

Seismic reflection and electrical resistivity imaging reveal pre-Quaternary glaciation in the Rocky Mountains (Unaweep Canyon, Colorado)

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Abstract

Unaweep Canyon (Uncompaghe 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 dataset is further complemented with a high-resolution electrical resistivity survey. Integrated with other geophysical and geological data, the results unambiguously demonstrate an overdeepened Precambrian basement with pronounced transverse U-shape and corroborate the hypothesis of a pre-Quaternary glacial origin. Our data constitute the first detailed and high-resolution image of a buried pre-Quaternary glacial valley in North America, and thus have far-reaching implications for our understanding of global ice houses as well as the tectonic conditions enabling preservation of such systems.

**Seismic reflection and electrical resistivity imaging reveal pre-Quaternary
glaciation in the Rocky Mountains (Unaweep Canyon, Colorado)**

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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 climate models.

Abstract

Unaweep Canyon (Uncompaghre 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

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1 Introduction

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 uniquely “overdeepened” longitudinal profiles (Preusser et al., 2010; Cook and Smith, 2012). Overdeepening is characterized by closed topographic depressions eroded below fluvial baselevel, and — barring a structural explanation — implies glacial excavation. 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). Excavation can reach several hundreds of meters (Fiebig et al., 2010).

Many seismic studies of Quaternary glacial valleys focus on the sediment fill and associated potential for groundwater resources, waste disposal, and hydrocarbon potential in the pre-Quaternary section (e.g., de Franco et al., 2009; Brückl et al., 2010; Bache et al. 2012; Bleibinhaus & Hilberg, 2012; Pomper et al., 2017; Burschil et al., 2018; Bataller et al., 2019). In this paper, 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 geologic 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 (Fig. 1). The canyon incises through Mesozoic strata into Precambrian basement but hosts a thick sediment fill of Pleistocene and possibly older age. It is overlapped 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 clastics 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).

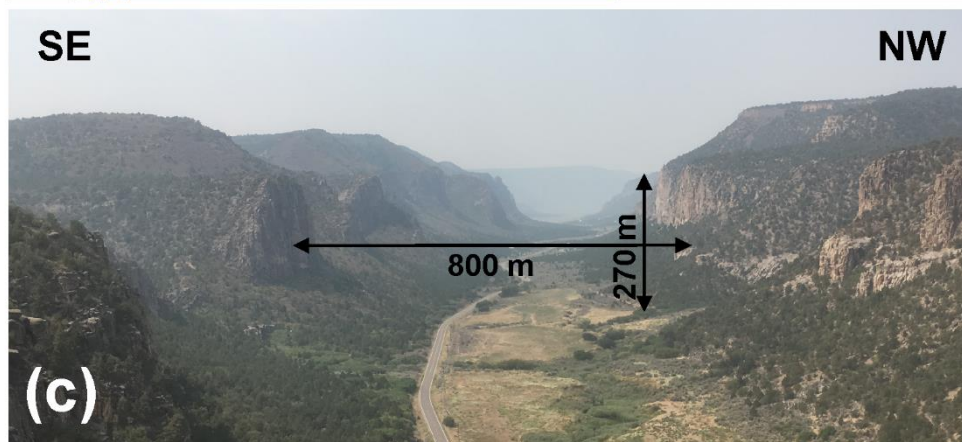
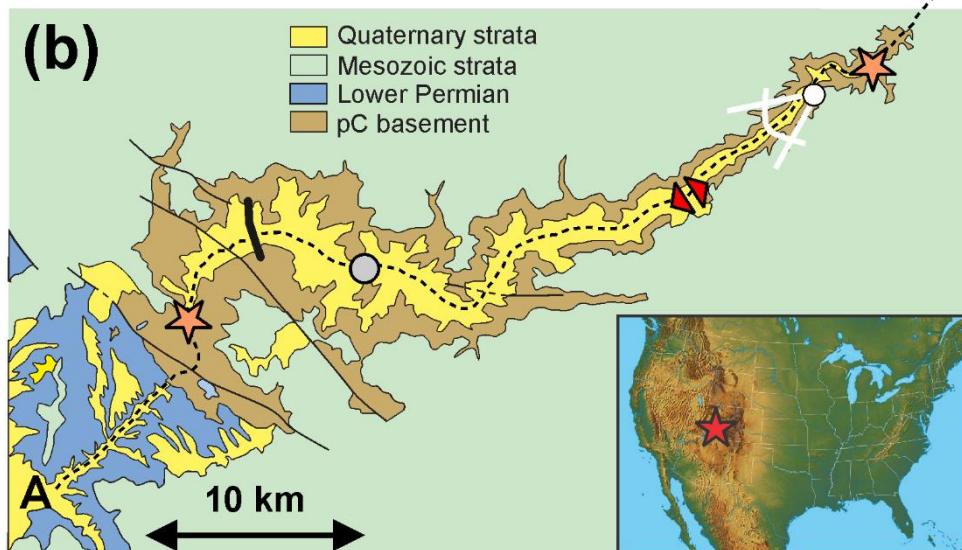
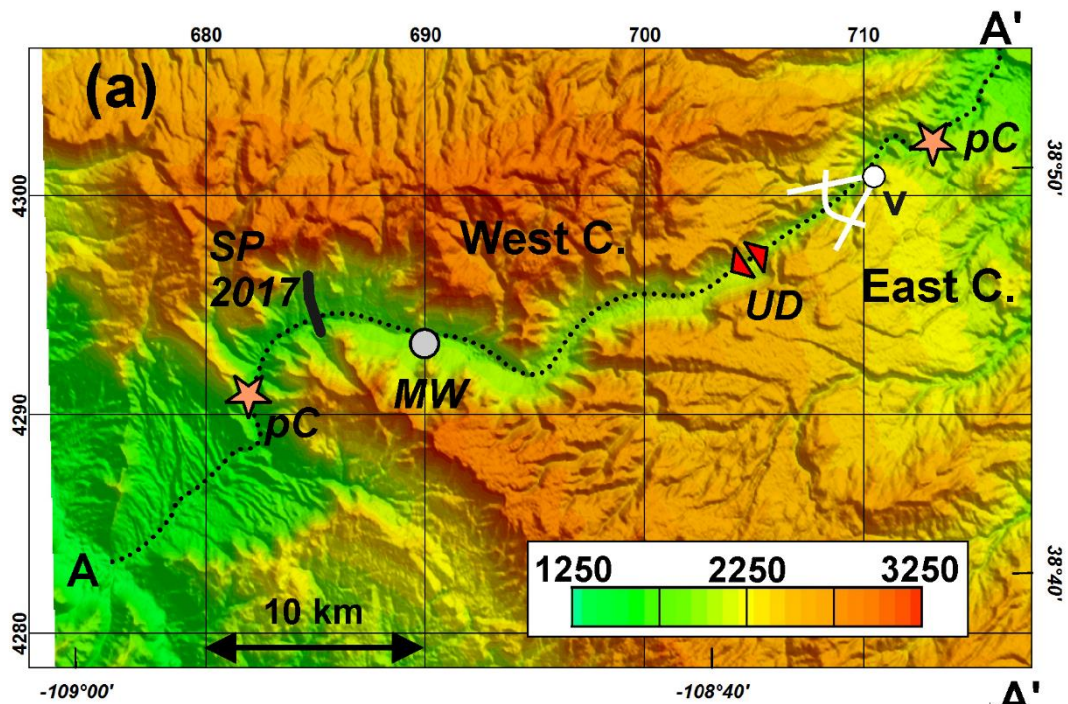


