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Grand Canyon landslide-dam and paleolake triggered by the Meteor Crater impact at 56 ka

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ABSTRACT

This paper hypothesizes that the Meteor Crater impact in Arizona, USA, 56,000 years ago triggered landslides in Grand Canyon that dammed the Colorado River and formed Nankoweap paleolake. This is compatible with shock and earthquake physics for the impact that infer a M5.4 seismic event, attenuated to an effective magnitude of M3.5 at Grand Canyon. Results that support the hypothesis include radiocarbon dating of driftwood and luminescence dating of associated slack-water lake sediments that are preserved in caves up to 60 m above the modern Colorado River. Radiocarbon ages from two locations, including Stanton's Cave, date the driftwood as 55.25 ± 2.44 ka (n = 4). Sediments associated with the driftwood gave a luminescence age of 56.00 ± 6.39 ka (n = 2). These six Grand Canyon dates, and three published ages for the Meteor Crater impact, show statistically indistinguishable results that support the hypothesis for a geologically instantaneous series of events with a mean age of 55.60 ± 1.30 ka. This work highlights the value of radiocarbon dating near the limits of the technique, integration of multiple dating methods, and seismic and landslide hazards associated with meteorite impacts in regions of extreme topography like Grand Canyon.

INTRODUCTION

Two iconic features of southwestern USA geology are linked by our hypothesis that the Barringer Meteorite Crater (Meteor Crater) impact in northern Arizona triggered cliff collapse in Grand Canyon 56,000 years ago that dammed the Colorado River. Here, we characterize and date sediments within hard-to-access dissolution caverns perched high above the river in the karstic Redwall Limestone of Marble Canyon. These data provide a breakthrough for reconstructing the history of ephemeral landslide-caused paleolakes in Grand Canyon and an example of an impact-generated seismic event of unique scale and setting.

Stanton's Cave is located at RM 32 (Fig. 1; RM = river miles downstream from Lees Ferry, Arizona). Its mouth is 44 m above river level (ARL). The sediment deposited in the cave has driftwood logs within bedded sand (Fig. 2A; Fig. S1 in the Supplemental Material[1]) that initially yielded a radiocarbon date (^{14}C) of >35,000 yr B.P. (Euler, 1984), later revised to 43,700 years +1800/−1500 yr B.P. (Ferguson, 1984), close to the ca. 50 ka limit of radiocarbon dating at that time.

The origin of the driftwood within the water-laid cave sediment might be explained in several ways: (1) a major Holocene flood (<4.5 ka) on the Colorado River (O'Connor et al., 1994); (2) Pleistocene glacial-interglacial cycles that left fill terraces as the canyon incised (Pederson et al., 2006); (3) a lake behind downstream lava dams and landslide dams that may have filled to this level (Crow et al., 2015; Robertson et al., 2021); and (4) a landslide dam and paleolake at Nankoweap Canyon (RM 52) that inundated Stanton's Cave and other caves (Hereford, 1984; Hereford et al., 1998).

SAMPLING

Four driftwood samples were collected from two different caves with entrances greater than 33 m ARL. The two from Stanton's Cave were originally collected in 1970 and included the previously radiocarbon-dated sample STC-01 (Ferguson 1984). Sample STC-01 [WK-50143*] is an eroded Douglas-fir (*Pseudotsuga menziesii*) log exhibiting signs it was weathered before being swept downriver and deposited in the cave. STC-70 [WK-50144*] is possibly a branch (*Populus* sp.) with an uneroded sur-

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[1] Supplemental Material. S1: cave deposit locations and photos; S2: radiocarbon dating; S3: infrared stimulated luminescence dating; S4: geochronology summary; S5: impact physics. Please visit https://doi.org/10.1130/GEOL.S.29396186 to access the supplemental material; contact editing@geosociety.org with any questions.

