



# GEOLOGY OF THE INTERMOUNTAIN WEST

*an open-access journal of the Utah Geological Association*

Volume 2

2015

## Stratigraphy and Fossil Plants from the Cutler Formation (Late Paleozoic) and their Paleoclimatic Implications, Eastern Paradox Basin, Colorado

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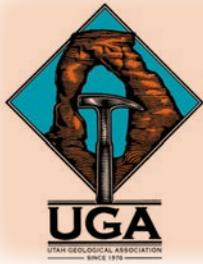
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Cover Photograph

The Palisade is a narrow ribbon-like mesa that rises abruptly from the surrounding area. A layer-cake succession of late Paleozoic to Jurassic-aged strata is exposed in the cliff faces that comprise the margins of The Palisade. Photograph by Kendall R. Grazul.



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## Stratigraphy and Fossil Plants from the Cutler Formation (Late Paleozoic) and their Paleoclimatic Implications, Eastern Paradox Basin, Colorado

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### ABSTRACT

Exposures of the late Paleozoic Cutler Formation, near the town of Gateway, Colorado, have traditionally been interpreted as the product of alluvial-fan deposition along the western flank of the Uncompahgre uplift and within the easternmost portion of the Paradox Basin. The Paradox Basin formed between the western margin of the Uncompahgre uplift, a segment of the Ancestral Rocky Mountains, and the western paleoshoreline of the North American portion of Pangea. This part of Pangea is commonly thought to have experienced semi-arid to arid conditions and warm temperatures during the Pennsylvanian and Permian. We present stratigraphic and fossil plant evidence in this paper to support prior interpretations that the Cutler near Gateway, Colorado, was deposited by alluvial fans that hosted localized wetland areas. Our findings are consistent with the results of prior studies that have suggested the climate in the area was warm, semi-arid, and ice-free at the time the plants described in this paper were living.

Plant fossils collected from the Cutler Formation came from two sites in The Palisade Wilderness Study Area (managed by the U.S. Department of the Interior, Bureau of Land Management) of western Colorado. The stratigraphic sections at the sites were composed mostly of pebble to cobble conglomerate and sandstone, but the fossil plants were mainly preserved in fine-grained intervals (fine-grained sandstone to siltstone). The preservation of plant fossils in the proximal Cutler Formation is remarkable because the surrounding sections consist mostly of conglomerate and sandstone interpreted as fluvial and debris-flow deposits. The fine-grained strata containing the plant horizons must have been deposited in a wet and protected setting, possibly a spring-fed abandoned channel on the alluvial fan. The plants and their surrounding sediment must have been rapidly buried in order to allow for long-term preservation of the fossils. It seems likely that vegetation was abundant in and adjacent to low-lying wet areas on the fan's surface, based on the abundance of plant fossils found at the two sites. The fossil plant assemblage includes *Calamites*, *Walchia*, and *Pecopteris*. The flora are interpreted to have lived near the apex of the alluvial-fan system. These fossils suggest that warm and at least seasonally and locally wet conditions existed in the area during the time that the plants were growing. More arid conditions during the late Paleozoic are suggested by the characteristics of some of the time-equivalent and near time-equivalent rocks exposed to the west of the study area in the central Paradox Basin.

Grazul, K.R., Huntoon, J.E., and O'Keefe, J.M.K., 2015, *Stratigraphy and fossil plants from the Cutler Formation (late Paleozoic) and their paleoclimatic implications, eastern Paradox Basin, Colorado: Geology of the Intermountain West*, v. 2, p. 9-27.

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## INTRODUCTION

This study focuses on the stratigraphy and paleobotany of a portion of the Cutler Formation (late Paleozoic) and their paleoclimatic implications for an area located near the modern-day town of Gateway, Colorado. For this study, samples were collected from sites located within The Palisade Wilderness Study Area (WSA) / Outstanding Natural Area (ONA) / Area of Critical Environmental Concern (ACEC), which is managed by the Grand Junction Field Office of the U.S. Department of Interior, Bureau of Land Management. The Palisade WSA is located in western Colorado, approximately 30 miles southwest of Grand Junction (figure 1). The Palisade WSA is named for a towering, ribbon-like mesa known as The Palisade.

In contrast to the The Palisade itself, the majority of The Palisade WSA consists of relatively subdued topography formed on the Cutler Formation. The Cutler was deposited along the western flank of the Uncompahgre uplift, a segment of the Ancestral Rocky Mountains, within the easternmost part of the Paradox Basin during the Pennsylvanian and Permian (Baker and Reeside, 1929; Turnbow, 1955). Exposures of the Cutler in The Palisade WSA include some of the most proximal deposits contained within the formation (Mack and Rasmussen, 1984). Canyons and gullies carved by modern

ephemeral streams provide outstanding three-dimensional exposures, making the area an ideal location for study of the proximal Cutler Formation.

Exposures of the Cutler Formation near Gateway have traditionally been interpreted as the products of deposition in an alluvial fan (Walker, 1967; Werner, 1974; Campbell, 1979; Mack and Rasmussen, 1984; Campbell, 2003). The Cutler near Gateway is commonly referred to as “the Gateway Fan.” Despite the conventional thought regarding the formation’s depositional environment, attempts to characterize the climate at the time of deposition have resulted in considerable debate. Evidence has been presented to support interpreted climate conditions ranging from ever-wet (Campbell, 1979), through seasonally wet and semi-arid to sub-humid (Mack and Rasmussen, 1984; Campbell, 2003), to semi-arid to arid (Walker, 1967; Werner, 1974).

Interpretations of semi-arid to arid conditions during the late Paleozoic are supported by the presence of halite, anhydrite, and gypsum in the Paradox Formation, which was deposited in the central portion of the Paradox Basin during the Pennsylvanian (Hite and Buckner, 1981). The Paradox Formation may be, in part, a lateral equivalent to the oldest parts of the Cutler Formation (Condon, 1997). Younger lateral equivalents in the central and western Paradox Basin region include Permian sandstones deposited in eolian environments (e.g., Cedar Mesa and White Rim Sandstones). These eolian sandstones, like the Paradox Formation, indicate arid conditions were dominant in the central Paradox Basin for extended periods during the time of deposition of the Cutler Formation (Nuccio and Condon, 1996).

In contrast to the traditional understanding of the Cutler Formation as the product of alluvial-fan deposition, Soreghan and others (2009) interpreted the Cutler in The Palisade WSA as a low-latitude, proglacial, fluvial-lacustrine deposit. This hypothesis suggested that tropical glaciers existed at low elevations and low latitudes in western Pangea during the late Paleozoic. More recently however, an analysis of plant fossils collected from the proximal Cutler Formation (Huntoon and others, 2014) led to the conclusion that interpretations of an alluvial fan origin for the formation near Gateway are justified.

