Comment on "Age and Evolution of the Grand Canyon Revealed by U-Pb Dating of Water Table–Type Speleothems"

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Polyak *et al*. (Reports, 7 March 2008, p. 1377) reported speleothem data leading to their inference that the western Grand Canyon incised much earlier than previously thought. This contradicts several lines of published geological knowledge in the region, hinges upon unjustified hydrogeological assumptions, and is based on two anomalous data points for which we offer alternative explanations.

The highly publicized conclusion of Polyak *et al*. (*1*) that the western end of the Grand Canyon is more than 10 million years older than previously thought ignores and contradicts long-established regional geologic knowledge. We ask that the authors provide a rigorous justification of both their assumptions and their interpretations, specifically in the context of the well-published geology of the region. Considering this, we propose alternative interpretations of their two anomalous western Grand Canyon data points.

The initial speleothem and geochronology results reported by Polyak *et al*. are potentially valuable, inasmuch as they approximate, to within tens of meters, the past groundwater table. However, the authors make two fundamental assumptions in the large step from their nine basic data points across the region to their interpretations about the region's topographic evolution. As stated in (*1*), they assume that apparent groundwater table lowering is a direct proxy for, or "equivalent" to, the depth of canyon incision by an axial river some distance away. In addition, they assume that this paleo-groundwater table was "flat," such that, lacking a gradient head, this groundwater would not flow or relate to topography at all. Both of these conditions are impossible in landscapes of high relief such as this. These assumptions are erroneous even in the broadest sense, considering the complicated spatial relation of the variably perched or confined modern groundwater table to today's diverse Grand Canyon geology and topography (*2*). We ask the authors to justify these key assumptions and explore more rigorously the resultant uncertainties in their data.

In terms of interpretations, we are particularly concerned that the primary conclusions of Polyak *et al*. rely on two anomalously old and anomalously positioned data points [sample sites 1 and 4 of figure 2 and table 1 in (*1*)]. These sites are situated 30 to 40 km away from the modern Colorado River and are similar to each other in height above it, but one is dated at ~7.6 million years ago (Ma) and the other is more than twice as old, at ~17 Ma. On the basis of these two data points, the authors conclude that by ~17 Ma, the western Grand Canyon had been substantially cut by a precursor drainage flowing to the west. This older western drainage hypothetically captured the upper Colorado River near where most people visit the national park today in the eastern Grand Canyon. Thus, Polyak *et al*. envision a major regional drainage, excavating a canyon on the scale of at least several hundred cubic kilometers.

First, the presence of such a precursor western canyon contradicts Lucchitta and Jeanne's study exploring this issue with dated basalt flows recording paleotopography in this area (*3*). Second, such an excavated mass of rock must go somewhere downstream, but this runs into the classic "Muddy Creek" problem of Grand Canyon geologic history (*4*–*7*). Their inferred early incision would have delivered an overwhelming volume of clastic sediment to the internally drained Grand Wash Trough basin between 17 and 9 Ma, with this basin itself incised by 7.6 Ma. These interpretations directly contradict our geologic knowledge of the sources of sediment and the timing of deposition and erosion in these places. The geology of the beautifully exposed and well-dated sedimentary basins of the southeastern Lake Mead region has been well published and reconfirmed over nearly 80 years of study, and we know that their clastic fill was locally sourced and then incised soon after, ~6 Ma (*4*–*8*). In fact, the evidence for no substantial drainage or canyon cutting feeding the basins of this area is the seminal recognition that jump-started scientific debate about the region's landscape evolution decades ago (*5*, *9*). Similarly, it is also well known that the Colorado River did not finally integrate through those downstream basins and deliver Plateau-derived sediment to the lower Colorado River region until between 6 and 5 Ma (*10*–*12*). Third, Polyak *et al*. seem to ignore the well-researched system of deep, gravel-filled Paleogene paleocanyons on the southwestern plateau that dominated local topography through Miocene time (*13*, *14*). These Eocene paleocanyons contain a direct and dated record of subsequent aggradation by northeast-flowing drainages from late Eocene until middle Miocene time or later, again contradicting Polyak *et al*.'s claims of a west-draining western Grand Canyon at this same time. In fact, one of these paleocanyons lies directly between their 17 Ma data point and the Grand Canyon, and it extends below the elevation of their sample, assuring that a distant western Grand Canyon is not being detected in their data. The conclusions of Polyak *et al*. therefore need to be reconciled with existing knowledge of the region.

