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Spencer G. Lucas, Karl Krainer, Sebastian Voigt, David S. Berman, and Amy Henrici

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THE LOWER PERMIAN ABO FORMATION IN THE NORTHERN SACRAMENTO MOUNTAINS, SOUTHERN NEW MEXICO

SPENCER G. LUCAS[1], KARL KRAINER[2], SEBASTIAN VOIGT[3], DAVID S. BERMAN[4], AND AMY HENRICI[4]
[1] New Mexico Museum of Natural History, Albuquerque, NM, spencer.lucas@state.nm.us
[2] Institute of Geology and Paleontology, University of Innsbruck, Innsbruck, Austria
[3] Urweltmuseum GEOSKOP/Burg Lichtenberg (Pfalz), Thallichtenberg, Germany
[4] Carnegie Museum of Natural History, Section of Vertebrate Paleontology, Pittsburgh, PA

ABSTRACT—We describe the lithostratigraphy, sedimentary petrography and vertebrate paleontology of the thickest known (~ 400 m thick) section of the Lower Permian Abo Formation, which is in the northern Sacramento Mountains of Otero County, New Mexico. This Abo section differs from other sections of the formation in its great thickness, lack of a clear subdivision into lower, mudstone-dominated and upper sandstone-dominated intervals (instead, it is a section of interbedded mudstone and sandstone/conglomerate without obvious subdivisions), and the presence of numerous beds of extrabasinal conglomerate, especially beds of basement-cobble conglomerate in the lower part. This lithologically distinct Abo lithosome is recognized by us as a new member of the Abo Formation, the Coyote Hills Member. The Coyote Hills Member is dominantly mudstone and siltstone representing floodplain deposits with intercalated conglomerate-sandstone sheets of a low sinuosity river system and thinner debris-flow conglomerates, small, thin channel-fill sandstones, and thin tabular sheetflood and splay sandstones. These strata were deposited in a more proximal facies compared to the Abo Formation in central and southern New Mexico, with higher amounts of basement-derived conglomerate and coarse-grained sandstone. Sediments were derived from a local source area in the Pedernal uplift composed mainly of granitic and granophyric rocks and deposited on an extensive alluvial plain that extended southward and southwestward toward the Hueco seaway. Fossils from the Coyote Hills Member are a few trace fossils and bones of fish, amphibians and pelycosaurs that are an assemblage of Coyotean (late Virgilian-late Wolfcampian) age. Regional correlation of the Abo Formation in the Sacramento Mountains suggests it is of middle-late Wolfcampian (and possibly early Leonardian) age.

INTRODUCTION

In the Sacramento Mountains of southern New Mexico, the Lower Permian Abo Formation is a southward thinning unit of siliciclastic red beds of nonmarine origin.

This thinning is rapid and dramatic, as a very thick and relatively coarse-grained Abo section in the northern Sacramento Mountains quickly thins and becomes much finer grained as it laterally grades into and interfingers southward with marine strata of the Lower Permian Hueco Group. Bachman and Hayes (1958), Otte (1959) and Pray (1961) documented these stratigraphic relationships and Speer (1983, 1986) represented the most recent, detailed studies of these strata. Here, we focus on Abo strata in the northern Sacramento Mountains (Fig. 1) to elucidate their stratigraphy, petrography, lithofacies and paleontology in order to interpret their sedimentology and age.

PREVIOUS STUDIES

Darton (1928) first recognized the presence of the Abo Formation in the northern Sacramento Mountains, but no detailed data on the unit were published until Otte (1959) presented an extensive study of the Upper Pennsylvanian and Lower Permian strata in that area. Otte (1959) thus documented the stratigraphy, lithology, thickness and sedimentation of the Abo Formation in the northern Sacramento Mountains. Working primarily to the south, Pray's (1961) observations on the Abo Formation overlapped and extended those of Otte (1959). These works (and that of Bachman and Hayes, 1958) demonstrated that a thick and relatively coarse-grained Abo section in the northern Sacramento Mountains (north of La Luz) thins rapidly southward, becomes much finer grained and interfingers to the south with marine strata of the Hueco Group (Fig. 2).

Vaughn (1969) reported vertebrate fossils from the Abo Formation in the northern Sacramento Mountains, primarily in the vicinities of Cottonwood and Laborcita canyons northeast of La Luz. He also noted a few specimens from localities in the underlying Bursum Formation ("Laborcita Formation" of his usage) to produce a combined Bursum-Abo faunal list of an elasmobranch, the acanthodian fish *Acanthodes* sp., palaeoniscoid fishes and a rhipidistian, an edopid similar to *Edops*, *Platyhystrix* cf. P. *rugosus*, a new dissorophid, and the pelycosaurs *Ophiacodon* sp., *Sphenacodon* cf. *S. ferox, Sphenacodon* sp. and *Edaphosaurus* cf. *E. novomexicanus*.

Speer (1983) undertook a study of the sedimentology of the Abo Formation in the northern Sacramento Mountains that is his unpublished masters thesis (Speer, 1986, published abstract). In 2012, we undertook studies of the Abo Formation from the Coyote Hills east of Tularosa down the Sacramento Mountains front to Culp Canyon south of Alamogordo. Previously, we had also studied the underlying Bursum (= Laborcita) Formation from northeast of Tularosa down the mountain front to the Jarilla Mountains near Orogrande (Lucas and Krainer, 2002, 2004)

LITHOSTRATIGRAPHY

Measured Section

We have measured detailed sections of the Abo Formation from the Coyote Hills northeast of Tularosa to Culp Canyon south of Alamogordo, along the entire transect shown in Figure 2. Here, we focus on the section in the Coyote Hills (Figs. 3, 4).

In the Coyote Hills, the Abo Formation is unusually thick and coarse-grained, including many conglomerate beds. We measured a complete section here of the Abo Formation that is approximately 400 m thick, which is the thickest outcrop section of the

Abo Formation known to us (maximum Abo thickness known elsewhere is 309 m: Lucas et al., 2013b). At this section, sandy mudstone of the Abo Formation rests directly on nodular limestone of the Bursum Formation, and gypsiferous siltstone forms the base of the Yeso Group above the Abo Formation (Figs. 3–4).

At the section of the Abo Formation we measured in the Coyote Hills (Figs. 3–4), most of the unit is mudstone (73% of the measured section), and sandstone (commonly pebbly) and extrabasinal conglomerate are significant components of the section (13% and 10%, respectively, of the measured section). Minor

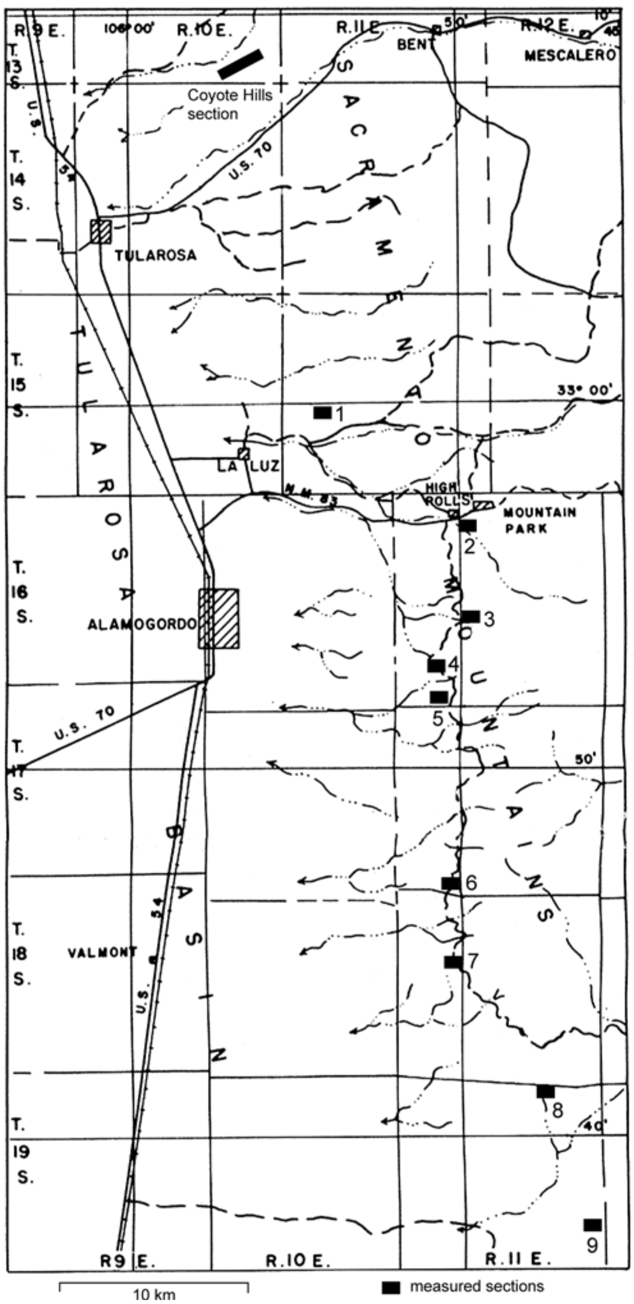


FIGURE 1. Index map showing location of Coyote Hills section northeast of Tularosa and the measured sections in Figure 2 (numbers) as well as Culp Canyon, which is the general area of Bachman and Hayes (1958) work. Base map adapted from Otte (1959).

lithologies are intrabasinal (calcrete-clast) conglomerate (3%) and ledge-forming calcrete (1%).

Mudstone is grayish red to reddish brown, slope-forming and often contains calcrete nodules and thin, discontinuous sandstone lenses. Mudstone beds range greatly in thickness, usually are 1–3 m thick, but a few beds, at 10–18 m thick, are the thickest beds of the Abo Formation.