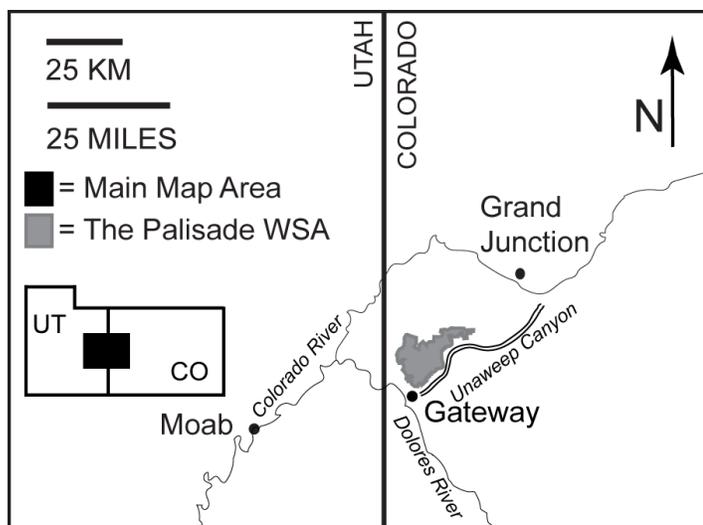


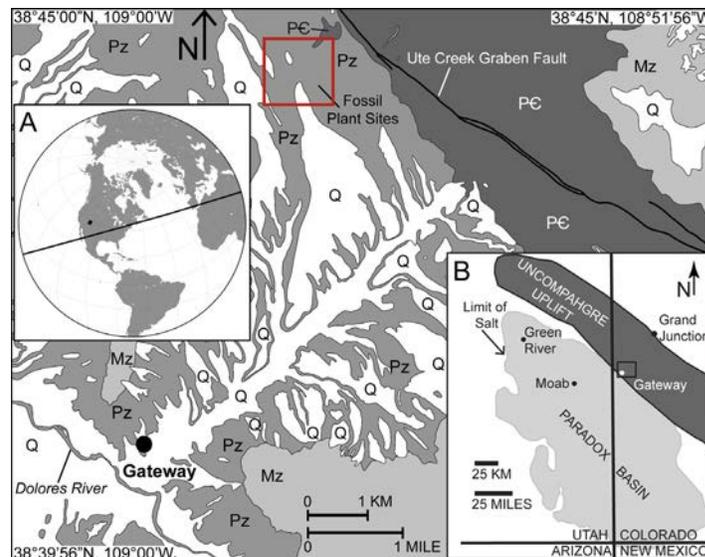
Figure 1. Location of The Palisade WSA in western Colorado. Colorado River, Dolores River, and Unaweep Canyon all shown on map. Inset map shows location of main map area in Utah and Colorado.

In addition to Huntoon and others (2014), other studies have investigated plant fossils and palynomorphs obtained from the proximal Cutler Formation (e.g., Werner, 1974; Mack and Rasmussen, 1984; Soreghan and others, 2007). The results of previous analyses provide a rich source of data that can be used to constrain interpretations regarding environmental conditions in the local area at the time of deposition of the Cutler. The additional plant fossils described in this paper support the interpretation of the Cutler as an alluvial-fan deposit. The plants and lithofacies also suggest that the climate in The Palisade WSA during the late Paleozoic was warm and that water was locally present on the upper reaches of the alluvial fan at the time of deposition. It seems that there must have been abundant vegetation in and adjacent to low-lying wet areas at the time the Cutler Formation was deposited based on the amount of fossilized plant material found.

## GEOLOGIC SETTING

During the late Paleozoic, the area that now makes up The Palisade WSA was located near the western margin of proto-North America at near-equatorial paleolatitudes (figure 2). The Palisade WSA was at that time bounded on the east by the southwestern faulted margin of the Uncompahgre uplift. This uplift was the westernmost outlier of the Ancestral Rocky Mountains. Segments of the Ancestral Rocky Mountains extended across late Paleozoic North America (Ye and others, 1996).

The Uncompahgre highlands rose and continuously eroded during the late Paleozoic. They contributed sediments that were deposited in and adjacent to the Paradox Basin, which was located to the west of the uplift. The Cutler Formation in The Palisade WSA consists of mostly coarse-grained sediment eroded from the Uncompahgre uplift (Werner, 1974) and deposited directly adjacent to its western margin in the easternmost part of the Paradox Basin. The Cutler reaches a maximum thickness of approximately 5 kilometers (Barbeau, 2003) proximal and medial to the Uncompahgre highland; The Palisade WSA is located along the flank of the uplift. The formation thins to about 500 meters (Barbeau, 2003) to the west and southwest



**Figure 2.** Simplified geologic map of the study area (modified from Huntoon and others, 2014). Geology modified from Carter (1955): PE = Precambrian rocks (dark gray); Pz = Paleozoic Cutler Formation (medium gray); Mz = Mesozoic strata (light gray); Q = Quaternary alluvium (white). Locations of fossil plant sites are indicated with the red box. Latitude and longitude shown for the northwest, northeast, and southwest corners of the map. (Inset A) Location of study area and late Paleozoic paleoequator (calculated by Smirnov, Michigan Technological University, personal communication, 2011). (Inset B) Location of study area; small rectangle enclosing Gateway is shown expanded as the main map in this figure.

across the Paradox Basin and undergoes lithofacies changes so that it is referred to as the Cutler Group (Condon, 1997) in the western part of the Paradox Basin. The lowermost part of the Cutler Formation and Group in areas more distal to the Uncompahgre uplift record cycles of marine flooding and evaporation in the Paradox Basin that resulted from long-term cycles of sea-level change during the late Paleozoic (Rankey, 1997). Reconstructions of the original thickness of the Cutler Formation, as well as precise determination of its current thickness in different areas, are subjects of much debate. Deformation of the Pennsylvanian Paradox Formation that occurred during deposition of the Cutler Formation resulted in the development of numerous salt-related structures (e.g., mini-basins, salt-walls) in the subsurface of the Paradox Basin (Trudgill, 2011). These features influenced deposition of the Cutler Formation and its lateral equivalents, including

the Cutler Group (Trudgill, 2011).

The proximal portions of the Cutler Formation are currently exposed near Gateway due in part to Laramide uplift (White and Jacobsen, 1983; Bump and Davis, 2003) that resulted in reactivation of one or more Paleozoic faults and development of additional faults along the southwest margin of the modern Uncompahgre Plateau (White and Jacobsen, 1983; Mankowski, 2003). Cenozoic uplift of the Colorado Plateau (Sahagian and others, 2002) and subsequent incision by the Colorado River and its tributaries produced the exposures examined in this study.

In The Palisade WSA, the Cutler Formation typically consists of pastel-colored (reddish, pinkish, purplish, and light grayish hues) proximal clastic rocks that are dominated by conglomerate and sandstone (Huntoon and others, 2014). Quartz and feldspar are the most abundant minerals within the Cutler, although biotite, hematite, epidote, muscovite, and opaque minerals are also common (Campbell, 2003). Although coarse sandstone and conglomerate beds are common in the Cutler Formation in the study area, the fossils described in this paper were primarily collected from fine-grained beds.

The proximal Cutler Formation was vegetated during the late Paleozoic. Recently, Huntoon and others (2014) described plants fossils from the Cutler, including *Pecopteris*, *Calamites*, *Archaeocalamites*, and *Neuropteris*. All of these plants are thought to have lived in environments with a high water table for a large portion of the year (Tidwell, 1998). Additionally, Mack and Rasmussen (1984) documented the presence of rhizcretions in the proximal Cutler Formation and Soreghan and others (2007) identified late Paleozoic palynomorphs (*Densosporites*, *Lycospora*, *Vesicaspora*, and *Florinites*) in samples they collected in and near The Palisade WSA.

## METHODS

The goal of this study was to document and describe plant fossils and fossil-bearing strata in the Cutler Formation within The Palisade WSA. In order to achieve this goal, fieldwork was conducted in the summer of 2014. Field investigations focused on two areas located to the west of the mouth of Unaweep Canyon, to the

north of West Creek and to the south and east of the topographic promontory known as The Palisade (see figure 3 and cover photograph). The area was mapped and samples were collected and transported to Michigan Technological University for further analysis.

The field study covered areas located on the Gateway and Two V Basin U.S. Geological Survey 7.5-minute topographic quadrangle maps. Locations were determined using hand-held Garmin Global Positioning System (GPS) units and the 1:24,000-scale topographic maps (Gateway and Two V Basin). Draws, side canyons, and ridges were explored in search of plant fossils. At the same time, the contact between the Cutler Formation and the Precambrian rocks that formed the core of the Uncompahgre uplift was traced and mapped. When fossil-bearing rocks were encountered, their locations were indicated on the field map. The occurrences of rocks with a lithology similar to the fossil-bearing strata were also mapped.