We argue that there are better interpretations of the two anomalous western Grand Canyon data points described in (*1*). Three to five kilometers of vertical slip along the Grand Wash fault is well documented between 16.5 and 8 Ma (and not before this time, as Polyak *et al*. state), forming the Grand Wash Trough and up to 1.6 km of topographic relief along the southwest edge of the Colorado Plateau (*6*, *8*). For the 7.6-Ma data point, which is much closer to the Grand Wash fault escarpment than to the modern canyon, this preceding and contemporaneous faulting suggests a groundwater connection from the plateau to adjacent springs in this lowering basin, not a topographic canyon off to the south (*7*, *15*). The older 17-Ma data point 30 km south of the Grand Canyon could be simply related to broad denudation and escarpment retreat in that area or, even more likely, to those closer, northeast-flowing paleocanyons mentioned above that predate the western Grand Canyon we see today.

The famous landscape of the Grand Canyon lies along the front lines of competing scientific and nonscientific views of Earth's antiquity and evolution. Regional geological knowledge of the Grand Canyon is especially rich and detailed, but it is already prone to unnecessary controversy and is frustratingly difficult to synthesize and communicate to the public. The report by Polyak *et al*. adds to the confusion rather than building upon previous science, and it therefore makes relating Grand Canyon science to the public even more challenging.

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Comment on "Age and Evolution of the Grand Canyon Revealed by U-Pb Dating of Water Table–Type Speleothems"

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Polyak *et al*. (Reports, 7 March 2008, p. 1377) reported that development of the western Grand Canyon began about 17 million years ago. However, their conclusion is based on an inappropriate conflation of Plio-Quaternary incision rates and longer-term rates derived from sites outside the Grand Canyon. Water-table declines at these sites were more likely related to local base-level changes and Miocene regional extensional tectonics.

In their geochronologic study of carbonate speleothems from within and near the Grand Canyon, Polyak *et al*. (*1*) reported 9 uranium-lead dates that record the approximate time of cave dewatering due to water-table decline. Their work provides valuable insights into the usefulness of this methodology for estimating river incision rates in general and incision rates of the Colorado River in the Grand Canyon during the past few million years in particular. However, the data they presented do not support their interpretations about the age of initial canyon development and they did not appropriately consider the results of other geologic studies that provide insight into the Neogene history of the region.

Two sample sites used by Polyak *et al*., located within the western Grand Canyon, yielded dates of less than 4 million years ago (Ma) (Fig. 1). These sites clearly are spatially related to canyon development and imply relatively low incision rates that are consistent with other recent findings (*2*). Incision rates inferred from these sample sites have no clear bearing, however, on the age of initial development of the western Grand Canyon. Geologic evidence indicates that the Colorado River arrived in the western Grand Canyon region 5 to 6 Ma (*3*–*5*) as a consequence of either upstream lake overflow (*6*, *7*), drainage capture by headward erosion (*3*, *8*), or some combination of these processes. The introduction of a major river into this area likely resulted in high initial incision rates followed by exponentially decaying rates, perhaps even including intermittent aggradation. Relatively low post–4 Ma incision rates in the western Grand Canyon are consistent with a pre–Colorado River canyon, rapid incision after introduction of the Colorado River, or both, but it is not appropriate to extrapolate these rates backward in time to estimate the age of the Grand Canyon.

The two sample sites that yielded older ages [sites 1 and 4 in (*1*)] are not in or directly connected with the western Grand Canyon and thus do not bear directly on Grand Canyon incision rates or the age of initial canyon development. Site 1 (7.5 Ma) is ~40 km north of the river in the Grand Wash Cliffs, in the footwall of the Grand Wash fault, a major normal fault that was active primarily between 16 and 10 Ma (*9*). From 11 to <7.5 Ma, limestone was accumulating in a large lake in the Grand Wash trough immediately west of the cliffs (*10*, *11*), which implies that base level in this area was relatively stable or slowly rising during that period. Given the location of site 1, water-table decline at 7.5 Ma may have been caused by local cliff erosion and retreat or base-level fall associated with spillover of the late Miocene lake and subsequent incision in Grand Wash trough, but any direct connection to Grand Canyon incision is unclear. Site 4 is about 90 km southeast of the mouth of the Grand Canyon and 30 km south of the Colorado River in the Grand Canyon. The 17-Ma date of water table decline is roughly coincident with inception of extension, surface lowering, and basin genesis in the Basin and Range province to the west (e.g., *9*–*14*). For a proto-canyon related to displacement on the Grand Wash fault to cause water-table decline at site 4, it would have had to develop and rapidly propagate tens of kilometers upstream through resistant strata. Furthermore, no evidence of clastic-sediment influx due to proto-Canyon excavation has been documented in Grand Wash trough; this has been the primary evidence against a west-flowing proto–Grand Canyon (*3*). A more plausible explanation is that the slope of the water table changed from east-dipping to west-dipping and that the water table declined throughout the western Grand Canyon region in the middle and late Miocene because of large-magnitude extension and regional subsidence in the Basin and Range province directly west of the Grand Wash fault (Fig. 1).

