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Key Points:

- We present the first high-resolution seismic image of a buried paleovalley shaped by alpine glaciation in Earth's pre-Quaternary record
- Our data support the hypothesis of late Paleozoic glaciation at latitudes and elevations lower than suggested by current paleoclimate models

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. Behm,
michael.behm@ou.edu

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Seismic Reflection and Electrical Resistivity Imaging Support Pre-Quaternary Glaciation in the Rocky Mountains (Unaweep Canyon, Colorado)

Anna Patterson[1], Michael Behm[1,2], Werner Chwatal[3], Adrian Flores-Orozco[4], Yichuan Wang[1,5], and Gerilyn S. Soreghan[1]

[1]School of Geosciences, University of Oklahoma, Norman, OK, USA, [2]Geodata Surveying and Monitoring Group, Leoben, Austria, [3]AFRY Austria GmbH, Vienna, Austria, [4]Department of Geodesy and Geoinformation, Vienna University of Technology, Vienna, Austria, [5]Department of Geoscience, University of Calgary, Calgary, AB, Canada

Abstract Unaweep Canyon (Uncompahgre Plateau, Colorado) represents an enigmatic landscape with a complex evolution. Interpretations for its origin have ranged from ancestral fluvial erosion in the late Cenozoic to glacial erosion in the Paleozoic, or some combination thereof, with significant implications for global climatic and large-scale tectonic reconstructions. To address the conflicting interpretations, we acquired a high-resolution seismic reflection profile to investigate the depth, structure, and sedimentary infill in the canyon. The data set is further complemented with an electrical resistivity survey. Integrated with other geophysical and geological data, the results show an overdeepened Precambrian basement with transverse U shape and support the hypothesis of a pre-Quaternary glacial origin. Our data constitute the first detailed image of a buried pre-Quaternary glacial valley in North America; if substantiated with core studies, these results have far-reaching implications for our understanding of global ice houses as well as the tectonic conditions, enabling preservation of such systems.

Plain Language Summary The shape of valleys depends on the processes that created them. Broad valleys with the transverse shape of a "U" are distinct signs of glaciers, which carved the valley in the bedrock. Since old valleys are filled up with sediments, we need geophysical tools to image their structure in the buried subsurface. Using such tools, we have found a buried U-shaped valley in western Colorado. Since we know from other observations that there were no glaciers in this specific location in the last ice age, the valley must have been created in a previous ice age. The most likely time period is the late Paleozoic, ca. 300 million years ago. Due to plate tectonics, the landmass of Colorado was located at the equator during that time. This implies that there was ice at the equator at this time, which further means there were globally much lower temperatures than we think. Our result is the first example in North America of a glacial mountain valley carved by an ancient glacier.

1. Introduction

Landscape shapes record processes of formation. In particular, fluvial processes typically exhibit V-shaped profiles with steep slopes, whereas glacial processes carve U-shaped valleys with variable slopes and overdeepenings (MacGregor et al., 2000; Prasicek et al., 2014). Overdeepened valleys are those with depths extending below fluvial base level (Preusser et al., 2010) and are key elements of glacial landscapes where warm-bed conditions exist(ed) (e.g., Benn & Evans, 1998; Cook & Swift, 2012). Such valleys are characterized by closed topographic depressions and are commonly eroded several hundred meters below the base level (Fiebig et al., 2010; Menzies, 1995; Preusser et al., 2010). Overdeepening on basement is unknown in canyons carved exclusively by fluvial processes (Cook & Swift, 2012; Huuse & Lykke-Andersen, 2000; Linton, 1963); rather, overdeepenings are considered "unambiguous features of glacially sculpted landscapes" (Pomper et al., 2017). Overdeepening occurs in cirques, valley outlets of alpine glaciers, and fjords and valleys draining continental ice sheets, related to perturbations in the bed that amplify the action of high-pressure meltwater (Hooke, 1991).

Seismic imaging has been widely used to characterize Quaternary glacial valleys and, together with drilling and other subsurface data, has demonstrated the distinctive propensity for glacial processes to produce not only U-shaped transverse profiles, but also uniquely overdeepened longitudinal profiles. Many seismic studies of Quaternary glacial valleys focus on the sediment fill and associated potential for groundwater resources or waste disposal (e.g., Bleibinhaus & Hilberg, 2012; Brückl et al., 2010; Burschil et al., 2018; de Franco et al., 2009; Pomper et al., 2017). In contrast, few studies have presented seismic imaging of pre-Quaternary glacial valleys, mostly in the context of hydrocarbon potential within the sediment fill (Bache et al., 2012; Bataller et al., 2019; Vesely et al., 2021).

