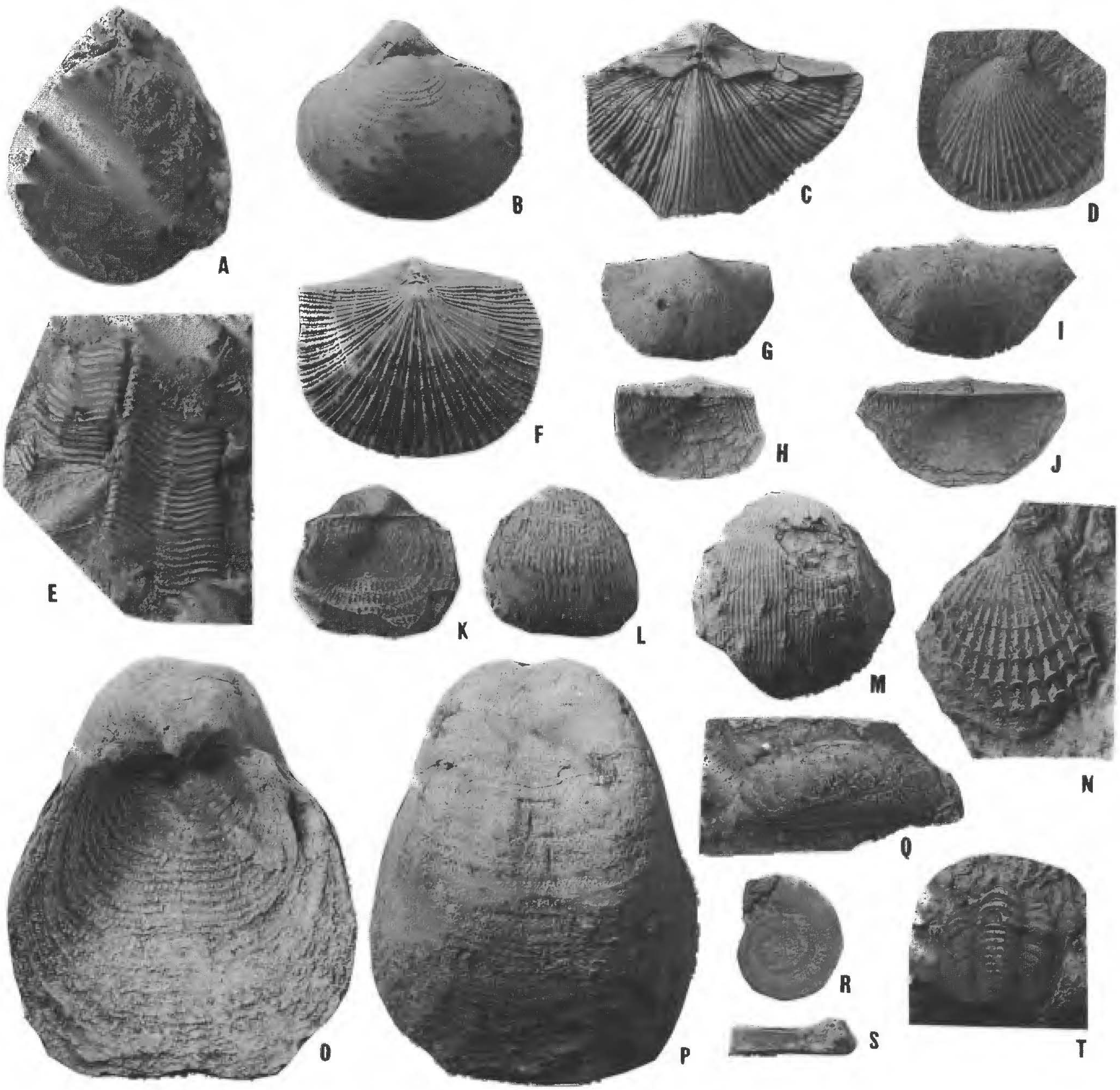

FIGURE 4. Selected invertebrates from the upper Wild Cow Formation (Virgilian) near Placitas. Figures A–E are from unit 2; figures. F–T are from unit 10. **A**, *Composita subtilita*, brachial view, P-28905, x2. **B**, *Phricodothyris perplexa*, brachial view, P-28904, x2. **C**, *Neospirifer dunbari*, brachial view, P-28900, xl. **D**, *Paleolima retifera*, right valve, P-28903, x2. **E**, Conulariid, fragmentary specimen, P-28902, x2. **F**, *Derbyia texana*, brachial view, P-28893, x2. **G–H**, *Neochonetes granulifer*, pedicle (P-28894) and brachial (P-28895) views, x2. **I–J**, *Neochonetes "transversalis,"* pedicle and brachial views, P-28896, x2. **K–L**, *Juresania* aff. *J. nebrascensis*, brachial and pedicle views, P-28891, xl. **M**, *Linoproductus prattenianus*, pedicle view, P-28892, xl. **N**, *Acanthopecten carboniferus*, left valve, P-28890, x2. **O–P**, *Echinaria semipunctata*, brachial and pedicle views, P-28899, xl. **Q**, *Volsellina subelliptica*, weathered left valve, P-28887, x2. **R–S**, *Amphiscapha muricata*, ventral (P-28897) and apertural (P-28898) views, x2. **T**, *Ditomopyge* sp., posterior thorax and pygidium, P-28888, x2.

steinkerns or are highly weathered, rendering precise identification difficult. *Acanthopecten carboniferus* (Fig. 4N), a species that does not occur above the Virgilian in the Midcontinent (Newell, 1937), and several species of *Aviculopecten*, are the most abundant bivalves, but *Paleolima retifera*, common in unit 2, is absent in unit 10. Also relatively common, although preserved mainly as steinkerns, is the elongate, small (length 15–20 mm) mytilid *Volsellina subelliptica* (Fig. 4Q). Gastropods are more abundant than bivalves in unit 10, but diversity is low. *Amphiscapha muricata* (Figs. 4R–S), a small, nearly planispiral species with a depressed spire and sharp basal carina, is by far the most common gastropod, and ranks second in abundance only to *Neochonetes granulifer* in the unit 10 assemblage. In the Midcontinent and Texas regions, *A. muricata* ranges