Sandstone beds are arkosic and many contain extrabasinal pebbles. Trough crossbeds are the dominant bedform of sandstone beds, but thinner beds tend to be horizontally laminated. Ripple lamination is very rare. Sandstone beds are typically about 1 m thick, but sometimes occur in multistoried intervals of sandstone and conglomerate that are 5–10 m thick.

Extrabasinal conglomerate of the Coyote Hills section of the Abo Formation consists of clasts of basement rock (mostly granite and quartzite) that range from granule to cobble size (Fig. 4C-E). Some of these conglomerates have crossbeds and graded bedding, but others are matrix supported and unstratified. Most of these conglomerate beds are 1–3 m thick.

Intrabasinal conglomerate beds are mostly present in the upper 125 m of the Coyote Hills section of the Abo Formation. The clasts in these conglomerates are dominantly intraformational rip-ups of calcrete. Bed thickness is mostly 1–3 m.

Although calcrete nodules are common in mudstone beds of the Coyote Hills Member, there are only a few persistent ledges of calcrete. These ledges are less than 1 m thick and composed of limestone with a nodular texture, much clastic impurity and rhizoliths.

Sandstone and Conglomerate Petrography

In the Coyote Hills section, sandstone of the Abo Formation is mostly medium- to coarse-grained (0.3–2 mm), locally pebbly, and moderately to poorly sorted. Most of the detrital grains are subangular to subrounded. Monocrystalline quartz is present in small amounts. Polycrystalline quartz is very rare and composed of large subindividuals. Detrital feldspars are abundant, mostly untwinned and altered, thus appearing reddish-brown under plane light. Alkali feldspar is very much dominant; subordinately, plagioclase is present, displaying polysynthetic twins (Figs. 5A-E).

Granitic rock fragments composed of large quartz and feldspar are common (Figs. 5C-D, 6D). Characteristic constituents are rock fragments displaying a typical granophyric texture of quartz that is micrographically intergrown with alkali feldspar (Fig. 5C-D). Radiating or branching, interconnected quartz crystals are set in a single crystal of alkali feldspar. Quartz crystals display angular, triangular or cuneiform sections (Fig. 6G-H). The rock from which these fragments are derived is granophyre. Porphyritic rock fragments are subordinate. A few rock fragments are composed of small feldspar and quartz grains. Very rare are basaltic rock fragments composed of plagioclase laths showing a seriate texture (Fig. 6F). A few grains are completely altered to chlorite, and rarely grains are completely altered to clay minerals (pseudomatrix). Locally sedimentary rock fragments derived from siltstone are pres-

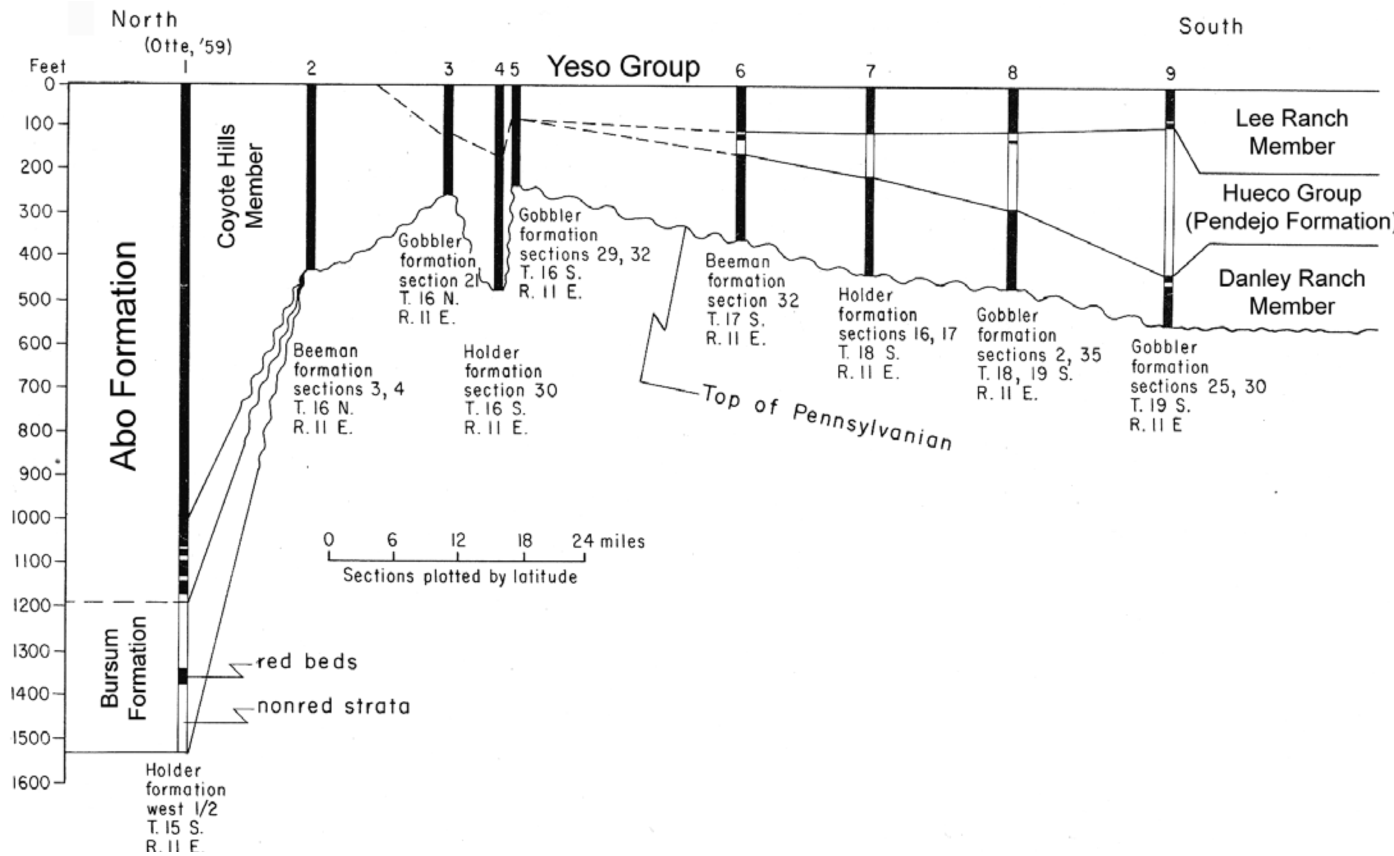


FIGURE 2. Cross section showing stratigraphic relationships of Abo Formation from north to south in the Sacramento Mountains (modified from Pray, 1961, fig. 26).

ent. In the upper part of the section, there are reworked micritic carbonate grains, probably derived from pedogenic carbonate beds (Figs. 5F, 6E). Metamorphic rock fragments and detrital mica are absent.

Locally, the sandstone contains small amounts of silty matrix. Pore space is generally filled with coarse, poikilotopic calcite cement that randomly replaces detrital feldspar grains (Figs. 5E, 6B-C). Locally, monocrystalline quartz grains display authigenic quartz overgrowths (Fig. 6A, C). Rarely, pore space is filled with microcrystalline quartz.

In the lower part of the section, conglomerate shows the same composition as does the sandstone, containing clasts of oriented intergrowths of quartz and feldspar and granitic rock fragments composed of large quartz and feldspar grains. Other clast types are rare. In the upper part of the section, conglomerate is mixed siliciclastic-carbonate in composition and contains abundant carbonate clasts derived from reworked paleocalcrete (indicated by wrinkled microcracks filled with coarse calcite: Fig. 6E). Other clasts include granitic rock fragments and oriented intergrowths of quartz and feldspar, micrograniti c rock fragments, and rare porphyritic rock fragments composed of microcrystalline groundmass and phenocrysts of quartz and feldspar. Sand-sized grains of mono- and polycrystalline quartz as well as altered detrital feldspars are present, too. Detrital grains are cemented by coarse blocky calcite.

Coyote Hills Member of the Abo Formation

Two Abo members have been named in central New Mexico, the Scholle and the Cañon de Espinoso Members (Lucas et al., 2005a, 2012a, 2012b, and 2013b). The Scholle Member is the lower, mudstone-dominated interval of the Abo Formation and is 40–140 m thick. Sandstone/conglomerate bodies in the Scholle Member are a minor part of the unit and are typically trough-crossbedded, lenticular and contain intraformational clasts.

The overlying Cañon de Espinoso Member is 58–256 m thick and is characterized by numerous, laterally persistent sandstone sheets that typically have ripple lamination. The Abo Formation consists of the Scholle and Cañon de Espinoso Members from the Jemez Mountains of Sandoval County through the Sandia Mountains of Bernalillo County, Lucero uplift of Valencia County, Abo type section in the Abo Pass area of Torrance County, Cerros de Amado of Socorro County, northern Oscura Mountains of Socorro County, southernmost Oscura Mountains (Mockingbird Gap area) of Lincoln County and the Fra Cristobal, Caballo and northern San Andres Mountains of Sierra County (Kottlowski et al., 1956; Lucas et al., 1999; Lucas and Zeigler, 2004; Lucas et al., 2005a, 2012a, b, 2013b; DiMichele et al., 2007). Thus, the entire Abo Formation outcrop belt to the west of the Sacramento Mountains can be assigned to these two members.