In this study, we use high-resolution seismic reflection imaging augmented by electrical resistivity data to characterize the bedrock depth and sediment fill of a partially buried valley, Unaweep Canyon in western Colorado. Although geological data establish that the canyon hosted an ancestral river as recently as ~1.4 Ma, our results demonstrate substantial overdeepening of a paleovalley that lies concealed beneath a substantial sediment fill and that cannot be explained by either fluvial erosion or structural disruptions. We use this observation to link the paleovalley to pre-Quaternary (late Paleozoic or Neoproterozoic) glaciation. Our study is the first documentation of a buried pre-Quaternary glacial valley in North America, and one of the first examples of an upland alpine glacial valley preserved in Earth's deep-time record.

2. Geologic Setting

Unaweep Canyon is a large gorge that bisects Colorado's Uncompahgre Plateau and is globally unique, named for the odd occurrence of a divide in its midst, from which two creeks flow in opposite directions (Figure 1). The canyon incises through Mesozoic strata into Precambrian basement but hosts a thick sediment fill of Pleistocene and possibly older age. It is onlapped by Permian strata at its western mouth that bury up to ~520 m of paleorelief on Precambrian basement (Soreghan et al., 2012, 2015). During the Pennsylvanian-Permian, the Uncompahgre uplift—a large block uplift of the Ancestral Rocky Mountains that encompassed the greater Uncompahgre Plateau and beyond—shed clastic sediments into the Paradox Basin to the west-southwest. By Mesozoic time, this region subsided and accumulated substantial sediment before the Cenozoic uplift that formed the modern Uncompahgre Plateau. During the latest Cenozoic, the ancestral Gunnison River flowed through Unaweep Canyon, prior to its abandonment of the canyon (~1.4 Ma) and partial backfilling (Balco et al., 2013; Soreghan et al., 2015).

Although the most commonly accepted model for the formation of Unaweep Canyon is an incision by the ancestral Gunnison or Colorado River (e.g., Aslan et al., 2008; Hood, 2009; Lohman, 1981), Soreghan et al. (2007, 2008, 2014, 2015) posited formation by late Paleozoic glaciation, followed by Permian burial and Cenozoic partial exhumation by the ancestral Gunnison River. This hypothesis remains controversial (e.g., Hood, 2009; Hood et al., 2009; Soreghan et al., 2008; Soreghan, Soreghan, et al., 2009; Soreghan, Sweet, et al., 2009), since it implies low-latitude and low-elevation glaciation for the late Paleozoic, which is not a feature of current climate models for that time. The hypothesis hinges in part on observations that suggest a pre-Mesozoic age for the landform (e.g., burial of Permian paleorelief) and inferred proglacial facies in the Permian fill, as well as a 320-m core that mostly penetrated Pleistocene strata but ~15 m of bas`al strata interpreted to date from the late Paleozoic based on palynological, provenance, and paleomagnetic data (Soreghan et al., 2008). Previous gravity surveys (Davogustto et al., 2005; Haffener, 2015; Soreghan et al., 2008) and electrical resistivity soundings (Oesleby, 1983) suggested the overdeepening of the Precambrian basement surface in the western canyon, but the solutions of those potential field methods are nonunique.

3. Methods

A 2.45-km N-S seismic 2-D reflection line was acquired across the widest part of Unaweep Canyon (Figures 1, and S1). The acquisition comprised 505 receiver locations deployed with nodal receivers and 264 shot locations. A truck-mounted impact hammer was used as the primary energy source (Patterson, 2019). Raw data hint at basement deepening in the southern part of the profile (Figure S2). Data processing followed a standard workflow for 2-D crooked-line reflection processing (e.g., Yilmaz, 2001; Text S1). Intermediate processing products (NMO stack, prestack time migration (PSTM), and PSTM velocity model) are shown in Figures S3 and S4, and the final result is the depth-converted PSTM image (Figure 2a).