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Figure 1. Extent of Nankoweap paleolake in Marble Canyon showing river miles below Lees Ferry. (A) Stanton's Cave; (B) Crystal Cave; and (C) RM 35.5 alcove; dated driftwood at star. (D) Impact at Meteor Crater and resulting ~M3.5 ground motion at Nankoweap Canyon. (E) Flyover image of Meteor Crater derived from digital elevation model (Kring, 2017).

face, suggesting it was torn from a living tree. Two additional samples of conifer driftwood were obtained from an alcove (an erosionally breached cave) at RM 35.5 where driftwood is embedded in horizontally bedded sand/silt (Fig. S1) at 33 m ARL (star in Fig. 1C); slack-water sediment also occurs at 44 m ARL (Fig. 2B) suggesting that the cave was filled progressively with sediment by a prograding delta undergoing seasonal fluctuations during paleolake infilling.

The wood samples were radiocarbon dated at two separate laboratories (Table S2). The re-dated Stanton's Cave samples were prepared at the University of Waikato, Hamilton, New Zealand, Radiometric Radiocarbon Dating Laboratory, by alpha-cellulose extraction and dated by high-precision liquid scintillation spectroscopy (Hogg et al., 2006, 2007). In parallel, pretreatment and radiocarbon measurements of cellulose extracted from wood within the driftwood deposits in the alcove at RM 35.5 used a base-acid-base-acid-bleaching chemical process and graphitization and accelerator mass spectrometry at the Chronos Radiocarbon Laboratory at

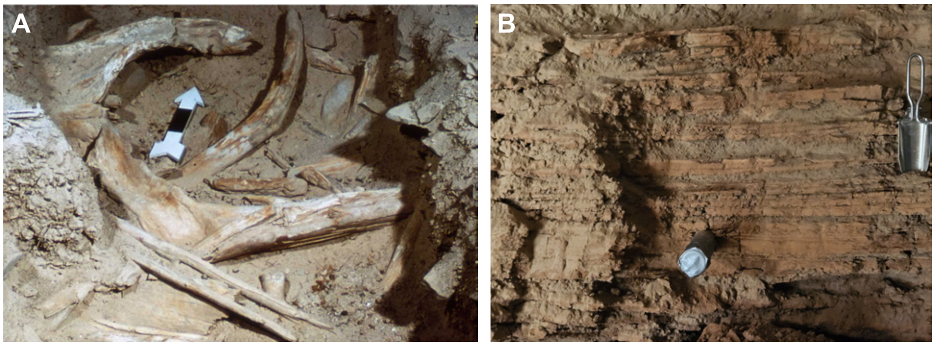

Figure 2. Cave deposits suggest the linkage of a dammed river and deposition of bedded sediment and driftwood. (A) Stanton's Cave driftwood logs; (B) sediments interpreted to record fluvial inputs from the Colorado River near the perimeter of an advancing delta, showing the infrared stimulated luminescence sample near RM 35.5 (river miles downstream from Lees Ferry, Arizona).

the University of New South Wales, Sydney, Australia (Turney et al., 2021). Cave sediment at RM 35.5 is preserved at two heights that may reflect filling of the cave by slack-water river deposits. Sediments were dated using infrared stimulated luminescence (IRSL) of feldspar sand at 50 °C and corrected for fading (loss of signal, Lamothe et al., 2003); see Table S3. The lower IRSL sample (Figs. 1C and S1) was taken from the same deposit as the wood (33 m ARL); the upper IRSL sample was at 44 m ARL (Figs. 2B and S1). Sample locations were surveyed using a laser range finder to obtain heights above river level; elevations relative to sea level were determined using Google Earth; each has probable error of several meters.