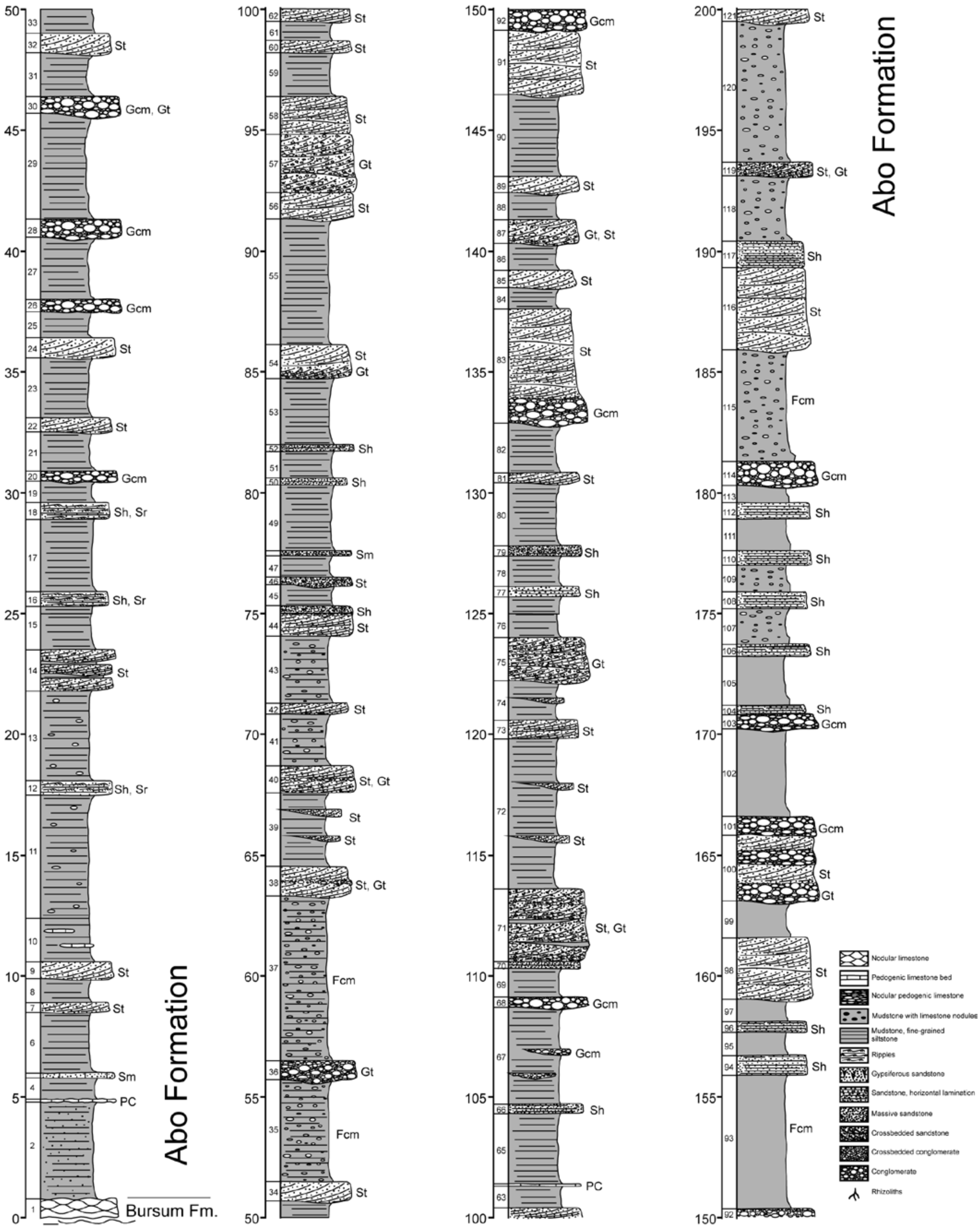
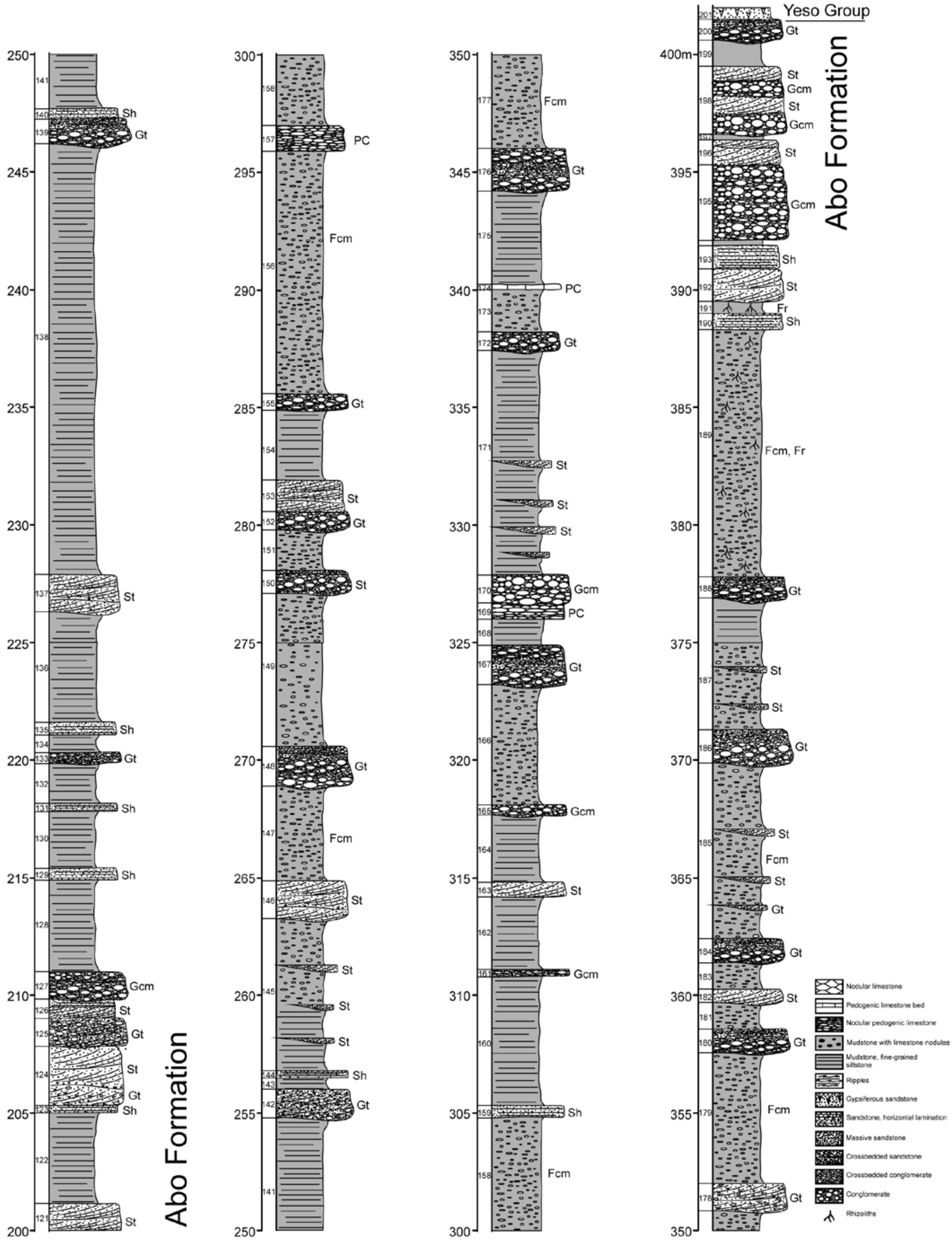


FIGURE 3. Measured stratigraphic section of the Abo Formation in the Coyote Hills. Base of section is at UTM zone 13 (NAD 83), 409629E, 3664641N and top is at 413264E, 3667863N. Section was thus measured in sections 34, 35 and 36, T13S, R10E. Lithofacies abbreviations along right side of columns are defined and discussed in the text.


Yeso Group
Abo Formation
Abo Formation
400m
Nodular limestone
Pedogenic limestone bed
Nodular pedogenic limestone
Mudstone with limestone nodules
Mudstone, fine-grained siltstone
Ripples
Gypsiferous sandstone
Sandstone, horizontal lamination
Massive sandstone
Crossbedded sandstone
Crossbedded conglomerate
Conglomerate
Rhizoliths

