An Exhumed Late Paleozoic Canyon in the Rocky Mountains: A Reply

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Introduction

We thank William Hood for his discussion of Soreghan et al. (2007). We recognize that our interpretation of the events leading to the formation of Unaweep Canyon, particularly our proposed Paleozoic age of the (ancestral) canyon, represents a significant departure from established models. Validation of our hypotheses regarding its age and origin would force revision of several long-accepted models, ranging from the Cenozoic tectonic and geomorphic evolution of this region to the climatic and perhaps tectonic framework of the Permo-Pennsylvanian tropics represented by this system. Accordingly, our work deserves close scrutiny, and Hood's discussion provides such an opportunity.

Hood (2009) begins his discussion by stating that Soreghan et al. (2007) presented the hypothesis that Unaweep Canyon is a Permian glacial valley that was filled by Paleozoic sediment and subsequently exhumed by Cenozoic rivers. To clarify, the focus of Soreghan et al. (2007) is the hypothesized Paleozoic age of the canyon, although we posed the question of a possible glacial origin in the final sentences of the article. A more complete analysis of the evidence for a glacial origin, however, appears in Soreghan et al. (2008), although only abstracts of this aspect (e.g., Soreghan et al. 2004) were published at the time that Hood submitted his discussion. Nevertheless, here we address all of the points raised by Hood; we treat each of his points using the subheadings he provides.

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Reexamination of the Field Evidence and Paleomagnetic Data

Massive Conglomerate and Diamictite with Paleozoic Palynomorphs. Hood notes that we described within Unaweep Canyon an inferred Permo-Pennsylvanian deposit consisting of (matrix to) "clast-supported" conglomerate composed entirely of Precambrian boulders and containing exclusively Permo-Pennsylvanian palynomorphs. Hood suggests that this deposit could instead be a talus deposit, which, he claims, would explain the lack of Mesozoic clasts. Hood explains the presence of Paleozoic palynomorphs as either (1) a product of transport by the ancestral Colorado River in Unaweep Canyon or (2) more likely, the result of wind transport from the Permo-Pennsylvanian Cutler deposits located west of Unaweep Canyon. The main evidence here is the presence of Paleozoic palynomorphs within this unit. As a point of fact, we have processed >20 samples from the suspected Paleozoic and immediately superjacent Cenozoic units exposed in western Unaweep Canyon, with palynomorph recovery in general very poor, and approximately 45 samples from various depths of our drill core, with typically better palynomorph recovery. Several samples with Paleozoic forms were rerun using virgin sample containers, to eliminate the possibility of contamination.

Hood's explanation of the Paleozoic palynomorphs here as a result of transport by the Colorado River seems far-fetched at best. First, the possible presence of the ancestral Colorado River in Unaweep Canyon remains speculative because the only tangible record of a large river in the canyon, indicated by the provenance of fluvial gravels and lake deposits within and near the canyon (Cater 1966, 1970; Aslan 2005; Kaplan 2006; Marra

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2008) records the ancestral Gunnison River. Second, Paleozoic strata do not occur within the Gunnison River drainage basin. Hence, the Gunnison River could not have delivered Paleozoic palynomorphs to Unaweep Canyon. Third, even allowing for the possibility that the ancestral Colorado River occupied Unaweep Canyon, transport of exclusively Paleozoic palynomorphs in this way poses major inconsistencies because the nearest exposures of upper Paleozoic strata traversed by the Colorado River upstream of Unaweep Canyon occur near Glenwood Springs, nearly 150 km away and across many kilometers of Mesozoic and Cenozoic strata. Thus, invoking the Colorado River to selectively entrain and deposit exclusively Paleozoic palynomorphs in Unaweep Canyon is very unlikely. Finally, the upper Paleozoic strata exposed in that part of the Colorado River drainage basin (the Eagle basin) nearest Unaweep Canyon were deeply buried, which should have imparted high thermal alteration indices (TAIs) in any recovered palynomorphs. Indeed, TAIs of palynomorphs from the Maroon Formation of this region are quite high (>3; G. S. Soreghan and C. F. Eble, unpublished data, 2001; Tramp et al. 2004), contrasting significantly with the TAIs of 1–2 for the Paleozoic palynomorphs we recovered from the deposits within Unaweep Canyon (Soreghan et al. 2008). Regarding the possibility of wind transport for the Paleozoic palynomorphs, we question why wind would selectively entrain and deposit only Paleozoic palynomorphs into this unit and not any Mesozoic forms from the (equally abundant) Mesozoic strata abounding in the region.

