THE LOWER PERMIAN ABO FORMATION IN CENTRAL NEW MEXICO

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Abstract—In central New Mexico, the Lower Permian (middle-upper Wolfcampian) Abo Formation generally overlies the Upper Pennsylvanian (Newwellian) Bursum Formation disconformably and is conformably overlain by the Lower Permian (Leonardian) Yeso Group. The Abo Formation is 100-309 m thick and can be divided into two members: (1) lower, Scholle Member, 40-140 m thick, mostly mudstone; and (2) upper, Cañon de Espinoso Member, 58-256 m thick, characterized by numerous sheet-like beds of sandstone. Across central New Mexico, the Abo Formation is a relatively uniform unit that is almost entirely mudstone and sandstone; minor lithologies are shale, siltstone, calcrete and intraformational conglomerate.

Abo Formation vertebrate fossils are of Coyotean age (late Virgilian-late Wolfcampian), and regional correlations indicate that the Abo Formation in central New Mexico is of middle-late Wolfcampian age. Trace fossils from the Abo Formation are an ichnoassemblage of rhizoliths, arthropod locomotion and feeding traces and tetrapod footprints of the *Scoyenia* ichnofacies. Fossil plants from the Abo Formation are mostly conifers and belong to two paleofloras: (1) red siltstone assemblages that are of low diversity at any given sampling site, and almost always dominated by either conifers or the peltasperm *Supaia*; (2) green shale/siltstone assemblages, locally more diverse, and still dominated by conifers, but with a significant component of cordaitaleans, callipterid peltasperms, and a wide variety of wetland plants. Invertebrate body fossils are rare and are only known in a carbonaceous shale in the northern Sandia Mountains (conchostracans) and the green shale, estuarine facies of the Abo Formation in the Caballo Mountains, which yields gastropods and diverse bivalves, including euryhaline pectins and myalinids. Vertebrate body fossils are mostly localized in strata of the Scholle Member and are a pelycosaur-dominated assemblage that includes lungfishes, palaeoniscoids, temnospondyl and lepospondyl amphibians, and diadectomorphs.

The Abo Formation is composed of various conglomerate, sandstone, nodular limestone and mudstone lithofacies that can be combined into three principal architectural elements: (1) sandstone sheets formed by amalgamated channels or by relatively unchannelized flow; (2) sandstone lenses and bodies that represent fluvial channels; and (3) siltstone/mudstone with pedogenic limestone that represents deposits of floodplains. Abo deposition took place on an extensive alluvial plain in which well-defined, bedload river channels within extensive muddy floodplains were succeeded by sandstone sheets formed by low sinuosity river deposits subject to episodic avulsion and sheetflooding. This change in stratigraphic architecture can be attributed to tectonic changes in which falling base level (relatively rapid subsidence) during deposition of the lower Abo was followed by episodically stable base level (slower subsidence) during deposition of the upper Abo.

INTRODUCTION

In central New Mexico (Fig. 1), siliciclastic red beds of the Lower Permian Abo Formation are a conspicuous lithostratigraphic unit in the upper Paleozoic section. Well exposed in the mountain ranges and other uplifted areas that border the Rio Grande rift (Fig. 1), study of Abo Formation outcrops during the last two decades has resulted in a much more refined understanding of their stratigraphy, paleontology, microfacies, correlation and depositional environments (e.g., Mack et al., 1991, 1995, 2003; Berman, 1993; Lucas et al., 2005a, 2012 a, b; DiMichele et al., 2007; Krainer and Lucas, 2010). Here, we review our current understanding of the Abo Formation in central New Mexico, which refers primarily to Sandoval, Bernalillo, Valencia, Torrance, Socorro and Sierra Counties (Fig. 1).

HISTORY OF STUDY

Stratigraphic study of the Abo Formation began with Lee (1909), who divided the Manzano Group of Herrick (1900) into the Abo, Yeso and San Andreas (sic) formations (Fig. 2). Lee (1909) named the “Abo sandstone” for “Abo Canyon” at the southern end of the Manzano Mountains (just north of Abo Pass), describing it as “coarse-grained sandstone, dark red to purple in color and usually conglomeratic at the base, with a subordinate amount of shale…. ” (p. 12). Lee (1909) included marine limestone in the base of the Abo sandstone that eventually became part of the underlying Bursum Formation. He also included a sandstone-dominated interval in the top of the Abo that was later included in the overlying Yeso Formation (Fig. 2).

Darton (1928) used Abo sandstone as had Lee (1909), including some strata later termed Bursum in the basal Abo, and some strata later termed Yeso in the upper Abo (Fig. 2). Recognition of the Abo Formation across central New Mexico owes much to Darton’s (1928) work.

Needham and Bates (1943) described type sections of the Abo and Yeso formations of Lee, and thereby modified somewhat his concepts of those units. Of note, Needham and Bates (1943) excluded marine limestones from the basal Abo Formation, a decision followed by all subsequent workers (Fig. 2).

FIGURE 1. Map of New Mexico, showing locations of outcrops of the Abo Formation discussed in the text.

The longstanding concept of the Abo and Yeso formations in central New Mexico comes from four maps published between 1946 and 1951 by the United States Geological Survey as part of its Oil and Gas Mapping Programs carried out during World War Two. These included maps of the Jemez Pueblo and Sierra Nacimiento in Sandoval County (Wood and Northrop, 1946), the Lucero uplift in Valencia County (Kelley and Wood, 1946), the Joyita Hills, Los Piños Mountains and northern Chupadera Mesa of Socorro County (Wilpolt, et al., 1946) and the Cerrillos del Coyote, northern Jornada del Muerto and southern Chupadera Mesa in Socorro County (Wilpolt and Wanek, 1951). These workers followed Needham and Bates (1943) in their placement of the base of the Abo Formation. Wilpolt et al. (1946) named the Bursum Formation to encompass the mixed marine-clastic interval immediately below the Abo Formation, whereas Kelley and Wood (1946) named that interval the Red Tanks Member of the Madera limestone (Fig. 2). Most significantly, Wilpolt et al. (1946) removed the upper sandstone interval from the Abo Formation, and called it the Meseta Blanca sandstone member of the Yeso Formation (a name proposed by Wood and Northrop, 1946).

Baars' (1962) important synthesis of Lower Permian stratigraphy on the Colorado Plateau used Abo Formation in the same sense as the published maps of 1946. However, he pointed out that the type section of the Meseta Blanca Member of the Yeso Formation near Jemez Pueblo is simply the same unit that Gregory (1917) had named the De Chelly Sandstone near Chinle, Arizona. Therefore, Baars (1962) abandoned the name Meseta Blanca and replaced it with De Chelly Sandstone, which he removed from the Yeso Formation.

The recommendations of Baars (1962), however, were not heeded for more than 40 years by geologists working in New Mexico, who continued to use the Abo-Yeso stratigraphy of the 1946 published maps (e.g., Hatchell et al., 1982; Cook et al., 1998; Dinterman, 2001; Mack and Dinterman, 2002; Seager and Mack, 2003; Kues and Giles, 2004). Nevertheless, our own work (Lucas et al., 1999, 2005, 2009, 2012a, b; Lucas and Krainer, 2004; Lucas and Zeigler, 2004; DiMichele et al., 2007) convinced us that some modifications of the Abo-Yeso stratigraphy were justified to produce a lithostratigraphic nomenclature that better reflects current understanding of the Lower Permian lithostratigraphy of central New Mexico. These modifications included recognizing two formal members within the Abo Formation, adopting Baars (1962) suggestion to abandon the name Meseta Blanca Member of Yeso Formation and replace it with DeChelly Sandstone, raising the Yeso Formation to group status and naming the siltstone-dominated facies of the lower Yeso south of the DeChelly erg the Arroyo de Alamillo Formation (Fig. 2).

STRATIGRAPHIC NOMENCLATURE

From the Abo type section in Valencia County southward into Socorro County, Lucas et al. (2005a) divided the Abo Formation into two members, a lower mudstone-dominated unit, the Scholle Member, and an upper unit with many sandstone sheets, the Cañon de Espinoso Member. The same subdivision of the Abo Formation is evident in Abo outcrops in the southern Jemez Mountains of Sandoval County (Lucas et al., 2012b), on the northern end of the Sandia uplift in Bernalillo County (Lucas et al., 1999), in the Lucero uplift of Valencia County (Lucas and Zeigler, 2004), in the Cerros de Amado-Joyita Hills area of Socorro County (Lucas et al., 2009), in the northern Oscura Mountains of Socorro County (DiMichele et al., 2007) and in the Fra Cristobal and Caballo Mountains of Sierra County (Lucas et al., 2012a). Therefore, we apply the member-level terminology of Lucas et al. (2005a) to the Abo Formation across central New Mexico (Fig. 3).

LITHOSTRATIGRAPHY

Contacts

Across central New Mexico, the Abo Formation generally overlies sedimentary rocks of Pennsylvanian age. Mostly, these are strata of the Virgilian-early Wolfcampian Bursum Formation, which are a succession of mixed carbonate and siliciclastic rocks of marine and nonmarine origin (e.g., Lucas and Krainer, 2004; Krainer and Lucas, 2009). Typically, the highest marine limestone bed underneath Abo red-bed siliciclastic strata is chosen as the Abo-Bursum contact. A similar criterion is used to distinguish the basal contact of the Abo Formation where it overlies older, Pennsylvanian marine rocks. In a few places that were positive areas (uplifts) of the Ancestral Rocky Mountain orogeny, the Abo Formation rests directly on Proterozoic basement. In central New Mexico, these are very localized areas in the Nacimiento uplift at the southern end of the Jemez Mountains (Woodward, 1987) and in the Joyita Hills of Socorro County (Kottlowski and Stewart, 1970).

Across central New Mexico, strata of the Lower Permian Yeso Group conformably overlie the Abo Formation. At most outcrops, there is either an interbedding of Abo and Yeso lithotypes over a stratigraphic interval of 10 m or less, or the base of the Yeso Group is picked at the lowest, non-arkosic, fine-grained sandstone bed or the lowest dolomite bed above Abo mudrock or arkosic sandstone (Fig. 4).

Thickness

The Abo ranges in thickness from about 100 to 300 m across central New Mexico (Table 1). The Scholle Member is 40 to 115 m thick, and the Cañon de Espinoso Member is 60 to 256 m thick. The Abo is thickest to the south, but there are no consistent thickness trends geographically. Instead, we suspect Abo thickness reflects the position of Ancestral Rocky Mountain uplifts, such as the relatively thin Abo section in the Cerros de Amado, just south of the Wolfcampian Joyita uplift.