from upper Virgilian to lower Wolfcampian (Yochelson, 1956). Nearly all other gastropods in unit 10 are bellerophontids —at least two species of *Retispira* and one species of *Euphemites*—that are the same as are present in the Virgilian of the Jemez Springs area (Kues, 1996). Trilobites (*Ditomopyge*, Fig. 4T) are uncommon in unit 10 but are relatively more abundant than in unit 2.

TABLE 2. Invertebrate taxa, number of specimens, and percentage of total (excluding bryozoan, echinoid and crinoid fragments) in unit 10 of section B (Fig. 2).

	Specimens	Percentage
BRACHIOPODS		
Neochonetes granulifer (Owen)	245	22.1
Juresania aff. *J. nebrascensis* (Owen)	86	7.7
Linoproductus prattenianus (Norwood and Pratten)	75	6.8
Neochonetes "transversalis" (Dunbar and Condra)	49	4.4
Derbyia spp.	43	3.9
Derbyia texana (Dunbar and Condra)	19	1.7
?*Pulchratia* sp.	12	1.1
Meekella striaticostata (Cox)	6	0.5
Echinaria semipunctata (Shepard)	4	0.4
Derbyia aff. *D. crassa* (Meek and Hayden)	3	0.3
Orbiculoidea missouriensis (Shumard)	2	0.2
Plicochonetes sp.	1	0.1
Reticulatia sp.	1	0.1
unidentified productoids	12	1.1
BIVALVES		
Acanthopecten carboniferus (Stevens)	58	5.2
Volsellina subelliptica (Meek)	36	3.2
Aviculopecten spp.	35	3.2
Aviculopecten cf. *A. occidentalis* (Shumard)	9	0.8
Pernopecten sp.	9	0.8
Edmondia sp.	9	0.8
Schizodus sp.	7	0.6
unidentified myalinids	7	0.6
Pseudomonotis equistriata (Beede)	3	0.3
Clavicosta echinata (Newell)	3	0.3
Astartella sp.	2	0.2
Aviculopinna sp.	2	0.2
Permophorus sp.	2	0.2
Paleyoldia stevensoni (Meek)	1	0.1
Leptodesma (Leptodesma) longa (Geinitz)	1	0.1
unidentified bivalves	22	2.0
GASTROPODS		
Amphiscapha muricata (Knight)	174	15.7
Retispira sp.	63	5.7
Retispira tenuilineata (Gurley)	38	3.4
Retispira cf. *R. eximia* (Yochelson)	17	1.5
Euphemites sp.	12	1.1
Strobeus sp.	5	0.5
unidentified gastropods	19	1.7
TRILOBITES		
Ditomopyge sp.	19	1.7

The remainder of the unit 10 fauna consists of abundant fragmentary crinoid stem ossicles and echinoid plates, and broken fenestrate, rhomboporoid and fistuliporoid bryozoan remains.