Hood also takes issue with the presence of modern pollen (together with Paleozoic palynomorphs) in the basal unit of our drill core and suggests this unit is instead a recent talus deposit with palynomorphs infiltrated from the Colorado or Gunnison River. Infiltration of palynomorphs through poorly consolidated strata is a known phenomenon (Kelso 1994). "Modern" (i.e., recent) palynomorphs are abundant in much of the canyon fill penetrated by the core (especially the reduced lacustrine strata), and so we hypothesized infiltration of this modern material into the suspected Paleozoic deposit. We fail, however, to fathom why Hood rejects our explanation and instead proposes infiltration of exclusively Paleozoic palynomorphs as delivered by either (1) the ancestral Gunnison River, which does not traverse Paleozoic strata, or (2) the ancestral Colorado River, which has not been shown to have occupied Unaweep Canyon. Furthermore, if these rivers had introduced Paleozoic palynomorphs, they should have similarly introduced Mesozoic material from the great expanse of Mesozoic underlying the drainage basins, and any Paleozoic forms should exhibit the higher TAIs indicative of the more deeply buried Paleozoic of the upper Colorado River (as noted above). Finally, Hood's suggestion that this lowest unit is a talus deposit simply does not match the sedimentology of the unit, which comprises diamictite locally exhibiting polyphase deformation (Soreghan et al. 2008).

Finally, Hood incorrectly states that Paleozoic palynomorphs and modern pollen also occur in the (Plio-Pleistocene) lacustrine unit of the drill core. As stated in Soreghan et al. (2007), however, only "modern" (Plio-Pleistocene) material occurs in the upwardly coarsening lacustrine unit of the drill core. One sample (at 298 m) within the thin (19 m) Precambrian-sourced transitional unit atop the basal diamictite contains Paleozoic palynopmorphs; aside from this, samples (three) containing Paleozoic palynomorphs occur only in the basal 5 m of the core. This is why we placed such significance on the occurrence of Paleozoic palynomorphs in the basal unit of the core. Thus, his argument of mixing and infiltration is simply untenable. The Quaternary alluvium of the roadcut did yield sparse and highly reworked Paleozoic palynomorphs, in addition to sparse Mesozoic forms, which we attribute to Cenozoic fluvial reworking of Paleozoic and more recent fill. We stand by this explanation.

Paleomagnetic Data

Hood (2009) takes issue with our paleomagnetic data, which indicate low (late Paleozoic) inclinations in the material from the basal drill core. He suggests that these low inclinations, which reside in hematite, could have formed at any time, and he calls on magnetite within the Precambrian basement-derived clasts to have influenced our hematite-bearing signal. To clarify, our data (from numerous samples in the basal core unit) exhibit low inclinations, meaning that this unit acquired a magnetization during the late Paleozoic, the last time that Colorado lay at low latitudes. We cannot determine (without further studies) whether this signal is a primary magnetization or a remagnetization, but regardless, the signal indicates that these strata acquired their magnetization in the late Paleozoic. Hood's statements regarding the possible influence of "a jumble of magnetite-bearing rocks comprising the diamictite" confounding the paleomagnetic signal is, given the multiple samples run, very unlikely.

Glacial Features and Implications of Permian Glacial Origin

As Hood (2009) stated, Cole and Young (1983) first suggested a glacial origin of the canyon, albeit a Quaternary glacial origin. We view the Cole and Young (1983) article as prescient and admire the observations forwarded in their article. However, we respectfully disagree with the assertion of a Quaternary glaciation in Unaweep Canyon, owing to its low elevation and the lack of any positive evidence for such glaciation, in the form of glacial deposits (Soreghan et al. 2007). Hood's comparison to the glaciation of nearby Grand Mesa is irrelevant, because unlike the Uncompahgre Plateau, Grand Mesa hosted a high-elevation (>3-km) ice cap, with the associated momentum to drive ice tongues to lower elevations than alpine glaciers of the region (Yeend 1969). Driving a large alpine glacier through Unaweep Canyon is untenable, because there is no sufficiently high-altitude ice cap that could have driven a glacier to such anomalously low elevations (Soreghan et al. 2007).

Hood also notes that our suggestion of a Permo-Pennsylvanian glacial terminus of 500–1000 m elevation contrasts with the high-elevation termini of modern equatorial glaciers; we agree completely. The implication, if our hypothesis is correct, is that the Earth was remarkably cold during the time(s) of formation of the canyon (an assertion now fully treated in Soreghan et al. 2008).