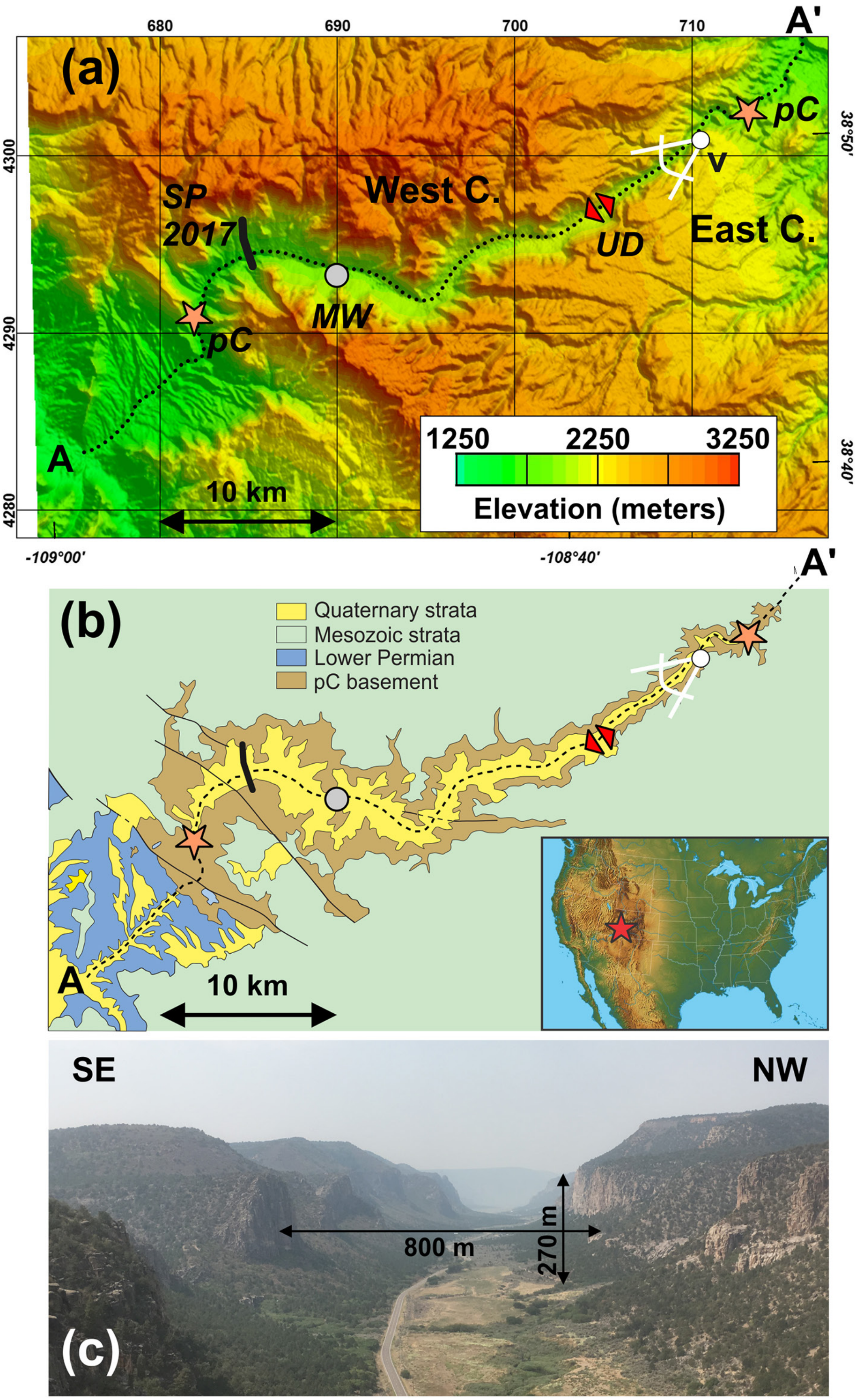

Figure 1. (a) Digital elevation model of Unaweep Canyon. UD (red triangles): Unaweep Divide; MW (gray dot): Massey well (core); SP 2017 (black line): Location of the seismic reflection profile in this study; pC (orange stars): Precambrian basement outcrops along the canyon floor; A-A': Longitudinal cross-section shown in Figure 5; v: Viewpoint of the photograph shown in (c). (b) Geologic map. (c) View into eastern Unaweep Canyon toward west.