Most of the identifiable taxa in unit 10, as in unit 2, have long Pennsylvanian ranges or range from the Pennsylvanian into the lower Wolfcampian (earliest Permian) in the Midcontinent and Texas areas. Many are also present in Virgilian strata near the top of the Madera Formation in the Jemez Springs area. Based on the stratigraphic distribution of several species noted above, which are known from Virgilian but not Wolfcampian strata in other areas, the age of unit 10, and therefore of the uppermost interval of the Wild Cow Formation north of Placitas, is most likely middle to (possibly) late Virgilian. The main vertebrate-bearing horizon (unit 9), between the two fossiliferous marine units discussed above, is therefore most likely of middle Virgilian age.

Wild Cow Formation: Vertebrates

The Placitas section is one of the few known sections of Pennsylvanian age in which rocks containing a diversity of tetrapod body fossils are intercalated with highly fossiliferous marine beds that contain age-diagnostic fossils. It thus provides a direct and precise cross-correlation of nonmarine and marine biostratigraphy. While several bone-bearing sites are now recorded in this section, the principal one is from a stratum belonging to the uppermost part of the Wild Cow Formation (Fig. 2, bed 9), which marine fossils just above indicate is of middle Virgilian age. Vertebrate fossils from this bed have been collected at various places along 2 km of outcrop strike, but the preponderance of material is localized within about 100 m of strike. Recovered elements are mostly fragmentary and, with the notable exception of a single collection, are unassociated.

At least three chondrichthyans are represented by isolated teeth, including a holocephalian tooth plate of *Deltodus*, and a large cladodont tooth, referable to the elasmobranch genus *Symmorium* (see Hunt et al., 1996, for similar teeth of *Deltodus* from the Abo Formation near Jemez Springs, and Zidek and Lucas, 1997, for nearly identical teeth of *Symmorium* from near Socorro). Diplodont teeth of the freshwater xenacanth shark *Orthacanthus* are common, though rarely intact (Fig. 5A). A single limestone nodule contains a fish skull tentatively identified as coelacanth.

The dipnoan genus *Sagenodus* is represented by several tooth plates (Fig. 5B), which closely resemble those illustrated by Hussakof (1911, pl. 27). While recorded from the Lower Permian of Utah and north-central Texas, this is the first record of a non-aestivating lungfish in the Permo–Pennsylvanian of New Mexico. Its occurrence implies existence of permanent bodies of fresh water and mesic conditions. Heretofore, only the aestivating lungfish *Gnathorhiza* has been found in New Mexico (Berman, 1976, 1979, 1993), which is an indicator of seasonal aridity.

Temnospondyl amphibians are represented by at least two taxa. The bizarre dissorophoid *Platyhystrix* is represented by several of its distinctive neural spines, which have the distinctive irregular ridges and knobs characteristic of the genus (e.g., Case, 1910; Williston, 1911; Berman et al., 1981) (Fig. 5C). A larger, typical rhachitome is represented by several characteristic intercentra and part of a neural spine. The latter are consistent with a form such as *Eryops*, common in the Permo–Pennsylvanian of New Mexico, but are not diagnostic at the generic level.

Especially interesting is the record of a large anthracosaur amphibian. A collection of associated vertebral elements (Fig. 5D–G) and a jaw fragment with intact teeth are similar to the embolomere genus *Neopteroplax*. Rare material from elsewhere in New Mexico represents a small embolomere sometimes identified as *Archeria* (Berman, 1993). Portions of a dentary with intact teeth have been recovered that are characteristic of the diadectomorph family Diadectidae.

The most common vertebrate fossils from the uppermost Wild Cow Formation near Placitas represent at least one large predatory pelycosaur as indicated by diverse postcranial elements, including limb bones and vertebrae that are assignable as either ophiacodontid or sphenacodontid (Fig. 5H–I). Two edaphosaurs may be present. Certainly, a larger species consistent with *Edaphosaurus novomexicanus* (Fig. 5J) is well represented by large neural spines with characteristic lateral tubercles (cf. Case, 1907; Romer and Price, 1940). Very small neural spines may be consistent with those of the insectivorous and early derivative edaphosaur *Ianthasaurus* from the Late Pennsylvanian of Kansas and Colorado but are best identified as Edaphosauridae, indet. (Fig. 5K).

Abo Formation

A variety of fossils occur in the Abo Formation north of Placitas. These include the fragmentary remains of one or more pelycosaurs and the embolomerous vertebral centra of the anthracosaur *Archeria*. Plant material, mostly the conifer *Walchia*, is present at three sites. One of these also produced the well-preserved tegmen of a blattoid insect. A track site (NMMNH locality 3925) bears impressions of the tetrapod ichnogenus *Dimetropus* (Fig. 5L) (cf. Lucas and Heckert, 1995a) and traces of an archaeognath insect. None of these fossils are age diagnostic, but are consistent with the Wolfcampian age usually assigned to the Abo.