Lithology

Scholle Member

The Scholle Member of the Abo Formation is mudstone dominated. Its sandstones are coarse-grained and conglomeratic and are trough-

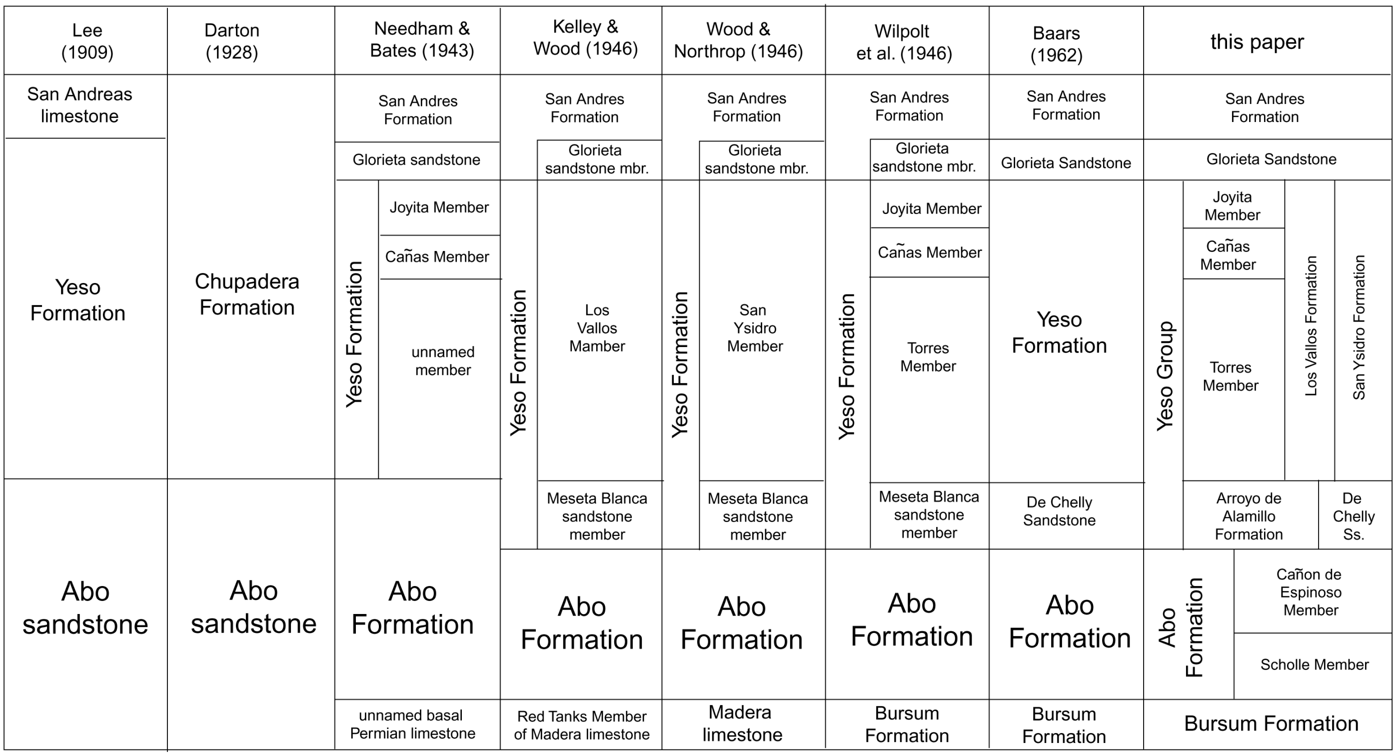


FIGURE 2. Development of lithostratigraphic nomenclature of the Abo Formation and adjacent strata in central New Mexico.

crossbedded, channelform deposits (Fig. 4). As a good example, the Scholle Member is well exposed at its type section at Abo Pass (Fig. 4), where it is ~ 140 m thick and consists of thick mudstone slopes (87% of the measured section) broken by thin ledges of trough-crossbedded sandstone and conglomerate (11% of the section), and minor calcrete ledges (2% of the section).

Cañon de Espinoso Member

The Cañon de Espinoso Member, though it may also be mudstone dominated, has a significant component of siltstone, and its sandstones are sheet-like bodies with prominent ripple and climbing-ripple bedforms. At its type section at Abo Pass (Fig. 4), the Cañon de Espinoso Member is ~ 170 m thick and consists mostly of slope-forming covered intervals of mudstone (70% of the section), but includes significant siltstone beds (9% of the section) and many thin ledges of climbing-ripple laminated sandstone (21% of the section).

Lithofacies

Within the Abo Formation, Krainer and Lucas (2010) and Lucas et al. (2012a, b) described 17 lithofacies types following the classification and lithofacies codes of Miall (1978, 1981, 1985, 1996, 2010). All lithofacies types are listed in Table 2.

These Abo lithofacies can be used to distinguish three architectural elements: (1) sandstone sheets, (2) intercalated thin sandstone beds and lenses, and (3) siltstone-mudstone. Sandstone sheets are the most characteristic facies assemblage in the Abo Formation and correspond to the architectural element CH (channel) and SB (sandy bedforms) of Miall (1996). Sandstone sheets are up to several m thick and form distinct, resistant ledges that can be traced laterally over long distances. The base is commonly erosive; locally, channels are cut into the underlying fine-grained sediments with a relief of up to about 3 m.

Two types of sandstone sheets are observed. Sandstone sheets composed dominantly of lithofacies St, minor Sl, Sh, Sm and rare Sr correspond to architectural element CH. Intercalated thin conglomerate layers and lenses within stacked cosets of multistory channel-fill successions represent conglomerate lags at the base of individual channels. These sandstone sheets were deposited in broad, shallow channels of a low sinuosity river system (Krainer and Lucas, 2010).

The other type of sandstone sheet is dominated by lithofacies Sr, associated with Sh, Sm and rare Sl, representing the architectural element SB. Individual sandstone beds are 0.1-5 m thick. Different types of ripple lamination are observed, such as isolated asymmetric current ripples or thin layers of current ripples that occur within fine-grained sediment. In thicker sandstones, climbing ripples are common. Both type A (erosional-stoss) and type B (depositional-stoss) climbing ripples are observed. Draped lamination is very rare. Climbing ripples may grade upwards into horizontal lamination. Mudcracks are common within the ripple-laminated sandstone units.

The flow conditions under which different types of ripple drift cross lamination are formed are well known from flume experiments (e.g., Jopling and Walker, 1968; Allen, 1973, 1985; Banks and Collinson, 1975; Ashley et al., 1982). Different types of climbing ripples are attributed to fluctuations in current velocity, variations in grain-size and the concentration of suspended sediment (Jopling and Walker, 1968). Climbing ripple sequences 10-20 cm thick are deposited within a few tens of hours. Draped lamination results from continuous fallout of sediment from suspension after ripple migration ceases or almost ceases. Ripple drift cross lamination is very common in glaciofluvial and glaciolacustrine sediments (Jopling and Walker, 1968; Gustavson et al., 1975), but is also known from other depositional environments.

In ripple-laminated sandstones of the Abo Formation, variations in height between the climbing ripple sets as well as fluctuations in the climbing angle are observed. These patterns result from fluctuations in flow velocity or fluctuations in sediment transport volume (Rubin, 1987). The sandstone sheets of architectural element SB were deposited in very broad, shallow channels of a braided stream system during periods of high influx of fine sand. They are essentially sheetflood deposits in which random fluctuations in flow velocity and depositional rate caused compound cross-bedding.

Sandstone beds and lenses are another prominent architectural element in the Abo Formation in central New Mexico Thin intercalated

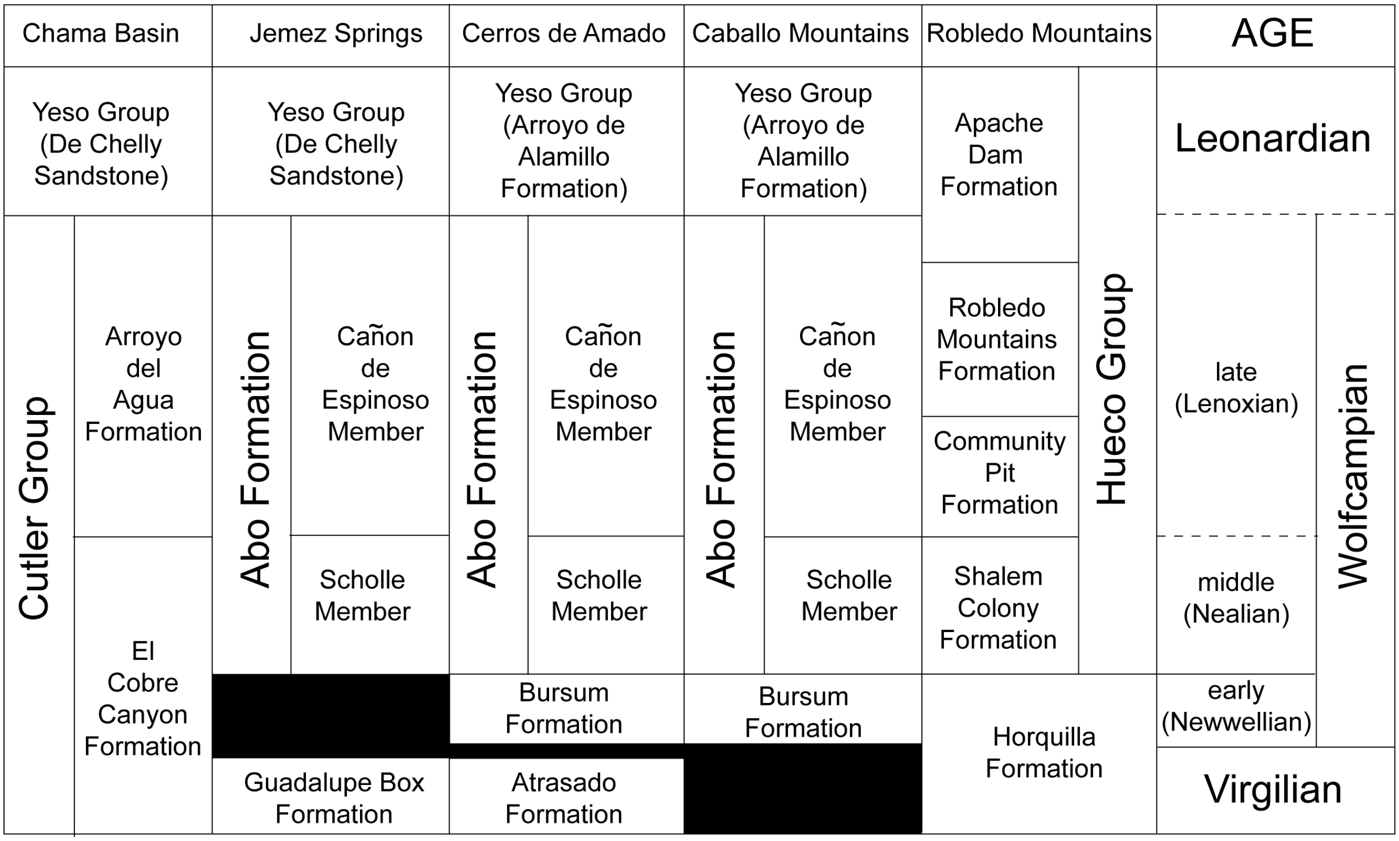


FIGURE 3. Correlation chart of Abo Formation and related stratigraphic units from north to south in New Mexico.

beds and lenses of coarse-grained siltstone to fine-grained sandstone are 0.1 to 0.5 m, rarely up to 1 m thick. They occur as single sandstone beds or as stacked units. Typical lithofacies are Sr, Sh, St and Sm, forming tabular or lense-shaped sandstone bodies. Krainer and Lucas (2010) interpreted the tabular sandstone beds as sheet splay deposits formed by sheet-like, non-channelized flow from a crevasse channel onto the floodplain, thus representing architectural element CS (crevasse splay) of the overbank environment (Miall, 2010). Sandstone lenses are interpreted as minor channel fills representing feeder channels (crevasse channels, architectural element CR of Miall, 2010) of the sheet splays. Such intercalated sandstone beds and lenses of limited lateral extent are characteristic elements of the overbank environment.