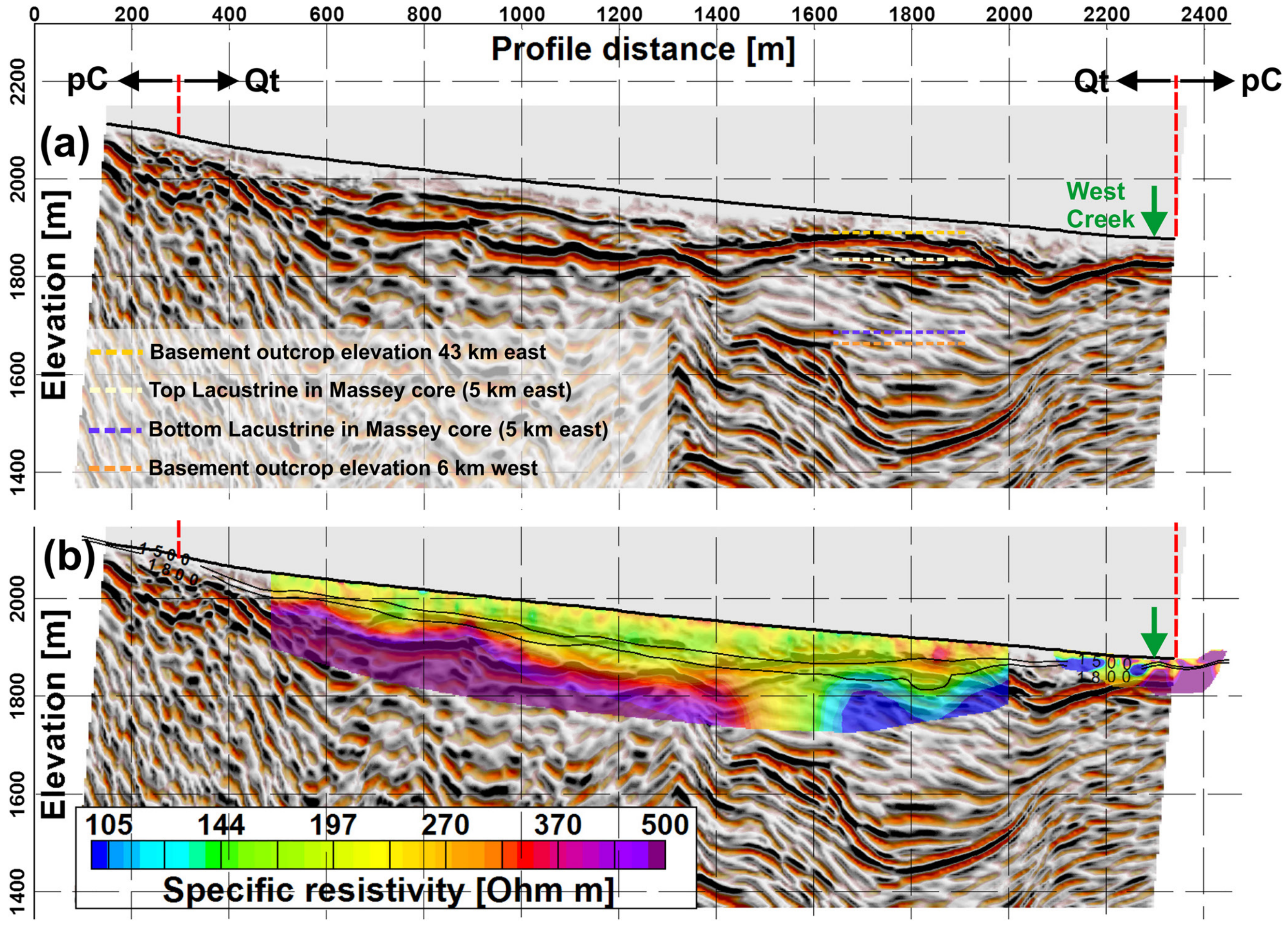

Figure 2. (a) Depth-converted prestack seismic time migration (PSTM) image and ground-truth data. Pc, Qt: Precambrian and Quaternary surface cover. Dashed lines: Elevations of basement outcrops along Unaweep Canyon and interpreted horizons in the Massey core. (b) Electrical resistivity tomography image superimposed on the PSTM image.

Complementary measurements in this study correspond to a co-located electrical resistivity tomography (ERT) profile (Figure 2b). The data coverage gap at profile distance ca. 2,000 m results from logistical constraints, since the ERT cables could not be deployed across the intersecting highway. Measurements were collected using an ARES II system (GF instruments) using 304 electrodes with a separation of 5 m. Measurements were collected with a Wenner gamma configuration, with a maximum separation between current and potential dipoles of 125 times the electrode spacing. To increase the signal-to-noise ratio for such readings, the ARES II unit permits the use of more than one electrode to form each pole of the current dipole. Inversion of the data was carried out with CRTomo (Kemna, 2000), a smoothness-constraint algorithm that solves the Helmholtz equation in the wave number domain to calculate the distribution of the electrical resistivity in an imaging plane. The inversion results converged to the measured resistances with a data error of 5% relative error and 0.01-Ohm absolute error.