Yeso, Glorieta, and San Andres formations

We did not observe any fossils north of Placitas in Permian strata that

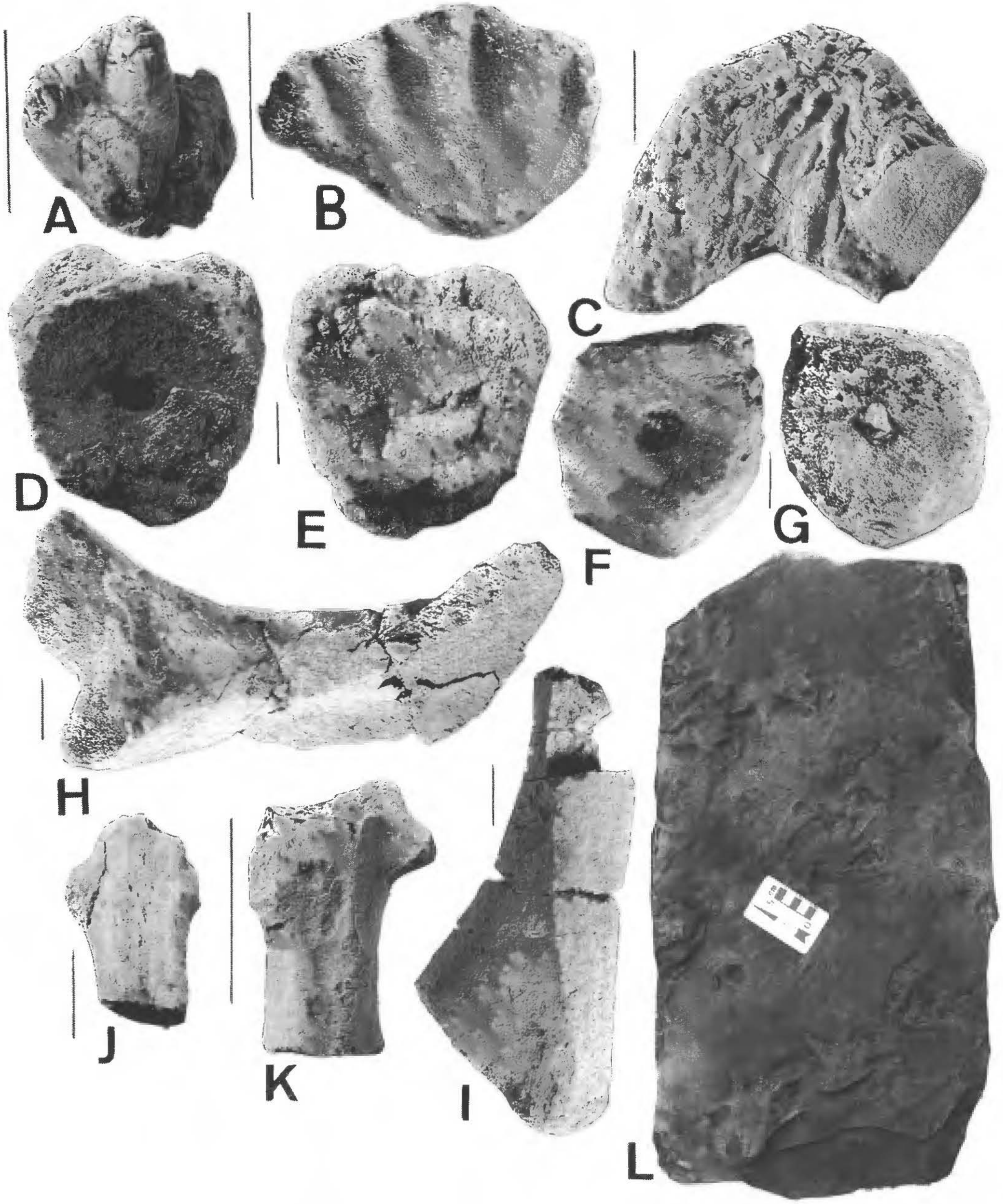

FIGURE 5. Selected vertebrate fossils from the Wild Cow and Abo formations near Placitas. **A**, *Orthacanthus* sp., tooth, NMMNH P-28881. **B**, *Sagenodus* sp., tooth plate, NMMNH P-28883. **C**, *Platyhystrix* sp., piece of neural spine, NMMNH P-28880. **D–G**, cf. *Neopteroplax* sp., vertebral centra, NMMNH P-28885, anterior and posterior views. **H**, *Pelycosaur*, incomplete left scapula, NMMNH P-28877. **I**, *Pelycosaur*, distal fibula?, NMMNH P-28878. **J**, *Edaphosaurus* sp., neural spine fragments, NMMNH P-28886. **K**, Edaphosauridae, indet., neural spine fragment, NMMNH P-28882. Scale bars = 1 cm; all fossils from NMMNH locality 3390, except cf. *Neopteroplax*, NMMNH P-28885, which is from locality 3419. L, Footprints of *Dimetropus* at NMMNH locality 3925; scale in cm.