Siltstone-mudstone is the third principal architectural element of the Abo Formation. Indeed, this lithology is the dominant lithofacies of the Abo Formation across central New Mexico, occurring as units up to tens of m thick that extend laterally over large distances. This facies is interpreted to represent floodplain deposits (architectural element FF – floodplain fines according to Miall) of the overbank environment resulting mainly from overbank sheet flow and from deposition from suspension during waning flood. Absence of lamination partly results from bioturbation. Intercalated limestone beds are interpreted as pedogenic limestones, indicating relatively long periods of soil formation under dry conditions (Mack and James, 1986; Mack et al., 1991).

Sandstone Petrography

To the north in central New Mexico (Jemez Mountains, Abo Pass), sandstone of the Abo Formation is classified as arkose (Fig. 5A, B, D, E, F) and lithic arenite (Fig. 5 G-H), subordinately as subarkose (Fig. 5C). The dominant grain type is monocrystalline quartz, and subordinate is polycrystalline quartz. Detrital feldspars, mostly potassium feldspars, including many microcline are common. Coarse-grained sandstone contains many granitic rock fragments; metamorphic rock fragments are rare. Individual sandstone layers contain sedimentary rock fragments, mainly carbonate grains (Fig. 5G-H), and subordinately reworked mudstone-siltstone grains are present. Sandstone contains small amounts of matrix (Fig. 5B). Quartz cement is present in many sandstones and occurs as authigenic overgrowths on detrital quartz grains (Fig. 5C-D). Most sandstones are cemented by coarse blocky calcite (Fig. 5A, C; see details in Krainer and Lucas, 2010).

In central New Mexico, towards the south (Fra Cristobal Mountains, Caballo Mountains) grain size decreases and sandstone is fine-grained. The decrease in grain size causes changes in composition: the amount of monocrystalline quartz is higher, whereas polycrystalline quartz and detrital feldspars are less abundant, and granitic and metamorphic rock fragments are almost absent (Lucas et al. 2012a). Due to the composition, sandstone is subarkose.

Clearly, the main source rock of the Abo Formation sandstones was granitic in composition; subordinately metamorphic rocks were reworked. Sedimentary rock fragments in the Abo Formation are mainly derived from intrabasinal reworking of pedogenic carbonate horizons (caliche).

Distribution

Our description of the Abo Formation relies primarily on seven outcrop areas in central New Mexico (Fig. 1). Clearly, the Abo Formation was deposited across all of central New Mexico, because it is always present on outcrop or in the subsurface unless it was removed by post-Early Permian erosion. Here, we briefly describe the key Abo outcrop areas in central New Mexico.

Jemez Mountains

The Abo Formation crops out extensively in the southern Jemez Mountains, particularly along the canyons formed by the Jemez River and its tributaries (Wood and Northrop, 1946; Osburn et al., 2002; Kelley

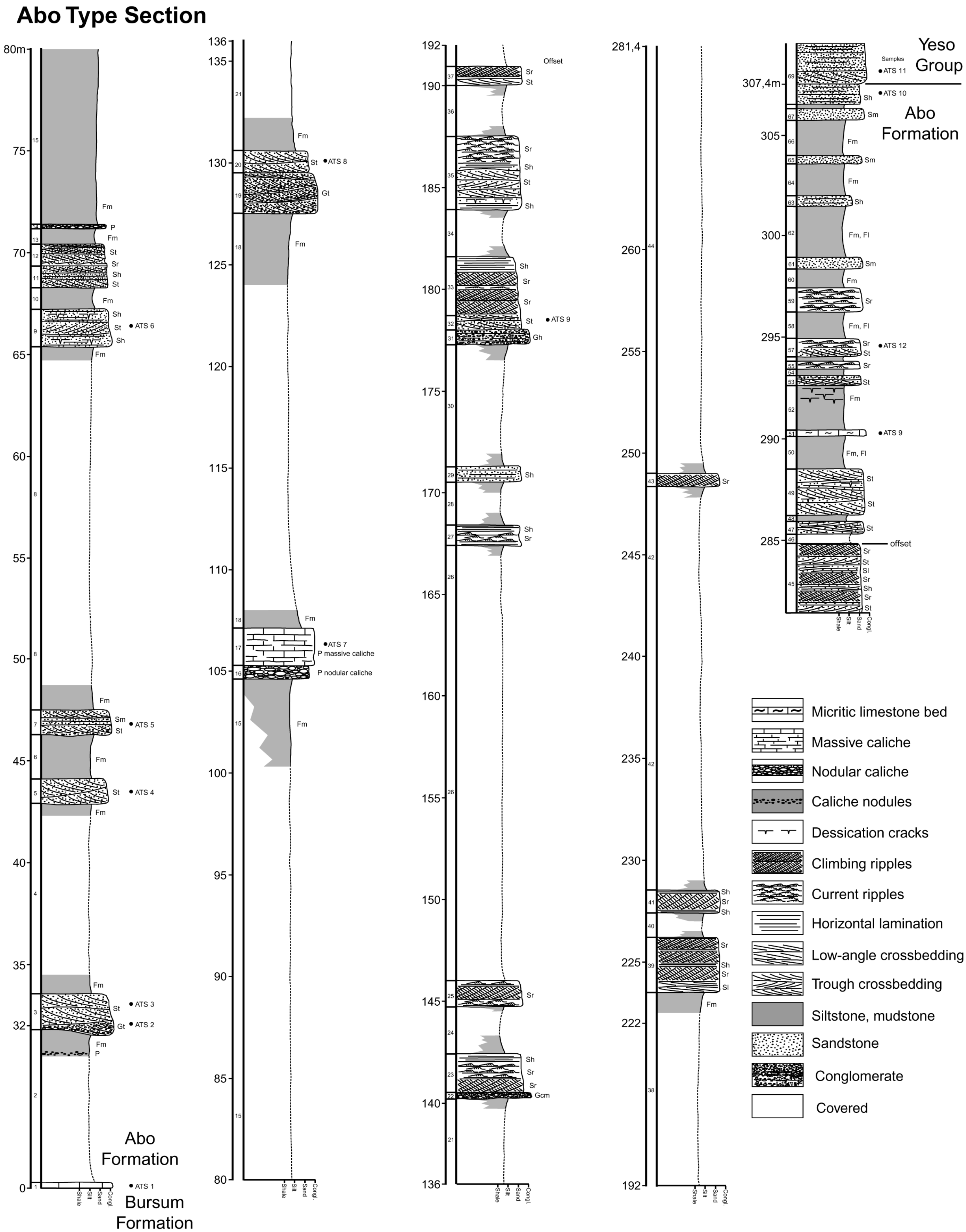


FIGURE 4. Type section of the Abo Formation at Abo Pass (from Lucas et al., 2005a).

TABLE 1. Thickness (in meters) of Abo Formation and members of Abo Formation at selected outcrop belts in central New Mexico.

Outcrop area	Scholle Member	Cañon de Espinoso Member	Total Abo thickness
Jemez Mountains	90-115	60-75	150-190
Sandia Mountains	40-50	60-70	100-120
Abo Pass	140	170	310
Lucero uplift	77	73	150
Cerros de Amado	42	58	100
Oscura Mountains	77	79	156
Fra Cristobal Mountains	40	254	294
Caballo Mountains	53-75	203-256	278-309

et al., 2003). Here, it is as much as 190 m thick and readily divided into the Scholle and Cañon de Espinoso members. The Abo Formation in this area also yields extensive assemblages of vertebrate fossils and a diverse paleoflora from one locality (Lucas et al., 2012b).

Sandia Mountains

An ~ 120-m thick section of the Abo Formation crops out on the northern end of the Sandia uplift, near Placitas (Kelley and Northrop, 1975; Lucas et al., 1999). In the Scholle Member here, a thin lens of carbonaceous shale yields conchostracans and a paleoflora (Knaus and Lucas, 2005; Martens and Lucas, 2005), and other beds yield a sparse assemblage of bones and pelycosaur footprints (Lucas et al., 1999).

Abo Pass

The type section of the Abo Formation and its two named members is located in Abo Pass, along the boundary of Valencia and Torrance Counties at the southern end of the Manzano Mountains. Here an ~ 190 m thick section of Abo Formation is exposed (Lee, 1909; Hatchell et al., 1982; Lucas et al., 2005a; Oviatt, 2010, 2011) (Fig. 4). Extensive fossil footprint assemblages, typically walchian-dominated plant assemblages and less prolific bone assemblages are present in the Abo here (Berman, 1993).

Lucero uplift

In the vicinity of Carrizo Mesa in the Lucero uplift of Valencia County, an ~ 150-m thick section of the Abo Formation crops out (Kelley and Wood, 1946; Lucas and Zeigler, 2004). These strata yield important footprint assemblages (Lucas et al., 2004).

Cerros de Amado-Joyita Hills

East of Socorro, a relatively thin section of Abo Formation (~ 100 m thick) crops out on numerous fault blocks in the complex structural zone extending from the Joyita Hills through the Cerros de Amado. Both members of the Abo are readily recognized here and yield important fossil assemblages of traces, plants and vertebrates (e.g., Hunt, 1983; DiMichele et al., 2007; Lucas et al., 2009; Spielmann et al., 2009)

Northern Oscura Mountains

Near Bingham in Socorro County, an extensive outcrop belt of Abo Formation is present between the Pennsylvanian strata on the northern dipslope of the Oscura Mountains and the Yeso Group strata that form the flanks of Chupadera Mesa to the north (Wilpolt et al., 1946). Here, the Abo Formation is about 150 m thick and readily divided into the Scholle and Cañon de Espinoso members. Strata of the Cañon de Espinoso Member yield important fossil assemblages of footprints and plants (DiMichele et al., 2007; Lucas and Spielmann, 2009).