4. Results and Discussion

We conduct our interpretation (Figure 3) in depth instead of time to incorporate stratigraphy known from a core located 5 km to the east ("Massey well"; Figure 1) and additional geophysical data (Figures S5–S6; Behm et al., 2019, 2020). In the absence of a well co-located with the seismic line, the PSTM velocity model was used for depth conversion. The interpretation considers uncertainties of seismic processing and imaging. Limitations in velocity model building and resolution can produce small-scale "migration smiles," and depth conversion of time-migrated data without a well tie can further produce lateral and vertical

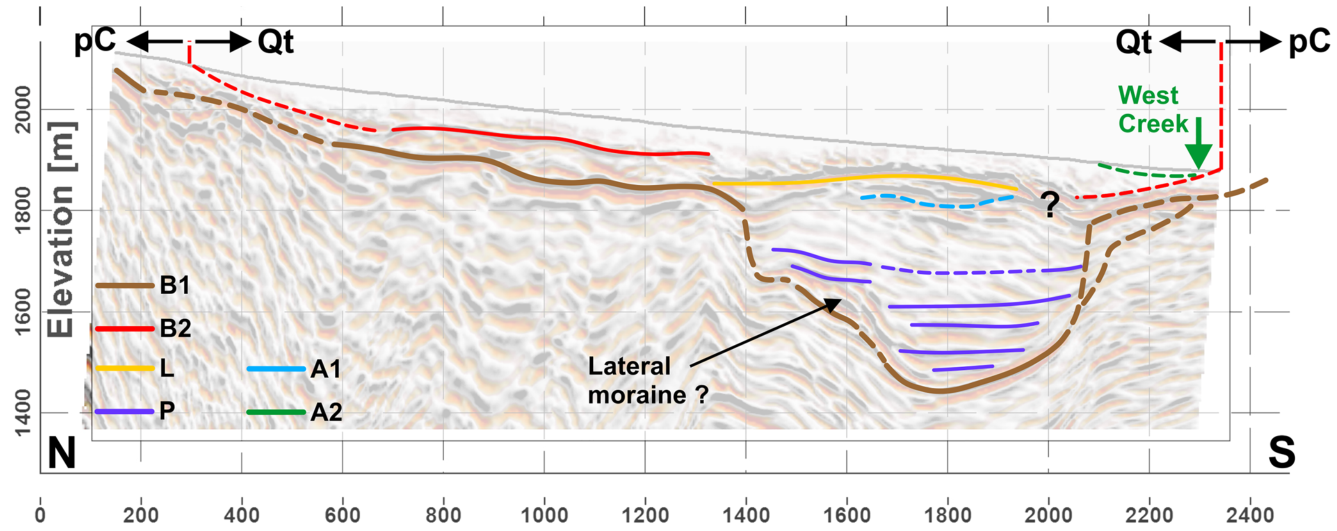

Figure 3. Integrated interpretation of the depth-converted prestack seismic time migration image, ground-truth data, and additional geophysical observables (Figures S4–S6). Dashed lines indicate where horizons are less well defined and/or are largely based on Supporting Information S1. B1: Consolidated Precambrian basement. The two different configurations at profile distances >2,000 m are explained in the text. B2: Top of Precambrian regolith and pre-Quaternary sediments; L: Reflector associated with a Cenozoic lacustrine unit; P: Pre-Quaternary strata; A1, A2: Deep and shallow aquifers.

distortions. Seismic 2-D cross-sections of distinct 3-D structures such as overdeepened valleys are prone to out-of-plane reflections, which can further bias the velocity model and the final image.