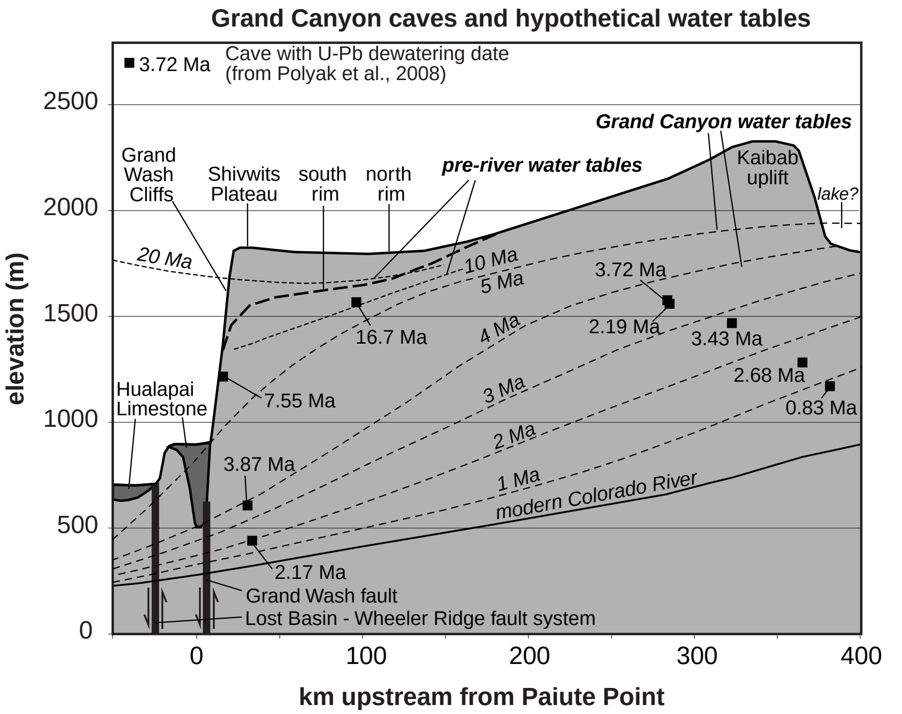

Fig. 1. Locations of caves studied by Polyak *et al*. (*1*) and hypothetical groundwater tables showing descent over time. Restoration of displacement on western faults recreates the highlands to the west, which were the inferred source of water that sustained an east-sloping water table in the western Grand Canyon region at 20 Ma. By 10 Ma, this highland no longer existed and the water table sloped westward. We infer that the 7.5 Ma dewatering of the Grand Wash Cliffs cave site occurred because of local base-level fall, due to erosional cliff retreat and/or to spillover of the lake that occupied the Grand Wash Trough.

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The authors' interpretation that their data support middle Miocene development of the western Grand Canyon is based on the broad similarity of Plio-Quaternary incision rates with longer-term "incision rates." Unfortunately, the two samples indicating middle to late Miocene water-table decline probably have no direct bearing on Grand Canyon incision. Other interpretations for water-table decline before the arrival of the Colorado River are much more compatible with regional geologic relations.

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Response to Comments on the "Age and Evolution of the Grand Canyon Revealed by U-Pb Dating of Water Table Type Speleothems"

Victor Polyak, *et al.*

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Response to Comments on the "Age and Evolution of the Grand Canyon Revealed by U-Pb Dating of Water Table–Type Speleothems"

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Pederson *et al*. and Pearthree *et al*. offer critical comments on our study of the age and evolution of the Grand Canyon. Both sets of authors question our use of incision rates from two sample sites located outside the canyon and present alternative interpretations of our data. As we explain, even without the sites in question, our data support a "precursor" western Grand Canyon older than 6 million years.