Fra Cristobal and Caballo Mountains

Strata of the Abo Formation exposed in the Fra Cristobal and Caballo Mountains of Sierra County can be assigned to the Scholle and overlying Cañon de Espinoso members. At about 300 m thick, these are the thickest Abo sections in central New Mexico and yield important assemblages of trace fossils, fossil plants and tetrapod bones (Lucas et al., 2012a). To the south of the Caballo Mountains, the Abo Formation disappears into the marine strata of the Lower Permian Hueco Group (Fig. 3). The shoreline of the Hueco seaway was for a time as far north as the Caballo Mountains, as evidenced by marine and estuarine facies in the lower part of the Abo Formation in the Derry and McLeod Hills (Lucas et al., 2012a).

PALEONTOLOGY AND AGE

Introduction

Trace fossils, fossil plants, invertebrate body fossils (mostly bivalves and conchostracans) and vertebrate bones and teeth have been recovered from the Abo Formation in central New Mexico. Here, we briefly review these fossil records.

Trace Fossils

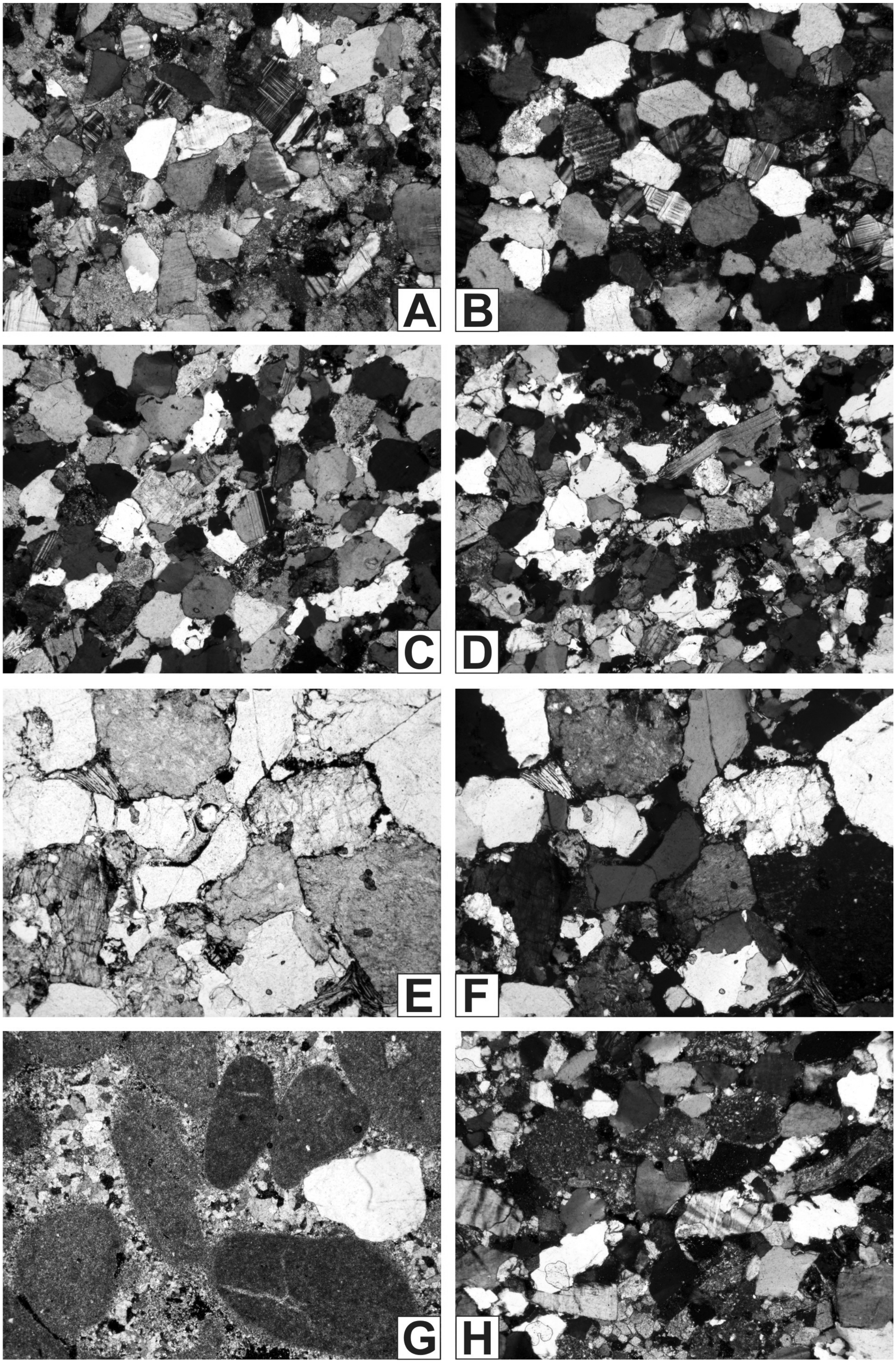
Traces are among the most common fossil remains in the red beds of the Abo Formation in central New Mexico. The collection of the New Mexico Museum of Natural History (NMMNH) houses about one thousand catalogued specimens of ichnofossils from more than 80 localities in the Abo Formation of the Sandia Mountains (15 specimens/6 localities), Abo Pass (105/8), Lucero uplift (44/10), Socorro area (Cerros de Amado and Joyita Hills, 267/20), northern Oscura Mountains (74/15), Fra Cristobal Mountains (99/3), and Caballo Mountains (366/22). Although Early Permian trace fossils from this part of the state have long been known (Degenhardt, 1840; Branson and Branson, 1946), significant work on them was not done before the 1990s (Lucas and Heckert, 1995). Since then, trace fossils from the Abo Formation of central New Mexico claim an almost continuously growing interest with regard to studies in ichnotaxonomy, biostratigraphy and paleoenvironmental analysis (e. g., Hunt and Lucas, 1998; Lucas et al., 1999, 2001, 2004, 2005a, b, 2009, 2012a; Lucas and Lerner, 2004; Hunt et al., 2005a-d; Minter et al., 2008; Lucas and Spielmann, 2009).

The Abo Formation in central New Mexico contains an ichnoassemblage of rhizoliths, invertebrate traces, and tetrapod tracks and coprolites (Fig. 6). Traces occur on clayey mud-drapes within reddish-brown, horizontally laminated, flaser-bedded or small-scale trough cross-bedded siltstone to very fine-grained sandstone. They are commonly accompanied by inorganic sedimentary surface structures such as tool marks, raindrop impressions, mud-cracks, and wrinkle marks. Root traces (Fig. 6A) are the most abundant biogenic structures and are preserved on approximately one third of the collected specimens. The record of fossil root traces is dominated by reddish-brown, mud-filled cylindrical tubes that measure less than 2 mm in cross section and run parallel to the bedding plane or dissect it at angles up to 90 degrees. Horizontal root traces may exhibit orthogonal dichotomous branching. Unfortunately, to date there is no reliable organ relationship between root traces and macrophytic remains from Abo red beds.

The Abo Formation in central New Mexico yields a diverse assemblage of moderately common invertebrate traces. Characteristic ichnotaxa include *Augerinoichnus helicoidales* (Fig. 6B), *Lithographus hieroglyphicus* (Fig. 6C), *Sphaerapus larvalis* (Fig. 6D), *Stiaria intermedia* (Fig. 6E), and *Tonganoxichnus robledoensis* (Fig. 6F), which are interpreted as locomotion and feeding traces of vermiform animals as well as pterygote and apterygote insects (Minter et al., 2008; Minter and Braddy,

TABLE 2. Lithofacies types of the Abo Formation (modified from Krainer and Lucas, 2010).

Facies code	Facies	Sedimentary structures	Interpretation
Gcm	clast-supported, poorly sorted conglomerate,sandy matrix, abundant reworked limestone clasts, subord. extraformational clasts and mudstone clasts	crude statificaton, erosional base, commonly grades into St	lag deposits
Gt	poorly sorted conglomerate, sandy matrix, abundant reworked limestone clasts, also extraformational clasts	trough crossbedding	channel fill
Se	pebbly sandstone, abundant rip-up clasts, rare	crude stratification, erosional base	scour fill
St-l	coarse, pebbly sandstone	large-scale trough crossbedding (> 1 m)	lateral accretion
St-m	coarse to fine-grained sandstone	medium-scale trough crossbedding (> 50 cm)	lower flow regime, 3d-dunes
St-s	medium to fine-grained sandstone	small-scale trough crossbedding (< 50 cm)	lower flow regime, 3d-dunes
Sp	medium to fine-grained sandstone	planar crossbedding	bars, sand waves
Sl	coarse to medium-grained sandst.	low-angle crossbedding	upper flow regime
Sh	mostly fine- to medium-grained sandstone	horizontal lamination	?upper flow regime
Sm	coarse- to fine-grained sandstone	massive, no bedding	sediment gravity flow deposit
Sr	fine-grained sandstone	asymmetric ripples, ripple cross-lamination (< 5 cm)	lower flow regime, current ripples
Sb	medium- to fine-grained sandst.	bioturbation structures	bioturbated
Pc	micritic limestone	nodular	paleocaliche
Fsm	mudstone - siltstone	massive	suspension deposit
Fl	mudstone - siltstone	laminated	overbank, waning flood deposit
Fm	mudstone - siltstone	massive, desiccation cracks	overbank deposit
Fr	mudstone - siltstone	massive, root structures	root horizon


A
B
C
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H

2009; Lucas et al., 2013b). Other recorded invertebrate traces from the Abo red beds of the study area are *Arborichnus*, *Cochlichnus*, *Diplichnites*, *Diplopodichnus*, *Kouphichnium*, *Monomorphichnus*, *Palaeophycus*, *Protovirgularia*, *Scoyenia*, *Skolithos*, *Stiallia* and *Striatichnium* (Lucas and Lerner, 2004; Minter and Braddy, 2009; Lucas et al., 2012a; SV pers. obs.). Mack et al. (1995) identified invertebrate burrows from Abo red beds of the Caballo Mountains as *Arenicolites* that, however, belong to *Scoyenia* and *Skolithos* (Lucas et al., 2012a). The diverse arthropod trace fossil assemblage described by Minter and Lucas (2009) from the Abo Formation in the Joyita Hills actually comes from strata of the Arroyo de Alamillo Formation of the Yeso Group based on our recent reevaluation of its stratigraphic position (Lucas et al., 2013a).