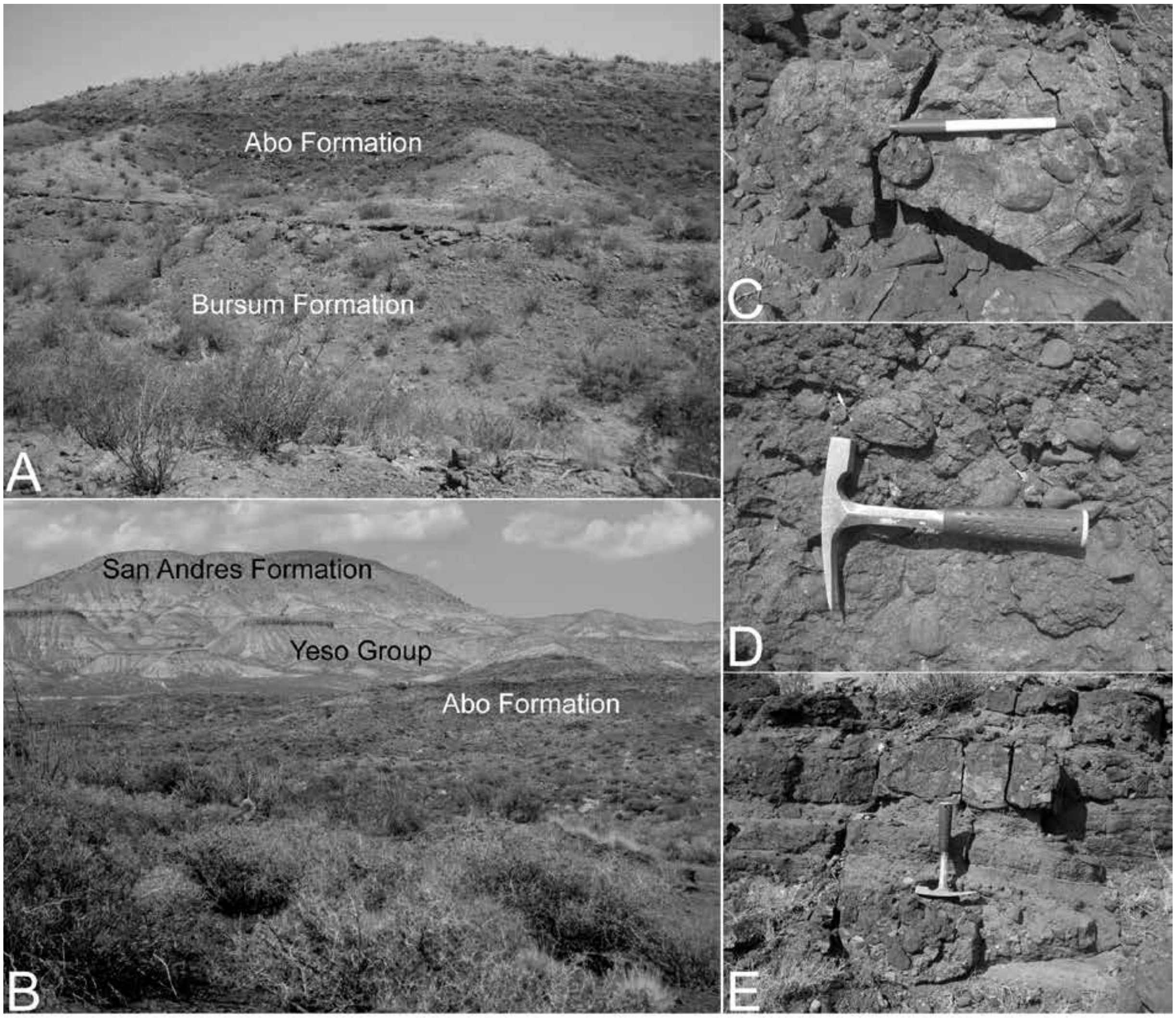


FIGURE 4. Photographs of selected outcrops of the Abo Formation in the Coyote Hills section. Overview of base A. and top B. of section. C-E. Characteristic extrabasinal conglomerates of the Coyote Hills Member of the Abo Formation.

In the southern Sacramento Mountains, Bachman and Hayes (1958) named two members of the Abo Formation, where it interfingers with marine, carbonate-dominated strata of the Hueco Group (Fig. 2). These are the Danley Ranch (lower) and Lee Ranch (upper) Members. The Danley Ranch Member is mostly mudstone, but locally contains some polymict, limestone-cobble conglomerates. It is the homotaxial equivalent of the Powwow conglomerate to the south (Lucas et al., 2011). The Lee Ranch Member is mudstone and ripple-laminated sandstone just below gypsum of the Yeso Group.

Clearly, the Abo Formation in the Coyote Hills is different from the other named members of the Abo Formation. Its thickness, stratigraphic architecture and lithology display these distinctive characteristics:

1) great thickness (up to 400 m), much thicker than any other Abo member and actually thicker than most complete Abo Formation sections;
2) no clear subdivision into lower, mud-dominated and upper sandy intervals, but instead a section of interbedded mudstone and sandstone/conglomerate without obvious subdivisions; and
3) presence of numerous beds of extrabasinal conglomerate, especially beds of basement-cobble conglomerate.

Therefore, we feel confident that the Abo Formation in the Coyote Hills is a distinctive lithosome of the Abo Formation, one restricted (based on current data) to the northern Sacramento Mountains (Fig. 2). It represents a localized lithofacies that deserves to be recognized as a new member of the Abo Formation. We thus name it the Coyote Hills Member and we regard our section in the Coyote Hills (Figs. 3, 4) as its type section.

SEDIMENTOLOGY

Lithofacies

Conglomerate

In the Abo Formation at the Coyote Hills section (Fig. 3), conglomerate units are 0.3–3.2 m thick. Most conglomerate beds appear massive (lithofacies Gcm), and a few beds display trough

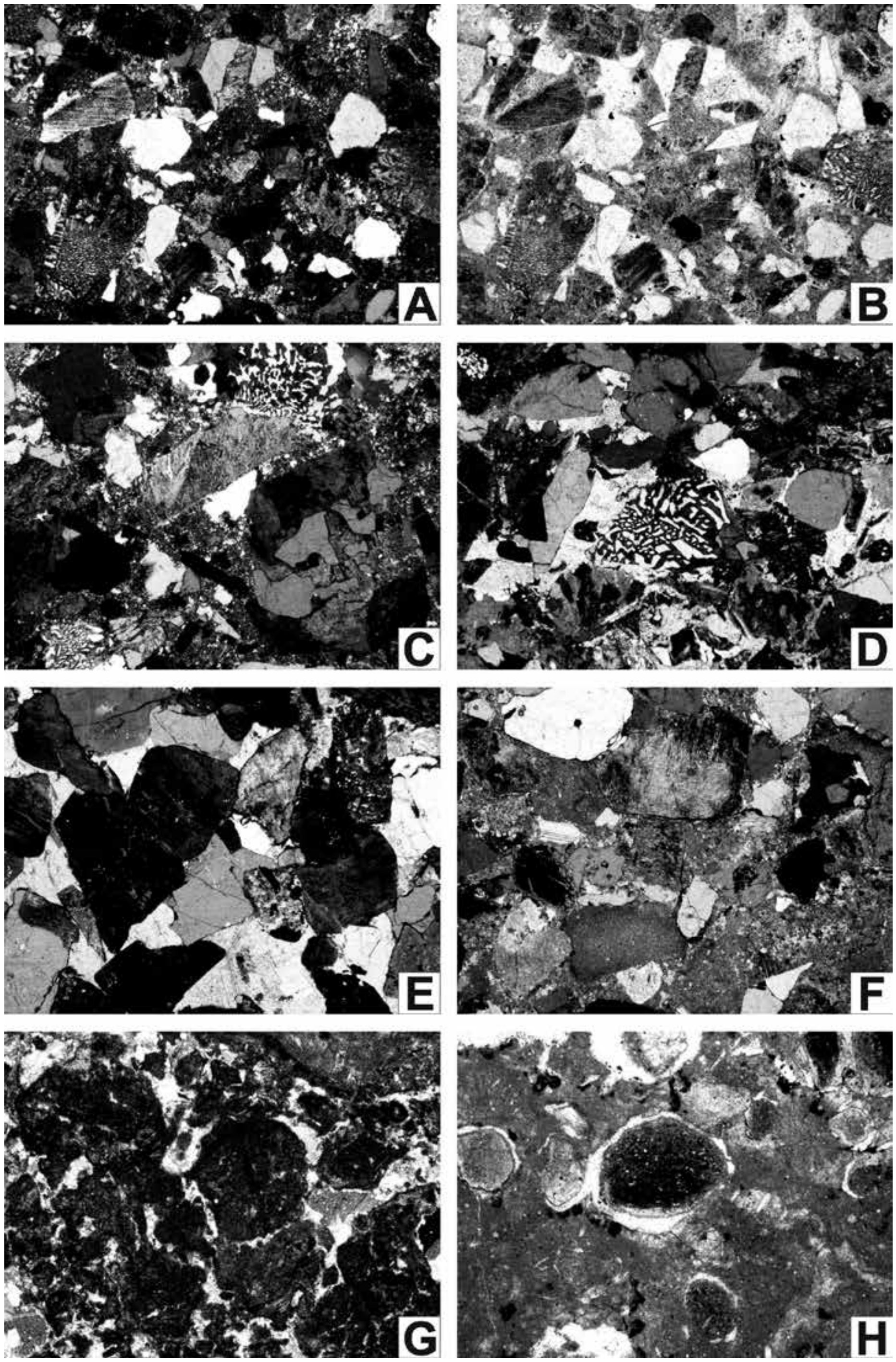


FIGURE 5. Thin section photographs of sandstone and paleocalcrete of the Abo Formation at the Coyote Hills section (Fig. 3). A-B. Sandstone composed of mono-, rare polycrystalline quartz, abundant detrital feldspars that are strongly altered, and a few granitic and granophyric rock fragments. Detrital grains are mostly subrounded and cemented by microcrystalline quartz. (A) Under polarized light, and (B) under plane light. Width of photograph is 3.2 mm (bed 117). C. Coarse-grained sandstone composed of subangular to subrounded grains including few mono- and polycrystalline quartz, many granitic and granophyric rock fragments and altered detrital feldspar grains, cemented by microcrystalline quartz. Polarized light, width of photograph is 3.2 mm (bed 66). D. Medium-grained sandstone containing monocrystalline quartz, many detrital feldspars, granitic and granophyric rock fragments (center). The detrital grains are cemented by coarse calcite. Polarized light, width of photograph is 3.2 mm (bed 11). E. Coarse-grained sandstone containing subangular to subrounded grains of monocrystalline quartz, altered detrital feldspars (dark) and granitic rock fragments cemented by coarse blocky calcite. Polarized light, width of photograph is 3.2 mm (bed 134). F. Coarse-grained sandstone containing monocrystalline quartz, detrital feldspars, granitic rock fragments and micritic carbonate grains cemented by calcite. Polarized light, width of photograph is 6.3 mm (bed 200). G. Nodular paleocalcrete composed of peloids and micritic nodules which display well developed circumgranular cracks. Plane light, width of photograph is 3.2 mm (bed 29). H. Paleocalcrete displaying nodular texture, composed of micritic nodules and rare detrital quartz and altered feldspar grains embedded in micritic matrix. Nodules are surrounded by circumgranular cracks. Plane light, width of photograph is 3.2 mm (bed 3).