Fossil plants and plant fragments were collected

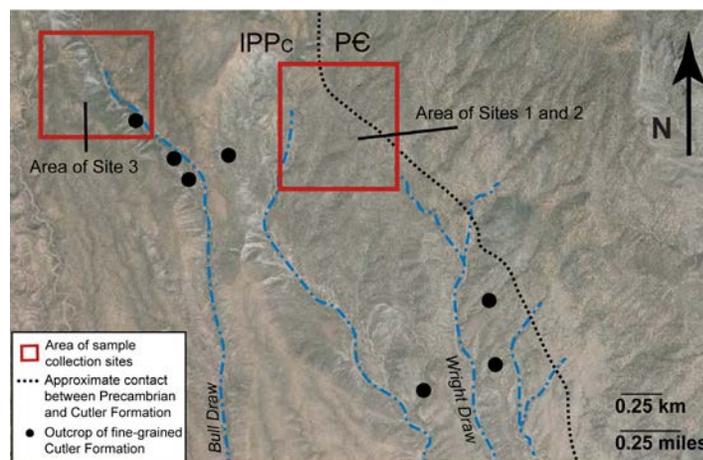


Figure 3. Aerial view of a portion of the study area. Approximate location of sample collection sites labeled. More precise location information withheld in compliance with Bureau of Land Management permitting requirements. Faulted contact between Precambrian granite and gneiss (labeled PE) and late Paleozoic sedimentary Cutler Formation (labeled IPPc) shown with dotted line. Locations of plant fossil localities are outlined with red boxes and are situated adjacent to the contact. Locations of sites containing relatively fine-grained material, similar in lithology to the fossil-bearing layers, are shown with black filled circles. Image from Google Earth and U.S. Department of Agriculture Farm Service Agency.

from two sites; USNM 43857 (site 1) and USNM 43856 (site 2). It is important to note that these sites are subdivisions of a prior collection site (USNM 43705) described in Huntoon and others (2014). The fossils were photographed in place, collected, and transported from the field for detailed description and identification in the laboratory. Measured sections were prepared for the two fossil-bearing sites. Hand samples were collected from the two fossil-bearing sites and from one non-productive site (USNM 43858, site 3) that was similar in lithology to the fossil-bearing rock. These hand samples were later processed in the laboratory in an attempt to retrieve late Paleozoic palynomorphs.

Despite careful searching, no other plant fossil localities were identified. Although lithofacies similar in color and grain size to the fossil-bearing units were encountered at several other sites, material exposed at the surface at the majority of those other sites was too unconsolidated to allow for successful collection of plant material, even if it was present. Extensive excavations were not undertaken however, so it is possible that better lithified material is present below the surface at some of those sites.

In the laboratory, the samples containing plant fossils were organized by type, renumbered, and re-photographed. Each fossil was described, and fine details were examined and sketched. Photographs and sketches were used to compare to plant fossils described in the literature in order to identify each specimen. All of the fossils are now housed in the type/illustrated collections of the National Museum of Natural History, Smithsonian Institution, Washington, D.C.

Hand samples were taken to Morehead State University for palynological processing and analysis. The hand samples were crushed to pass through a 1-mm mesh sieve, and 2 gram sub-samples were split from each crushed hand sample using a microriffler. The material was demineralized and deflocculated in preparation for the extraction of organic material. The O'Keefe Method was used to process the samples (O'Keefe and others, 2011; O'Keefe and Eble, 2012). Permanent slides were prepared and inventoried for palynomorphs. Unfortunately, no identifiable late Paleozoic palynomorphs were obtained.

## DESCRIPTION OF PLANT FOSSIL SITES

The plant fossils were described and collected from two sites (figure 3) located near the faulted contact between the Cutler Formation and the Precambrian granite and gneiss that formed the core of the Uncompahgre uplift of the Ancestral Rocky Mountains (figure 4). In the vicinity of the plant fossil sites, the Cutler Formation is cut by reverse faults (possibly reactivated during the Laramide orogeny) that place Precambrian rock above the Cutler Formation and older Cutler on top of younger Cutler (Mankowski, 2003). These structural complications make it difficult to trace individual stratigraphic horizons across the study area. The intervals containing the plant fossils at the two sites are 2 to 3 meters thick, a small fraction of the total modern-day thickness of the Cutler Formation near Gateway, which has been estimated at 150 to 300 meters (Condon, 1997). Below is a detailed description of the fossil-plant horizons and the fossil plants collected at each site.



**Figure 4. Faulted contact between late Paleozoic Cutler Formation (left of hammer) and Precambrian granite (right of hammer). The Precambrian granite is up on the east-northeast relative to the Cutler Formation on the west-southwest. View is to the northwest. Fault trace strikes N. 20° W., and dips 60° NE. Both plant fossil sites are located near the faulted contact between the Cutler Formation and the Precambrian rocks.**

## Site 1

### Stratigraphic Description

The fossil-plant horizon at site 1 (USNM 43857) is at the top of an approximately 3-meter thick section that consists of three units (figures 5 and 6). Unit 1, the lowest unit in the measured section, is a dark gray, poorly sorted, matrix-supported boulder conglomerate (figure 5). It contains subangular to subrounded randomly oriented clasts composed of granite and gneiss. The lower unit also contains approximately 50% clasts with a maximum size of 35 centimeters and an average size of 5 centimeters. The matrix is very coarse to fine-grained sandstone consisting of angular to subangular grains of quartz and feldspar. The base is not exposed. Unit 1 is interpreted as a debris-flow deposit.

Unit 2 is an olive-black, poorly sorted, sandy, pebble to cobble conglomerate with angular clasts of feldspar and quartz. It contains approximately 40% clasts with a maximum size of 4 centimeters and an average size of 0.5 centimeters. The matrix is mudstone to very coarse sandstone. This unit contains alternating layers of coarse- and fine-grained strata interrupted by scattered lenses of sandstone and sandy siltstone on the or-

der of 1 to 5 centimeters thick. Unit 2 is interpreted as the product of fluvial deposition.

Unit 3 contains the fossil-bearing horizon. It has a maximum thickness of 10 centimeters and consists of moderate yellowish-brown, thinly laminated, micaceous siltstone to fine-grained sandstone. This unit is interpreted as the product of deposition under slack-water conditions in a fluvial system due to the abundance of fine-grained material, including flakes of mica.

### Fossil Content

Four distinct specimens of identifiable plant fossils were collected from site 1. The first group of identifiable specimens are all members of the genus *Calamites*. Many small and incomplete calamitean fragments were found at this location. The best preserved specimen (figure 7) is 13.5 centimeters long and 3 centimeters wide. This sample appears to be an incomplete external stem cast (DiMichele and Falcon-Lang, 2012). The external surface of the cast is longitudinally ribbed with grooved indentations. The ribs are 0.1 centimeters wide. There are three nodes visible on the specimen and the ribs alternate at the nodes, as is typical of *Calamites* (Tidwell, 1998). The fossil is light brown in color and is present in a moderate yellowish-brown siltstone.

The second specimen collected is *Walchia*. It is 2.6 centimeters long and 0.3 to 0.5 centimeters wide (figure 8). The scale-like leaves are oval and come to a point where they join the stem. Each leaf is approximately 0.2 centimeters long and 0.1 centimeters wide and is oriented at an acute angle to the center stem. *Walchia* is characterized by narrow branches with small, upright leaves that taper to a point (Arnold, 1941), as is evident in this specimen. No veins are visible on the impressions of individual leaves. The specimen is moderate yellowish-brown and is present in a pale yellowish-brown siltstone.

