Cosmogenic-nuclide burial ages for Pleistocene sedimentary fill in Unaweep Canyon, Colorado, USA

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Abstract

We applied both single-sample and isochron methods of cosmogenic-nuclide burial dating to determine the age of the sedimentary fill in Unaweep Canyon, western Colorado, USA. This stratigraphic sequence is of interest because it documents capture and diversion of the ancestral Gunnison River by the Colorado River during late Cenozoic incision of the Colorado Plateau. Seven 26Al-10Be burial ages from sedimentary infill penetrated by a borehole in central Unaweep Canyon, as well as a 26Al-10Be burial isochron age formed by multiple clasts and grain-size separates in a sample from the stratigraphically lower Gateway gravels, indicate that canyon blockage, initiation of lacustrine sediment accumulation, and presumed river capture, took place 1.41 ± 0.19 Ma. Lacustrine sedimentation ceased 1.34 ± 0.13 Ma.

Keywords: Unaweep Canyon, Pleistocene, Cenozoic, river incision, river capture, Gunnison River, Colorado Plateau, aluminum-26, beryllium-10, burial dating, burial isochron dating

1. Unaweep Canyon

Unaweep Canyon forms a 70-km-long wind gap through the Uncompaghre Plateau in western Colorado, exposing Proterozoic basement beneath the Mesozoic cover of the plateau. It stretches from near the confluence of the Colorado and Gunnison Rivers near its northeast end to the Dolores River near its southwest end (Figure 1). The name “Unaweep” (“canyon with two mouths”) denotes the fact that it currently contains two small streams (East Creek and West Creek) flowing away from a topographic divide at 2150 m elevation in the center of the canyon (Figures 1,2). Beginning with the Hayden Survey of the late 1800’s (Peale, 1877; Gannett, 1882), all observers have agreed that the drainage area of modern East and West Creeks is grossly inadequate to account for canyon incision. Although the canyon has been hypothesized to have been formed by Quaternary glacial erosion (Cole and Young, 1983), its low elevation relative to other glaciated parts of the Rockies makes this unlikely. Most researchers agree that the canyon was formed by late Cenozoic fluvial incision due to past occupation by the Gunnison River, the Colorado River, or both (Peale, 1877; Gannett, 1882; Cater, 1966; Hunt, 1969; Sinnock, 1981; Scott et al., 2001; Steven, 2002). In this hypothesis, the present arched long profile of the canyon would represent a deformed bedrock river profile. However, a geophysical survey by Oesleby (1978) and, subsequently, a drillcore collected by Soreghan et al. (2007), showed that the canyon long profile does not reflect bedrock topography; rather, the canyon contains a thick fill of unconsolidated Cenozoic sediments (Figure 2) overlying Paleozoic sedimentary rocks (Soreghan et al., 2007). The base of this sedimentary fill comprises sediment with Gunnison River provenance; additionally, gravels of similar lithology crop out at both ends of the canyon, recording past occupation of the canyon by an ancestral Gunnison River (Lohman, 1961, 1965; Aslan et al., 2005, 2008b; Kaplan, 2006). A thick (150 m) lacustrine succession overlies the former river channel in the subsurface in the central canyon; this presumably records creation of accommoda-
tion space within the canyon by damming of its downstream end. Surficial mapping in the western end of the canyon indicates that the blockage was most likely a large bedrock landslide (Kaplan, 2006; Marra, 2008). The lacustrine interval is capped by a series of paleosols and then by a further 150 m of locally derived, poorly sorted gravels (Marra, 2008). This upper unit is contiguous with modern alluvial fan deposition from canyon walls. Thus, the subsurface stratigraphic section in the central canyon records complete filling of the lake followed by additional subaerial accumulation of alluvial and/or colluvial sediment derived from hillslope erosion.

These stratigraphic relationships show that neotectonic uplift of the Uncompahgre Plateau is not required to explain canyon abandonment. Presumably, the landslide dam of the canyon caused capture and diversion of the Gunnison River into its present course. Thus, canyon abandonment was the result of river capture during regional Cenozoic incision.

In this paper, we use the technique of cosmogenic-nuclide burial dating to determine the age of the sedimentary fill in Unaweep Canyon. Previous estimates of the age of canyon abandonment were mostly based on comparison of the depth of incision by the present Gunnison River below the basal gravels in Unaweep Canyon (700 m) with regional incision rates inferred from a variety of evidence. These analyses suggested canyon abandonment sometime between 0.8 - 3.1 Ma (Kaplan, 2006; Aslan et al., 2008b). A single cosmogenic-nuclide measurement from the ancestral Gunnison River gravels exposed at Cactus Park at the east end of Unaweep Canyon (Figures 1, 2) yielded an apparent burial age of 1.06 ± 0.38 Ma (Aslan et al., 2008a), which presumably represents a basal age for the canyon fill. This paper describes additional cosmogenic-nuclide burial ages from 14 samples of both the basal gravels and the sedimentary fill penetrated by the borehole in the central canyon.

2. Stratigraphic context of samples

We collected samples from two sites: the borehole in the central canyon (Soreghan et al., 2007; Marra, 2008) and the basal Gunnison River gravels exposed at sites in the west end of the canyon. Here we describe the stratigraphic context of these samples as it pertains to the assumptions needed to compute cosmogenic-nuclide burial ages.