Figure 1.

(a) Digital elevation model of Unaweep Canyon. UD: Unaweep Divide; MW: Massey well (core); SP 2017: location of the seismic reflection profile (Fig. 2) in this study; pC: Precambrian basement outcrops along the canyon floor. A-A': longitudinal cross-section shown in Fig. 4. v: Viewpoint of (c). (b) Geologic map of the area shown in (a). (c) View into Eastern Unaweep Canyon towards West. Indicated dimensions show horizontal distance of vertical basement cliffs and vertical distance from plateau to the valley floor.

Although the most commonly accepted model for the formation of Unaweep Canyon is incision by the ancestral Gunnison or Colorado river (e.g., Lohman, 1981; Aslan et al., 2008; Hood, 2009), 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., Soreghan et al., 2008; Hood 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 period. 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 penetrated mostly Pleistocene strata but ~15 m of basal strata interpreted to date from the late Paleozoic (Soreghan et al., 2008). Previous gravity surveys (Soreghan et al., 2008) and electrical resistivity soundings (Oesleby, 1983) suggested possible overdeepening of the Precambrian basement surface in the western canyon, but the solutions are non-unique, hence the controversy persists.

3 Methods

A 2.45 km N-S seismic 2D reflection line was acquired across the widest part of Unaweep Canyon (Fig. 1b, supplemental material 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 (S2). Data processing followed a standard workflow for 2D crooked line reflection processing (e.g., Yilmaz 2001; S3). Intermediate processing products (NMO stack, pre-stack time migration (PSTM), PSTM velocity model) strongly suggest a U-shaped basement surface (S4, S5), and the final result is the depth-converted PSTM image (Fig. 2a).

Complementary measurements in this study correspond to a co-located electrical resistivity tomography (ERT) profile (Fig. 2b). The data coverage gap at profile distance ca. 2000 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 to use more than one electrode to form each pole of the current dipole. Inversion of the data was carried out with CRTomo (by 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.

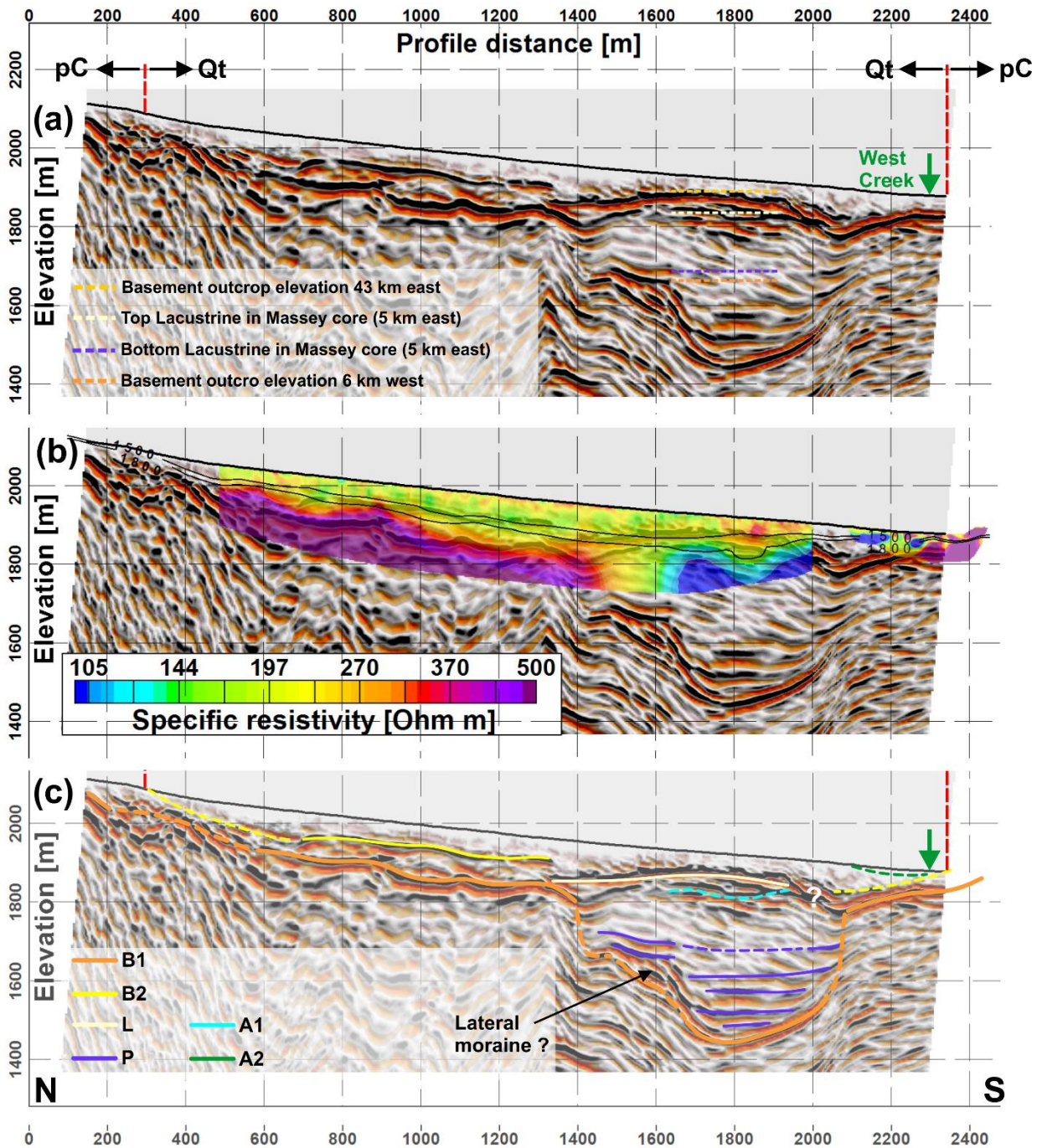


Figure 2.