The third specimen collected is a *Pecopteris* fossil (figure 9). It has a rachis that is 15 centimeters long, 0.3 centimeters wide, and is straight and heavy as is common for *Pecopteris* (Wittry, 2006). The pinnae alternate along the stem. Some impressions of the pinnae are very faint, but those that are recognizable measure between 5 and 6 centimeters long and 0.5 to 1 centimeter wide. The pinnae come to a point at their

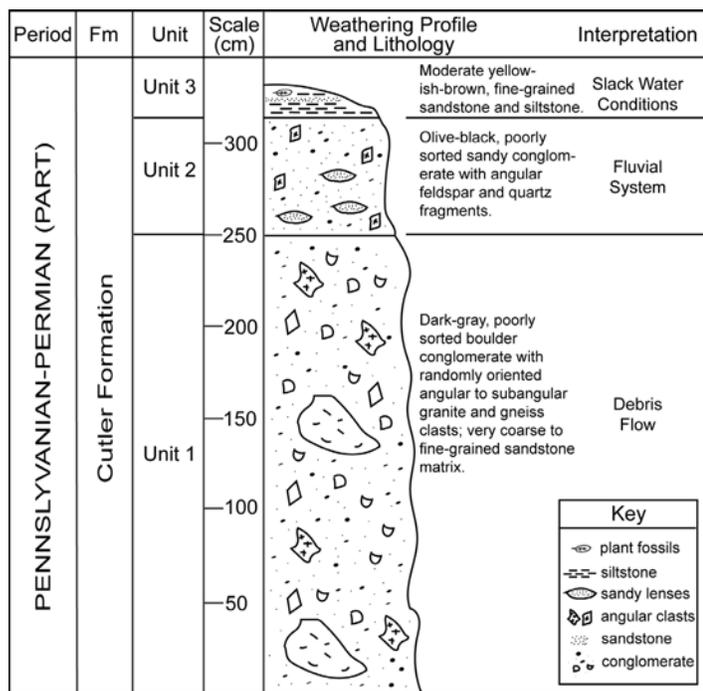


Figure 5. Measured section of site 1. Plant fossil horizon is in fine-grained strata of unit 3. See main text for description.

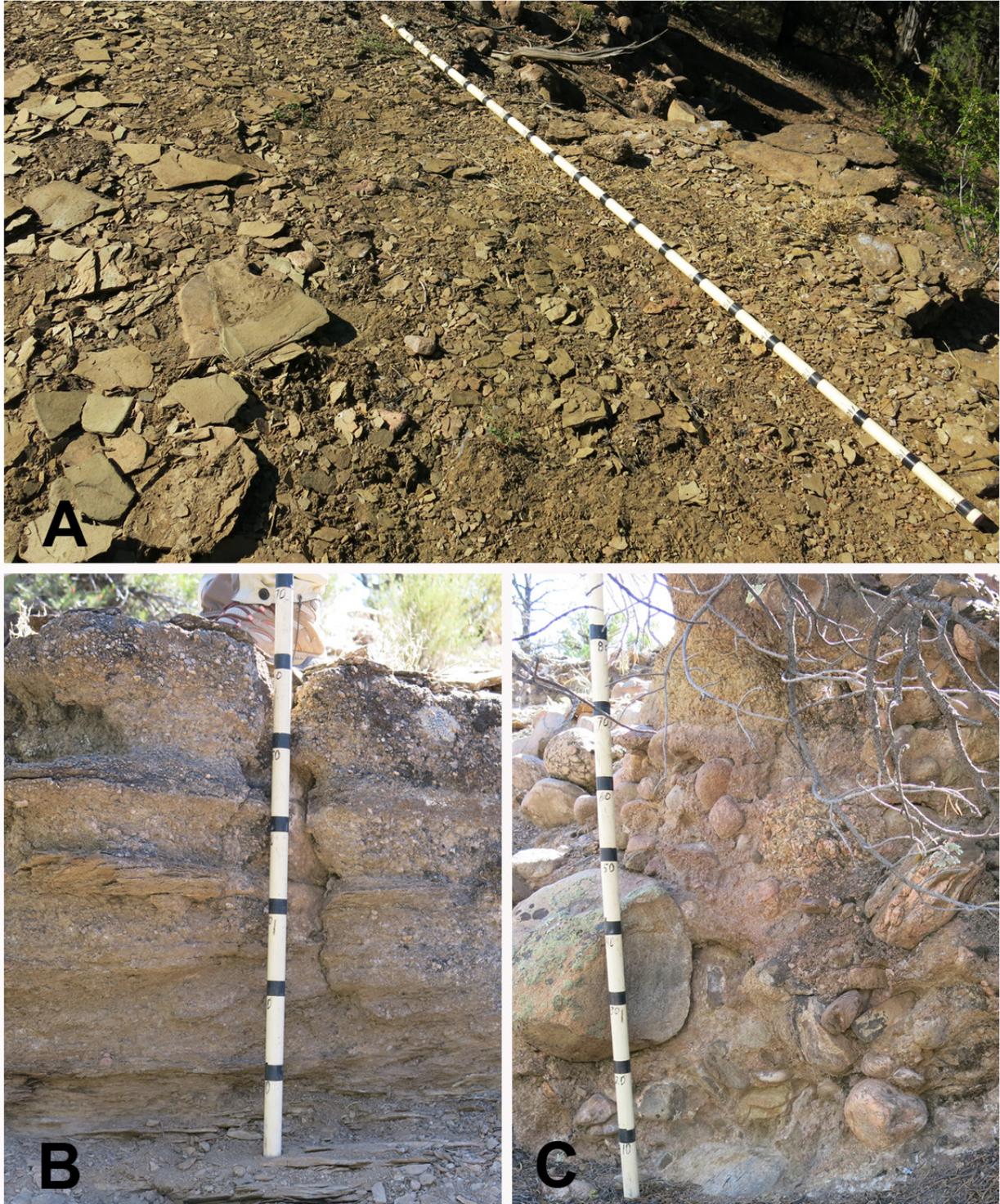


Figure 6. Photographs of site 1 (Jacob's staff marked in 10 centimeter increments). (A) Surface view of top of fossil-bearing unit 3 as it is exposed along the crest of a ridge. (B) Conglomerate and sandstone beds typical of unit 2. (C) Conglomeratic beds of unit 1 near base of the measured section.

distal ends. As is typical of *Pecopteris*, the pinnae consist of small pinnules with a broad basal attachment to the costa and slight confluence between adjacent pinnules

(DiMichele and others, 2010). The stem is moderate brown. Both the fronds and surrounding siltstone are moderate yellowish-brown in color.



Figure 7. Specimen of *Calamites* (specimen dimensions = 13.5 cm x 3 cm) at site 1 (USNM 43857). USNM Specimen 611005.

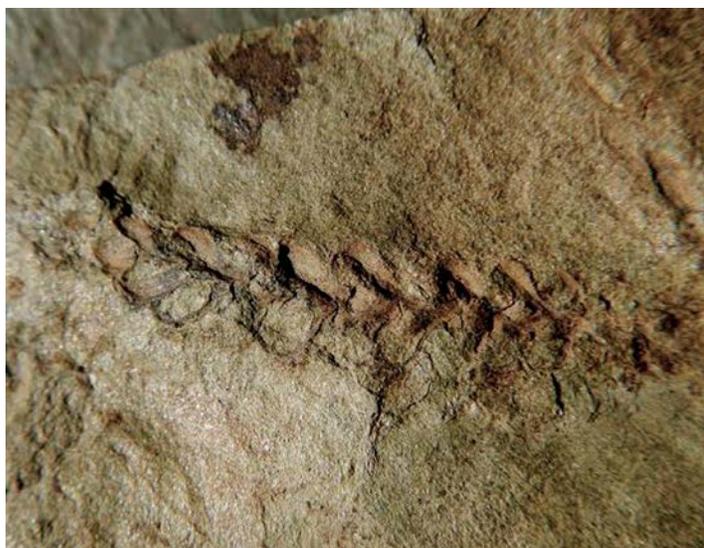


Figure 8. Specimen of *Walchia* (specimen dimensions = 2.6 cm x 0.4 cm) at site 1 (USNM 43857). USNM Specimen 611006.