Tetrapod tracks from the Abo Formation of central New Mexico are relatively diverse and remarkably abundant (Hunt et al., 1995, 2005a, d; Lucas et al., 1995, 1999, 2001, 2004, 2005a, b, 2009, 2012a; Lucas and Spielmann, 2009). According to a comprehensive revision (SV, unpublished) they can be assigned to *Batrachichnus salamandroides* (Fig. 6G), *Limnopus vagus*, *Amphisauropus kablikae* (Fig. 6H), *Ichniotherium cottae*, *Dimetropus leisnerianus*, *Tambachichnium schmidti*, *Varanopus* sp., *Hyloidichnus bifurcatus* (Fig. 6I), *Erpetopus willistoni*, and *Dromopus lacertoides* (Fig. 6J). More than 80% of all finds belong to *B. salamandroides* and *D. lacertoides*, which most likely represent tracks of small temnospondyls and araeoscelid diapsids (Lucas et al., 2005a, b; Haubold and Lucas, 2003; Voigt, 2005). *Limnopus*, *Amphisauropus*, *Ichniotherium*, *Dimetropus*, *Tambachichnium*, *Varanopus*, *Hyloidichnus*, and *Erpetopus* are supposed tracks of large temnospondyls (Haubold, 1996), seymouriamorphs (Haubold, 2000; Lucas et al., 2001; Voigt, 2005), diadectomorphs (Voigt et al., 2007), "pelycosaurian-grade" synapsids (Haubold, 2000; Voigt, 2005), and captorhinomorphs (Haubold, 2000; Voigt et al., 2009) and are relatively rare. Vertebrate coprolites are well documented from one Abo Formation locality in Socorro County (Cantrell et al., 2012).

Though the trace fossils of the Abo Formation in central New Mexico exclusively represent assemblages of the *Scoyenia* ichnofacies, their lateral and vertical distribution is not necessarily uniform. Invertebrate traces are most common and diverse in the south and near the base and top of the formation (Lucas et al., 2004, 2005a, b, 2012a, 2013b). Seymouriamorph and diadectomorph footprints (*Amphisauropus*, *Ichniotherium*) are most common or even restricted to the northern and central part of the study area (Hunt and Lucas, 1998; Lucas et al., 2001, 2009; Hunt et al., 2005b, d; Voigt and Lucas, 2012). These observations may reflect paleogeography and paleoenvironment as invertebrate traces are apparently most diverse and abundant in coastal plains and tidal flats (Minter and Braddy, 2009; Lucas et al., 2012a; Voigt et al., 2013) and, diadectomorph tracks especially appear to indicate inland paleoecosystems (Hunt and Lucas, 1998; Hunt et al., 2005b; Voigt and Lucas, 2012).

The ichnofauna of the Abo Formation in central New Mexico is of Early Permian age based mainly on some of the tetrapod ichnotaxa. *Amphisauropus* and *Ichniotherium* co-occur exclusively in Cisuralian deposits (Haubold, 2000; Voigt, 2005). This age is confirmed by the relative abundance of "pelycosaurian"'-grade tetrapod tracks (*Dimetropus*, *Tambachichnium*). A significant change in the tetrapod ichnofauna has recently been recorded for the uppermost part (0-6 m below the top) of the Abo Formation, where supposed captorhinomorph footprints (*Varanopus*, *Hyloidichnus*, *Erpetopus*) are dominant and even more common than the otherwise ubiquitous *Batrachichnus* and *Dromopus* (Lucas et al., 2013a; pers. obs. SV). The first appearance of the invertebrate ichnotaxon *Sphaerapus* in the upper third of the Abo Formation also may be stratigraphically significant; this appearance may reflect an evolutionary innovation in the ecology of beetle larvae (Lucas et al., 2013b).

Fossil Plants

Fossil plants (particularly conifer impressions) were observed at many Abo Formation outcrops in central New Mexico, particularly in red sandstones/siltstones (Figs. 7-8). The collections can be divided broadly into two groups, based on both facies and floristic content.

The most common of these facies consists of thinly bedded red sandstones/siltstones. Such deposits frequently contain both plant debris and trackways of vertebrates and invertebrates. In the Caballo Mountains, as elsewhere in the outcrop area of the red sandstone/siltstone facies of the Abo, these fossiliferous beds tend to be sheet sandstones tens to hundreds of meters in areal extent and of varying thickness, from a meter to several meters. They generally fine upward, with the fossiliferous intervals in the upper portions, where the plant remains typically occur on thin claystone drapes or interbeds between thin layers of siltstone or sandstone (Lucas et al., 2005b,c). At many sites in the red siltstone facies, plants occur often in association with vertebrate and invertebrate trackways (e.g., Lucas et al., 2005b, c). In such settings, the enclosed paleoflora appears to be parautochthonous to allochthonous.

The flora of the Abo Formation red beds has been collected for many years by field geologists, and large collections are extant in both the New Mexico Museum of Natural History and Science, and the National Museum of Natural History. However, few papers have been published characterizing the flora, primarily because it is preserved mainly as casts and molds, thus not particularly suitable for studies of plant anatomy and morphology, at least with traditionally applied techniques. Nonetheless, preservation is satisfactory for systematic analyses of the flora (Hunt, 1983; Lucas et al., 2009; DiMichele et al., 2013). Our study, of 172 sample sites, indicates that the flora has the following composition:

1. Conifers: present in 82% of the sites, the most common being *Walchia piniformis* (Figs. 7.1 and 7.2)
2. Supaioid peltasperms: present in 28% of the sites, consisting of two species, *Supaia thinnfeldioides* (25% of the sites) (Fig. 7.3) and *Supaia anomala* (6% of the sites).
3. Callipterid peltasperms: present in 12% of the sites, primarily represented by *Autunia conferta* (Fig. 7.1).

Rare elements include a *Glossopteris*-like plant from the Zuni Mountains in northern New Mexico, the possible cycadophyte *Taeniopteris*, *Dicranophyllum*, a coniferophyte (Figure 6.2), *Cordaites*, the foliage of often very large, conifer-like woody plants, and scattered occurrences of the tree fern *Pecopteris*, and the sphenopsids *Calamites*

FIGURE 5 (facing page). Abo Sandstone petrography. **A**, Arkosic sandstone composed of mono-and polycrystalline quartz, detrital feldspars and rare granitic rock fragments. The detrital grains are cemented by calcite. Sample JR 17, Jemez River, polarized light, width of photograph is 6.3 mm. **B**, Arkosic sandstone composed of detrital quartz grains, many detrital feldspars, rare granitic rock fragments and some matrix. Calcite cement is absent. Sample GI 23, Gilman, polarized light, width of photograph is 6.3 mm. **C**, Subarkose containing quartz grains, some detrital feldspars and rare granitic rock fragments. Grains are cemented by quartz which occurs as overgrowths on detrital grains and coarse calcite cement. Sample ATS 3, type section at Abo Pass, polarized light, width of photograph is 3.2 mm. **D**, Arkosic sandstone containing detrital quartz and feldspar grains, rare granitic rock fragments and mica. Grains are cemented by quartz in form of authigenic overgrowths. Sample ATS 4, type section at Abo Pass, polarized light, width of photograph is 3.2 mm. **E-F**, Coarse-grained arkosic sandstone containing abundant detrital potassium feldspars which due to slight alteration appear as brownish grains under plane light (**F**). The sandstone contains some matrix but lacks calcite cement. Sample ATS 5, type section at Abo Pass, **E** under polarized light, width of photographs is 3.2 mm. **G**, Coarse-grained sandstone (lithic arenite) containing well rounded sedimentary rock fragments (micritic carbonate grains) and rare detrital quartz, cemented by calcite. Sample GI 17, Gilman, polarized light, width of photograph is 6.3 mm. **H**, Sandstone composed of detrital quartz, feldspar, sedimentary rock fragments (fine-grained carbonate grains) and rare granitic rock fragments, cemented by calcite. Sample GI 15, Gilman, polarized light, width of photograph is 6.3 mm.

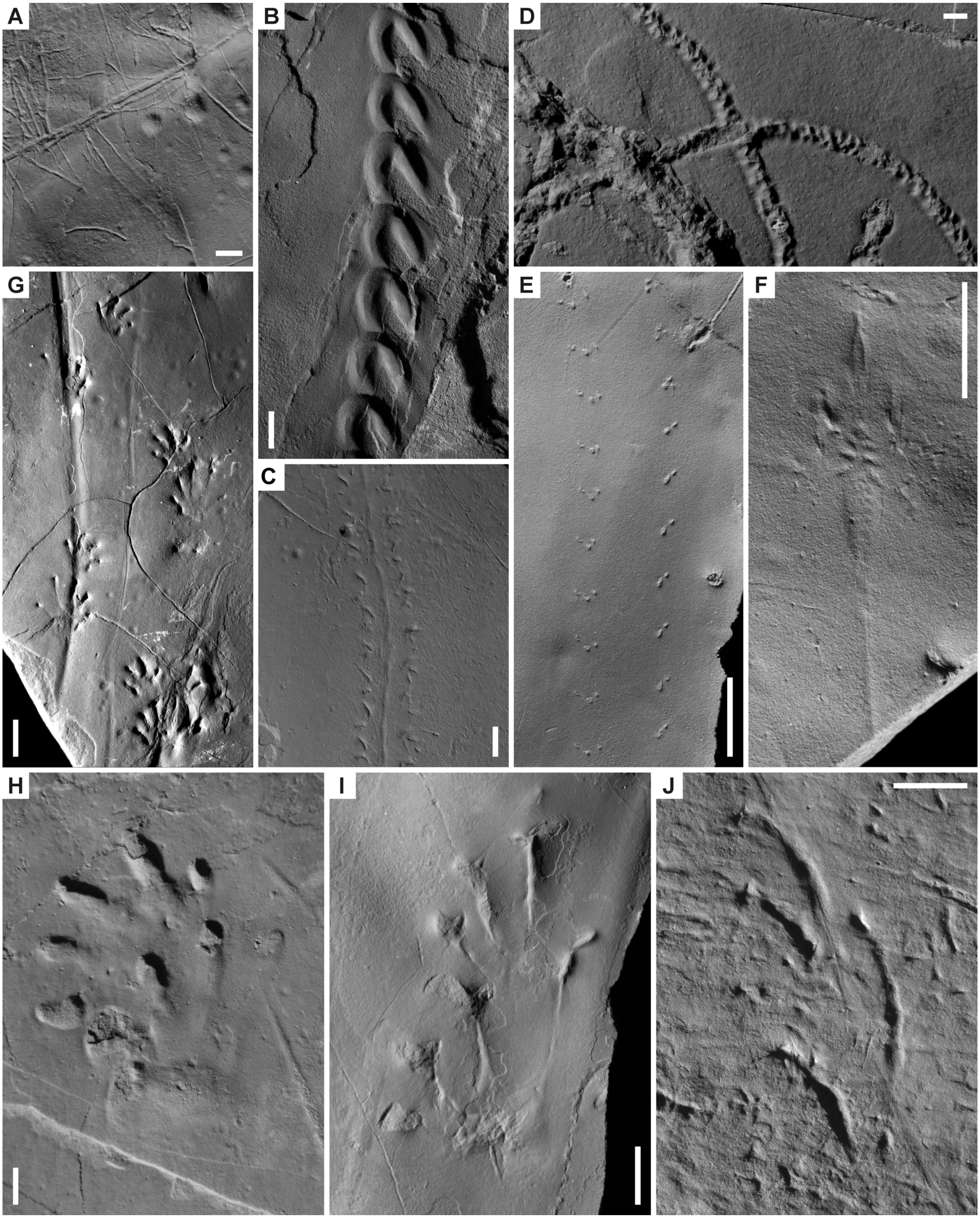

FIGURE 6. Selected trace fossils from the Abo Formation in central New Mexico. **A**, Root traces, NMMNH P-66088. **B**, *Augerinoichnus helicoidales*, NMMNH P-25990. **C**, *Lithographus hieroglyphicus*, NMMNH P-66598. **D**, *Sphaerapus larvalis*, NMMNH P-66550. **E**, *Stiaria intermedia*, NMMNH P-45778. **F**, *Tonganoxichnus robledoensis*, NMMNH P-65064. **G**, *Batrachichnus salamandroides*, NMMNH P-40901. **H**, *Amphisauropus kablikae*, NMMNH P-31338. **I**, *Hyloidichnus bifurcatus*, NMMNH P-65088. **J**, *Dromopus lacertoides*, NMMNH P-65114. Scale bars equal 10 mm.