GEOCHRONOLOGY RESULTS

Our radiocarbon dates are just older than the radiocarbon curve IntCal20 (Reimer et al., 2020), but close to the limits of data from Hulu Cave (Cheng et al., 2018; Fig. S2). Thus, for calibration, we use a smoothing spline trend-line projection of the Hulu data projected back in time, given that significant ^{14}C deviations caused by supernova, solar events, rapid geomagnetic field or global carbon cycle changes, which could theoretically disrupt a smooth transition, are currently undetectable at this extreme age. Our calibrated ages from samples STC-01 and STC-70 from Stanton's Cave are 54.84 ± 4.71 ka and 55.27 ± 4.73 ka (2s; Table S2), ~10 k.y. older than the 43.7 ka dates on these previous samples. This demonstrates the remarkable preservation of biological material in these dry caves and improvements of ^{14}C dating (Hogg et al., 2006, 2007). The dated wood samples in RM 35.5 alcove of two samples (six replicates) yielded a weighted mean age of 55.19 ± 2.16 ka. See Table S2 for uncalibrated (B.P.) and calibrated (calendar; ka) ages and Table S4 for tabulated individual ages and means.

Two IRSL dates from RM 35.5 alcove were from cm-thick horizontal beds of water-laid loose sand and silt (Fig. 2B) that resemble deltaic sediments deposited in modern-day Lake Mead. The lower sample (Fig. S1) returned an age of 59.58 ± 8.67 ka (2se) that is within error of the mean 55.19 ± 2.16 ka mean wood age from the same deposit. The upper sample (Fig. 2B) returned an IRSL age of 51.74 ± 9.45 ka (2se).

Agreement of the ^{14}C and IRSL dating, and the statistically indistinguishable ages obtained from cave sediment separated by ~3 river miles (5 km) at similar elevations of 30–45 m ARL, suggests a common origin. Ferguson (1984) found that modern driftwood deposits along the Colorado River have annual rings that span 957 years, but outer rings indicate the trees died within the past few hundred years. Euler (1984) and Hereford (1984) suggested that the geometry of jumbled diverse wood types and sizes at Stanton's Cave indicate that the driftwood was deposited in a single event. Our dating is consistent with a single depositional event that took place in different caves within the accuracy and precision of the combined ^{14}C and IRSL weighted mean age of 55.21 ± 1.75 ka (Table S4).

NANKOWEAP LANDSLIDE DAM

Conceptualizations of the proposed dam at Nankoweap Canyon are shown in Figures 3A and S1. Parts of the Nankoweap Creek delta contain 5-m-scale angular blocks of Kaibab Limestone in a finer-grained breccia of Paleozoic rock debris (Fig. 3B). The nearest exposure of Kaibab Limestone in Nankoweap Creek is many kilometers upstream, such that the blocks are inferred to have been derived from the cliffs on the opposite (east) side of the Colorado River. The lack of stratification in the dam material suggests that it was emplaced by a single landslide event. The only attempt to date the landslide used the uranium-trend method on carbonate soil at the top of the landslide debris and suggested an age of 210 ± 25 ka (Machette and Rosholt, 1989); this method and age have been questioned because of open-system behavior in the soil carbonates (Muhs et al., 1989). At location 1 (Fig. 3A), paleodam material overlies and is inset into Colorado River terrace gravels (M3 of Pederson et al., 2006; dated elsewhere at 71–64 ka) indicating that the river had incised ~10 m below the M3 tread at the time the paleo-