(a) Pre-stack seismic time migration (PSTM) image and ground-truth data. Pc, Qt: Precambrian and quaternary surface cover. Dashed lines show elevations of basement outcrops (Fig. 1) along

Unaweeep Canyon and interpreted horizons in the Massey core. (b) Electrical resistivity tomography image superimposed on the PSTM image. (c) Integrated interpretation of the PSTM image, ground-truth data, and additional geophysical observables (supplemental material S5 – S7). Dashed lines indicate where horizons are less well defined and/or are largely based on supplemental data. B1: Consolidated Precambrian basement. B2: Top of Precambrian regolith and pre-Quaternary sediments. L: Reflector associated with a Cenozoic lacustrine unit. P: pre-Quaternary sediments. A1, A2: Top of deep and shallow aquifers.

4 Interpretation and discussion

We conduct our interpretation (Fig. 2c) in depth instead of time to incorporate stratigraphy known from a core located 5 km to the east (‘Massey well’; Fig. 1) and additional geophysical data (S6 – S8; Behm et al., (2019, 2020)). In 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 produce further lateral and vertical distortions. Seismic 2D cross-sections of distinct 3D structures such as overdeepened valleys are prone to out-of-plane reflections which can further bias the velocity model and the final image. Our interpretation also integrates additional geophysical data (S6, S7) and the stratigraphic information from the distant Massey well core.

In the near surface (<150 m depth), the PSTM velocity model (S5) and the depth-converted migrated image (Fig. 2) fit well with tomographic P-wave velocity inversion (S6), S-wave velocities from surface wave inversion (S7), and the ERT data (Fig. 2b). In particular, the

deepening of the basement at profile distances 1400 m to 2100 m is qualitatively corroborated by the lack of high P- and S-wave velocities and low electrical resistivity.

Horizon 'B1' represents consolidated Precambrian basement with P-wave velocities in the range of 4500 to 5500 m/s (S6), suggesting a significant degree of weathering. Poor imaging between profile distances 200 – 600 m relates in part to use of a weaker seismic source signal (sledgehammer) necessitated by access limitations. At profile distances 1400 m and 2100 m, we interpret abrupt and near-vertical descent of the basement surface. Between profile distances 1700 m and 2000 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 horizontal distance between the vertical cliffs (~700 m) is comparable to the exposed basement morphology in eastern Unaweep Canyon (Fig. 1c).

The consolidated basement is correlated with resistivities > 350 Ohm m. The overall moderate basement resistivities (400 - 1000 Ohm m) suggest a significant amount of fluid-filled fractures due to significant weathering.

Horizon 'B2' is clearly established in parts of the northern section of the profile only. Based on the constraining 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 sandstones given its low resistivity (DR8).

In the overdeepened section, a continuous reflector ('L') appears at ca. 1850 m elevation between profile distances 1300 m and 1900 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 (Soreghan et al. 2007, 2015; Balco et al. 2013).

In the central part (profile distance 1700 – 2000 m) we associate increased reflectivity below ‘L’ with a strong drop in electrical resistivity (Fig. 2b), where resistivities < 120 Ohm m are interpreted for aquifers in sand, suggesting the occurrence of an aquifer (horizon ‘A1’) in the lacustrine unit. We also superimpose the 1500 m/s and 1800 m/s contour lines from the tomographic P-wave velocity model (S6). Depending on the porosity, this velocity range is often taken as proxy for a groundwater table in sand (Knight and Endres, 2005). It is noted that the apparent depression in the resistivity structure (ca. profile distance 1850 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 2100 – 2300 m). Due to a gap in the resistivity acquisition line, we cannot conclusively comment on a potential connection/exchange between the two aquifers. However, it appears unlikely as the shallow aquifer is related to West Creek situated at profile distance 2300 m.

Several horizontal reflectors (‘P’) appear in the overdeepened section between ca. 1670 m and 1480 m elevation. The shallowest one is apparent close to the basement cliffs, 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. Tilted and basement-parallel reflectors with low interval velocities occur adjacent to and below ‘P’ (S5).

Fig. 3 shows a detail of the over-deepened 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 colluvium and ca. 140 m lacustrine sand/silt. The top of the lacustrine unit ($\lambda\lambda$) 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 Fig. 2c) as pre-Quaternary strata with a total thickness of ~250 m.