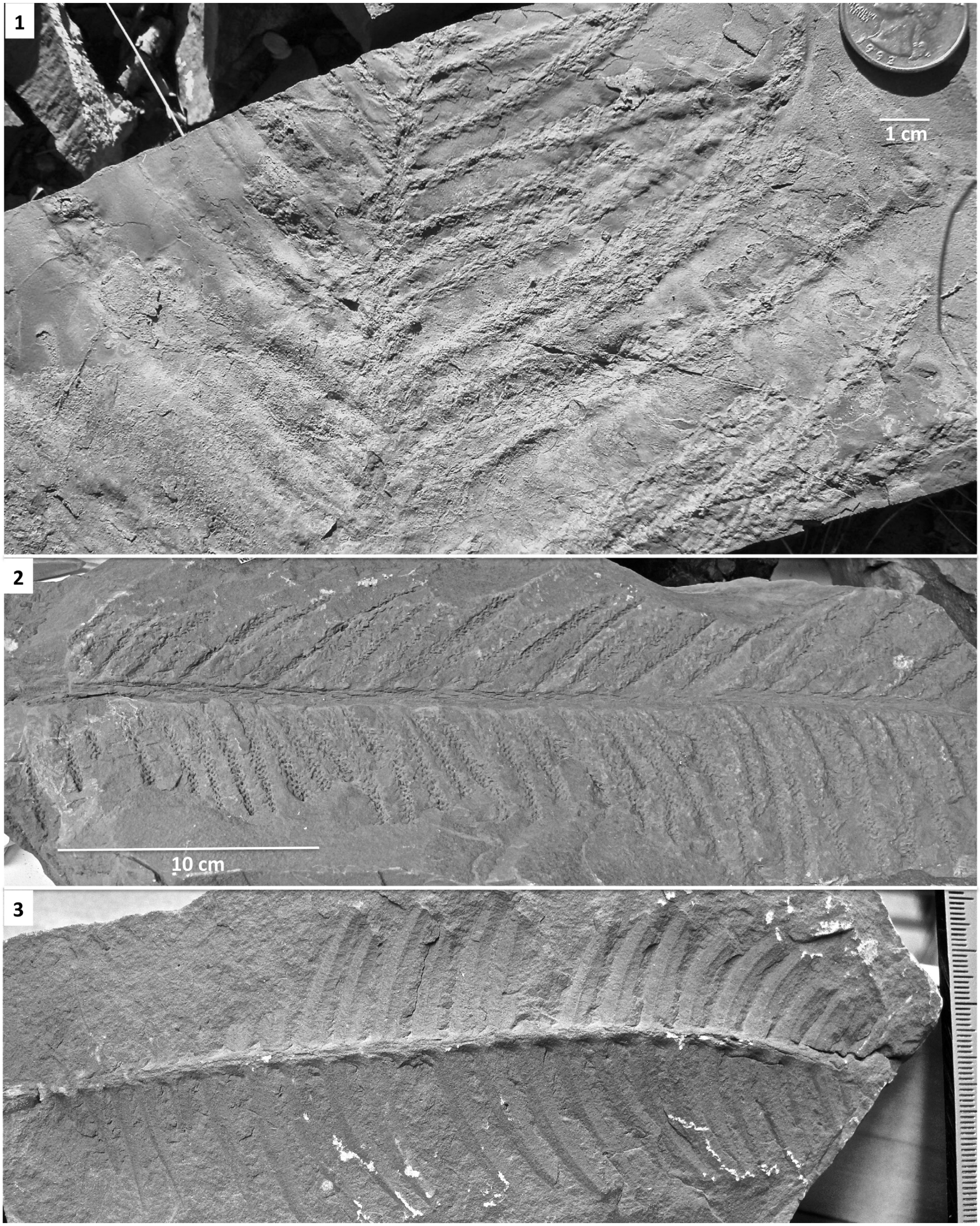

FIGURE 7. Principal Abo plants, preserved as molds or sediment casts of molds. Clearly the plant parts were quite stiff, perhaps dried out, at the time of deposition. **1**, *Walchia piniformis*, portion of a large lateral branch bearing the typically needle-like, upwardly curving leaves. Note that part of the branch is buried in a fine claystone. Field photograph, USNM Specimen 558250, USNM locality 43446. **2**, *Walchia piniformis*, nearly intact lateral branch mold. USNM Specimen 558251, USNM locality 43557. **3**, *Supaia thinnfeldioides*, one-half of a small forked frond showing the long, typically pointed, pinnules. USNM specimen 558252, USGS locality 8977. All scales in centimeters.

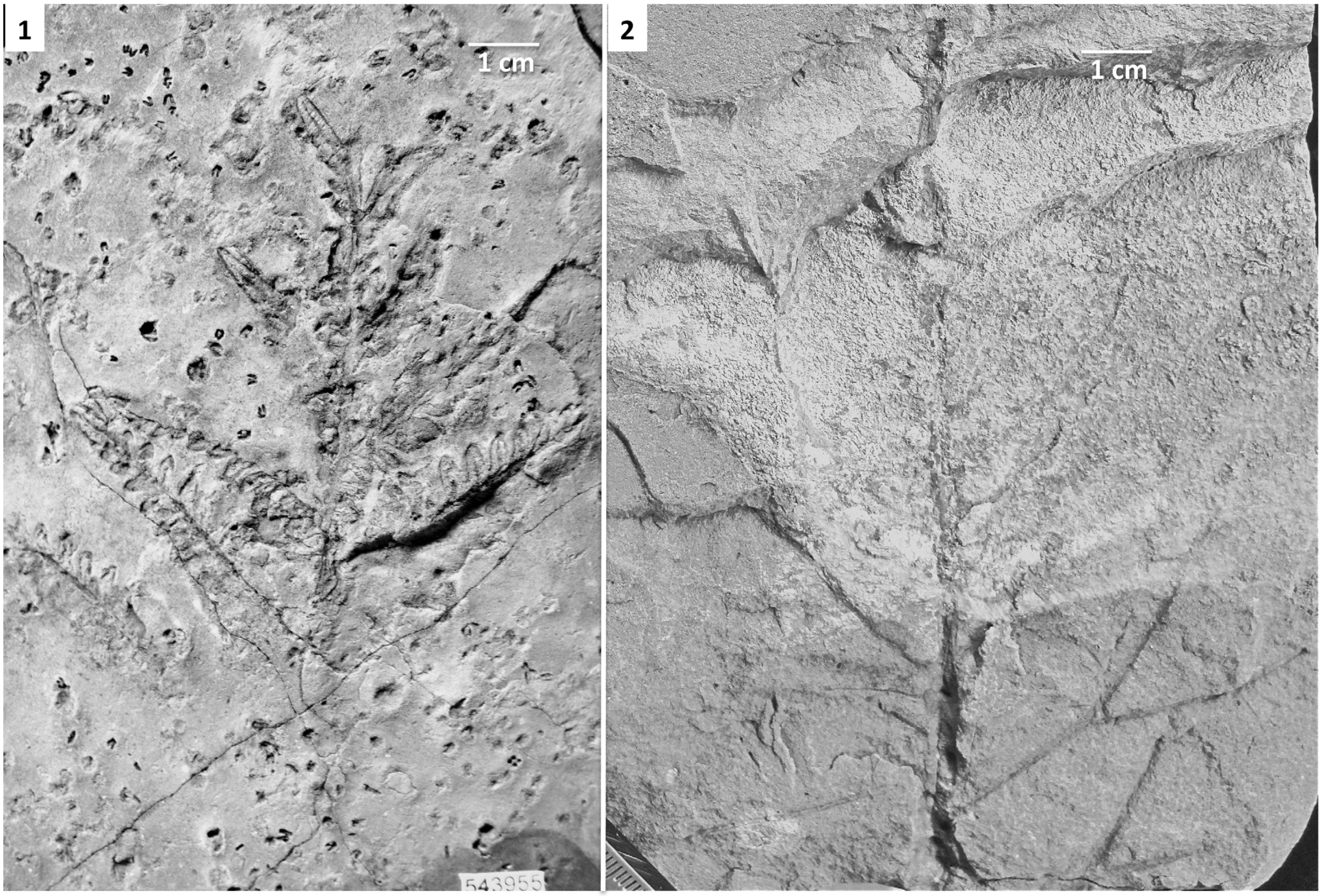

FIGURE 8. Minor Abo plants. Preserved as molds. **1**, *Autunia conferta*, a callipterid peltasperm. This species was, for many years, considered to be a diagnostic fossil for the Permian. USNM Specimen 543955, USNM locality 42251. **2**, *Dicranophyllum*, a coniferopsid. Note the forked leaves at the lower right of the photograph. USNM Specimen 558253, USNM locality 43614. Scales in centimeters.

and *Sphenophyllum*, the pteridosperm *Neuropteris*, and fern foliage *Sphenopteris*. With the exception of these last four taxa, which indicate substrates with high water tables for much of the year, the floral composition is typical of environments with seasonal moisture deficits. Furthermore, it is most common to find either conifers or supaioids as the dominant plant, and only rarely to find them in mixtures, though such mixtures do occur. DiMichele et al. (2012) suggest *Supaia thinnfeldioides* to be a colonizer of stream margins, in areas with high levels of flood disturbance.

Much less common, and found mainly in the lowermost portion of the Abo, are greenish gray to light gray shales/siltstones (the green/gray shale facies discussed above), most often with poorly-developed bedding, and fragmentary, often jumbled, variably dense plant material that appears allochthonous. Such deposits contain occasional evidence of rooting and may be mottled, as if overprinted by pedogenesis. On outcrop, most of these deposits are lenticular and appear to be channel fills. Some have conglomeratic layers at the base. The green shale/siltstones appear to be quite distinct depositionally from the red sandstones/siltstones, representing shallow channel bodies in coastal plain settings, with fresh to brackish salinities. The plants are intimately associated with invertebrates (see below), including pectinaceans and myalinids, other pelecypods and microchonchids, and also with fragmentary remains of fish.