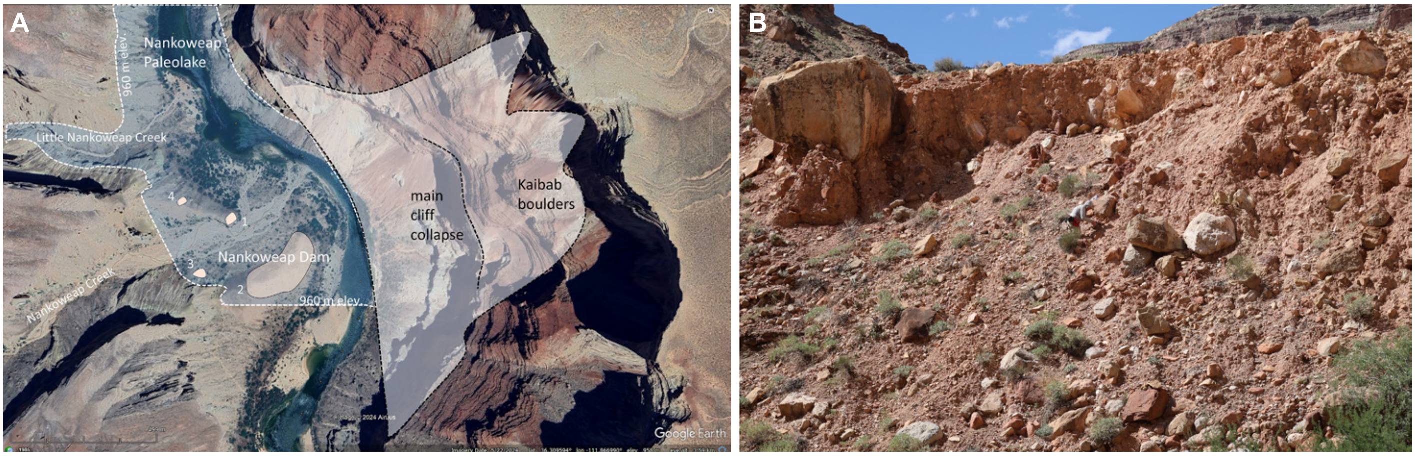

Figure 3. (A) Nankoweap dam conceptualization and dam remnants 1–4. (B) Unstratified dam deposit with large Kaibab Limestone boulders at location 1; circle shows person for scale.

dam formed, consistent with a 56 ka paleodam. Remnants of dam material (1–4 of Fig. 3A) have elevations as high as 920 m asl elevation, which approaches the 940 m elevation of the highest wood and sediment found in the caves (Fig. 4). At locations 2 and 4 (Fig. 3A) thin lags of distinctive rounded and far-traveled Colorado River gravels overlie angular dam material at various heights suggesting that the dam was progressively eroded as the river overtopped the dam.

EVALUATING CAVE DEPOSITS IN MARBLE CANYON

Alternative possible origins for the driftwood within water-laid cave deposits in Marble Canyon generate specific predictions for the age and character of the deposits. The largest known modern floods on the Colorado River recorded near Lees Ferry were the 5660 m^3/s 1984 CE flood and the 8500 m^3/s 1200−1600 yr B.P. flood (O'Connor et al., 1994; revised discharge from Topping et al., 2003). The 8500 m^3/s flood raised the river level near Lees Ferry ~15 m (O'Connor et al., 1994). Changes in water depth from flooding depend on the canyon's cross section at a given location, but the 8500 m^3/s level, approximately extrapolated downstream as the red line in Figure 4, would have been >50 m below the estimated 283,000 m^3/sec flow needed to raise the modern river level to the entrance of Stanton's Cave (Hereford, 1984; Hereford et al., 1998). Thus, both the heights and the ca. 55 ka age of the Stanton's and RM 35.5 deposits preclude a Holocene flood origin.

Late Pleistocene river levels were periodically at the elevations of the caves as the river aggraded and incised in response to glacial-interglacial cycles that were superimposed on average canyon incision of ~160 m/m.y. (Crow et al., 2014). For example, the 71−64 ka M3 Pleistocene terrace had treads up to 37 m ARL (Pederson et al., 2006). Our dated deposits are 5–10 m above the maximum M3 aggradation (37 m ARL), and similar but undated wood (RM 35.5 alcove) and sand deposits (in Stanton's) extend ~20 m higher (Fig. 4). M3 aggradation likely spanned tens of thousands of years, predated the cave deposits by 5–10 ka, deposited gravels and cross-bedded sands, and had transitioned to incision by 56 ka (Pederson et al., 2006). Thus, the alcove deposits are not well explained by M3 terrace aggradation. Downstream lava dams and lava cascades (Crow et al., 2015) and landslide dams (Robertson et al., 2021) definitively do not match the ages and heights of Marble Canyon cave deposits (Fig. 4).