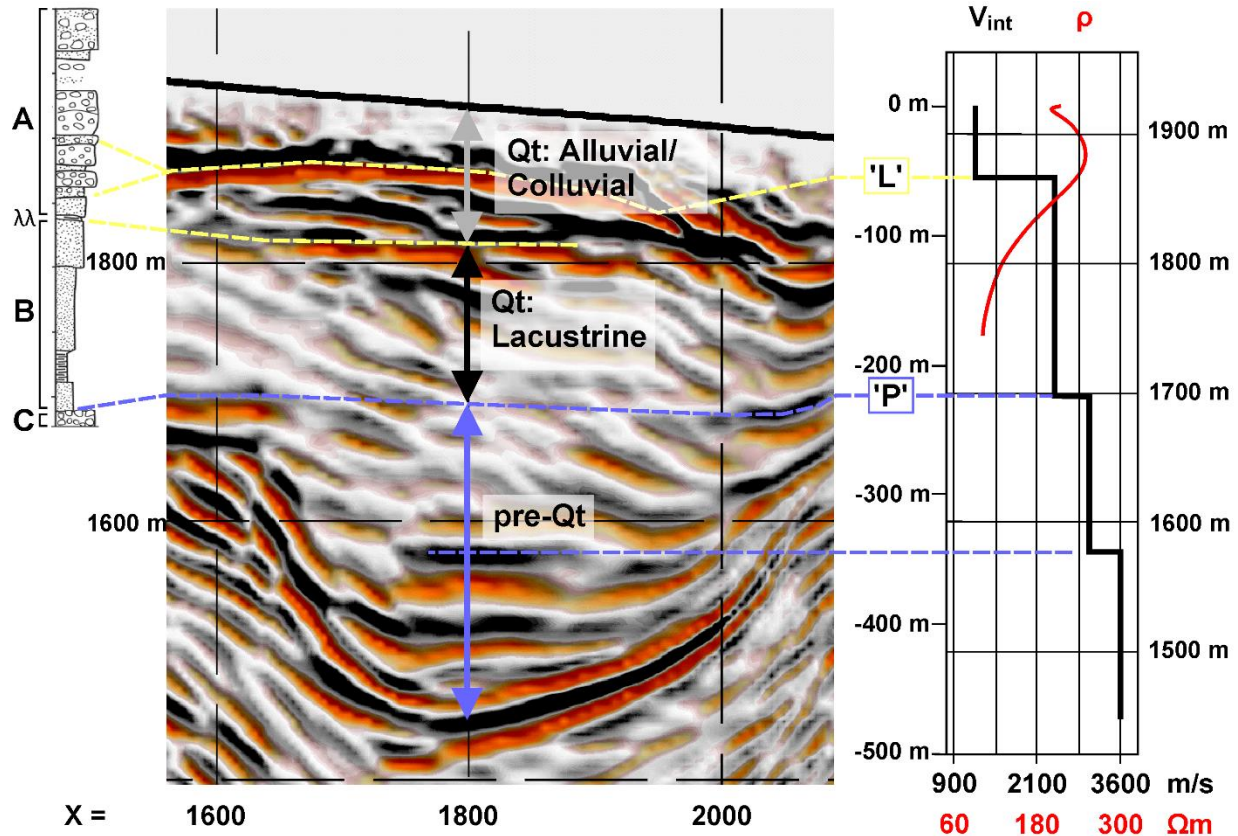
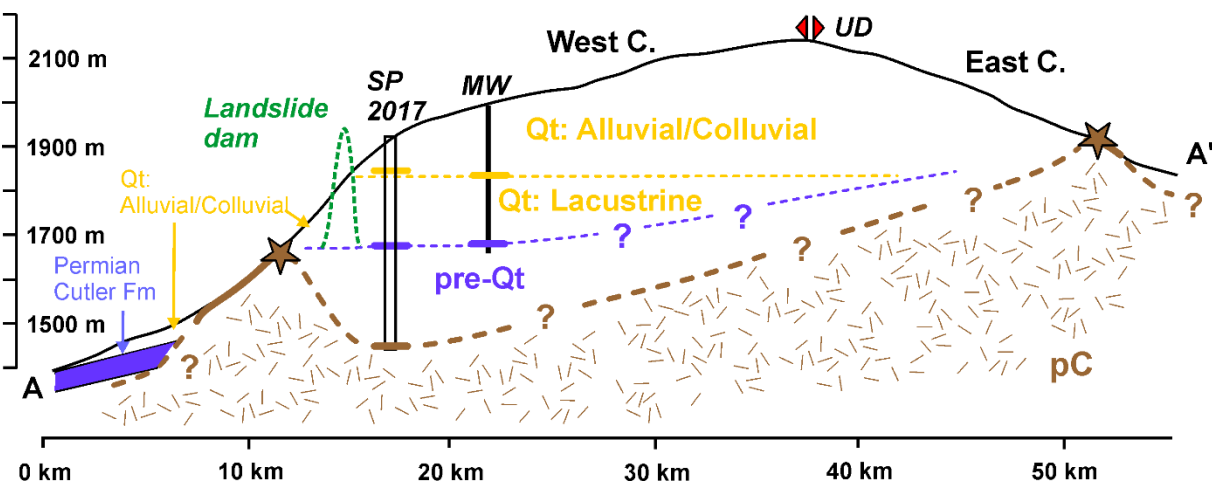


Figure 3.

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 $X=1800$ 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' indicate top of interpreted reflectors as in Fig. 2b. Core

sections after Balco et al. 2013: A – Qt Alluvium / Colluvium; λλ – Paleosoils; B – Qt Lacustrine;
C – Pz Diamict

The integration of our interpretation with the stratigraphy of the Massey core and basement outcrops enables construction of a longitudinal section along the canyon (Fig. 4). The overdeepened character of the Precambrian basement surface of Unawep 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, Unawep Canyon compares to the “alpine glacier” and “fjord” types. In that context, we speculate that the aforementioned tilted basal reflectors with low interval velocities might represent a lateral moraine (Fig. 2b), and that the lowermost stratified section of the valley fill could be indicative of a ground moraine.



208 *Figure 4.*

209 *Hypothesized vertical section along Unaweep Canyon following the dashed line in Fig. 1. Black*
210 *solid line: Topography along West and East Creek. UD: Unaweep Divide. MW: Massey well. SP*
211 *2017: Location of seismic profile. Dashed yellow line: Top of the lacustrine unit. Dashed purple*
212 *line: Top of pre-Quaternary strata. Dashed brown line: Overdeepened Precambrian basement.*
213 *Solid yellow/purple bars and brown lines show according observations from the seismic profile,*
214 *the well, and surface geology. Location of the 1.4 – 1.3 Ma landslide dam according to Balco et*
215 *al. 2013.*

216

217 Seismic interpretations of Paleozoic glacial valley fill in other parts of the world (Bache et al.
218 2012; Bataller et al. 2019) reveal complex stratigraphy representative of repeated glacier advances
219 and retreats, with additional complications arising from subsequent erosion, deformation, and
220 sedimentation events. Lack of a well penetration here precludes precise characterization of the
221 nature and age of the valley fill. We note however that the top of the pre-Quaternary strata aligns
222 with the fluvial base level of the ancestral Gunnison river 1.4 Ma ago (Balco et al., 2013; Soreghan
223 et al, 2015).

224 Soreghan et al. (2008) hypothesized that Unaweep Canyon was carved in the Late Paleozoic ice
225 age (LPIA). The modern elevation of the Uncompaghre Plateau, together with lack of evidence for
226 recent glaciation precludes Pleistocene glaciation here (Soreghan et al., 2007). The morphology of
227 the preserved bedrock surface, partial exhumation of a paleovalley at the western mouth of the
228 canyon, and the inferred proglacial facies of the Permian fill here all support the Paleozoic

hypothesis (Soreghan et al., 2009, 2015). Our results corroborate this hypothesis, implying that Fig. 2 represents the first image of a glacial valley from a pre-Quaternary ice age in North America. The accepted model for the late Paleozoic Ice Age (LPIA) holds that glaciation occurred across the Gondwanan continents, at latitudes $>\sim 31^{\circ}\text{S}$ (Evans, 2003). In contrast, during the late Paleozoic, the Uncompahgre uplift was within $\sim 11^{\circ}$ 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 about ~ 1200 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 over-deepened 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 Mountains 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 modelling and motivate new field and modeling research in search of new evidence for glaciations in other parts of the Carboniferous-Permian tropics.