overlie the Abo Formation. Therefore, the ages we assign those units are those based on regional age data, not on data available at Placitas (Fig. 6).

DISCUSSION

Correlation of the Upper Pennsylvanian–Permian section at Placitas to the geological time scale (Fig. 6) is based on the comments made above. For the Virgilian part of the section fossils provide a strong basis for age assignment; a Wolfcampian age for the Abo Formation is consistent with, but not well demonstrated, by fossils; and a Leonardian age is assigned to overlying Permian strata based on their regional age assignments, not on fossils collected at Placitas.

The Upper Pennsylvanian–Permian section at Placitas is significant for three reasons:

1. This is the singlemost complete, well-exposed Permian section around the Sandia uplift.
2. At Placitas, well-preserved and diverse marine invertebrate assemblages are present.
3. The youngest Virgilian strata at Placitas include conglomerates that yield a diversity of fossil vertebrates. This is a rare case where a clear cross-correlation of vertebrate taxa to Upper Pennsylvanian marine biostratigraphy is possible.

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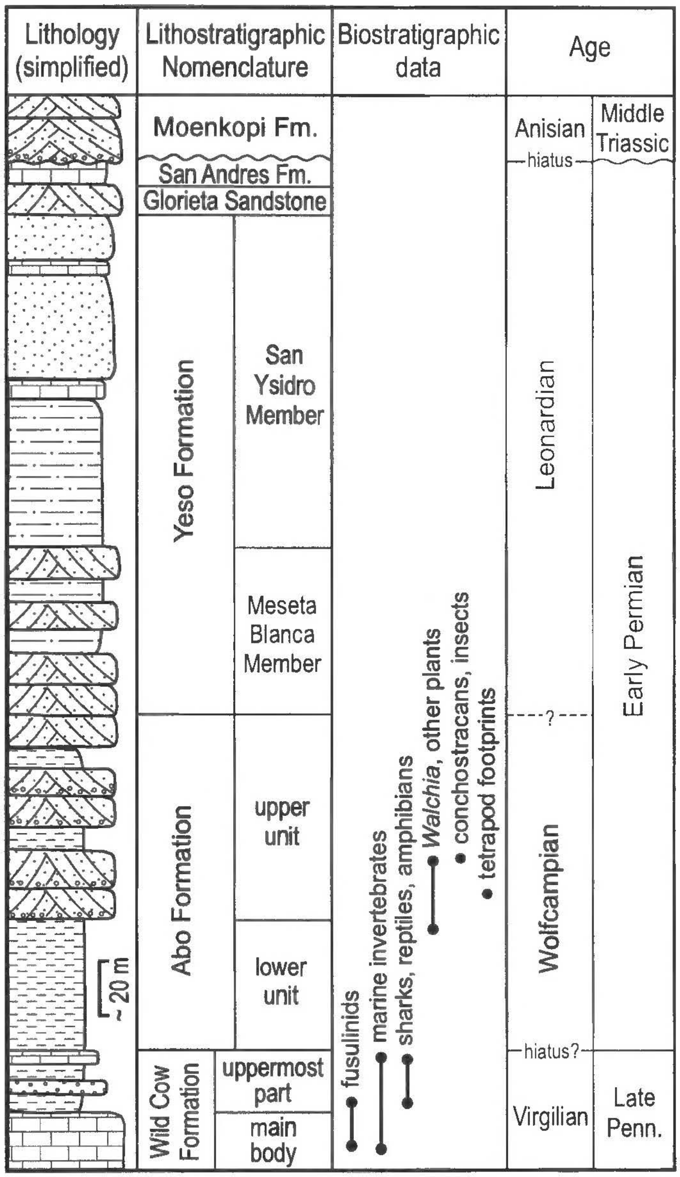

FIGURE 6. Summary of Upper Pennsylvanian–Permian stratigraphy, biostratigraphy, and age assignments north of Placitas.