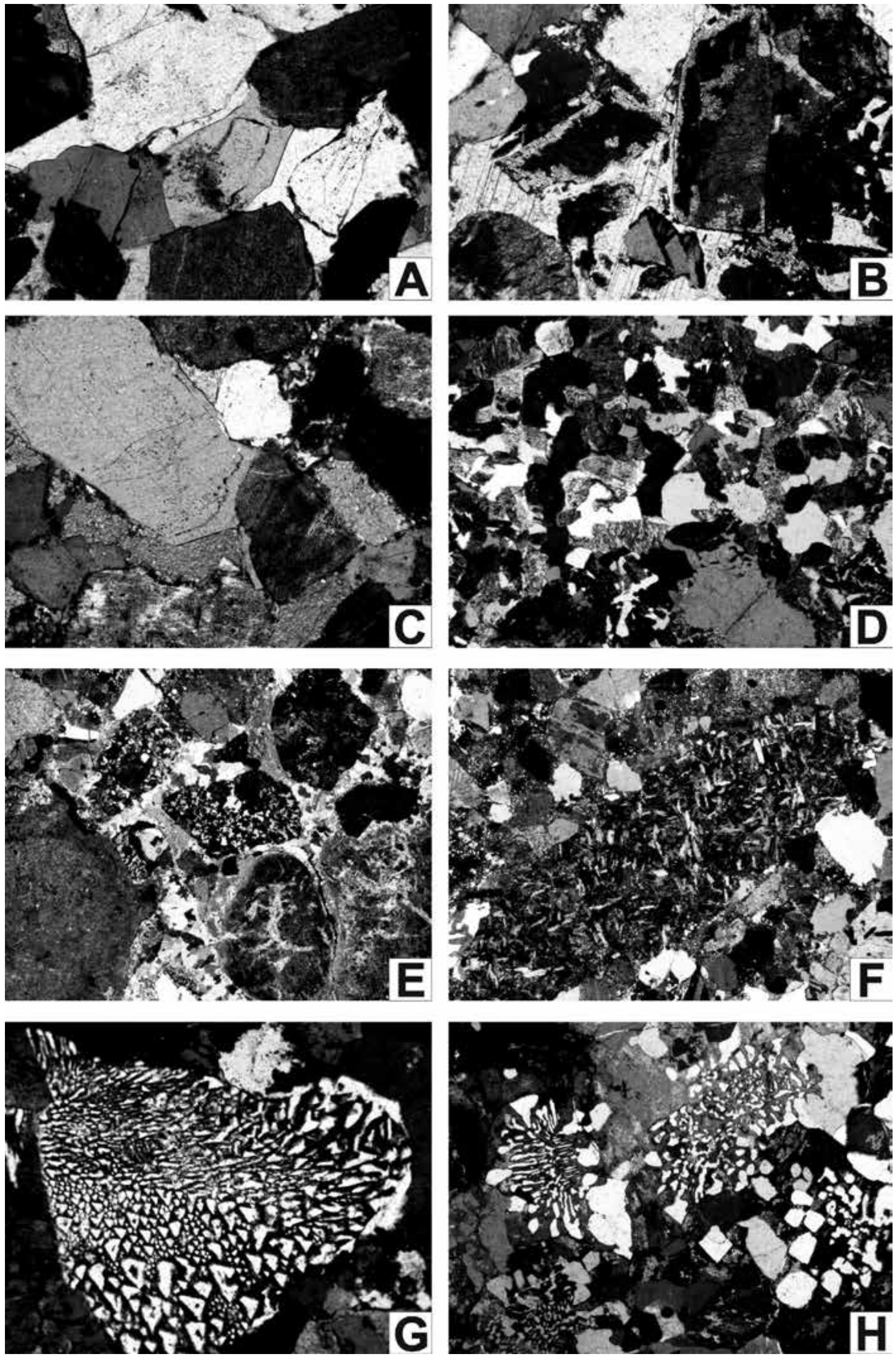


FIGURE 6. Thin section photographs of sandstone and conglomerate of the Abo Formation in the Coyote Hills section (Fig. 3). A. Medium-grained sandstone in which monocrystalline quartz grains are cemented by well-developed authigenic overgrowths. Dark grains are altered feldspars. Some calcite cement is present (lower part). Polarized light, width of photograph is 1.2 mm (bed 134). B. Medium-grained sandstone in which the detrital grains are cemented by coarse, blocky calcite. Two detrital feldspar grains in the center are altered and randomly replaced by calcite. Polarized light, width of photograph is 1.2 mm (bed 11). C. Coarse-grained sandstone composed of monocrystalline quartz, detrital feldspars and granitic rock fragments. The large quartz grains displays authigenic overgrowths. Remaining pore space is filled with coarse calcite cement. Polarized light, width of photograph is 1.2 mm (bed 5). D. Granitic rock fragment from a pebbly sandstone. The rock fragment is composed of quartz and alkali feldspars that are slightly altered. Polarized light, width of photograph is 3.2mm (bed 103). E. Fine-grained conglomerate containing porphyritic and granitic rock fragments, detrital feldspars and brownish carbonate grains derived from reworking of paleocalcrete, some displaying shrinkage fissures (lower right). Grains are cemented by calcite. Polarized light, width of photograph is 6.3 mm (bed 150). F. Large basaltic rock fragment composed of feldspar laths that are lightly altered, embedded in a pebbly sandstone. Polarized light, width of photograph is 6.3 mm (bed 103). G. Granophyric rock fragment in a coarse-grained sandstone with partly triangular and partly cuneiform quartz crystals intergrown with alkali feldspar. Polarized light, width of photograph is 1.2 mm (bed 124). H. Granophyre rock fragment in a pebbly sandstone. Granophyre shows typical grains of intergrown quartz and alkali feldspar. Alkali feldspar is slightly altered and appears brownish. Polarized light, width of photograph is 3.2 mm (bed 148).

crossbedding (lithofacies Gt). The conglomerate is poorly sorted, grain supported, and maximum grain size is approximately 20 cm. Rarely, matrix-supported conglomerate is present (lithofacies Gmm). Locally, thin conglomerate lenses are intercalated in mudstone. Some conglomerate beds display an erosive base.

In the lower part of the section, the conglomerate is mainly composed of basement-derived clasts with only minor amounts of reworked calcrete clasts. In the upper part of the section (above bed 156: Fig. 3), conglomerate beds are mainly composed of reworked calcrete clasts and rare basement-derived clasts.

Lithofacies Gcm is interpreted to represent pseudoplastic debris flows, lithofacies Gmm represents high-strength viscous debris flows, and lithofacies Gt represents gravelly channel fills (Miall, 1996).

Sandstone

Sandstone beds in the Abo Formation at the Coyote Hills section occur as thin lenses and tabular beds (0.2–0.5 m thick) and thicker, crossbedded sandstone-conglomerate sheets with a maximum thickness of 3.4 m. The following lithofacies types are observed:

1) Massive sandstone (lithofacies Sm), which occurs as thin tabular sandstone sheets. This lithofacies is rare, and more abundant in the lower part of the section. This lithofacies formed during sheet floods (sediment gravity flow deposits).
2) Ripple-laminated sandstone (lithofacies Sr), alternating with horizontally laminated sandstone within thin tabular sandstone sheets. Lithofacies Sr is present but uncommon in the lower part of the section. This lithofacies represents current ripples of the lower flow regime.
3) Horizontally laminated sandstone (lithofacies Sh) occurs as thin tabular sandstone sheets. This lithofacies is more abundant in the lower part of the section. Lithofacies Sh is the product of plane bed flow of the upper flow regime.
4) Trough crossbedded sandstone (lithofacies St) occurs as thin lenses and beds, as well as thicker sandstone beds and stacked units. Some beds display an erosive base. Crossbedded sandstone is commonly coarse-grained, partly pebbly. At the base of some thicker sandstone units conglomerate is present, and the conglomerate-sandstone succession displays a fining-upward trend. Lithofacies St represents channel-fill deposits that formed by the migration of dunes in the river bed.

Mudstone-Siltstone

Mudstone-siltstone intervals in the Abo Formation in the Coyote Hills are up to 18.3 m thick, and mostly the thickness is less than 10 m. The dominant color is red, but subordinately purple, brownish and gray mudstone-siltstone beds are present. Most mudstone-siltstone intervals appear massive, blocky, and rarely laminated. Many mudstone-siltstone intervals contain numerous pedogenic carbonate nodules. In the uppermost part of the section, root structures (rhizoliths) are locally present (lithofacies Fr).

Mudstone-siltstone lithofacies are interpreted as floodplain deposits that mainly formed by settling from sheetfloods. Laminated mudstone-siltstone is probably the product of deposition from suspension. Lamination is mostly absent, probably because of bioturbation and pedogenic processes.

Pedogenic carbonate

In the Abo Formation in the Coyote Hills, pedogenic carbonate beds (lithofacies PC) are 0.1–0.7 m thick and nodular. In thin section these carbonate beds display an inhomogeneous texture and are composed of micrite and peloidal micrite that contains micritic nodules and, locally, a few detrital quartz and feldspar grains. Characteristic features are wrinkled shrinkage cracks and (subordinately) circumgranular cracks around micritic nodules filled with calcite cement (Fig. 5G-H). Locally root structures are observed, but other fossils are absent.

Architectural Elements

Lithofacies types similar to those in the Coyote Hills Member have been described from the Abo Formation of northern and central New Mexico (Krainer and Lucas, 2010; Lucas et al., 2005a, 2012b). Conglomerate and sandstone lithofacies occur either as thin intercalations or form thicker units composed of different lithofacies types displaying a distinct geometry (“architectural elements” of Miall, 1985, 1996, 2010).

At the Coyote Hills section, the following lithofacies assemblages are observed:

1) Thin, tabular sandstone beds (<0.5 m) composed of lithofacies Sh, and subordinately, Sr and Sm, form architecural element SB (sandy bedforms).
2) Thin sandstone beds, composed predominantly of lithofacies St, and displaying lenticular (channel fill) geometry form architectural element CH (minor channel fills).
3) Thin conglomerate beds composed mainly of lithofacies Gcm, subordinately of Gt and Gmm, locally displaying a fining upward trend and grading into thin sandstone (Sh, St). This lithofacies can be assigned to architectural element SG (sediment gravity flow), interbedded with SB (sand bedforms) or GB (gravel bars and bedforms) and laterally extending over several meters.
4) Thicker units composed of alternating conglomerate-sandstone lithofacies (Gcm, Gt, St) or conglomerate (Gcm, Gt) to pebbly sandstone (St) at the base, grading into stacked sandstone intervals (St) showing a distinct fining-upward trend. This lithofacies is assigned to architectural element CH, as in 2 above, forming sheet-like bodies that can be traced laterally over tens of meters.
5) Siltstone-mudstone intervals (lithofacies Fl, Fsm, Fr) form sheet-like units that can be traced laterally over longer distances. These lithofacies form architectural element FF (floodplain fines).