Finally, Hood notes that there are no buried tributaries in Unaweep Canyon, as might be expected given the hypothesis of a late Paleozoic origin of the canyon. We do not understand this assertion, given that discovery of any such tributaries would require drilling various sites along the canyon edges where the Precambrian surface remains buried, which has not been done. There are, however, many examples of tributary systems that appear "beheaded" (cross cut) by Mesozoic strata (examples in Soreghan et al. 2007), which suggest a pre-Mesozoic origin of the Precambrian gorge of the canyon. Similarly, Hood suggests that there should be other exhumed canyons on the Uncompahgre Plateau. Yes, we agree that there might indeed be other canyons, but we need to search for them using geophysical approaches.

Interaction with Laramide Structural Features

Hood concludes his discussion by addressing structural aspects of the canyon, culminating in presentation of a cross section that appears to show the (hypothesized) Paleozoic base of Unaweep Canyon sloping upward in a downstream direction, which Hood notes as "impossible" for a stream and improbable for a glacier. Here, we address each of Hood's points in the order in which they occur in the text.

Hood begins this section by noting that Unaweep Canyon traverses the "asymmetric anticline" of the Uncompahgre Plateau and is further disrupted by the Ute Creek Graben at its western end. He suggests that the faults of the graben postdate the Cretaceous Dakota Formation, with an offset of "as much as 244 m" (a value addressed further below). The fault that bounds the northeast margin of the Ute Creek Graben on Williams's (1964) map is shown to end just south of Unaweep Canyon. The presumed (on-trend) continuation of this fault north of the canyon is Hood's fault *A* and juxtaposes the Dakota Formation against the Triassic Kayenta-Wingate approximately 8 km north of Hood's section line within Unaweep Canyon. Whether his 244 m offset is measured from this fault is unclear, because Hood suggests a redrawing of the boundaries of the Ute Creek Graben to align the western part of the northeast-boundary fault (fault *A* in his fig. 1) with the canyon. Yet, his cross section utilizes the faults as shown by Williams (1964). Nevertheless, he reasons that his inferred fault (queried continuation of his fault *A*), which offsets Mesozoic strata, must control the trend of the canyon, implying (to him) that the canyon postdates the faulting. Aside from the speculation posed here regarding fault trends and offsets, even if the fault controls the (modern) canyon, the earliest fault motion is unknown; the map pattern reveals only that the fault has moved since the deposition of the Dakota Formation. Like many faults of the region, this fault could be a reactivation of a Paleozoic or even Precambrian feature and thus could have controlled the direction of a paleocanyon. Hence, we reject Hood's speculation of dating the canyon via fault orientation.

Hood similarly speculates that the abrupt change in orientation of the canyon 1.2 km east of the canyon's western mouth as depicted on the Williams (1964) map provides further evidence of a post-Dakota fault control of the canyon. Cater's (1955*b*) more detailed map of this part of the canyon depicts the sharpest bend offset from the westernmost Ute Creek Graben fault by several hundred meters, so it is unclear why Hood attributes such significance to this bend. Nevertheless, we agree that this part of the canyon, which represents only the westernmost 1.2 km of a >40-km-long canyon is probably overprinted substantially by recent action, because West Creek here has incised completely through all canyon fill and into Precambrian basement, effectively eroding the Paleozoic paleosurface. Hood concludes that a young fault control of this part of the canyon indicates the canyon is younger than the westernmost Ute Creek Graben fault. We disagree with this reasoning; it indicates only that the westernmost, highly incised 1.2 km of this canyon may reflect young (incision) events.

Finally, Hood attempts to assess the (longitudinal) shape of the buried canyon floor by hanging a cross section from the Chinle Formation along the canyon to illustrate his depiction of the canyon at Chinle (Triassic) time. There are many problems with this cross section. Fundamentally, he fails to (1) clarify the line of section, (2) justify calculation of fault offset, and (3) accurately depict mapped units. Furthermore, his assumptions regarding (1) the path of the paleocanyon and (2) the structure in the western canyon are demonstrably speculative. We detail these points below.