We reported uranium-lead dating evidence that incision of the Grand Canyon began in the west 17 million years ago (Ma) and accelerated in the east ~3.7 Ma (*1*). Pederson *et al*. (*2*) and Pearthree *et al*. (*3*) raise a number of concerns about our analysis, which we address here. We recognize that some of the controversy generated by our paper relates to the definition of the Grand Canyon. In our study (*1*), and in this response, we view the Grand Canyon as that canyon one sees from the rim and also that which includes all possible canyon-forming processes that ultimately resulted in the entire canyon (including the canyons that existed before the integration of the Colorado River).

We would first like to address the objection made by both Pederson *et al*. (*2*) and Pearthree *et al*. (*3*) to the so-called "Muddy Creek" problem, which involves the relative lack of siliciclastic sediment in the 16- to 6-million-year-old Muddy Creek Formation at the mouth of the Grand Canyon. Sediment should seemingly exist in this region if there was a "precursor" western Grand Canyon before 6 Ma that extended from the Grand Wash Cliffs to the west side of the Kaibab arch. We are aware of the previous literature on this issue, beginning with Longwell's (*4*) first mention of it. However, we feel that there may be other reasons for the paucity of sediment that the technical comment authors may not have considered or be aware of. One possible reason for the lack of siliciclastics that was recently offered (*5*) invoked a "precursor" western canyon having only 1 to 2% of the runoff of a modern Colorado River discharge, which consequently resulted in a relatively small amount of eroded sediment. Another reason could be that if a Laramide "proto" Grand Canyon did exist in the central Grand Canyon, as recently proposed (*6*, *7*), then the lack of siliciclastics in the Muddy Creek Formation could have been because the upper Paleozoic clastic units (Toroweap, Coconino, and Supai) had already been largely incised in the Laramide. Given that the incision of these units happened earlier in time, very little clastic material would have been supplied by a 16- to 6-Ma precursor canyon that followed this earlier incised paleocanyon route (*7*). Incision in Upper Granite Gorge down to about Mississippian level by 16 Ma (*6*) could also explain the presence of the 11- to 6-Ma Hualapai Limestone Member of the Muddy Creek Formation: The Mississippian Redwall karst aquifer was dewatered by this incision, releasing carbonate-rich water that flowed to the mouth of the "precursor" western canyon to be deposited as the Hualapai Limestone. A logical source of so much carbonate-rich water was an age-equivalent precursor canyon that had severed the flow of water in the Redwall aquifer, causing it to drain to the mouth of the canyon.

Pederson *et al*. (*2*) argue that an older western Grand Canyon contradicts long-established regional knowledge. Although it is true that this concept does contradict pre–early 1990s knowledge, it does not contradict more recent findings (*7*–*12*), including a paper on the pre–Colorado River drainage in the Western Grand Canyon (*5*). The 16- to 6-Ma "western" canyon that we proposed is similar in both age and extent to that proposed by Young (*5*).

Contrary to Pederson *et al*.'s (*2*) reading of our study, we never assumed that the water table was flat. Rather we stated that "[f]or simplicity and consistency, all apparent water table descent rates are based on a relatively flat water table over time." We are aware that the water table in a place like the Grand Canyon cannot be flat. In reality, it is influenced by structure, stratigraphy, and topography. Furthermore, in karst systems, it is often difficult to refer to a water table at all because karst aquifers can be very irregular and discontinuous (*13*). Our "relatively flat water table" was taken only as a first-order assumption [similar to that illustrated by Pearthree *et al*. in figure 1 in (*3*)].

Our Grand Canyon Caverns data point [site 4 in (*1*)] was criticized by both Pearthree *et al*. (*3*) and Pederson *et al*. (*2*) as being located too far from the canyon to correlate with canyon incision. However, our reason for using this data point was that it represents a water-table datum that predates most canyon incision and Basin and Range down-faulting. The idea was that the general terrain of the western Grand Canyon area at this time (17 Ma) could have been relatively flat, and thus a fairly continuous water table could have extended across a large regional area, including the Basin and Range. Because water tables are often a subdued reflection of the topography, a relatively flat water table at 17 Ma is a viable scenario.