Depositional System

The Abo Formation of the Coyote Hills is thicker and was deposited in a more proximal depositional environment than the Abo Formation in central and southern New Mexico, with higher amounts of basement-derived conglomerate and coarse-grained sandstone. The facies is composed mostly of mudstone and siltstone representing floodplain deposits with intercalated thicker conglomerate sandstone sheets of a low sinuosity river system and thin debris-flow conglomerates, small, thin channel-fill sandstones, and thin tabular sheetflood and splay sandstones. Sediments were deposited on an extensive alluvial plain that extended southward and southwestward toward the Hueco seaway, and were derived from a local source area in the Pedernal uplift composed mainly of granitic and granophyric rocks. Speer (1983, 1986) reached a similar conclusion.

We interpret thicker conglomerate-sandstone sheets (architectural element CH) as deposits of broad and shallow channels of low sinuosity rivers that developed on an extensive alluvial plain extending from the Pedernal uplift towards the Orogrande Basin (to the southwest). Conglomerate-sandstone sheets are separated by thicker floodplain deposits (architectural element FF), which were frequently inundated by sediment gravity flows (debris flows, element SG, indicative of local high relief), sheetfloods and splays (thin tabular sandstone intercalations, element SB) and minor sandy channel fills (element CH). On the floodplain, local pedogenic processes formed calcrete nodules and paleocalcrete beds and rhizolith horizons.

If we further compare the Coyote Hills Member to the Abo Formation of the Caballo and Fra Cristobal Mountains of Sierra County, the deposits of the Coyote Hills Member differ dramatically in facies and petrography. In general, the facies at Coyote Hills is coarser grained. In the Caballo and Fra Cristobal Mountains, conglomerates comprise less than 1% of the entire Abo section and are composed of carbonate clasts (mostly reworked pedogenic calcretes). Sandstone in the Caballo and Fra Cristobal Mountains comprises about 19% of the section, and compared to the Abo Formation in the Coyote Hills, is fine- to very fine-grained with an average grain-size of approximately 0.2 mm (Lucas et al., 2012a). Lithofacies Gcm is rare, Gt is absent, lithofacies St is less common than at the Coyote Hills, Sh and Sm are more common, and lithofacies Sr is the most common lithofacies in the Abo Formation of the Caballo and Fra Cristobal Mountains. Architectural elements of the Abo Formation in the Caballo and Fra Cristobal Mountains are CH (channel) and SB (sandy bedforms). Element SB is similar, but rare and thinner in the Coyote Hills. Element CH differs significantly. Element SG is only present in the Coyote Hills.

In the Caballo and Fra Cristobal Mountains, element CH forms sandstone sheets, composed dominantly of lithofacies St, minor Sl, Sh, Sm and rare Sr. These sandstone sheets are interpreted to represent deposits of broad, shallow channels of low sinuosity rivers (Krainer and Lucas, 2010). Element SB is much more common in the Caballo Mountains and forms sandstone sheets up to 5 m thick composed dominantly of lithofacies Sr, associated with Sh, Sm and rare Sl. This element is very rare at the Coyote Hills. Element CH composed of lithofacies St, which forms thin lenses representing minor channel fills intercalated in fine-grained floodplain deposits at the Coyote Hills, is absent in the Caballo and Fra Cristobal Mountains.

Deposition of the Abo Formation to the west and southwest of the Coyote Hills, for example in the Fra Cristobal and Caballo Mountains of Sierra County, was on a distal, low-gradient alluvial plain on which rivers flowed primarily from the margin of the source areas in northern New Mexico (Uncompahgre uplift) towards the shoreline of the Hueco seaway in southern New Mexico. Farther south, in the southern Caballo Mountains and Derry Hills, nonmarine Abo sediments interfinger with estuarine and marine sediments of the Hueco Group (Lucas et al., 2012a).

Abo deposition took place under seasonally dry and wet periods (monsoonal climate) (Seager and Mack, 2003; Kues and Giles, 2004; Lucas et al., 2012a). Sediments of the Abo Formation at Coyote Hills represent deposits of a proximal alluvial plain adjacent to the Pedernal uplift, comparable with some respect to the sediments of the Arroyo del Agua Formation of the Cutler Group in northern New Mexico (Lucas and Krainer, 2005).

The main source areas for the Abo sediments of the Caballo and Fra Cristobal Mountains were the Uncompahgre uplift and San Luis highland in northern New Mexico, and, to a lesser extent the Peñasco uplift and probably also the Zuni-Defiance uplift (Seager and Mack, 2003). The main source rocks at the Coyote Hills were granophyre (a textural variety of granite) and granitic rocks, and subordinately, basaltic rocks. Granophyre forms when granitic melts intrude near the surface and crystallize relatively quickly, causing the simultaneous crystallization of quartz and feldspar, producing a characteristic granophyric texture. There is no evidence for the presence of metamorphic rocks in the source area. Sedimentary rock fragments (micritic carbonate clasts), which are a common constituent in conglomerate and sandstone in the upper part of the Coyote Hills section, were derived from the reworking of paleocalcrete (intrabasinal). Petrography of the Abo sediments at the Coyote Hills indicates a local source area in the Pedernal uplift composed mainly of granite and granophyre (probably of the southern "granite-rhyolite province" of Precambrian basement: Karlstrom et al. 2004, fig. 1).

PALEONTOLOGY, AGE AND CORRELATION

Paleontology

Both Otte (1959) and Vaughn (1969) noted large quantities of petrified wood in the Coyote Hills Member. However, our field observations did not confirm more petrified wood (as transported clasts in sandstones and conglomerates) than is characteristic of other Abo outcrops.

Trace fossils are rare in the Coyote Hills Member, which seems mainly due to taphonomic reasons. The member almost totally lacks fine-grained sandstone beds with mud drapes, desiccation cracks, raindrop impressions, microbially induced sedimentary structures and other marks that are usually associated with trace fossils in other members of the Abo Formation (Hunt et al., 1995; Lucas et al., 1995, 2002, 2004, 2005b, 2005c, 2009, 2012a; DiMichele et al., 2007; Lucas and Spielmann, 2009). Despite intensive exploration in 2012, only two sites with trace fossils were found in the Coyote Hills Member. These are NMMNH localities 8791 and 8792. Both sites are in the uppermost part of the section

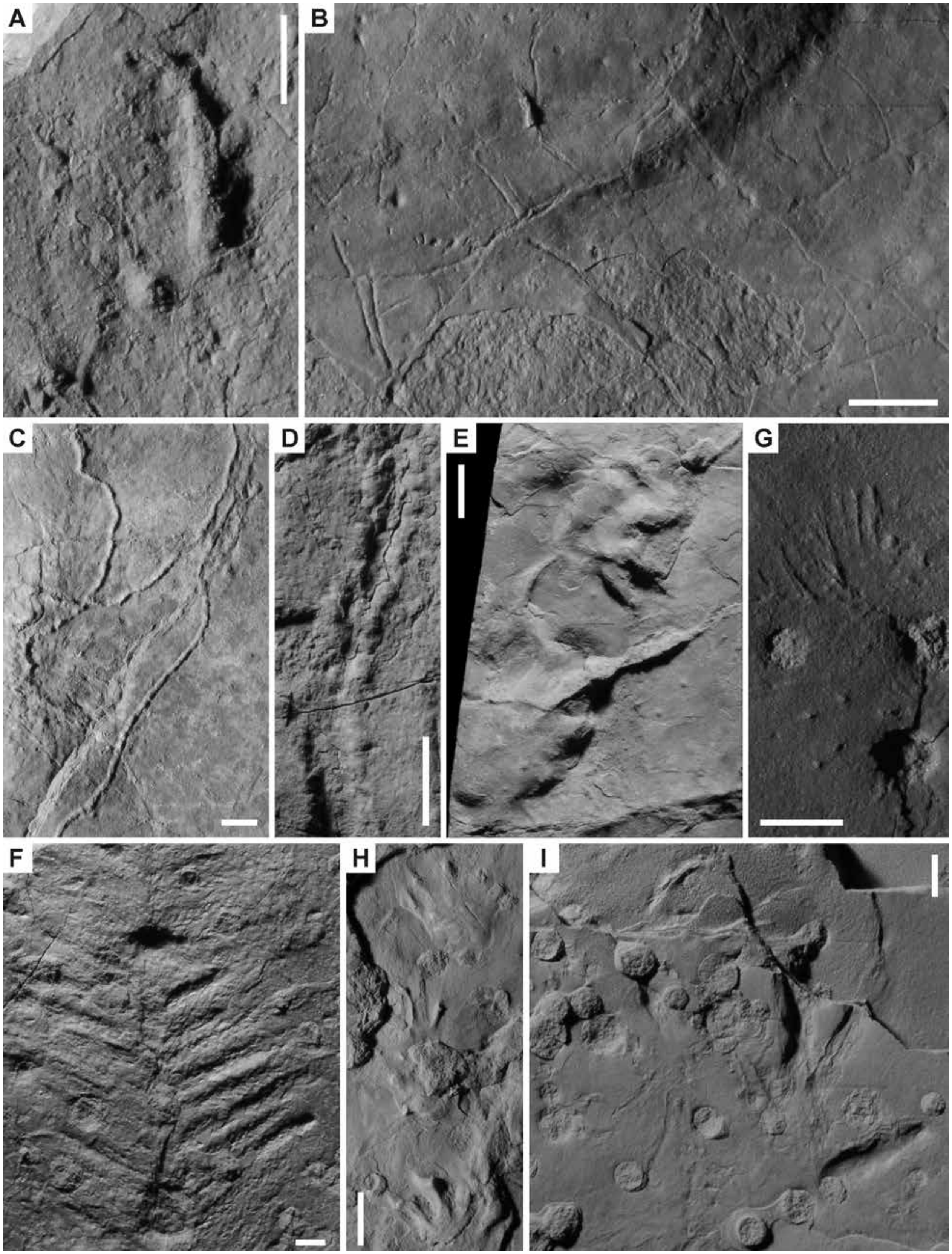


FIGURE 7. Trace fossils from the Coyote Hills Member (A-E) and the Abo Formation south of U.S. Highway 70 (F-I). A. *Dromopus*, NMMNH (New Mexico Museum of Natural History) P-66554; B. Root traces, NMMNH P-66555; C. cf. *Helminthoidichnites*, NMMNH P- 66557; D. *Sphaerapus*, NMMNH P-66562; E. tetrapod tracks indet., NMMNH P-66556; F. walchian conifer branch, NMMNH P-66565; G. cf. *Stiallia*, NMMNH P-66566; H. cf. *Batrachichnus*, NMMNH P-66564; I. *Dromopus*, NMMNH P-66563; *Skolithos* can be seen in specimens G-I. Scale bars equal 1 cm.