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APPENDIX 1—MEASURED SECTIONS

Section A

Section starts at 373854E 3912693N and ends at 374310E, 3912760N, in UTM Zone 13, using datum NAD27. Strata dip 15° to N40°E.

Unit	Lithology	Thickness (m)
Moenkopi Formation:		
53	Sandstone, trough crossbedded.	not measured
San Andres Formation:		
Dip is 46°		
52	Sandy limestone. Sandstone is fine- to medium-grained, subrounded quartz floating in the limestone matrix; limestone is micrite, grayish orange (10YR7/4); very calcareous; forms a hogback.	5.1
Glorieta Sandstone:		
51	Metaquartzite; medium- to coarse-grained, subrounded, moderately sorted, quartz sandstone; very pale orange (10YR8/2) when fresh, weathers to dark grayish brown (10YR4/2); trough crossbedded.	1.1
50	Sandy limestone; lithology like unit 52; yellowish gray (5Y7/2).	1.9
49	Metaquartzite; same lithology and color as unit 51, but not as metamorphosed.	1.7
48	Sedimentary breccia; angular sandstone chunks in a sandstone matrix. Sandstone clasts are up to 1 cm in diameter; medium- to coarse-grained, subangular quartz; pale brown (5YR5/2); sandstone matrix is grayish orange (10YR7/4); very calcareous.	1.5
47	Sandstone; very fine- to fine-grained, lithic quartzarenite; grayish orange (10YR7/4); trough crossbedded.	5.0
Yeso Formation:		
San Ysidro Member:		
46	Sandstone; very fine-grained, silty, hematitic litharenite; light brown (5YR5/6); calcareous; very gypsiferous; forms a slope.	16.0
45	Limestone and sandstone. Limestone is coarsely crystalline micrite, pale yellowish brown (10YR6/2); sandstone is very fine-grained, subrounded, quartzose, gypsiferous, slightly micaceous litharenite, moderate orange pink (10R7/4) with mottles of very light gray (N8); very calcareous.	1.3
44	Sandstone; same lithology and color as unit 46, but not gypsiferous; forms a slope.	9.7
43	Gypsiferous limestone; coarsely crystalline, with selenite crystals and vuggy; pale yellowish brown (10YR6/2); forms a ledge.	1.3
42	Same lithology and color as unit 46, but not gypsiferous.	10.2
41	Silty sandstone; very fine-grained litharenite, light brown (5YR5/6); not calcareous; intensively ripple laminated; some limestone nodules; forms a ledgy, rolling topography.	64.0
40	Same lithology and color as unit 41; with salt casts on surfaces; ripple laminated; forms ledges.	9.0
39	Sandstone; very fine-grained micaceous litharenite, pale reddish brown (10R5/4); not calcareous; ripple laminated; forms a hackley slope.	3.2
Meseta Blanca Member:		
38	Sandstone; medium- to coarse-grained, well-rounded quartz; pinkish gray (5YR8/1); not calcareous; trough-crossbedded dune sand; upper part forms top of cliff.	2.0
37	Sandstone; medium- to very coarse-grained quartz; grayish orange pink (5YR7/2); not calcareous; ripple-laminated sheet dune sand.	5.3
36	Sandstone; very fine- to medium-grained, subrounded, poorly sorted litharenite; pale reddish brown (10R5/4); not calcareous; ripple laminated; forms a slope. Change dip to 46° for units 36–52.	10.6
35	Sandstone; fine- to very coarse-grained arkose; light brown (5YR6/4); slightly calcareous; trough crossbedded; dune bounding surfaces every 2–3 m.	12.0
34	Sandy siltstone/silty sandstone; very fine-grained litharenite; light brown (5YR5/6); not calcareous; trough crossbedded.	10.2
33	Sandy siltstone; mostly grayish red (10R4/2) with lesser grayish orange pink (5YR7/2); slightly calcareous; waterlaid; forms a slope. Change dip to 27° for units 33–35.	2.0
32	Sandy siltstone; pale reddish brown (10R5/4); not calcareous; trough crossbedded.	17.2
Abo Formation:		
31	Sandstone; medium-grained, subangular, micaceous arkose; pale red (10R6/2); not calcareous; laminar to low-angle trough crossbedded.	2.6
30	Sandy siltstone/silty sandstone; very fine-grained micaceous litharenite; pale reddish brown (10R5/4) and pinkish gray (5YR8/1); not calcareous; laminar to ripple laminated, very fine laminae; raindrop impressions.	6.8
29	Sandstone; fine- to medium-grained, subrounded arkose; moderate red (5R5/4); very calcareous; multistoried trough crossbedded.	5.2
28	Sandstone; very fine- to medium-grained, poorly sorted arkose; pale reddish brown (10R5/4); not calcareous; ripple laminated.	4.5
27	Sandstone; medium- to coarse-grained, subangular arkose; pale reddish brown (10R5/4); calcareous; multi-storied trough crossbedded.	5.5
26	Covered; same lithology and color as unit 24?	4.4
25	Silty sandstone; very fine-grained, subangular arkose; dark reddish brown (10R3/4); calcareous; ripple	