In the near surface (<150-m depth), the PSTM velocity model (Figure S4) and the depth-converted migrated image fit well with tomographic P-wave velocity inversion (Figure S5), S-wave velocities from surface-wave inversion (Figure S6; Behm et al., 2019), and the ERT data (Figure 2b). In particular, the deepening of the basement "B1" at profile distances 1,400 m–2,100 m is supported by the lack of high P- and S-wave velocities and low electrical resistivity. This horizon "B1" represents consolidated Precambrian basement with P-wave velocities in the range of 4,500–5,500 m/s (Behm et al., 2019), suggesting a significant degree of weathering. The basement is correlated with resistivities >350 Ohm m. The overall moderate basement resistivities (<1,000 Ohm m) suggest a high amount of fluid-filled fractures and support the inference of significant weathering. Poor imaging between profile distances 200–600 m relates in part to use of a weaker seismic source signal (sledgehammer). Between profile distances 1,400 and 2,000 m, the basement surface forms a pronounced U shape with a maximum depth of 490 m below the modern surface. This deepest point is also 220 m below the western basement outcrop at 6-km lateral distance and therefore unambiguously establishes an overdeepened valley floor. The interpretation of the southern flank of the U (profile distances > 2,050 m) is more challenging. While there is a strong reflector in an elevation around 1,830 m, deeper sub-horizontal (e.g., intrasedimentary) events appear to be drawn for a short distance below this reflector. We attribute this ambiguity to a lack of resolution in our 2-D data set, compounded by methodological limitations mentioned above. Complementary geophysical data (resistivity, P-wave, and S-wave velocities) suggest that the basement surface dips northward at profile distances between ~2,150 and 2,250 m. Consequently, in Figure 3, we indicate the two end members of the proposed basement configurations in this section of the profile. The horizontal distance between the buried valley walls (~700–900 m, depending on the interpretation of the southern flank) is comparable to the exposed basement morphology in eastern Unaweep Canyon (Figure 1c; ~800 m). The inferred U shape persists through the intermediate seismic processing products such as the NMO stack, the PSTM velocity model, and the PSTM image in time (Figures S3 and S4).

Apparent disruptions in shallow reflectors (B2, L) around profile distance ca. 1,350 m may suggest vertical faulting north of the overdeepening. However, the vertical displacement here is only ca. 50 m, and neither the seismic image nor the electrical resistivity distribution of the basement directly below indicates vertical offsets. The basement outcrops on the north and south sides of the seismic transect are not vertically offset from one another.

Horizon "B2" appears along the northern section of the profile. Based on the surface geology, we infer it separates Quaternary cover from underlying Precambrian regolith. The lower layer may also include a significant component of pre-Quaternary shale or sandstone, given its low resistivity. In the overdeepened section, a continuous reflector ("L") appears at ca. 1,850-m elevation between profile distances 1,300 and 1,900 m. This horizon approximates (within ~50 m) the top of a lacustrine unit identified in the Massey core, recording a late Pleistocene lake resulting from a river blockage ~1.4 Ma (Balco et al., 2013; Soreghan et al., 2007, 2015).

In the central part (profile distance 1,700–2,000 m), we associate increased reflectivity below "L" with a strong drop in the electrical resistivity (Figure 2b), where resistivities <120 Ohm m are interpreted for an aquifer (horizon "A1") in the lacustrine unit. We also superimpose the 1,500 and 1,800 m/s contour lines from the tomographic P-wave velocity model. This velocity range is taken as a proxy for a groundwater table in sand (Knight & Endres, 2005). The apparent depression in the resistivity structure at profile distance ~1,850 m correlates with the independently derived P-wave velocity distribution. Accordingly, a shallow local aquifer in alluvium/colluvium ("A2") could explain the low resistivity at West Creek (profile distance 2,100–2,300 m). A gap in the resistivity acquisition line precludes a conclusive interpretation of a connection/exchange between the two aquifers.

Several horizontal reflectors ("P") appear in the overdeepened section between ca. 1,670- and 1,480-m elevation. The shallowest one is apparently close to the basement flanks, but images poorly in the central part. This might relate to the aquifer "A1," as water saturation of the lacustrine unit increases seismic velocity and reduces the impedance contrast with underlying strata. A clinoform-like appearance of these reflectors at the southern side is regarded as an artifact of the depth conversion, as the reflectors are aligned horizontally in the PSTM image in the time domain (Figure S3). The velocity model used for the depth conversion is the smoothed interval velocity model derived from PSTM processing (Figure S4). In the lateral transition from the sediment fill to the canyon walls, the smoothed velocities are likely biased toward too high values, which lead to vertical distortions of the reflectors after the depth conversion. Consequently, we consider the PSTM image in time for the interpretation and emphasize horizontal layering of those reflectors. If, alternatively, the clinoform appearance is real, it presumably reflects oblique progradation in the lacustrine interval, which records deltaic backfilling (Soreghan et al., 2007, 2015).

Figure 4 shows a detail of the overdeepened section with the elevation-referenced stratigraphy of the Massey core as well as the interval velocity and electrical resistivity extracted at the central location of the seismic profile. We interpret the Pleistocene sediments to comprise ca. 100 m of colluvium and ca. 140 m of lacustrine sand/silt. The top of the lacustrine unit (λλ) might be represented by the flat and weak impedance contrast below "L." Based on the correlation with the Massey core, we interpret the sequence below (reflectors "P" in Figure 2c) as pre-Quaternary strata with a total thickness of ~250 m. However, this thickness represents a maximum estimate, since the top of the pre-Quaternary strata might also be associated with the velocity increase just below 1,600-m elevation.