From the labeling of the "Present valley floor" on Hood's cross section, we presume that the section line follows the course of modern West Creek. However, the current floor of the canyon containing Quaternary fill commonly exceeds 1.5 km in width (2.5 km locally), and the gravity profiles in the canyon indicate significant asymmetry to the transverse profiles (Davogustto et al. 2005; Davogustto 2006; Soreghan et al. 2008). Hence, placement of the line of section is critical to any attempted reconstruction of the canyon profile. Only one absolute data point exists for the (minimum) depth of the valley floor to Precambrian basement within the whole of Unaweep Canyon: the University of Oklahoma (OU) drill hole. Hence, any reconstruction of the longitudinal shape of the valley floor constitutes pure and unsubstantiated speculation. The geophysical data cited by Hood infers depths in parts of the canyon east of the drill hole but no information on transverse profiles. We especially question all of Hood's reconstruction west of the OU drill hole. Within Ute Creek Graben, for example, Hood's cross section shows a wedge of valley fill, yet his map shows essentially no valley fill; this inconsistency calls into question the methods of cross-section construction. Nevertheless, although neither Williams (1964) nor Hood depict fill within the graben, mapping by Kaplan (2006) documents substantial fill. Moreover, a north-south (transverse) gravity profile along the northeastern margin of the graben shows 320 m

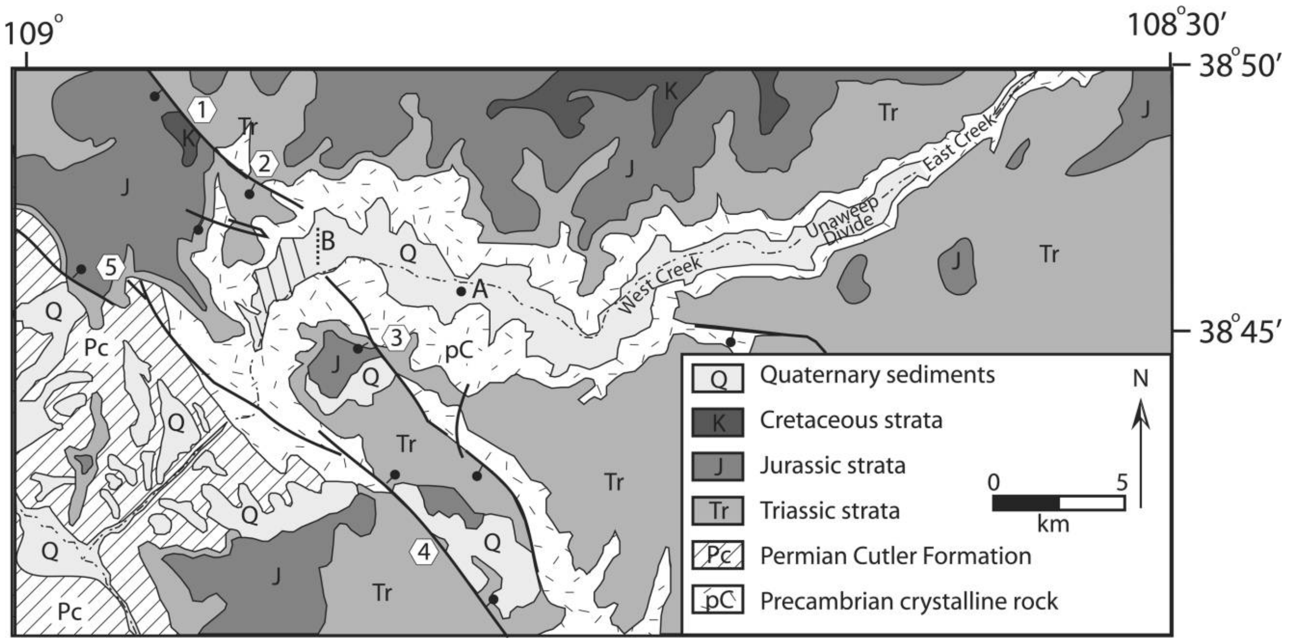

Figure 1. Simplified geologic map of Unaweep Canyon modified from Williams (1964). Cretaceous strata include the Burro Canyon Formation and Dakota Sandstone; Jurassic strata include the Entrada Sandstone, the Summerville Formation, and the Morrison Formation; Triassic strata include the Moenkopi Formation (southwest region only), the Chinle Formation, the Wingate Sandstone, and the Kayenta Formation. Numbers *1–5* denote locations of displacement estimates (table 1) on faults bounding Ute Creek Graben. Cross-hatched area of Quaternary fill in western canyon is from mapping of Kaplan (2006). The University of Oklahoma drill core location is denoted by *A*, and *B* denotes the gravity line of Davogustto (2006). See text for further discussion.