We, therefore, support and refine the Nankoweap paleolake hypothesis (Hereford, 1984; Hereford et al., 1998). Temporary damming of the Colorado River at Nankoweap Canyon due to cliff collapse is inferred to have raised water levels above the M3 terrace level to ~940 m elevation above sea level to create an upstream lake more than 83-km long. Pleistocene Colorado River water and sediment budgets at ca. 56 ka, during the Marine Isotope Stage 3 interglacial, are not known, but based on analogy to the reservoirs of Lake Mead and Lake Powell in the modern interglacial period (Ferrari, 2008), such a lake would have filled with water within years (Crow et al., 2015) and with deltaic sand and/or silt within several centuries, timeframes that are not resolvable within the ~1000 yr uncertainty of the current radiocarbon dating. Gravels would have dropped out near Lees Ferry.

IMPACT AND EARTHQUAKE PHYSICS

Impact-generated seismic events are revealed in different ways in the geologic record depending on scale and setting. The separate Miocene Ries and Steinheim impacts in Germany generated seismites in a sedimentary basin 80–150 km from the impact sites likely due to M8.5 and M6.4 earthquakes, respectively (Buchner et al., 2022). The Tunguska impact air blast of 1908 CE generated an observed M5.0 earthquake, but an associated impact crater is not known (Ben-Menahem, 1975). Meteor Crater impact, on the Kaibab Limestone bedrock surface, is proposed here to have produced a novel response in the form of cliff collapse in Grand Canyon with little sedimentary record in the erosional bedrock landscape, except for ephemeral paleolake deposits preserved in caves.

Meteor Crater was excavated by a dense (~7.8 g/cc) iron asteroid moving with a cosmic velocity more than 11 km/s that produced a 10−15 megaton impact event (Kring, 2017). Assuming a seismic efficiency of 1×10^{-4} (the fraction of the impact's kinetic energy that is portioned into seismic energy; Schultz and