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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 dataset name “Unawweep” and the year “2017”.

Supplemental Material

Supplemental materials S1 – S7 can be found in the online version of this article.

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Supplemental material to Patterson et al. **“Seismic reflection and electrical resistivity imaging reveals pre-Quaternary glaciation in the Rocky Mountains (Unaweep Canyon, Colorado)”**

Figure S1 (next page): Map view of the acquisition. Grid coordinates are in UTM Zone 12N.

Cyan line: Three-component 5 Hz Fairfield ‘ZLand’ seismic recorders at 5 m spacing (120 stations). Blue line: One-component 4.5 Hz Reftek ‘Texan’ seismic recorders at 5 m spacing. Grey dots: Manual sledge hammer source locations at 10 m spacing. Red dots: Nitrogen-pressured impact source A200 locations at 10 m / 5 m spacing. Yellow dashed line: Location of the vertical projection plane used in Figs. 2,3, DR5 – DR8. Labels indicate profile distance (in meters) shown in those figure axes. Qt, pC: Quaternary and Precambrian surface cover. White lines: Elevation contours (m).

A detailed description of the survey layout is provided in Patterson (2019).

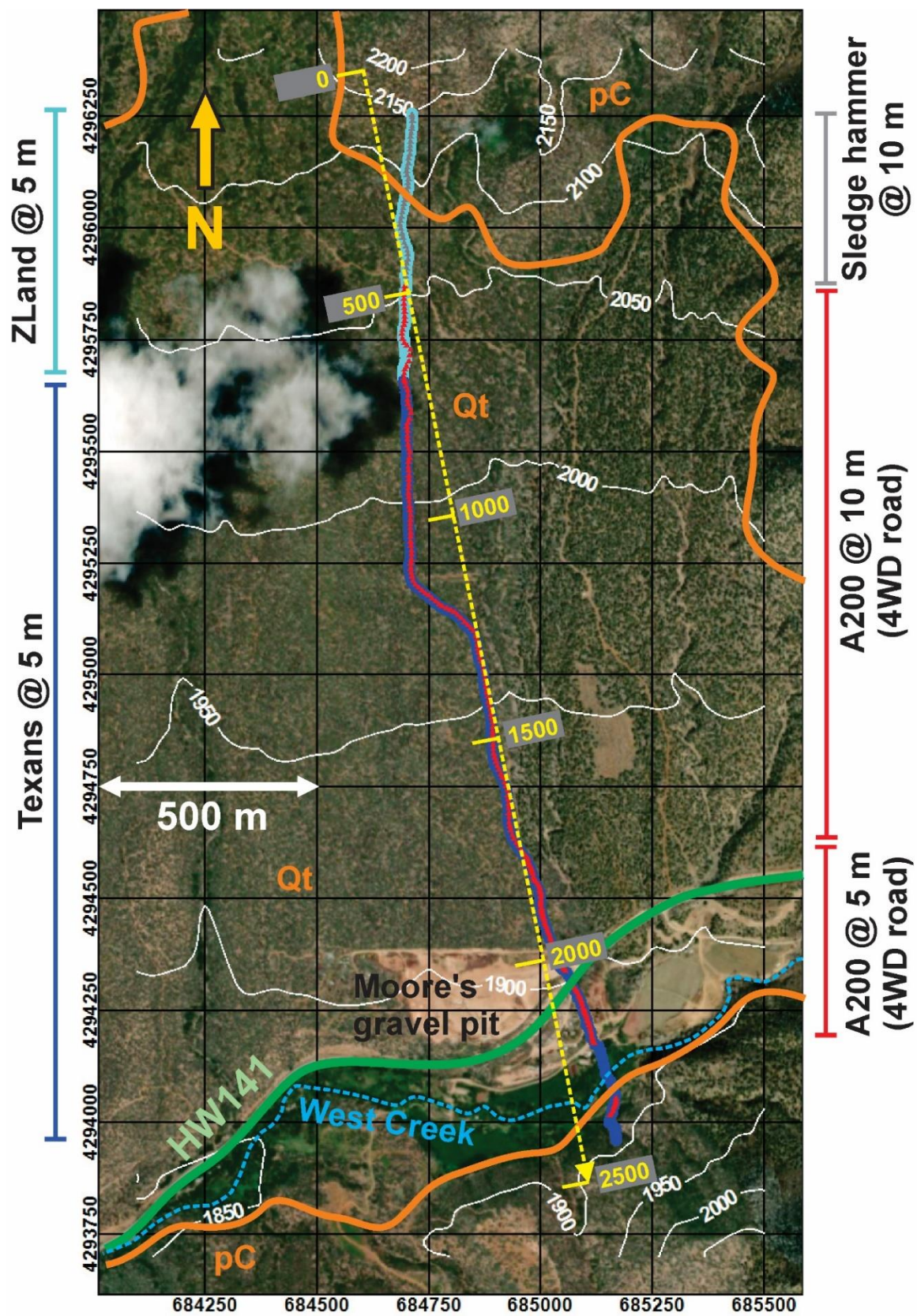
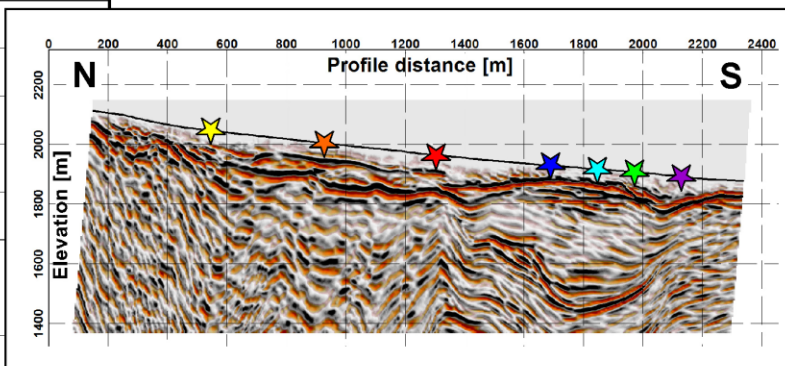
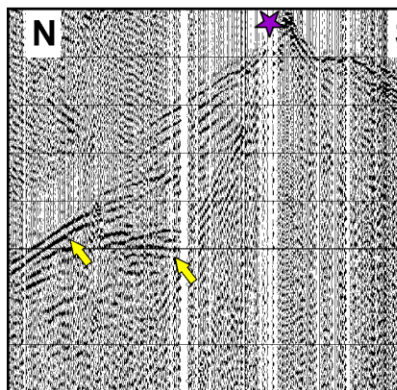
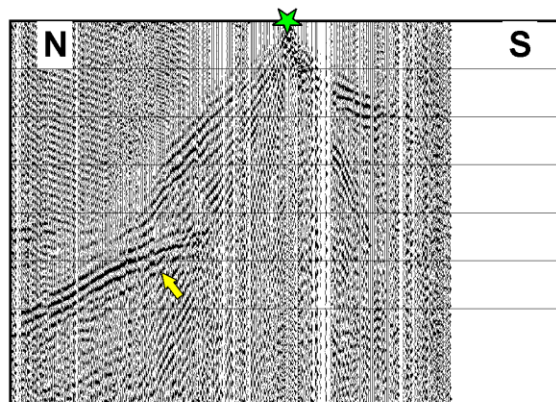
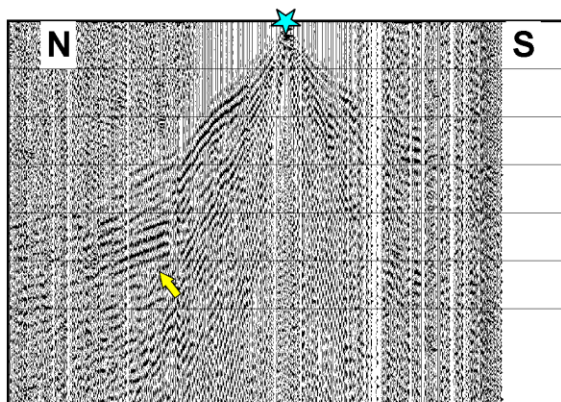
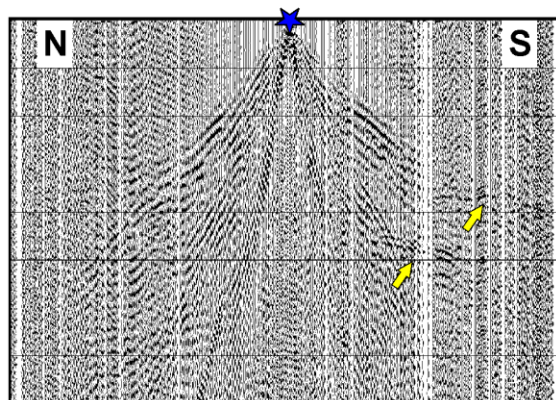
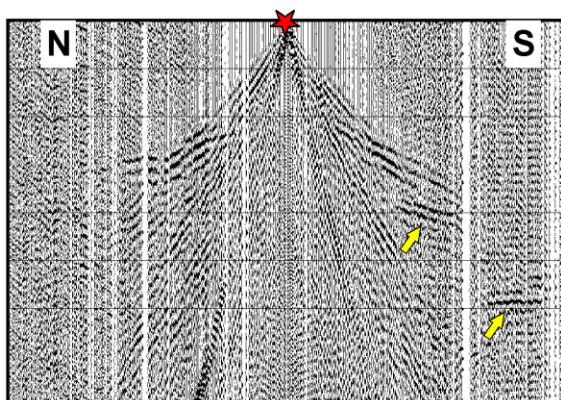
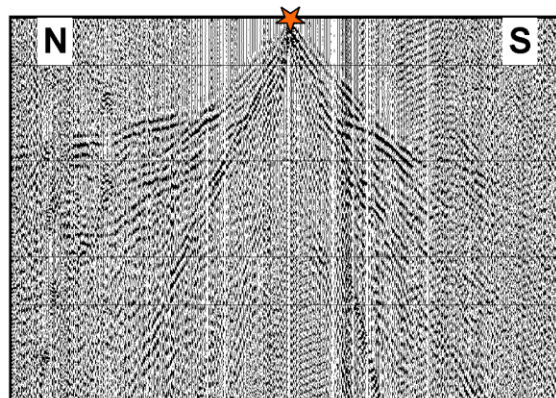
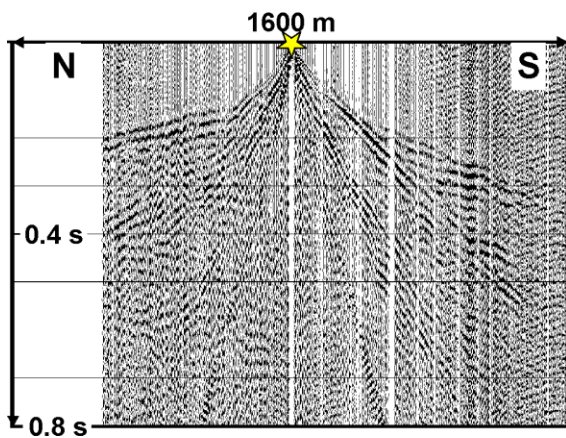