Unit	Lithology	Thickness (m)
	laminated; forms a ledge.	1.1
24	Mudstone with lenses of pebble conglomerate and shale; mudstone is pale reddish brown (10R5/4); calcareous; conglomerate lenses are clast supported with calcrete-mudstone clasts up to 1 cm in diameter; pale reddish brown (10R5/4); calcareous; shale lens only at NMMNH locality 3922 is dark gray (N3) and not calcareous; forms a slope.	9.0
23	Same lithology and color as unit 25; trough crossbedded and ripple laminated; forms a platy ledge; fossil tracks.	1.1
22	Silty mudstone; mostly pale reddish brown (10R5/4) with mottles of pale yellowish brown (10YR6/2); crinoid packstone.	4.8
21	Sandstone; very fine-grained, subangular arkose; light gray (N7); calcareous; ripple laminated; forms ledges with interbeds of shale.	2.7
20	Mudstone and conglomerate; mudstone is pale reddish brown (10R5/4); calcareous; conglomerate has matrix of calcareous mudstone; clasts are well-rounded lithic pebbles up to 1 cm in diameter; pale yellowish brown (10YR6/2); very calcareous.	0.9
19	Sandstone; fine- to medium-grained micaceous arkose; pinkish gray (5YR8/1); slightly calcareous; trough crossbedded; forms a ledgy cliff.	1.2
18	Conglomerate and shale; conglomerate clasts are limestone pebbles up to 1 cm in diameter; light grayish brown (5YR6/1); matrix is medium- to coarse-grained arkosic sandstone, grayish red (10R5/2), calcareous; shale is laminar and green; unit is partly covered.	3.1
17	Sandstone; fine- to medium-grained, subrounded arkose; pale red (5R6/2); not calcareous; trough crossbedded; forms a ledgy cliff.	3.8
16	Same lithology and color as unit 18.	4.4
15	Sandstone; fine- to medium-grained arkose; pinkish gray (5YR8/1); calcareous; trough crossbedded; forms a ledgy cliff; contains *Walchia.*	3.3
14	Sandy siltstone; medium light gray (N6); calcareous.	4.0
13	Silty mudstone and shale; mudstone is pale red (10R6/2); very calcareous; shale is lenticular, waxy, yellowish gray (5Y7/2); not calcareous; contains plant debris; encrinite occurs in middle of unit; mostly covered; forms a slope; fossil bone and coprolites (NMMNH locality 3927).	10.5
12	Sandstone; very fine- to fine-grained arkose; grayish red (10R4/2); very calcareous; hummocky and ripple laminated, with some trough crossbeds; forms a ledge.	2.3
11	Same lithology and color as unit 13, but no encrinite; mostly covered.	6.0
10	Conglomerate; clast supported; clasts are limestone, up to 0.5 cm in diameter, pale brown (5YR5/2); very calcareous; trough crossbedded; fines upward; forms a ledge.	1.5
9	Same lithology and color as unit 13, but well exposed.	23.3
Wild Cow Formation (uppermost):		
8	Limestone; micrite; medium dark gray (N4); forms a ledge.	0.3
7	Silty mudstone and sandstone; mudstone is pale red (10R6/2); very calcareous; sandstone is very fine-grained, subrounded arkose; grayish red (10R4/2); calcareous; ripple laminated.	3.2
6	Conglomerate; clasts are quartz and feldspar, vary from very coarse sandstone up to 0.5 cm, moderate reddish brown (10R4/6) and light gray (N7); matrix is angular quartz, brownish gray (5YR4/1); calcareous; trough crossbedded; contains chalcedony and fossil bone; forms a ledge.	2.0
5	Limestone and shale; limestone is nodular; light brownish gray (5YR6/1); shale is red, a minor component.	1.1
4	Mudstone and nodular limestone debris; mudstone is grayish red (10R4/2); very calcareous; limestone is nodular; light brownish gray (5YR6/1); forms a slope.	4.6
3	Limestone, nodular, medium light gray (N6); shelly; mostly covered.	6.0
2	Sandy siltstone; light gray (N7); calcareous.	1.2
Wild Cow Formation (main body):		
1	Limestone; bioclastic packstone; pale yellowish brown (10YR6/2); uppermost 0.2 m is nodular; forms a ledge.	not measured

Section B

Strata dip 12° to N50°E. Section starts at 373720E, 3912373N and ends at 373841E, 3912431N in UTM Zone 13, using datum NAD27.