The gray-bed paleoflora is superficially similar to that of the red beds in being dominated by conifers. Analysis of 30 sampling sites indicates that conifers occur at 73%, the most commonly occurring being, as in the red beds, *Walchia piniformis*. However, the flora at any given gray-bed site tends to be more diverse than those in the red beds, the gray-bed sites on-average yielding about 5 taxa per excavation. These accessory taxa include the cordaitalean foliage, *Cordaites* at 40% of the sampling sites, a diversity of callipterid peltasperms at 37%, calamitalean stems at 33% and a variety of medullosan pteridosperms at nearly 30% of the sites (including, among others, *Neuropteris*, *Neurodontopteris*, *Odontopteris*, and *Alethopteris*). Other notable elements, because they are so much more widely occurring than in the red beds, include the tree-fern foliage *Pecopteris* (20%), *Taeniopteris* spp. (13%), the wetland lycopsid *Sigillaria brardii* (13%), and the peculiar lyginopterid pteridosperm *Sphenopteridium manzanitanum* (10%), a dominant element in the late Missourian flora of the Kinney Brick Company Quarry (Lucas et al., 2011c).

In summary, Abo paleofloras suggest conifer-dominated landscapes, containing a number of different species and genera of conifers. However, the red and gray facies present quite different pictures of this landscape and may represent different species-pools, with overlap only among the most abundant of those species. Most of the subdominant plants in the red beds are indicators of seasonality with only small local areas of wetlands on the landscape. The Abo red beds flora almost completely lacks ground cover or understory elements, which are expected to be greatly under-represented in the fossil record (Scheihing, 1980), due to their low growth habit or shelter from winds. In contrast, the gray beds capture a large component of wetland species, suggesting wetland corridors, perhaps fringing the channels in which these floras are preserved, surrounded closely by much drier interfluves, probably under a seasonal climate. Such deposits also include some ground cover elements.

The differences in composition and diversity between the red and gray facies emphasize the peculiarity of the extremely low diversity in the much more widely occurring and often densely fossiliferous Abo Formation red-bed plant deposits. These compositional and diversity differences are not easily attributable to some kind of taphonomic filtering. Such an interpretation might suggest that the red beds preserve only the most decay resistant of plant remains. However, the gray floras also have such forms as cordaitalean foliage, one of the most transport and decay resistant elements in late Paleozoic, equatorial vegetation. Furthermore, rare bits of callipterids, tree ferns and calamitaleans indicate that these plants were somewhere present on the red-beds landscape, yet they all remain almost absent from red-beds deposits. In addition, the red beds often preserve plant remains in dense mats, including large, nearly intact branches and fronds, often found crosscutting bedding planes. The former tend to occur in the finest claystone facies, suggesting deposition from suspension, thus not a sedimentary setting that would have subjected more delicate kinds of foliage to differential destruction during transport. Finally, the dominant elements in the red beds, conifers and supaioid peltasperms, are structurally quite distinct and likely would have had very different transport properties, both from viewpoints of survival and likelihood of being carried by streams; the rare co-occurrence of these two forms, particularly as dominant elements, further suggests that taphonomic biases have not created the distinctive red-beds flora.

Invertebrate Paleontology

Invertebrate body fossils are present in the Abo Formation at only a few outcrops—notably in the northern Sandia Mountains and in the Caballo Mountains.

In the northern Sandia Mountains near Placitas, the Abo Formation includes an unusual lens of carbonaceous shale in the Scholle Member (Lucas et al., 1999). Martens and Lucas (2005) documented conchostracans from this shale.

In the southern Caballo Mountains, the calcareous shells of microconchid gastropods and at least three different kinds of bivalves are present in the greenish-gray shale and siltstone beds of the lower Abo Formation, which Lucas et al. (2012a) identified as an estuarine facies. Pectinacean bivalves, some of which can be assigned to Dunbarella, and myalinid bivalves, are particularly common. Pectinaceans are marine to brackish water bivalves, as are myalinids. Thus, their presence indicates marine or brackish waters in the estuarine facies.

Fossil Vertebrates

Fossil bones and teeth are common locally in the Abo Formation in outcrops in Socorro and Sandoval Counties and in the correlative strata of the Cutler Group in Rio Arriba County, New Mexico (e.g., Berman, 1993; Lucas et al., 2010, 2012b). Of the seven primary Abo Formation outcrop areas listed above under "Distribution," those designated as the Sandia, the northern Oscura Mountains and the Lucero uplift have not yielded identifiable skeletal remains of vertebrates. A survey of the vertebrate fossils from the other four outcrop areas was first reported by Berman (1993), who used, in part, different designations, with some having a far lesser aerial extent. Jemez Mountains, Abo Pass, Cerros de Amado-Joyita Hills, and Fra-Cristobal and Caballo mountains outcrop areas proposed here were referred to by Berman (1993) as the Jemez Springs, Los Pinos Mountains, Socorro, and Caballo Mountains (limited to Caballo Mountains) localities, respectively. It should be noted that in 1993 Berman also reported vertebrate fossils from several sites in the Lucero uplift area that he believed to be from the Abo Formation, but that are now considered to be from the underlying Upper Pennsylvanian (upper Virgilian) Red Tanks Member of the Bursum Formation (Harris et al., 2004). The Red Tanks terrestrial vertebrates, with the exception of the addition of the basal synapsids, a caseid and *Edaphosaurus*, and a bolosaurid reptile and the absence of the amphibians *Zatrachys*, *Platyhystrix*, and *Diplocaulus* and the basal synapsid *Ophiacodon* (Harris et al., 2004), otherwise duplicate the faunal list recorded here for the Abo Formation (see below).

In 1993, Berman presented taxonomic lists of vertebrates from each of the four vertebrate-bearing Abo Formation outcrop areas listed above. All have been revisited several times by joint or single collecting parties of the New Mexico Museum of Natural History and Science (NMMNHS) and the Carnegie Museum of Natural History (CM), which has resulted not only in extensive new collections, but also discovery of new fossiliferous sites. Collections are housed not only at both institutions, but also the University of New Mexico, Albuquerque.

The Abo Formation vertebrate taxa are reported at generic or higher levels (Table 3) for each of the four, vertebrate-producing, outcrop areas mentioned above. The fragmentary condition of the vast majority of the specimens prevents confident species assignation. The Abo Formation vertebrate assemblage is summarized from the following publications: Romer (1937); Romer and Price (1940); Langston (1952, 1953); Vaughn (1969); Olson and Vaughn (1970); Berman (1976, 1977, 1979, 1993); Berman and Reisz (1980, 1986); Harris et al. (2005); Madalena et al. (2007); Spielmann et al. (2009); Lucas et al. (2009a, b, 2012b); and Cantrell et al. (2011).

Although most of the taxa have been identified on the basis of fragments or single elements, many are represented by partial, articulated specimens, including skulls and postcrania, some of which have received detailed descriptions: (1) from the Jemez Mountains area a new species of *Sphenacodon*, *S. ferocior* Romer, 1937, based on a skull and anterior vertebrae (Romer, 1937; Romer and Price, 1940; Spielmann et al., 2010); a partial vertebral column of an embolomere, possibly *Archeria*; a new species of *Dimetrodon*, *D. occidentalis* Berman, 1977, based on elements of the mandible and a partially articulated string of mid-dorsal vertebrae (Berman, 1977) (Fig. 9A); a new species of *Trimerorhachis*, *T. sandovalensis* Berman and Reisz, 1980, based on a nearly complete skull and a large, articulated portion of the postcranium (Berman and Reisz, 1980) (Fig. 9B); and a partial skull of *Sphenacodon ferox* (Lucas et al., 2012b); (2) from the Abo Pass area a new species of the lungfish *Gnathorhiza*, *G. bothrotreta*, Berman, 1976, based on complete skulls of individuals preserved in aestivation burrows (Berman, 1976, 1979) (Fig. 9D-E); (3) from a specific, highly fossiliferous site within the Cerros de Amado-Joyita Hills area, designated as the Gallina Well locality (Berman, 1993), closely associated, disarticulated elements of the skull and postcranium of an indeterminate captorhinomorph reptile (Berman and Reisz, 1986) and a partial skull of *Diplocaulus* (Harris et al., 2005) (Fig. 9C), and from the same outcrop area dorsal vertebrae and neural spine fragments of a specimen of *Dimetrodon* (Lucas et al., 2009).

Clearly, the above distributions suggest that most of the vertebrates, particularly the highly terrestrial tetrapods (*Platyhystrix*, *Trimerorhachis*, *Diadectes*, and basal synapsids), were widely distributed throughout the Abo Formation, whereas others (xenacanth, paleoniscoid, *Gnathorhiza*, *Eryops*, *Zatrachys*, embolomere, and lepospondyls) were undoubtedly restricted to localized freshwater pond/lake or stream environments. Among the identified taxa, only *Gnathorhiza* and perhaps also *Trimerorhachis* and *Diplocaulus* provide an important insight into climatic conditions during the deposition of the Abo Formation. Most notable in this respect are the *Gnathorhiza bothrotreta* specimens from the Abo Pass outcrop area that are preserved in aestivation burrow casts within a freshwater limestone believed to be a small pond or lake deposit. Outside of the Lower Permian of Texas and Oklahoma, this represents the only known occurrence of aestivation burrows containing *Gnathorhiza* still preserved in place. A single, eroded-free burrow containing skeletal remains of *Gnathorhiza* was reported from the Lower Permian El Cobre Canyon Formation of El Cobre Canyon, New Mexico (Berman, 1993) and the Eskridge Shale of Nebraska (Huttenlocker et al., 2005). Preservation of *Gnathorhiza* in an aestivating life phase clearly indicates a prevailing climate punctuated by periods of severe seasonal drought. Interestingly, in the same deposit are small skulls of *Trimerorhachis* and articulated strings of vertebrae associated with partial or disarticulated skulls of *Diplocaulus*. Olson (1958, 1977) sus-

TABLE 3. Fossil vertebrate taxa from the Abo Formation in central New Mexico.

	Jemez Mountains	Abo Pass	Cerros de Amado-Joyita Hills	Fra Cristobal and Caballo Mountains
Elasmobranch fish				
Xenacanth				
Probably *Orthocanthus*	X			X
Paleoniscoid fish			X	
Dipnoan (Lungfish)				
Gnathorhiza	X	X		
Amphibians				
Temnospondyls				
Eryops	X		X	
Zatrachys	X		X	
Platyhystrix	X	X	X	
A dissorophid		X		
Trimerorhachis	X	X	X	X
Embolomere, ?*Archeria*	X			
Lepospondyl				
Diplocaulus	X	X	X	X
Diadectomorph				
Diadectes	X		X	
Reptiles				
Captorhinomorph				
Captorhinid			X	
Basal Synapsids				
Ophiacodon	X	X	X	
Sphenacodon	X		X	
Sphenacodontid indet.	X			
Dimetrodon	X		X	X

pected that both forms may have been capable of aestivation, at least during early stages of life; he contended that they were clearly capable of surviving severe drying conditions, even as adults.