Figure 9. Specimen of *Pecopteris* (specimen dimensions = 15 cm x 8 cm) at site 1 (USNM 43857). USNM Specimen 611007.

The last identifiable specimen found at site 1 is another *Pecopteris* specimen (figure 10). The specimen is 5 centimeters long and 3 centimeters wide at the base. The pinnules, which are about 0.4 centimeters wide, get progressively smaller away from the base of the pinna. *Pecopteris* tends to have alternate, closely spaced, and straight-sided pinnules (Wittry, 2006). Each pinnule is rounded and has a well-defined rib in the center. The pinnules have flat bases where attached to the stem. The pecopterid is moderate yellowish-brown in a pale yellowish-brown siltstone.

## Site 2

### Stratigraphic Description

Site 2 (USNM 43856) is located very close to, but stratigraphically below, site 1 in the Cutler Formation and within 100 meters of the faulted contact with Precambrian rocks of the Uncompahgre uplift (figures 3 and 4). The section at site 2 is approximately 2 meters thick and consists of three units (figures 11 through 13). The basal unit 1 and the capping unit 3 are very similar to unit 2 described at site 1. Units 1 and 3 at site 2 are interpreted as the product of fluvial deposition. The middle unit at site 2, which contains the majority of the plant fossils, is approximately 70 centimeters thick and consists of interbedded coarse- and fine-grained strata. The coarse-grained strata of unit 2 are medium- to very coarse grained, reddish-orange sandstone less than 5 centimeters in thickness. The relatively fine-grained

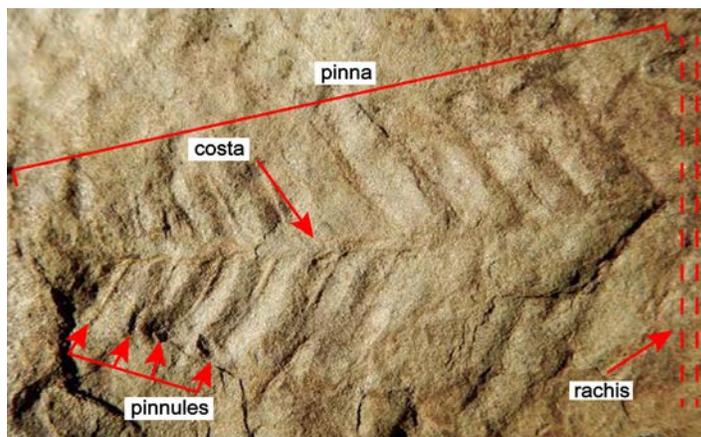


Figure 10. Specimen of *Pecopteris* (specimen dimensions = 5 cm x 3 cm) at site 1 (USNM 43857). USNM Specimen 611008.

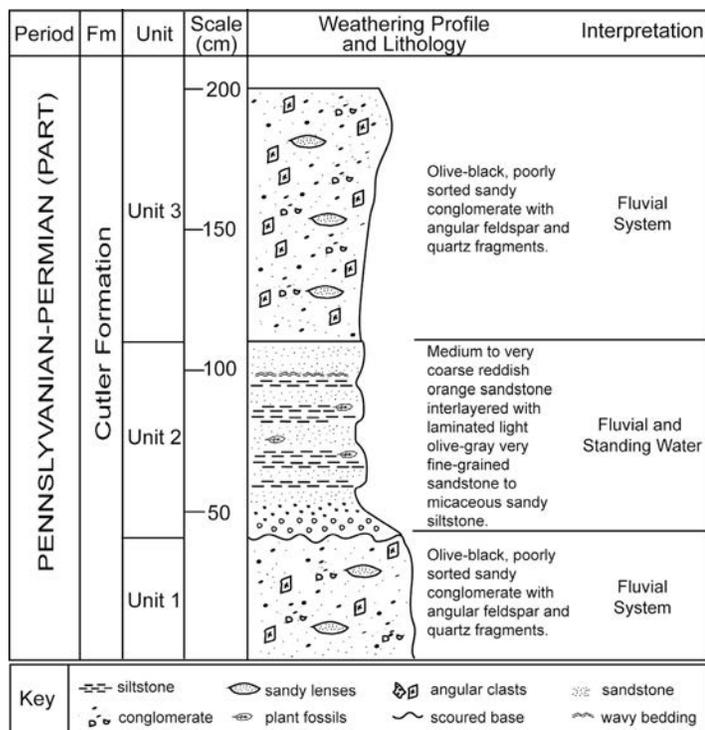


Figure 11. Measured section of site 2. Fine-grained strata of unit 2 contain the majority of the plant fossils at site 2. See main text for description.

strata consist of thinly laminated light olive-gray, very fine grained sandstone to micaceous sandy siltstone. Unit 2 at site 2 has a scoured basal boundary and fines upward overall. The best preserved plant fossils at site 2 were found within the fine-grained strata of unit 2, although the coarser strata within unit 2 also contained fossil fragments. Some of the thinly laminated micaceous beds within unit 2 show small-scale wavy deformation that is possibly due to compression. Unit 2 is interpreted as the product of deposition under standing-water conditions in a fluvial system. Unit 3 at site 2 also contained some plant material including a calamitean fragment that appears to have been preserved in place in an upright orientation (figure 13).

### Fossil Content

Four identifiable plant fossils were collected from site 2. The first *Pecopteris* specimen (figure 14) collected at site 2 is 3.5 centimeters in length and 4.5 centimeters at its widest point. A partial stem is visible with fragments of pinnae attached in a v-shaped pattern. The pinnae are alternately arranged and 2.2 to 3 centimeters