In response to Pearthree *et al*. (*3*), we would like to present our data in a somewhat different form to illustrate the unlikelihood of a strictly <6-Ma Grand Canyon (Fig. 1). Site 4 represents Grand Canyon Caverns, our highest data point and earliest water-table position before canyon incision and Basin and Range faulting. The dashed line labeled A indicates an interpretation of a slow, steady rate of western Grand Canyon incision. The heavy dark lines follow a path of incision evolution, integrating mammillary calcite at sites 1, 2, 3, and 4 by decreasing age and ele-

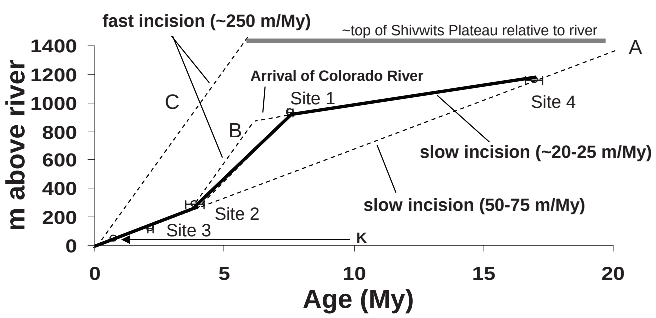

Fig. 1. Proposed incision history models for the western Grand Canyon from the U-Pb ages and apparent incision rates of Polyak *et al*. (*1*). These are models for this response and they assume that canyon incision was responsible for water table declines. These models do not take into account pre-17 Ma canyon-forming processes that may have contributed to the origin of the Grand Canyon (*6*, *7*) or the effects due to faulting (*15*). Site 1, Grand Wash Cliffs (7.55 Ma, 123 m/My); Site 2, Cave B (3.87 Ma, 75 m/My); Site 3, Dry Canyon (2.17 Ma, 55 m/My); Site 4, Grand Canyon Caverns (16.96 Ma, 68 m/My). K, data from (*15*).

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vation. These lines suggest a very slow incision rate for 9.5 million years (My) (from 17 to 7.5 Ma), followed by fast incision for ~3.5 My, and then slower incision again over the last 3 to 4 My. The dashed line labeled B assumes that a fast incision episode started at 6 Ma and was a direct consequence of the integration of the Colorado River through the Grand Canyon at 6 to 5 Ma (Fig. 1, "Arrival of Colorado River"). Then, slower incision has continued over the last 3 to 4 My. We submit that this incision history model derived from our data makes sense with respect to a "precursor" western canyon, where a small river in a limited hydrologic basin would have produced very slow incision; when the Colorado River arrived, incision would have been substantially higher, followed by slower incision up to the present. This interpretation of the data agrees with Pearthree *et al*.'s (*3*) statement that "[t]he introduction of a major river into this area likely resulted in high initial incision rates followed by exponentially decaying rates, perhaps even including intermittent aggradation."

The dashed line C in Fig. 1 assumes that the Colorado River carved the western Grand Canyon from the top of the Shivwits Plateau down to its current elevation in 6 My, using the more traditional model (*14*). In this scenario, the Colorado River would have been well above our mammillary sites, including our highest oldest site, and very fast average incision rates of ~250 m/My would have been needed for that entire period. We feel that such fast rates are unlikely and that they are not compatible with our data and the data (not interpretations) of others (*15*). Our sites 1, 2, and 3 are in the western block and show with respect to the river, and with respect to each other, that incision rates were slow for at least 3.9 My. It is our opinion that the least likely scenario (from our data) is a <6-My incision of the entire western Grand Canyon.

Pearthree *et al*. (*3*) are correct about the age (7.5 Ma) of the mammillaries along the Grand Wash Cliffs (site 1) being time-correlative with Lake Hualapai in the Grand Wash trough (11 to 6 Ma). If this lake extended somewhat farther north than the northern outcrop of the Hualapai Limestone shown by Lucchitta (*16*), then the water table indicated by these mammillaries could have sloped to Lake Hualapai, which would have been the regional base level for incision. If this were the case, then the rate of water-table descent at site 1 could have mimicked the rate of incision of the "precursor" western canyon as set by this same Lake Hualapai base level, whatever elevation it might have been at that time. However, faults often act as groundwater barriers (*17*), and it is likely that the 7.5-Ma water table at site 1 could not have made an effective connection with Lake Hualapai through the Grand Wash fault system. If this was the case, the water table may have been hydrologically coupled, not to Lake Hualapai, but to an incising precursor canyon further south.

Our interpretation of our data (*1*) can and should be questioned, but we see no absolute data that negates it. The fact that our data produce incision rates in areas close to the river and in good agreement with the incision rates of others (*15*) and with the history of the eastern Grand Canyon is a validation of our approach and methodology. Before (*1*), no studies produced paleo-water table positions or incision rates from absolute data beyond 70 m above the Colorado River and 0.75 Ma. Thus, we view our model as an opportunity to converge on critical ideas and questions related to the age of the Grand Canyon.

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