Unit	Lithology	Thickness (m)
Abo Formation:		
13	Sandstone and minor conglomerate; sandstone is medium-grained, micaceous arkose ("granite wash"); pale brown (5YR5/2); not calcareous; conglomerate clasts are quartz and feldspar, vary from very coarse-grained up to 0.5 cm in diameter, moderate reddish brown (10R4/6) and light gray (N7); matrix is brownish gray (5YR4/1) angular quartz; calcareous; trough crossbedded; forms a ledge.	2.0
12	Shale and sandstone; shale is brick red; sandstone is fine-grained, very micaceous litharenite; pale reddish brown (10R5/4); very calcareous; lenticular, ripple laminated; forms a slope.	7.4
Wild Cow Formation (uppermost):		
11	Limestone; bioclastic packstone, very-fine shell hash; coarsely recrystallized; medium light gray (N6) and brownish gray (5YR6/1); forms a ledge; invertebrate fossils.	0.3
10	Silty mudstone; blocky; grayish red (10R4/2); bioturbated; very calcareous.	3.2
9	Limestone and conglomerate; limestone is brownish gray (5YR4/1) micrite; conglomerate clasts are limestone pebbles, most are very coarse-grained to 0.5 cm; clast supported; pale yellowish brown (10YR6/2); forms a ledge; very calcareous; main bone-bed localities.	0.2
8	Mudstone; slightly sandy, bentonitic; light greenish gray (5GY8/1) with pale red (5R6/2) mottles; very calcareous.	3.1
7	Conglomerate; same lithology and color as unit 9 conglomerate; lower bone bed; forms a ledge.	0.1
6	Limestone; nodular, micritic; pale yellowish brown (10YR6/2) and pale reddish brown (10R5/4).	1.1
5	Sandy siltstone, laminar, medium light gray (N6); contains some nodular limestone like unit 6.	1.2
Wild Cow Formation (main body):		
4	Limestone; fusulinid packstone; light brownish gray (5YR6/1); bivalves; forms a ledge.	0.1
3	Limestone, nodular, micritic; medium gray (N5); calcareous; fossiliferous; forms a slope.	1.7
2	Shale; grayish green.	0.6
1	Limestone; fusulinid-brachiopod-crinoid packstone; light brownish gray (5YR6/1); forms a ledge.	not measured

APPENDIX 2—FOSSIL LOCALITIES

NMMNH locality	UTM coordinates (Zone 13, NAD27)		Formation	Stratigraphic unit (Fig. 2)	Fossils
L-3390	373800E	3912100N	Wild Cow	sec. A, units units 7, 10	inverts, bone
L-3391	373993E	3912509N	Abo	sec. B, unit 15	*Walchia*
L-3392	373403E	3912612N	Abo	sec. B, unit 22	inverts
L-3393	373888E	3912860N	Wild Cow	sec. B, unit 10	inverts
L-3394	373964E	3912600N	Abo	sec. A, unit 22	crinoids
L-3395	373891E	3912734N	Wild Cow	sec. B, unit 9	vertebrate bone
L-3396	373777E	3911847N	Wild Cow	sec. B, unit 1	inverts
L-3397	373819E	3911655N	Wild Cow	sec. B, unit 1	inverts, fusulinids
L-3398	373736E	3911519N	Wild Cow	sec. B, unit 1	inverts
L-3399	373773E	3911445N	Wild Cow	sec. B, unit 1	inverts
L-3400	373772E	3911210N	Wild Cow	sec. B, unit 1	inverts
L-3401	373862E	3911936N	Wild Cow	sec. B, unit 1	inverts, fusulinids
L-3402	373860E	3911874N	Wild Cow	sec. B, unit 1	inverts, fusulinids
L-3403	373810E	3911954N	Wild Cow	sec. B, unit 1	inverts
L-3922	374312E	3912285N	Abo	sec. A, unit 24	insects, plants, bone
L-3923	374312E	3912285N	Abo	sec. A, unit 24	bone
L-3925	374210E	3911770N	Abo	sec. A, unit 33	tetrapod tracks
L-3926	374022E	3911544N	Abo	sec. A, unit 13	bone
L-3927	374022E	3911684N	Abo	sec. A, unit 13	bone, coprolites
L-3928	374081E	3910981N	Wild Cow	sec. B, unit 7	bone, fusulinids