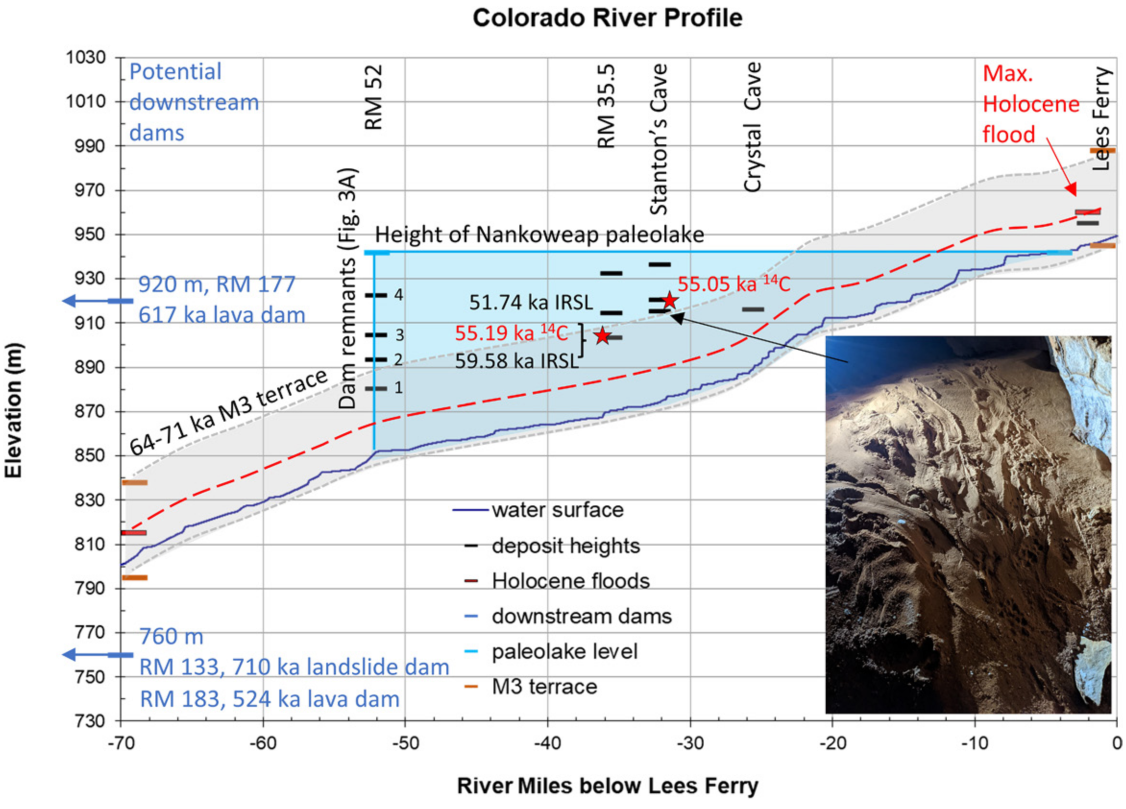

Figure 4. Heights and ages of Marble Canyon cave deposits plotted on the Birdseye (1924) river profile. Maximum 8495 m^3/s flood height from the past 4500 years shown by red line; 64–71 ka M3 terrace in gray. A prograding delta would have filled this lake within ~100 years. Inset shows beaver tracks in Vasey's Cave with entrance 37 m vertically above the river (S1) such that beaver access would have required a paleolake; photo by J. Ballensky. IRSL—infrared stimulated luminescence; RM—river miles downstream from Lees Ferry, Arizona.

Gault, 1975), this would have generated a M5.2–M5.4 seismic event (Kring, 2017). At the 160-km distance to Nankoweap, the effective magnitude of M3.3–M3.5 (using Richter's [1958] relationship) may have triggered a landslide (Fig. 1). Less conservatively, higher seismic efficiency (e.g., 10^{-2}; Toon et al., 1997) would have produced a M5.8–M6.0 seismic event with an effective magnitude of M3.9–M4.1 at Nankoweap Canyon.

Dates for the Meteor Crater impact include a thermoluminescence date of shock metamorphosed rocks (49.00 ± 6.00 ka; 2σ; Sutton, 1985) and cosmogenic nuclide exposure ages (^{36}Cl and ^{10}Be-^{26}Al) on ejected rocks (Phillips et al., 1991; Nishiizumi et al., 1991) that give recalculated ages of 56.00 ± 2.40 ka (Marrero et al., 2010) and 61.10 ± 4.80 ka (Barrows et al., 2019). The weighted mean of these ages for the impact combined with our four radiocarbon and two IRSL ages from cave deposits is 55.60 ± 1.30 ka, with a chi-square value showing the ages are statistically similar to each other (Table S4). We interpret this age, obtained from multiple geochronological methods, as the time of the hypothesized impact and lake-filling events (Table S4).

Alternatively, random gravitational collapse or a fault-related seismic event may have caused the landslide. Events up to ~M5 have been recorded in the Eminence and Blue Springs fault systems in the past 100 years, although there are no known epicenters at Nankoweap Canyon (Graham, 2020; Crossey et al., 2024). Further testing of whether the Meteor Crater impact event was the probable trigger for the Nankoweap landslide will benefit from more precise dating of the impact, stratigraphic characterization and dating of additional cave deposits, modeling of stress concentrations at cliff edges due to surface waves, and search for other landslides and seismites of this age elsewhere in the region.

CONCLUSIONS

Horizontally bedded sand and/or silt with embedded driftwood is preserved ~40–60 m above the modern Colorado River level within caves and alcoves of Marble Canyon, including Stanton's Cave. This supports the hypothesis that Nankoweap paleolake and its associated deltaic sediment extended 80 km upstream to near Lees Ferry. We cannot rule out the possibility that the landslide-lake could have been triggered by random gravitational collapse or local seismicity. However, the meteorite impact, the massive landslide, the lake deposits, and the driftwood high above river level are all rare and unusual occurrences. The mean of radiocarbon dates from driftwood, IRSL dates from cave sediment, and dates on the Meteor Crater impact converge into a narrow window of time at 55.60 ± 1.30 ka, which gives credence to the hypothesis that they were causally related.

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