Using terrestrial vertebrates as index fossils, Lucas (2005, 2006) has divided the latest Pennsylvanian (Virgilian) and Permian into 10 time intervals referred to as land-vertebrate faunachrons, abbreviated LVF. Unfortunately, vertebrates from the Abo Formation do not provide a precise basis for biochronological correlations other than a Coyotean LVF of Virgilian-Wolfcampian age. Abo vertebrates consistently occur in the lower portion of the formation (Scholle Member).

AGE OF THE ABO FORMATION

The age of the Abo Formation has long and correctly been perceived to be Early Permian. As stated above, the Bursum Formation, which is the geologically youngest unit beneath the Abo is of late Virgilian-early Wolfcampian (Newwellian = "Bursumian") age (Lucas and Krainer, 2004). These are Late Pennsylvanian strata using the conodont-defined base of the Permian, which places the Pennsylvanian-Permian boundary within the Wolfcampian, close to the early-middle Wolfcampian boundary (e.g., Lucas et al., 2002). Correlation of the base of the Abo Formation to the Powwow Conglomerate of the Hueco Group in West Texas also suggests that the age of the base of the Abo Formation is close to the early-middle Wolfcampian boundary (Lucas et al., 2011a, b). Therefore, assigning a middle Wolfcampian (Nealian) age to the base of the Abo Formation can be supported by regional stratigraphic relationships. And, as noted above, some of the tetrapod footprint ichnotaxa known from the Abo Formation are restricted to Lower Permian strata elsewhere.

The upper age limit of the Abo Formation is less certainly known. Traditionally, geologists working in New Mexico have equated the Abo-Yeso contact with the Wolfcampian-Leonardian boundary. Red-bed facies of the Abo Formation that intertongue with the upper part of the Hueco Group in southern New Mexico are interbedded with marine rocks of late Wolfcampian age (e.g., Lucas et al., 2011b). On face value this could indicate that the Abo is no younger than late Wolfcampian, but it is not clear that the red-bed intertongues in the Hueco Group represent the uppermost Abo Formation. This leaves open the possibility that the uppermost Abo is of early Leonardian age.

Unfortunately, fossils from the Abo Formation in central New Mexico contribute little to further resolving its precise age. Most of the ichnofossils, plant fossils and invertebrate body fossils are characteristic Late Pennsylvanian-Early Permian taxa that provide no precise age determinations within that time interval. The tetrapod body fossils are characteristic of the Coyotean land-vertebrate faunachron, which spans part of the Virgilian through much of the Wolfcampian (Lucas, 2006). Thus, regional correlation of the Abo Formation as of middle-late Wolfcampian age is not contradicted by the available fossil evidence. Also, within current temporal resolution, equating the Abo-Yeso contact to the Wolfcampian-Leonardian boundary is a good approximation.

DEPOSITIONAL ENVIRONMENTS

The overall, regional deposition of the Abo Formation is well understood as having taken place on a low-gradient alluvial plain in which rivers flowed primarily to the south toward the shoreline of the Hueco seaway in southern New Mexico (Kues and Giles, 2004). Thus, Seager and Mack (2003, p. 29) well stated that "the Abo fluvial system was characterized by widely dispersed silt-bed or very fine sand-bed rivers, broad, well-oxidized floodplains, and evidence in both the channel and floodplain strata for marked seasonality of paleoclimate" and that deposition was "strongly influenced by the overall dry and megamonsoonal climate postulated for Pangea in Early Permian time." The Abo Formation thus well represents the concept of "wet red beds" deposited during the late Paleozoic across much of tropical Pangea (e.g., Schneider et al., 2010).

Abo mudstones with calcrete paleosols represent extensive muddy floodplains subjected to seasonal aridity. Lenticular intraformational conglomerate beds and crossbedded sandstone bodies are channel deposits

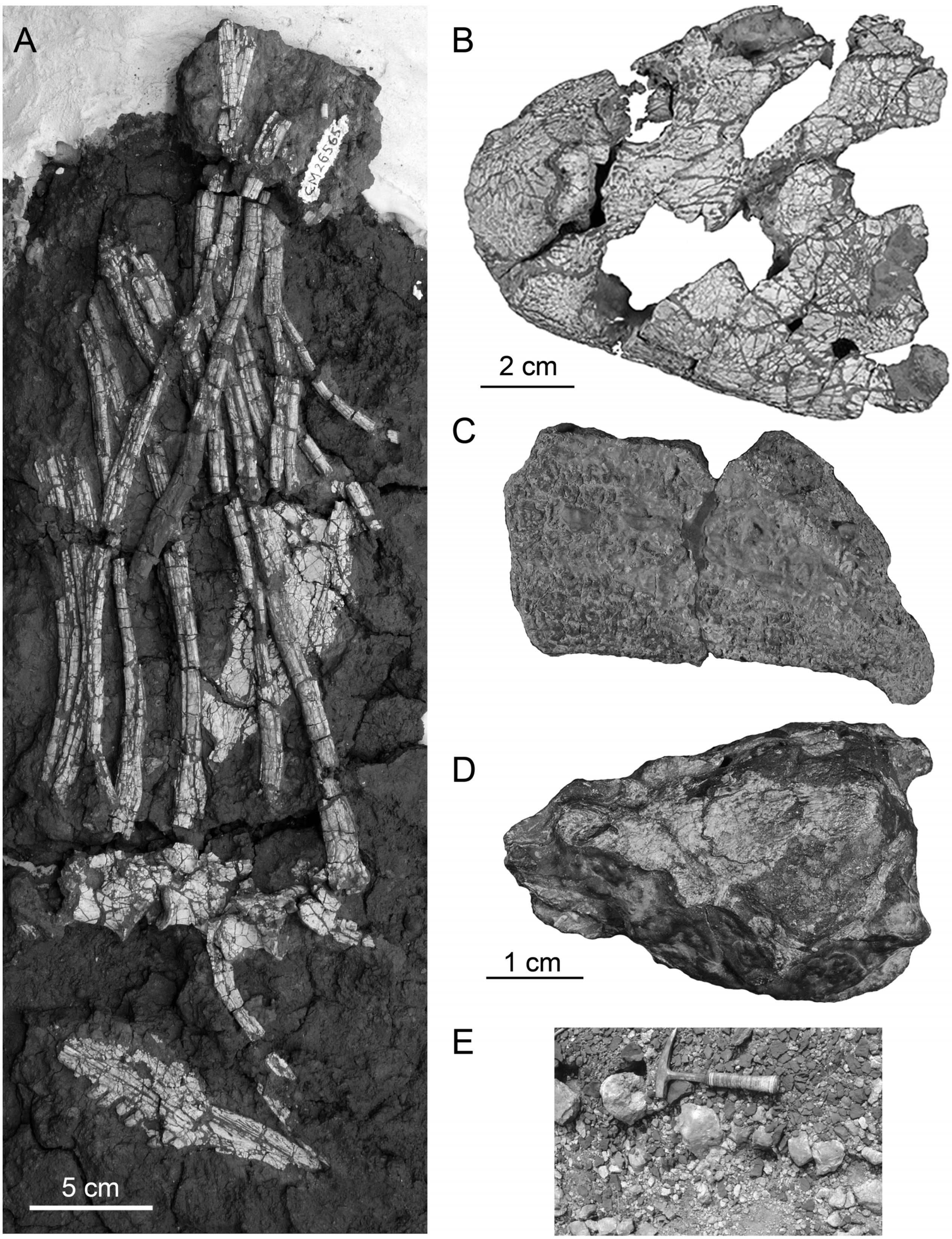

FIGURE 9. Selected vertebrate fossils from the Abo Formation, New Mexico. **A**, *Dimetrodon occidentalis*, holotype, CM 26565, large portion of dorsal sail elements and left mandible (angular, anterior coronoid and dentary) from the Jemez Mountains. **B**, *Trimerorhachis sandovalensis*, holotype, CM 38025, greater portion of skull in dorsal view from the Jemez Mountains. **C**, Right posterior portion of *Diplocaulus* skull, CM 38011, in dorsal view from the Gallina Well locality of the Cerros de Amado-Joyita Hills area. **D-E**, *Gnathorhiza bothrotreta*, referred specimen CM 30741, skull in dorsal view (anterior to left), and in place aestivation burrows casts containing in some *G. bothrotreta* preserved in a freshwater lake/pond deposit limestone in the Abo Pass area, respectively.

that accumulated during times of relatively rapid base-level fall. These are strata of the Scholle Member. Sheet sandstones characteristic of the Cañon de Espinoso Member indicate times of base level stability or relatively slow fall when Abo channels avulsed and spread across the floodplain to form thin, laterally extensive tabular sandstone bodies (Blakey and Gubitosa, 1984).

Some facies change is observed within the Abo Formation along a south-to-north transect in central New Mexico. Thus, conglomerate is very rare in Abo sections to the south, in Sierra County, comprising less than 1% of the total section, and consist entirely of reworked carbonate clasts (pedogenic carbonates). In addition, although the amount of sandstone is similar between Sierra County and the Abo type section in Torrance County, the average grain size is strikingly smaller in Sierra County outcrops (mostly < 0.2 mm) than in the Abo type section (average grain sizes > 0.5 mm). The small grain size is responsible for the different petrographic composition, particularly for the smaller amount of detrital feldspars, polycrystalline quartz grains and almost total absence of granitic and metamorphic rock fragments.

Bivalves from the greenish shale intervals in the Abo red beds in the Caballo Mountains indicate a brackish to marine environment. Lucas et al. (2012a) interpreted these shales as estuarine deposits based on their stratigraphic architecture and the association of terrestrial plants with marine bivalves. Intercalated conglomerates probably represent tidal-fluvial channel fills, and the fine-grained sandstone intercalations are distributary mouth bar deposits. These brackish to marine intercalations indicate that the Hueco transgression during the Wolfcampian reached as far north as the southern Caballo Mountains.

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At the top of the Abo type section, north of Abo Pass, brown sandstone at the base of the Lower Permian Yeso Group (base of the Arroyo de Alamillo Formation) at the top of the roadcut overlie repetitively-bedded sandstones, siltstones and mudstones of the upper member (Cañon de Espinoso Member) of the Lower Permian Abo Formation. Thin, laterally extensive sandstone beds of the Abo mostly represent unchannelized flow (sheetfloods), and Abo mudrocks contain numerous calcrete nodules and rhizoliths indicative of paleosol formation.