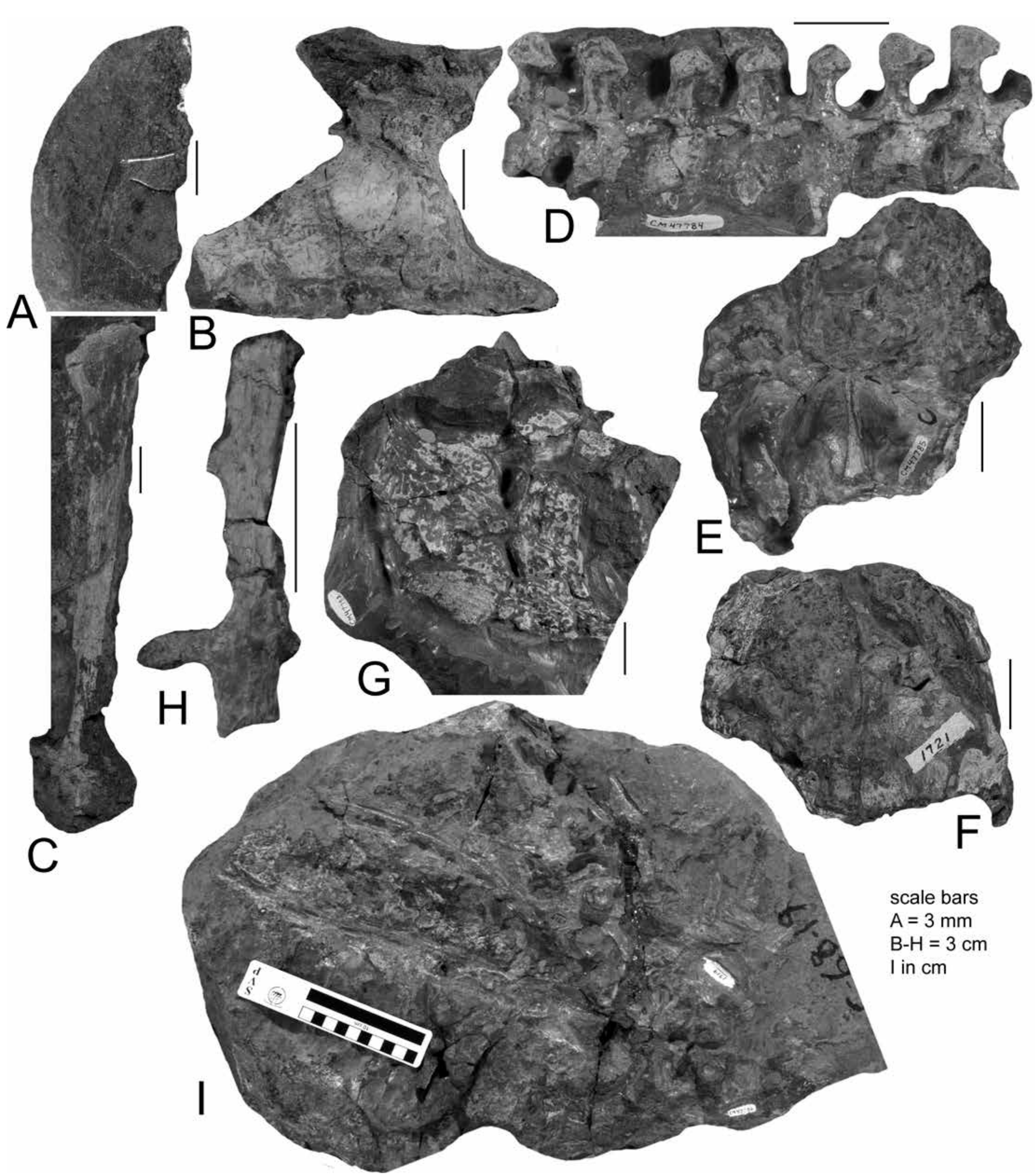


FIGURE 8. Selected vertebrate fossils from the Abo Formation in the Coyote Hills. A. Rhipidistian scale, CM (Carnegie Museum of Natural History) 47792. B. *Diadectes*? pelvis, CM 86786. C. *Platyhystrix* neural spine, CM 47783. D. Dissorophid vertebrae, CM 47784. E-F. Dissorophid skull, CM 47785. G. Temnospondyl skull fragment, CM 47782. H. *Edaphosaurus* spine fragment, CM 86786. I. *Edaphosaurus* vertebrae and ribs, CM 47786.

about 10 m below the base of the Yeso Group (bed 191: Fig. 3). NMMNH locality 8791 is an exposure of pale reddish-gray, silty to fine-grained sandy beds with mud drapes, raindrop impressions and poorly preserved tracks of *Dromopus* (Fig. 7A).

The lithology of NMMNH locality 8792 is quite similar, but the fossil content is more diverse, including root traces, various invertebrate traces and tetrapod tracks (Fig. 7B-E). Remarkable is the presence of *Sphaerapus*, a distinct invertebrate trace that is already known from several other places in the Abo Formation of New Mexico, e.g., Lucero uplift, Socorro area, and the Oscura and Caballo Mountains. *Sphaerapus* first occurs in the upper third of the local Abo section, suggesting that it is of stratigraphic significance, and the respective beds are not older than late Artinskian in age (Lucas et al., 2013a). The depositional paleoenvironment of the trace fossil-bearing beds at NMMNH localities 8791 and 8792 can be interpreted as shallow ephemeral pools or ponds.

Compared to the Coyote Hills Member, trace fossils seem to be more common in the Abo Formation south of U.S. Highway 70. This is in agreement with observations pointing to a significant lateral facies change from north to south in the Tularosa area (Otte, 1959; Pray, 1961; Fig. 2). In 2012, a short stop along the forest road (FR 90, the "west side road"), south of High Rolls, resulted in the discovery of NMMNH locality 8793. This site is close to section no. 3 of Otte (1959) and exposes alternating reddish-brown siltstone and fine-grained sandstone with mudcracks, walchian conifer remains, invertebrate traces assigned to *Skolithos* and cf. *Stiallia* as well as tetrapod tracks identified as cf. *Batrachichnus* and *Dromopus* (Fig. 7F-I). This site is about 10 m below the base of the Yeso Group and is in strata laterally equivalent to the Lee Ranch Member of the Abo Formation in the southern Sacramento Mountains (Bachman and Hayes, 1958; Speer, 1983; Fig. 2).

The principal fossils known from the Coyote Hills Member are the vertebrate fossils mentioned but not illustrated or fully documented by Vaughn (1969; also see Berman, 1993). Here, we document and illustrate (Fig. 8) some of these fossils. We also note that we recently discovered one other vertebrate fossil locality.

Vaughn (1969) collected and described a moderately extensive assemblage of vertebrate fossils from several localities in the uppermost level of the Laborcita Member of the Bursum Formation and the lowermost level of the overlying Coyote Hills Member of the Abo Formation in the Coyote Hills. To date, this has been the only such study of vertebrate fossils from this area. Most of the specimens consist of poorly preserved, isolated elements, or rarely small, articulated portions of skeletons. Unfortunately, none of these specimens were illustrated by Vaughn (1969) or have been restudied since his publication. Here we illustrate (Fig. 8) some of the specimens, as well as suggest alternatives to or further proof of his identifications. Yet, even so, almost all of the information presented here is taken from Vaughn (1969). We also report here the recent discovery of a new locality in the Coyote Hills Member. Vaughn's entire Coyote Hills collection has been transferred from the collections of the University of California, Los Angeles (acronym UCLA VP), to those of the Carnegie Museum of Natural History, Pittsburgh, Pennsylvania (acronym CM). Only a small portion of the specimens Vaughn (1969) described were cataloged by him, and those not cataloged were, unfortunately, not accompanied by his identifications. Further complicating an accounting of the collection, a couple of specimens that were not cataloged but described by Vaughn cannot be located but are simply noted as "not located." However, the majority of the specimens described but not cataloged by Vaughn could be located and were assigned CM numbers. Where applicable, both CM and UCLA VP catalog numbers are given.