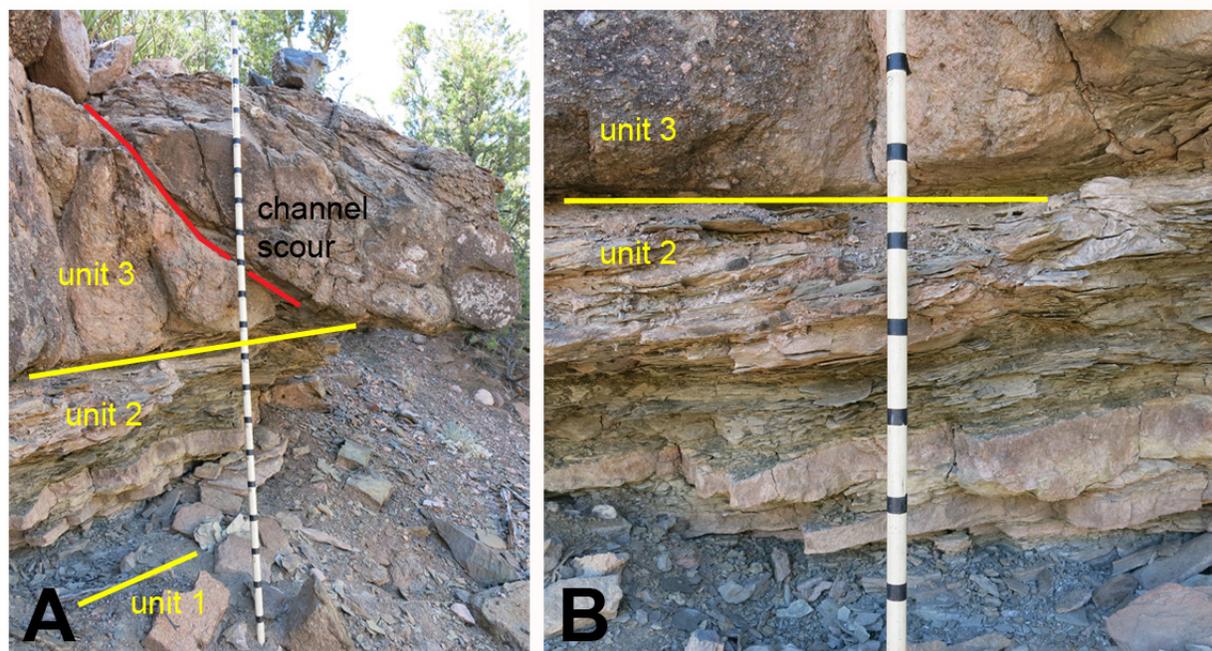
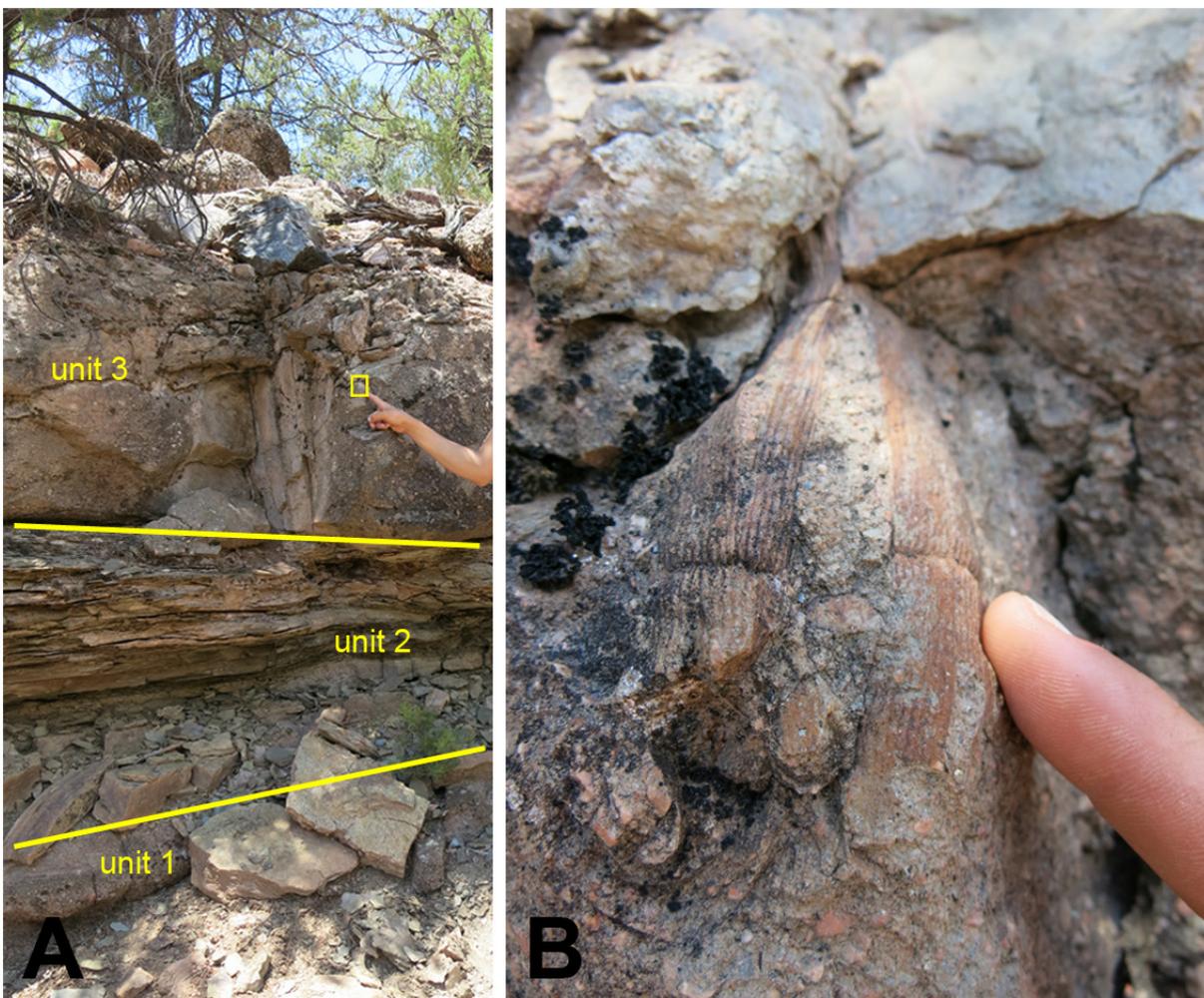


Figure 12. Photographs of measured section at site 2 (Jacob's staff marked in 10 centimeter increments). (A) View of full measured section. The location of the contact between units 1 and 2 is obscured by float in the photo; the approximate position of the contact is as shown. Location of a scoured channel within unit 3 is shown in red near the top of the measured section and outcrop. (B) Close-up view of unit 2 and base of unit 3 at site 2.



**Figure 13. Calamitean fragment in place in unit 3 at site 2. (A) Outcrop-scale view of part of the measured section with person pointing to calamitean fragment. (B) Close-up view of calamitean fragment.**

long and 0.1 to 0.5 centimeters wide. Pinnae become thinner away from the site of attachment to the stem and come to a point at the distal tips. Similar to the *Pecopteris* specimen from site 1, there are small pinnules with a broad basal attachment to the costa and slight confluence between adjacent pinnules (DiMichele and others, 2010). The specimen is olive-gray within a dark greenish-gray micaceous siltstone.

A second *Pecopteris* specimen (figure 15) was collected from site 2. It is 3 centimeters long and 1 centimeter wide. The pinnules in this specimen are 0.5 centimeters long, 0.4 centimeters wide, rounded, and adhered to the stem along the entire base. The pinnules are alternately arranged, closely spaced, and generally attached nearly perpendicular to the mid-rib (Wittry, 2006). Sparse venation is present and appears to be

widely forked and one-time divided, as is characteristic of pecopterids (W.A. DiMichele, Smithsonian Museum of Natural History, personal communication, 2015). The fossil is grayish brown within a moderate yellowish-brown siltstone.

Site 2 also yielded *Walchia* specimens. The best preserved *Walchia* fossil (figure 16) from site 2 is 2.8 centimeters long and 0.3 centimeters wide. The specimen is characterized by narrow branches with small, upright leaves that taper to a point (Arnold, 1941). The leaves are seed shaped and also come to a point where they are attached to the stem. Each leaf is 0.3 centimeters long and the average width is on the order of 0.1 centimeters. The fossil is brownish-gray within a dark greenish-gray micaceous siltstone.

A small fossil calamitean cone (figure 17), possibly



Figure 14. Specimen of *Pecopteris* (specimen dimensions = 3.5 cm x 4 cm) at site 2 (USNM 43856). USNM Specimen 611009.

from the genus *Palaeostachya*, is 1.8 centimeters long and 0.4 centimeters wide. The different kinds of calamitean cones cannot always be recognized without clear preservation of the spore-bearing organs (Arnold, 1958). These organs are not distinguishable in this specimen. The cone is incomplete because the base and stem are not preserved. The central axis has regularly spaced discs with whorls of bracts extending from the sides (Arnold, 1958). The fossil is preserved as an olive-gray impression in a dark greenish-gray micaceous siltstone.