The integration of our interpretation with the stratigraphy of the Massey core and basement outcrops enables the construction of a longitudinal section along the canyon (Figure 5). The overdeepened character of the Precambrian basement surface of Unaweep Canyon is unambiguous. The observed U shape (cross-section) and the lack of faults of sufficient displacement to accommodate the overdeepening (Soreghan et al., 2015) strongly support a glacial origin. Bache et al. (2012) classified glaciogenic incision processes according to basement geometry and rock type. Given the depth, longitudinal and lateral extent, and setting within crystalline basement, Unaweep Canyon compares to the "alpine glacier" and "fjord" types.

Seismic interpretations of Paleozoic glacial valley fill in other parts of the world (Bache et al., 2012; Bataller et al., 2019) reveal complex stratigraphy representative of repeated glacier advances and retreats, with additional complications arising from subsequent erosion, deformation, and sedimentation events. Lack of a well penetration here precludes precise characterization of the nature and age of the valley fill. We note however that the top of the pre-Quaternary strata aligns with the fluvial base level of the ancestral Gunnison River 1.4 Ma ago (Balco et al., 2013; Soreghan et al., 2015).

Soreghan et al. (2008) hypothesized that Unaweep Canyon was carved in the late Paleozoic ice age (LPIA). The modern elevation of the Uncompahgre Plateau together with a lack of evidence for recent glaciation

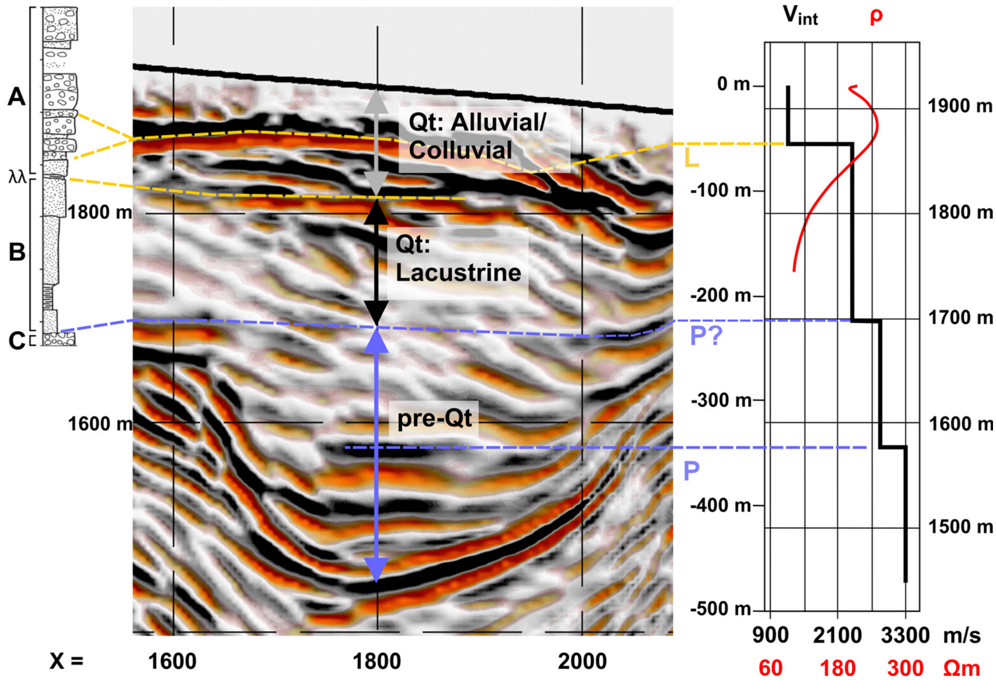

Figure 4. Correlation of the overdeepened section with the stratigraphy of the distant Massey core, interval velocities (V_{int}), and electrical resistivity (ρ). V_{int} and ρ are extracted at the central location $X = 1{,}800$ m. Discrepancies in elevation are attributed to the approximate velocity model, the distance (5 km) to the core, and lateral variation along the seismic section. Vertical axis represents elevation and depth below surface. "L" and "P": top of interpreted reflectors. Core sections after Balco et al. (2013): A—Qt alluvium/colluvium; λλ—Paleosoils; B—Qt lacustrine; and C—Pz Diamict.

precludes Pleistocene glaciation here (Soreghan et al., 2007). The morphology of the preserved bedrock surface, partial exhumation of a paleovalley at the western mouth of the canyon, and the inferred proglacial facies of the Permian fill here all support the Paleozoic hypothesis (Soreghan, Sweet, et al., 2009, 2015). Our results corroborate this hypothesis, implying that Figure 2 represents the first image of a glacial valley from a pre-Quaternary ice age in North America.