Table 1. Ranges of Displacements on Faults Bounding Ute Creek Graben

Graben fault (map no.)	Location relative to West Creek	Displacement (m)	Data source
Northeast margin (1)	8 km north	301	Williams 1964
Northeast margin (2)	4 km north	139	Williams 1964
Northeast margin (3)	4 km south	67–128[1a]	Cater 1955*b*
Southwest margin (4)	8 km south	80–210[a]	Cater 1955*b*
Southwest margin (5)	8 km north	85–162[a]	Cater 1955*b*

[a] Values are maximums that assume near-complete removal of the youngest unit faulted; the range reflects the range of stratal thicknesses for the map area reported by Cater (1955*b*).

of fill, with the thickest fill located 0.6 km north of West Creek. These data show that, in this locality, the course of West Creek and the keel of the hypothesized paleocanyon do not coincide, invalidating Hood's reconstruction of the buried valley floor and highlighting an incorrect assumption of his cross-section line. When the true fill thickness is considered, Hood's depiction of the abrupt uphill displacement at the northeast graben margin ceases to exist. Hood's apparent placement of the section line along West Creek here is especially puzzling given his earlier (Hood 2009) citation of our work suggesting the keel of the paleocanyon here is offset from West Creek.

Furthermore, it is unclear how Hood arrived at the value of 244 m for offset on the faults of the Ute Creek Graben. The only data available for this estimation are the 1 : 250,000 scale compilation of Williams (1964), which shows the faults of the entire graben north and south of the canyon, and the 1 : 24,000 map of Cater (1955*b*), which shows the southern part of the graben. Unfortunately, many stratigraphic intervals are lumped on the Williams (1964) map, owing to its small scale, leading to large ranges in estimates of displacement using the stratal thicknesses listed in the map key. We therefore estimated displacement along these faults by measuring stratal thicknesses directly from the map in the sites along the graben faults that juxtapose Mesozoic strata. For the Cater (1955*a*) map, which depicts a much larger scale and corresponding greater detail, we used stratal thicknesses listed on the map key. Using this approach, our measurements of displacement along the northeastern bounding faults nearest (within 4 km of) West Creek range from (maximums of) 67–139 m and 80–210 m on the southwestern bounding faults (fig. 1; table 1); furthermore, displacements on the NE bounding fault decrease toward the canyon such that our estimates are maxima, and all are less than Hood's estimate. We reiterate the importance of the exact placement of the cross-section line, given the lateral change in fault displacements, the great width of the paleocanyon in many areas, the great thickness of fill, and the probable transverse asymmetry of the paleocanyon. The assumption that the deepest course of the paleocanyon follows modern West Creek is demonstrably incorrect.

Finally, Hood's reconstructed elevation of the Precambrian at the western mouth of Unaweep Canyon appears to show an uphill swing of the basement surface. The reconstruction here assumes invariant thickness of the Chinle Formation across the map area and a horizontal deposition surface. Yet, Cater's (1955*a*) detailed map demonstrates significant thickness variation (>200 m) in both the Chinle and Moenkopi formations approaching Unaweep Canyon, which both wedge and thin onto the (ancient) Uncompahgre Uplift, refuting both of Hood's assumptions. Furthermore, restoring the Chinle Formation to horizontal outside of the Ute Creek Graben necessitates projection of the Chinle-Precambrian surface from a distance of >6 km into the section line, because this is the only location outside (southwest) of the graben that exposes the Chinle Formation atop the Precambrian. Indeed, using Cater's (1955*b*) more detailed map, our estimate of the elevation difference between the Chinle-Precambrian surface and West Creek exceeds Hood's by >300 m. This discrepancy is huge, and calls into question the accuracy of Hood's section here. Elsewhere southwest of the graben, the Chinle is juxtaposed atop Moenkopi and Cutler formations, precluding reconstruction of the Chinle-Precambrian contact. These data nullify the accuracy of Hood's reconstruction.

Ultimately, the reconstruction of the longitudinal profile of the canyon is a three-dimensional problem that Hood has cast in two dimensions, using a variety of both unsubstantiated and incorrect assumptions and speculation, and the 17.5 times vertical exaggeration of the profile qualifies as geologic hyperbole.

Conclusions

We reiterate our thanks to Hood for his discussion but find that all of his points stem from misrepresentation, misunderstanding, or pure speculation, and none refutes our evidence for a late Paleozoic age for ancestral Unaweep Canyon. Hence, we stand by our hypothesis of the Paleozoic age of the canyon, as argued in Soreghan et al. (2007) from (1) geomorphologic cross-cutting relationships, (2) provenance, (3) palynology, and (4) paleomagnetism, and the origin of the canyon as inferred from the multiple lines of evidence published more recently (Soreghan et al. 2008). We appreciate the opportunity to shed further light on aspects of the geology that are important to the hypothesis.

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