Figure S2 (next page): Selected shot gathers (raw data) along the profile after application of a bandpass filter (30 – 60 – 130 – 160 Hz) and AGC with 500 ms window length. Vertical and lateral extent is identical for all shot gathers (+/- 800 m offset, 0.8 seconds recording time). The colored stars correspond to the shot locations at the profile shown in the PSTM image. The yellow arrows highlight asymmetric and skewed reflection arrivals and are indicative of a complex subsurface structure with sudden changes in basement depth.



Data have been processed independently with Haliburton ProMAX and SLB Vista, providing similar results in terms of subsurface structure and velocities. The final results are from the Vista processing sequence, which turned out to image the data slightly better.

1. Trace editing, crooked line geometry application, CMP binning (bin size 5 m)
2. First arrival picking, elevation and refraction statics, reduction to floating datum
3. Initial Signal processing: Bandpass filter (10-25-90-130 Hz), AGC (window length 250 ms), notch filters, FK filter, Top and bottom mute
4. Predictive Deconvolution: Operator length 120 ms; Prediction lag = second zero crossing of the autocorrelation, taper length 20 ms, pre-whitening 2%
5. CMP sorting and velocity analysis: Super gathers of 10 CMP bins, offset restriction 150 – 950 m, bandpass filter 10-15-80-100 Hz
6. Velocity model smoothing
7. NMO stack: Offset restriction 100 – 600 m, stack normalization by the square root of the number of traces, stretch mute 100%*
8. Residual power statics calculation and application, new NMO stack (Fig. DR4)
9. Iterative PSTM velocity and PSTM aperture angle analysis
10. Velocity model smoothing
11. PSTM: Offset restriction 100 – 600 m, rephasing filter, stack normalization by the square root of the number of traces, anti-alias filter 15-75 Hz, stretch mute 100%*(Fig. DR4)
12. Depth conversion with the smoothed PSTM velocity model
13. Bandpass filter (10-15-65-80 Hz), AGC (window length 300 ms), mean scaler, trace mix (weights 1-3-1) (Fig. 2)

*: A large stretch mute was required to image the shallow basement ‘B1’ in the left part of the profile and the reflector ‘L’. We attribute this uncommonly high value to a large velocity gradient in the sedimentary cover above the reflectors, which causes reflection rays to arrive at larger offsets.