### Site 3

Site 3 (figure 18, USNM 43858) contained no plant fossils, but was sampled for pollen, spores, and other organic material. Site 3 is a massive to cross-stratified, grayish-purple pebble conglomerate that contains lenses of micaceous, platy siltstone. Siltstone lenses average 3 centimeters thick with the largest lens reaching 5 centimeters in thickness. We sampled a lens that extended for several meters horizontally. The unit as a whole is exposed for several tens of meters along the west side of Bull Draw (figure 3). The coarse-grained components of the unit contained angular



Figure 15. Specimen of *Pecopteris* (specimen dimensions = 3 cm x 1 cm) at site 2 (USNM 43856). USNM Specimen 611010.

clasts, averaging 1 centimeter in diameter, of feldspar and granite supported by matrix consisting of silt- to clay-sized particles. The fine-grained (siltstone) lenses at site 3 are similar to the fossil-bearing horizons at sites 1 and 2 in terms of grain size and platy texture, but contained lesser amounts of mica. Organic material obtained from the sample collected at site 3 contained only modern palynomorphs and charcoal. The cross-stratified conglomerate at site 3 reflects deposition by fluvial processes. The lenses of micaceous, platy siltstone were deposited under low-flow or standing-water conditions.



Figure 16. Specimen of *Walchia* (specimen dimensions = 2.8 cm x 0.3 cm) at site 2 (USNM 43856). USNM Specimen 611011.

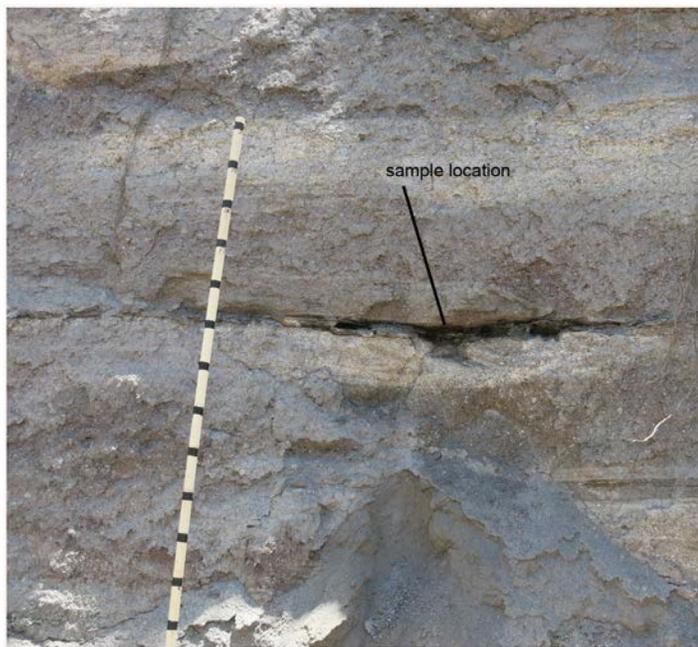


Figure 17. Specimen of a calamitean cone (specimen dimensions = 1.8 cm x 0.4 cm) at site 2 (USNM 43856). USNM Specimen 611012.

## DISCUSSION

The stratigraphic successions at the three sites described for this study included pebble conglomerate that was deposited by fluvial processes. All three sites contained evidence of variations in depositional energy through time. At sites 1 and 2, fluctuations in flow strength were indicated by the presence of alternating

layers of relatively coarse and fine material. The finest layers at all three sites consisted of platy, micaceous fine-grained sandstone to siltstone that was deposited under standing-water or low-flow conditions. Only site 1 included matrix-supported boulder conglomerate containing subrounded randomly oriented clasts up to 35 centimeters in diameter that is interpreted as a debris-flow deposit. In aggregate, the stratigraphic



**Figure 18.** Photograph of site 3 (Jacob's staff marked in 10 centimeter increments) showing the sampled dark-gray micaceous siltstone. Surrounding material, and the majority of the outcrop consists of grayish-purple pebble conglomerate.

ic successions at the three sites reflect subaerial deposition in an environment that experienced variability in discharge and sediment supply through time. The coarsest materials, within the debris-flow deposits, required substantial energy for transport (and probably steep slopes) whereas the finest materials would have only been deposited and preserved in protected settings under low-energy flow conditions.

Taken together, the lithologic characteristics documented at the three sites suggest that deposition occurred near the apex of an alluvial fan (Huntoon and others, 2014). Debris flows would have been active during high-discharge events that flushed accumulated debris from the Uncompahgre highland toward the west where it could be deposited in the easternmost part of the Paradox Basin. Although fluvial deposition was the dominant depositional process at each of the three sites, moderate to high energy down-fan flows were temporarily interrupted at each site for an extended period of time. The interruption of down-fan fluvial transport probably resulted from channel abandonment. Large floods in arid and semi-arid climates can cause avulsion of the main fan channel, shifting the locus of deposition

to previously inactive parts of the fan (Chawner, 1935). Abandoned or blocked fluvial channels are generally recognized as good sites for the potential preservation of plant material in continental environments (Gastaldo and Demko, 2011). If the downstream end of an abandoned channel is blocked by vegetation or debris, the abandoned channel may experience standing-water conditions. The occurrence of low-flow or standing-water conditions in small, localized sites during deposition of the Cutler Formation is suggested by the presence of the fine-grained layers, including micaceous siltstone, at each of the three sites. Extremely small shear stresses are required to move platy mica grains and these grains would have been transported far downstream by flows of any appreciable strength. Deposition of micaceous siltstone must have occurred in protected areas under standing-water or very low-energy flow conditions. Although ultimately short-lived, the protected, quiet-water sites existed for a sufficient amount time for fine-grained sediment and plant material to be deposited. Overall, the characteristics of the strata at sites 1 and 2 (including debris-flow, fluvial, and slack-water deposits) indicate that the area was at least seasonally and locally wet during deposition of the fossil-bearing strata.

Preservation of both the fine-grained sediment and the fossil plants required rapid burial and subsidence. Rapid burial was required to protect the fine-grained sediment and plant material from post-depositional erosion. Subsidence was required to ensure that the plant material was maintained at depths below the water table so that it could be preserved (Gastaldo and Demko, 2011). Unusual conditions were required for both the deposition and preservation of the fine-grained plant-bearing layers as well as the plant fossils themselves. Although many protected, vegetated wetland sites may have existed at the time of deposition of the proximal Cutler Formation, micaceous siltstone layers are now uncommon. This is not surprising, given that the majority of the Cutler in The Palisade WSA was deposited under conditions that would have easily transported silt and sand-sized materials downstream. Where present, the majority of the remaining preserved occurrences of micaceous siltstone in the Cutler Formation in the study area are devoid of even small frag-

ments of plant material. Again, this is not unexpected because fragile plant material would not have survived any appreciable downstream transport, and would have been rapidly degraded if it remained at or near the surface for any length of time.

The fossil flora found near Gateway are a mixture of species typical of seasonally dry environments as well as wetland settings. Most of the plant fossils collected from the Cutler Formation are, however, known to have inhabited environments dominated by wet conditions (Tidwell, 1998). For example, *Calamites* has been found in both coal swamps and flood basins (Gastaldo, 1986, 1987), and is tolerant of excessive flooding and sediment burial (Gastaldo and others, 1995; DiMichele and others, 2001). *Pecopteris* has been found in Carboniferous coal swamps, but is also known from relatively dry Permian environments (DiMichele and others, 2001).