As reported by Vaughn (1969), fossils from the Laborcita Member are preserved almost entirely in dense, nodular carbonate concretions weathered from a several-foot thick green-gray shale. The bulk of the remains are of the acanthodian fish *Acanthodes* and include scales (single and in patches: CM 89916–89917), spines (CM 89918/UCLA VP 1718, CM 88923), a scapula, and other elements; some specimens were also found in the shale. In addition, the nodules also produced paleoniscoid scales (CM 88919, 88922), scales and dermal bones fragments, and associated scales and partial dermal skull roof fragments of a rhipidistian crossopterygian fish (CM 89920, 89924), a xenacanth shark tooth (CM 89925), a partial mandible of a possible microsaur (CM 89936), a vertebra of the pelycosaurian reptile *Sphenacodon* cf. *S. ferox* (CM 89921), and fragments of large tetrapod bones. There is no basis to dispute these identifications.

Of the vertebrates listed above, the possible microsaur (CM 89936) deserves further comment, as this taxon is otherwise unreported from the late Paleozoic of New Mexico. It consists of the approximate anterior half of a 2 cm long, badly eroded left mandible in medial view that includes portions of the dentary and splenial. Much of the medial surface of the dentary is eroded away, exposing a posteriorly widening Meckelian canal. A thin splint of bone measuring 5.5 mm long, occupying most of the anterior, ventral margin of the dentary and reaching to within 4.0 mm of the jaw symphysis, is believed to be a remnant of the splenial. It is the dentary dentition, that is nearly completely eroded away, that suggests CM 89936 is a microsaur. The presence of an estimated nine teeth, which occupy the entire 2 cm length of the dentary, is based on alveoli and/or remnants of the teeth, though the original number was probably close to 12. At the broken posterior margin of the dentary is a remnant of a very small tooth that is followed closely anteriorly by a large tooth exposed as a vertical, sagittal section. It is the only tooth whose entire outline is preserved, which describes a rather bulbous, blunt, cone-shaped structure with an approximate basal width of 4 mm and a height of 5 mm. Based mainly on alveoli and remnants of tooth bases, it was noticeably larger, at least in basal width, than the preceding three teeth (basal widths ca. 2.0 mm), after which the series exhibits a further marked reduction in size anteriorly. At the symphysis is a very small, narrow, bluntly pointed tooth measuring about a 1.0 mm in height. On the basis of the relative sizes of the teeth, particularly the presence of a single, dominant tooth near the posterior end of the preserved series, the low number of teeth, and that the larger teeth were presumably shaped like that of the dominant tooth, the dentition most closely describes those of gymnarthrid microsaurs, such as *Euryodus* and

Cardiocephalus. However, if the identification of the splenial is correct, it is strikingly different from those of gymnarthrids which are anteroposteriorly short and closely associated with the symphysis, and extending the full height of the medial surface of the mandible.

The majority of vertebrates described by Vaughn (1969), however, were collected from the lowermost levels of the Coyote Hills Member of the Abo Formation. As described by Vaughn (1969, p. 6), all the vertebrates are derived from a ~15 m thick band "…generally in the form of a sandwich with a sandstone-conglomerates above, a coarse conglomerate with quartzite pebbles below, and a mudstone with some nodular limestone between." Whereas bone was found in all three layers, most was from finer-grained lenses within the conglomerates. In addition to abundant bone fragments, Vaughn identified labyrinthodont amphibian and pelycosaurian reptile taxa based on isolated elements and partial, articulated portions of skeletons.

Three dissorophid amphibian specimens indicate the presence of at least two taxa: (1) *Platyhystrix* cf. *P. rugosus*, based on a single dorsal vertebra (CM 47783/ UCLA VP 1732: Fig. 8C) that is unique to the genus in possessing an extremely long neural spine that is laterally compressed, distally expanded, and covered for most of its dorsal length by "sculpturing" (presumably dermal in origin); (2) an articulated string of seven vertebrae with attached ribs believed to be dorsals (CM 47784/ UCLA VP 1722: Fig. 8D) that are characteristic of dissorophids in the neural spines being capped by rugose, pitted, dome-like capes of dermal "armor;" and (3) a large, incomplete, badly weathered, three-dimensional skull (CM 47785/ UCLA VP 1721: Fig. 8E-F) that is characteristic of dissorophids in having the cheeks oriented essentially vertical to the horizontally flat roof to produce a high, box-like morphology and possessing enormous interpterygoid vacuities. The pelycosaurian reptiles are represented by three forms: (1) *Edaphosaurus* cf. *E. novomexicanus*, based on four closely associated vertebrae, two of which are nearly complete, and rib fragments (CM 47786/ UCLA VP 1719: Fig. 8I); (2) *Ophiacodon* sp., based on a fragmentary vertebra (CM 89926); and (3) *Sphenacodon* sp., based on a vertebral neural spine (CM 89929).

Vaughn's (1969) descriptions of two of the above dissorophid specimens warrant a few comments. In contrast to his identification of the articulated string of seven dissorophid vertebrae as dorsals (CM 47784), we believe it is more likely that they are anteriormost caudals for the following reasons: the neural arches are smoothly fused with the pleurocentra, the pedicles of the neural arches lack transverse processes, and the ribs appear to articulate close to the ventral margins of the central elements. In addition, the ribs are typical of the caudal region in being short and curved strongly posteriorly. As is typical of most dissorophids, there is no visible, sutural line of division between the sculptured expansion of the neural spine tips believed to be of dermal bone origin and the endochrondral bone of the lower portion of the spine. As noted by Vaughn, dissorophid "armor" is highly variable, and the specimen described here cannot be matched with that of any known form.

We agree with the identification of the skull, CM 47785, as highly likely dissorophid based on his observations that is has a high, box-like morphology and enormous interpterygoid vacuities. An additional feature not noted by Vaughn, the sutural pattern, which, although only partially preserved, shows no signs of deviating from that of dissorophids. Although the skull, as speculated by Vaughn, is of an appropriate size to that of either the *Platyhystrix* dorsal vertebra (CM 47783) or the articulated string of dissorophid-like caudal vertebrae (CM 47784), this seems unlikely. If the caudals belonged to *Platyhystrix*, the neural spines would be expected to be much shorter versions of the dorsals. It should also be pointed out that remnants of the dermal sculpturing along the lateral borders of the skull table and adjoining portions of the cheek of the skull CM 47785 do not exhibit any signs or remnants of the nodular or papillose sculpting that is unique to *Platyhystrix* (Berman et al., 1981). Vaughn also noted a left pelvis (CM 89915: Fig. 8B) found near the *Platyhystrix* vertebra he believed to be of dissorophid aspect. However, in our judgment it is much too large and of the wrong morphology to belong to a dissorophid and more likely belongs to a diadectomorph, most probably *Diadectes*.

In addition to the vertebrates from the above principal, producing level of the Abo Formation, Vaughn described also a few vertebrates from fine-grained sandstones: a rhipidistian scale (CM 47792/UCLA VP 1720: Fig. 8A), a fragmentary vertebral neural spine of the pelycosaur *Edaphosaurus* cf. *E. novomexicanus* (CM 86786: Fig. 8H), the posterior portion of a large labyrinthodont skull (CM 47782: Fig. 8G), and bone fragments. By far the most interesting and perplexing specimen of this list to identify is the posterior portion of the labyrinthodont skull (CM 47782). Vaughn (1969) concluded that it pertains to an edopid close to, if not belonging to, a rhachitome (more proper usage temnospondyl) amphibian of a form similar to the Lower Permian *Edops*, possibly congeneric with *Edops craigi* (Romer and Witter, 1942). His analysis was based mainly on the skull roof, which, as he described, is badly fragmented with the pieces often being marginally incomplete and widely displaced. Yet, he states that the skull table, preserved from between the orbits to the occipital margin, is fairly well preserved, and that the sutural pattern, though only partially traceable, is characteristic of Permian temnospondyls. Most importantly, in reaching an edopid identification, Vaughn relied heavily on the recognition of an intertemporal bone, a primitive feature that is extremely rare among Permian amphibians. However, in a re-examination of the skull roof we could locate only a few possible remnants of the sutural pattern, none of which suggests the presence of an intertemporal. Vaughn also listed two other cranial features of CM 47782 he considered characteristic of edopids: moderately developed interpterygoid vacuities and a highly mobile basicranial articulation. Both these features, however, can be found in many temnospondyls, and assignment of CM 47782 we believe is, therefore, best left as Temnospondyli indeterminate.

Age and Correlation

The trace fossils (especially *Sphaerapus*) from the upper part of the Coyote Hills Member suggest it correlates to upper Abo or lower Yeso strata to the northwest, in Socorro and Torrance

Counties (Lucas et al., 2013a). The vertebrate body fossils from the lower part of the Coyote Hills Member are of taxa found in the Abo Formation to the northwest and in the Cutler Group in the Chama basin of northern New Mexico. These vertebrates are characteristic of the Coyotean land-vertebrate faunachron of Lucas (2006), which is of late Virgilian-late Wolfcampian age. Fusulinids from the Laborcita Member of the Bursum Formation beneath the Coyote Hills Member are of early Wolfcampian age (Steiner and Williams, 1968). Thus, biostratigraphic constraints suggest a middle-late Wolfcampian (early Leonardian?) age range for the Coyote Hills Member.

Regionally, the base of the Abo Formation in the Sacramento Mountains is correlated to the Powwow Conglomerate Member of the Hueco Canyon Formation in the Hueco Mountains to the southeast (e.g., Pray, 1961; Ross and Ross, 1985; Lucas et al., 2011). This suggests that the base of the Abo Formation is of middle Wolfcampian age. Assigning an upper age limit to the Abo Formation in the Sacramento Mountains is more difficult, and some workers consider it to be of early Leonardian age (e.g., Bachman and Hayes, 1958). Indeed, available data indicate the upper Abo is close in age to the Wolfcamp-Leonard boundary. Thus, we regard the Coyote Hills Member of the Abo Formation to be middle-late Wolfcampian in age, and possibly (but not certainly) as young as early Leonardian in its upper part.

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The typical oyster *(Flemingostrea elegans)* of the basal Gallup Sandstone. *Photo courtesy of Geoffrey Rawling.*