Table S3: Processing sequence and parameters

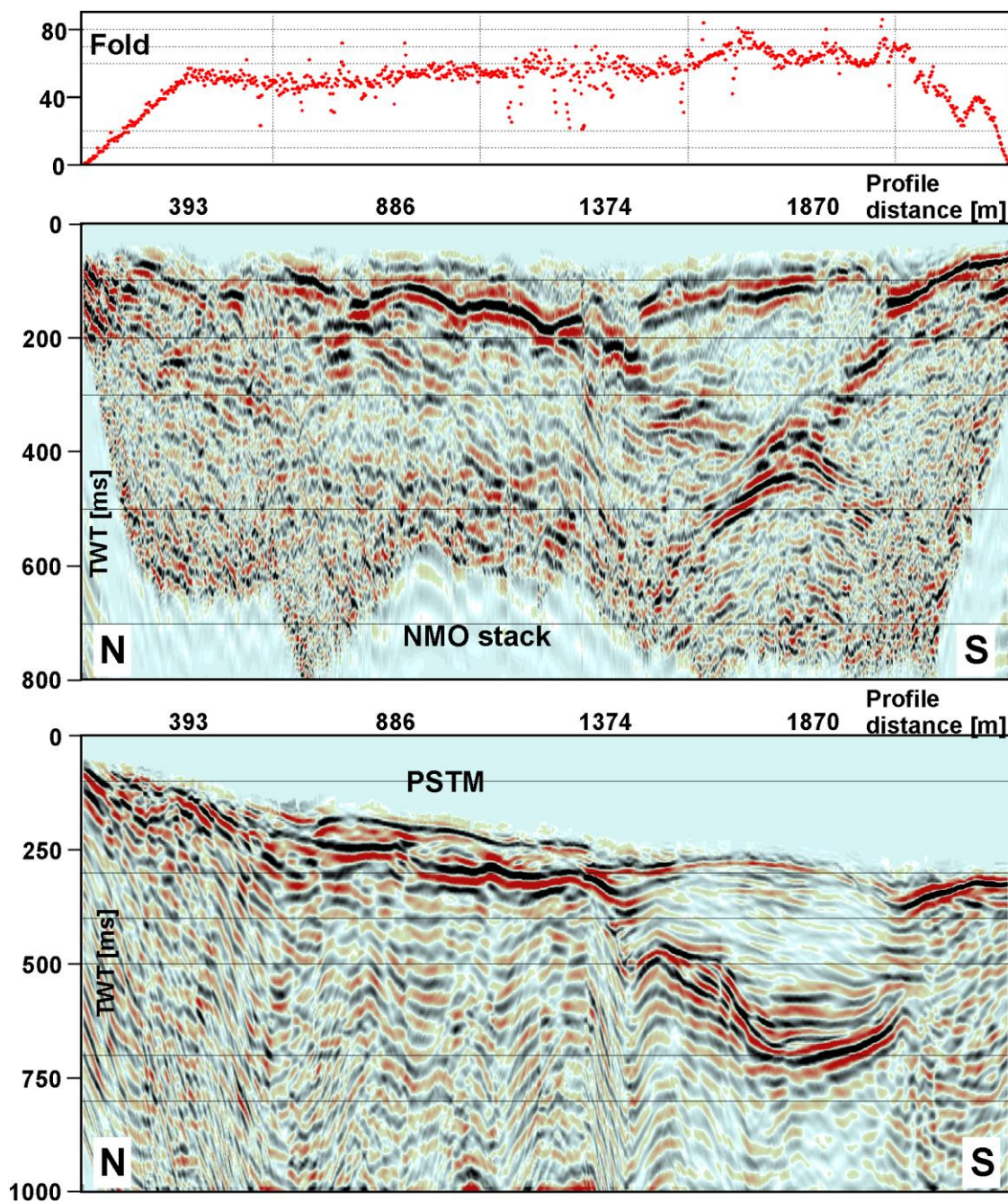


Figure S4: NMO stack referenced to the floating datum with corresponding fold, and PSTM image referenced to the final datum. The fold scatters is due to the crooked line bins. The stack clearly shows significant overdeepening and is indicative of a U-shaped structure (e.g., compare to de Franco et al., 2009, Figs. 3 and 5). The superposition of the horizontal reflectors and the diffraction hyperbola (profile distances 1400 – 1900 m) illustrates the necessity of pre-stack time migration. Both NMO stack and PSTM image are bandpass filtered (10-15-65-80 Hz) and scaled with AGC (window length 500 ms)

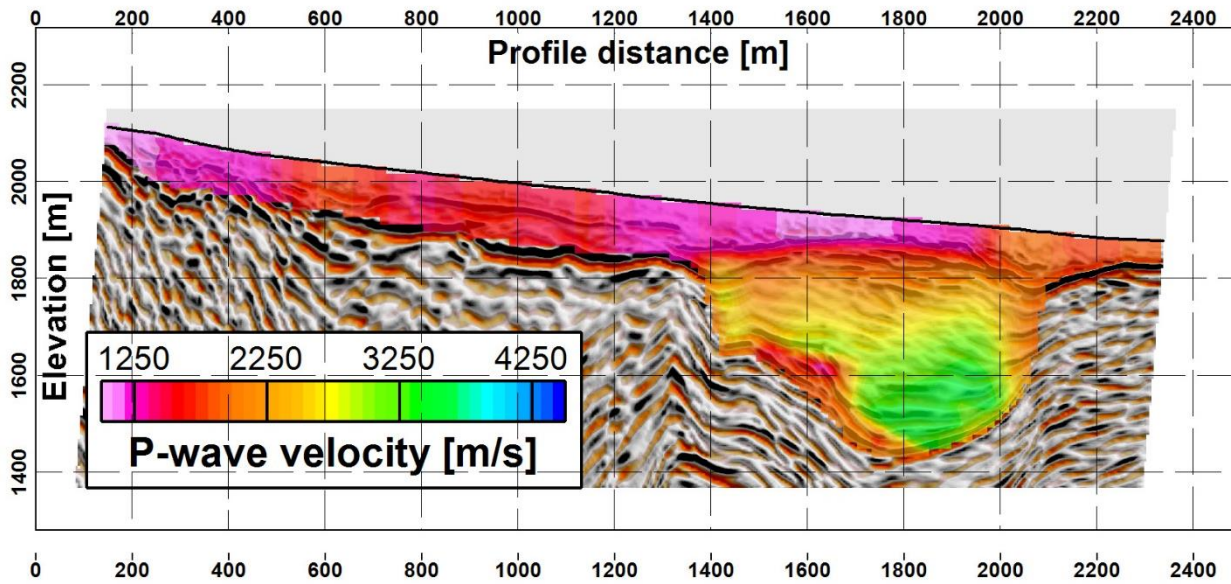


Figure S5: Smoothed and depth-converted PSTM interval velocity model. In absence of a local well, this velocity model was also used for the time-to-depth conversion of the PSTM image.