Although most of the plants are interpreted to have lived in a wide variety of wetland settings, walchian conifers were stress-tolerant plants that lived in relatively dry habitats (Rothwell and others, 1997). Coniferous genera such as *Walchia* have long been considered a common constituent of the Permian flora, but *Walchia* also occurs in association with typical Pennsylvanian genera (Arnold, 1941). The appearance of *Walchia* in the mid-continent region is thought to reflect increasing aridity (Arnold, 1941). The presence of *Walchia* in the Cutler Formation may be a good indication of the regional or background climate in the area at the time of deposition. Arid to semi-arid climate conditions in upland settings would have confined the wetland species described above to parts of the landscape with high water tables (DiMichele and others, 2014). Whereas the wet-tolerant plants may have grown in low-lying and wet abandoned channels, the *Walchia* probably grew in drier settings surrounding the geographically isolated wetlands. The wet areas were more favorable for fossil preservation than the drier areas, potentially making the wetland plants appear more abundant than they actually were (DiMichele and others, 2014).

Preliminary analysis of the paleomagnetic signature of the rocks in the collection area suggested that the Cutler Formation near sites 1 and 2 was deposited near the equator during the late Pennsylvanian (Mankowski,

2003). A late Pennsylvanian age was also suggested by the presence of *Archaeocalamites* in the proximal Cutler Formation (Huntoon and others, 2014). *Archaeocalamites* was more common during the Pennsylvanian but tended to be increasingly rare in the Permian (Mamay and Bateman, 1991; W.A. DiMichele, Smithsonian Museum of Natural History, personal communication, 2015). Therefore, a late Pennsylvanian age for the deposits at sites 1 and 2 seems likely but is not fully confirmed. Intraformational faults (Mankowski, 2003) in the Cutler Formation in the The Palisade WSA place relatively older Cutler above relatively younger Cutler, making stratigraphic relations difficult to determine with certainty. Nevertheless, it seems likely that although the fossil-bearing rocks are now exposed at the surface, they are part of the older portions of the Cutler Formation. The fossil-bearing rocks are almost certainly older than the Cutler Formation strata exposed around the Gateway town site, where they are likely Permian in age and are unconformably overlain by the Triassic Moenkopi Formation.

Whether the deposits at sites 1 and 2 are late Pennsylvanian or Permian in age, deposition occurred at near-equatorial paleolatitudes (Blakey and Ranney, 2008). Warm temperatures and humid conditions at the time of deposition might be expected for such a location, particularly a site along the margin of a highland such as the Uncompahgre uplift. Pennsylvanian evaporites and Permian eolian rocks deposited in the central Paradox Basin to the west of The Palisade WSA indicate that extended episodes of aridity affected western equatorial Pangea however. Despite the common interpretation that warm and wet conditions persisted across large portions of midcontinent North America during the Pennsylvanian (Scotese and McKerrow, 1990), the western equatorial margin of Pangea appears to have experienced warm and dry conditions, at least intermittently, throughout the late Paleozoic. The fossils and their encasing strata appear to indicate climate conditions more similar to those experienced in the central Paradox Basin than in the midcontinent. A semi-arid background climate with seasonally concentrated precipitation is inferred based on the lithologic characteristics and fossil content at sites 1 and 2. Semi-arid

conditions would have allowed for the establishment of *Walchia*. Seasonally concentrated precipitation would have produced the debris flow and fluvial deposits documented at the two sites. Wetter conditions in abandoned channels would have provided ideal conditions for the growth of wet-tolerant plants such as *Calamites* and *Pecopteris*. It must be noted that the two sites described in this study represent only a small part of the total time interval represented by the Cutler Formation and that the climate in the region experienced substantial variability at multiple temporal scales during the late Paleozoic (Langford and Chan, 1988; Dubiel and others, 1996; Rankey, 1997; Stanesco and others, 2000; Mountney, 2006; Cain and Mountney, 2009; Jordan and Mountney, 2010, 2012; Huntoon and others, 2014).

Huntoon and others (2014) proposed a detailed model for the deposition of the proximal Cutler Formation and associated formations deposited in the central Paradox Basin. In their model, climate and sea-level change are the primary processes controlling deposition. During the late Paleozoic, sediment was eroded from the Uncompahgre uplift and deposited along the margins of the adjacent Paradox Basin. Subsidence of the Paradox Basin foreland was an ongoing process resulting from faulting along the western margin of the Uncompahgre uplift and compaction of previously deposited sediment (Huntoon and others, 2014). Deposition in the rapidly subsiding basin would have been conducive to fossil preservation even under seasonal semi-arid conditions (Looy and others, 2014). As stated earlier, rapid subsidence would have kept the fossil-bearing strata at depths below the water table, as is required for the preservation of plant material (Gastaldo and Demko, 2011).

It is notable that both of the fossil-bearing sites were located directly to the west of a faulted contact between the Cutler Formation and the Precambrian rocks of the Uncompahgre uplift (figure 3). It is possible that the proximity of the fault to the fossil-bearing horizons was important in the preservation of the plant material. If the fault was active at the time the fossil-bearing layers were deposited, freshwater springs may have reached the surface along the fault providing an abundant source of water for any plants living nearby in abandoned chan-

nels. Upon burial, proximity to the fault may have resulted in preferential cementation of the Cutler adjacent to the contact.

## CONCLUSIONS

The observations made of the Cutler Formation in The Palisade WSA near Gateway (Colorado) indicate that the rocks were deposited in a proximal alluvial-fan environment. The fossils preserved at two sites in the proximal Cutler are probably late Pennsylvanian in age. They suggest deposition occurred under warm and locally wet conditions under a semi-arid background climate. Although most of the plants collected at the two sites are known from wet environments, the presence of *Walchia* indicates drier conditions. The inference that warm temperatures and dry conditions were experienced in the Paradox Basin region during deposition of the Cutler Formation is consistent with the occurrence of evaporite and eolian deposits in late Paleozoic rocks deposited to the west of the study area.

Alluvial fans are sites of transport of large volumes of sediment and do not provide an ideal setting for fossil preservation. In order to be preserved, plants grew and died in a protected setting and must have been rapidly buried. Based on the characteristics of the fossils and their encasing strata, it seems that the fossils were deposited in small, isolated wetland areas that formed in abandoned channels in the proximal reaches of the alluvial fan. These abandoned channels may have been fed by springs emerging from the faulted western margin of the Uncompahgre uplift. Although preserved plant material is rare in the proximal Cutler Formation, the two occurrences documented here provide new information about climate conditions during deposition of some of the older portions of the late Paleozoic Cutler. Based on these results it appears that vegetation was common in and adjacent to low-lying wet areas at the time some of the older portions of the Cutler Formation were being deposited.

## ACKNOWLEDGMENTS

We thank the Bureau of Land Management for its assistance with this project; it would not have been

possible without the help and advice provided by Harley Armstrong, Madeline Grant-Hoffman, and David (Scott) Gerwe. The work was conducted under U.S. Department of the Interior, Bureau of Land Management Colorado State Office Paleontological Resources Use Permits COC76491 and COC76492. We thank Dr. Bill DiMichele, Smithsonian Museum of Natural History, for his assistance and patience in helping us to identify and interpret plant material collected for this and other studies of the Cutler Formation. We also thank Dr. DiMichele for agreeing to allow us to use the National Museum of Natural History as the repository for our samples. We thank Dan Chaney, Smithsonian Museum of Natural History, for his guidance in preparing the samples for shipment to the Smithsonian. We thank Jack Stanesco, Red Rocks Community College, for his assistance in the field. We thank the reviewers of this manuscript (Doug Sprinkel and Tom Chidsey, Utah Geological Survey; Steve Schamel, GeoX Consulting; Brooks Britt, Brigham Young University; and Jerry Waanders, consulting palynologist) for their helpful comments. Finally, we thank the Michigan Space Grant Consortium for its financial support, which made it possible for the first author to first visit the study area during a field-based course for pre-college teachers that was taught by the second author and offered as a graduate course by Michigan Technological University.

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