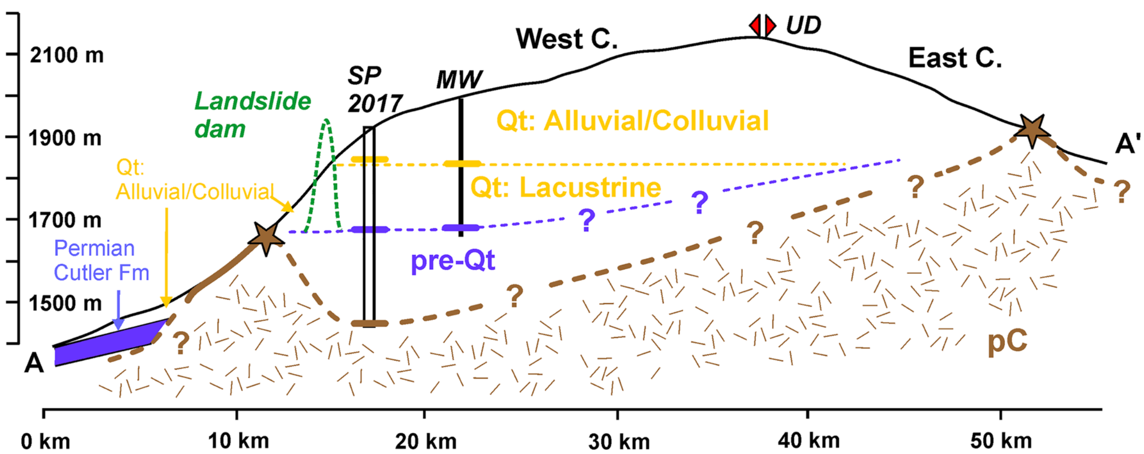

Figure 5. Hypothesized vertical section along Unaweep Canyon following profile A-A' (Figure 1). Black solid line: Topography along West and East Creek. UD: Unaweep divide; MW: Massey well; SP 2017: Location of seismic profile. Yellow line: Top of the lacustrine unit. Purple line: Top of pre-Quaternary strata. Brown line: Precambrian basement. Solid yellow/purple bars and brown lines show observations from the seismic profile, the well, and surface geology. Location of the 1.4–1.3 Ma landslide dam according to Balco et al. (2013).

The accepted model for the LPIA holds that glaciation occurred across the Gondwanan continents, at latitudes >~31°S (Evans, 2003). In contrast, during the late Paleozoic, the Uncompahgre uplift was within ~11° of the equator and 60–80 km from the nearest shoreline, implying that the paleoelevation near the contact between the Permian Cutler Formation and Precambrian basement of the paleovalley was ~1,200-m elevation (Soreghan et al., 2014). If this hypothesis is valid, then Unaweep Canyon represents a partially exhumed paleovalley recording *upland* alpine glaciation—the first imaged example in Earth's pre-Quaternary equatorial record. Although the combination of all geological and geophysical observations favors the late Paleozoic glaciation hypothesis, we cannot eliminate the possibility that Unaweep Canyon preserves one or more Snowball Earth periods in the Neoproterozoic (Hoffman et al., 2017). Determining between these options will require coring and dating of the overdeepened section.

5. Conclusions

Our results present the first high-resolution image of a buried paleovalley shaped by alpine glaciation in Earth's pre-Quaternary record. Combined with previously established evidence, the most parsimonious explanation is that the Unaweep paleovalley was carved in the LPIA, at relatively low elevations and low latitude, thus challenging climate models for that period and posing the question of how the paleoupland was preserved. Alternatively, the seismic image might capture an even older (e.g., Neoproterozoic) glaciation. If Paleozoic, our results imply remarkable preservation of an alpine glacial system, requiring subsidence of the Ancestral Rocky Mountain highlands immediately following their uplift. It furthermore suggests the possible existence of additional buried paleovalleys atop the Uncompahgre Plateau, which might be imaged with airborne geophysical tools (Pugin et al., 2014). Ultimately, our observations invite refinements in climate modeling and motivate new field and modeling research in search of new evidence for glaciations in other parts of the Carboniferous-Permian tropics.

Data Availability Statement

Waveform data used in this study can be downloaded from Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) located at https://ds.iris.edu/SeismiQuery/assembled.phtml through specifying the data set name “Unaweep” and the year “2017.”

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