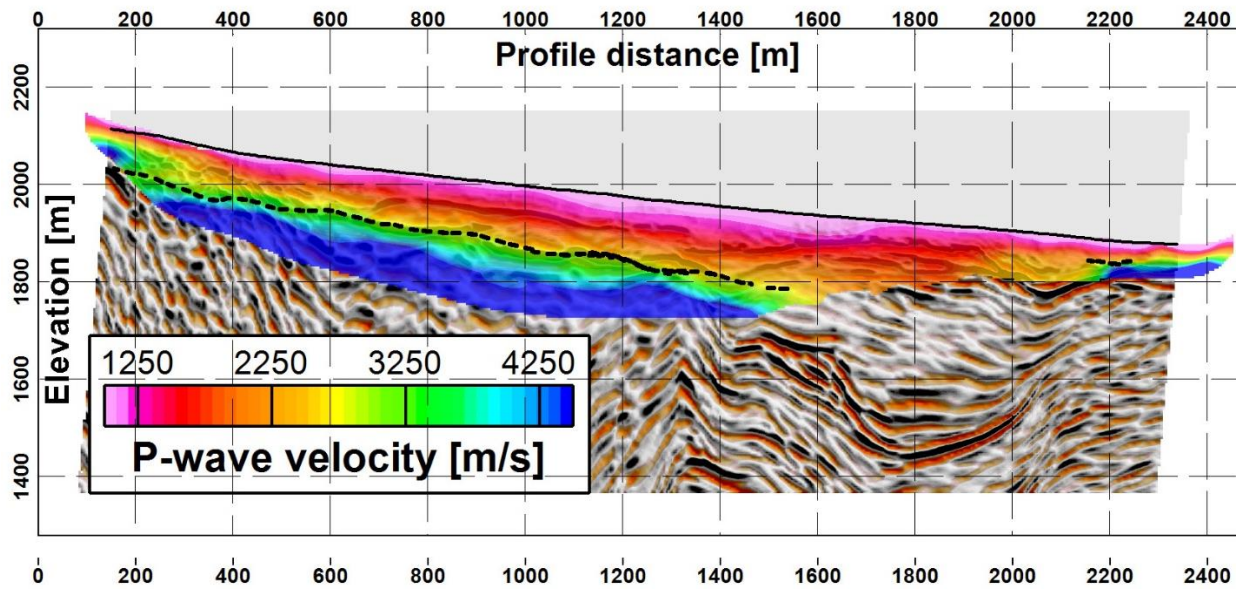


Figure S6: Tomographic velocity model and refractor depth (black dashed line) based on first arrival travel times (see Behm et al., 2019 for details). The lack of basement rock velocities (> 4000 m/s) and the absence of a well-defined refractor coincides with the area of overdeepening (profile distance 1500 – 2100 m). Tomographic velocities and refractor depth were established independently from reflection processing.

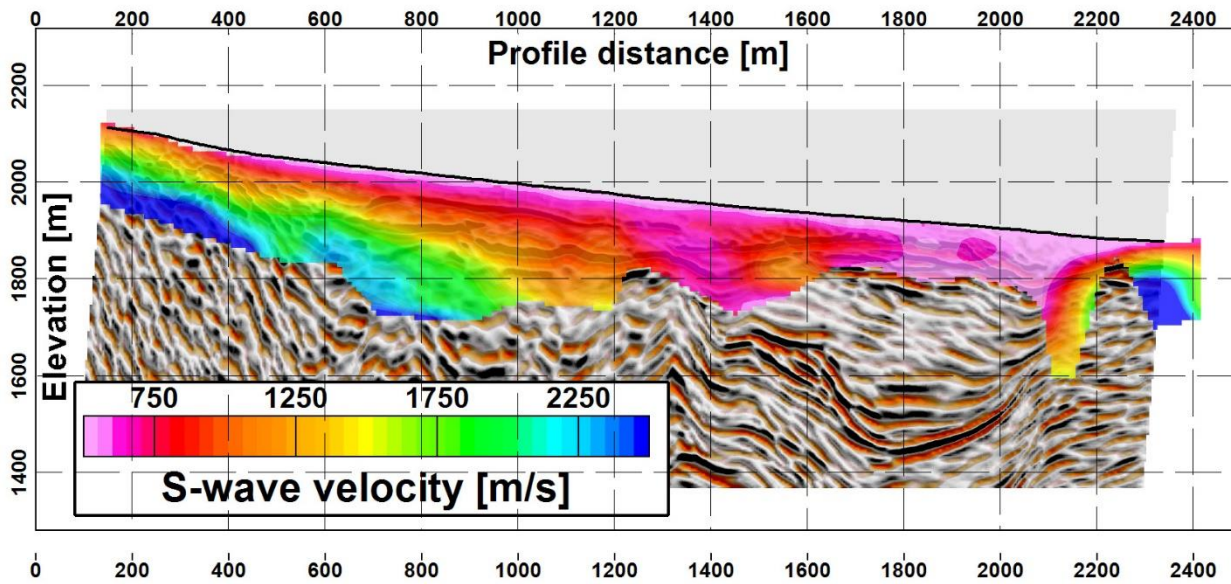


Figure S7: Shear wave velocity model based on surface wave inversion (see Behm et al., 2019 for details). The low velocities in the deeper section are indicative of significantly weathered basement rock. The resolution and accuracy of surface wave inversion is in general inferior to travel time tomography, but nonetheless we observe a similar structure as in figures 2, S5, and S6 (shallowing of basement towards the north, sudden change from deep basement to shallow basement at profile distance ca. 2100 m).