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-

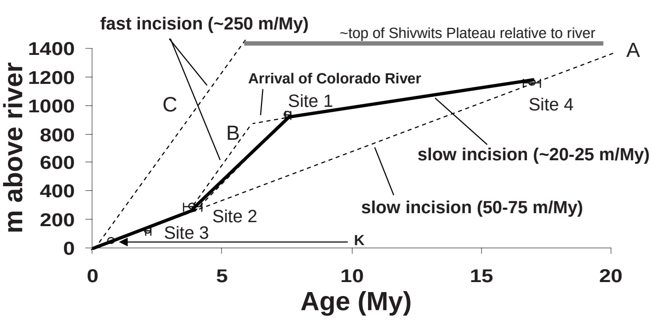

Fig. 1. Proposed incision history models for the western Grand Canyon from the U-Pb ages and apparent incision rates of Polyak *et al*. (*1*). These are models for this response and they assume that canyon incision was responsible for water table declines. These models do not take into account pre-17 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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