The borehole is located at 38°46.05 N, 108°48.86 W, at an elevation of 1994 m (Figure 1). We collected two samples from the lacustrine unit that overlies basement in the borehole (202.4 and 243.6 m depth; Figure 2; Table 1). This unit spans 120 m of core and generally coarsens upward from clay and silt to medium sand; the units we sampled were relatively sandy. The composition of this unit indicates a Gunnison River provenance (Soreghan et al., 2007; Marra, 2008), so we assume that these sediments were derived from surface erosion in the watershed of the Gunnison River upstream of Cactus Park. Because they were deposited in a lake whose surface elevation was near 1825 m (Figure 2), they experienced instantaneous burial in ~35 and ~80 m of water, respectively.

Two samples collected from the paleosol sequence capping the lacustrine unit (164.3 and 164.6 m depth) consisted of fine to medium sand with the same lithology as the underlying lacustrine sediments. Thus, they were also derived from erosion in the upstream Gunnison basin. However, they were deposited at or near the time of complete lake filling, so they were not instantaneously buried at the time of deposition. Instead, they were gradually buried as the overlying section accumulated.

We collected two samples (one at 112.7 m depth and one at 116.6 m depth) from the upper colluvial unit in the borehole. This unit consists of poorly sorted, crudely stratified sand and gravel containing clasts of Mesozoic sandstone and Precambrian basement that match lithologies exposed on nearby canyon walls. Thus, this unit was derived from erosion of the canyon walls near the borehole site. We sampled the sandy matrix of this unit. Again, these samples were not buried instantaneously but gradually as the overlying section accumulated.

Finally, we collected samples of the basal Gunnison River gravels from two sites at the western end of the canyon (Figures 1, 2, 3). These sites expose the Gateway Gravels of Kaplan (2006), which consist of clast-supported fluvial cobble gravel containing volcanic rocks of Gunnison River provenance. The Gateway gravels occur atop bedrock straths between 1514-1615 m and represent at least three terrace levels. Our sample sites lie on the lowest of these. Paleocurrent indicators indicate flow to the west, consistent with canyon occupation by a paleo-Gunnison River (Kaplan, 2006). They are presumably correlative with the Cactus Park gravels at the eastern end of the canyon (Figure 2). We collected samples at two sites (Figure 3). At one site where these gravels were exposed in a newly excavated gravel pit (“Site 2” in Table 1 and Figures 1 and 2; 38°43.16 N, 108°65.07 W, 1515 m elevation), we collected three cobble-sized clasts of quartz-rich lithologies (quartzite and felsic intrusive) as well as samples of the sandy matrix. At a second, natural, exposure (“Site 1”; 38°43.16 N, 108°55.88 W, 1534 m elevation), we excavated ~1 m beneath the present surface and collected a single sample of 55 clasts of pebble gravel. We presume that all these samples originated from surface erosion in the upstream Gunnison watershed. However, these gravels are at present only 1-5 meters thick at our sample sites, and it is unclear what their original depositional thickness was. Thus, we have little constraint on the postdepositional burial depths of these samples. As discussed in more detail later, we address this issue by applying an isochron method of burial dating that does not require knowledge of this information.
3. Analytical methods and results

We extracted quartz from these samples by crushing (the clasts), sieving to appropriate grain sizes (crushed clasts and sediment samples) and repeated etching in dilute HF. Al and Be extraction and purification took place at two laboratories, at the U. of Washington and the U. of Vermont, and involved standard methods of HF dissolution and column chromatography (Stone, 2004). Both labs employed a ⁹Be carrier prepared from deep-mined beryl. We measured total Al concentrations by ICP-OES at UW and UVM, and measured Al and Be isotope ratios by accelerator mass spectrometry at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Total carrier and process blanks at UW and UVM contained 18000 ± 4000 and 9000 ± 2000 atoms ¹⁰Be respectively (0.1 - 1.5 % of total ¹⁰Be present) and 65000 ± 40000 and 375000 ± 215000 atoms ²⁶Al respectively (0.01 - 0.2 % of total ²⁶Al present). Table 1 and Figures 4 and 5 show ¹⁰Be and ²⁶Al concentrations. Both UW and UVM analysed replicate splits of purified quartz for one sample (UNW04-369.5, at 112.7 m depth in the borehole); results agree at stated uncertainties (Table 1).

4. Burial age computations

The method of calculating a burial age from measured cosmogenic nuclide concentrations depends on the exposure and burial history of the sample. Thus, interpreting ⁹Be-²⁶Al measurements as a burial age involves i) using geologic evidence to determine the sequence of exposure and burial events that the sample experienced, and then ii) choosing a calculation method appropriate to that exposure-burial history.

The simplest approach to burial dating applies when the following conditions are met: i) a sample originates exposure-burial history. Thus, we calculated burial ages for these samples using Equations (1-2) with present burial depths and values of ²⁶Al concentrations), and the burial age equations (1-2) contain two unknown parameters: the source area erosion rate \(\epsilon\) and the burial age \(t_b\). As we have two measurements (⁹Be and ²⁶Al concentrations), the pair of equations can be solved for both unknowns. These equations apply to our two deepest borehole samples (202 and 244 m depth); geologic evidence indicates that these sediments were derived from surface erosion in the upstream Gunnison catchment and buried instantaneously by deposition in a lake. Strictly, they did not remain at a constant depth between the time of burial and the present, because after lake filling they were further buried by accumulation of the upper alluvial fan unit. However, the initial burial was deep enough (~35 and ~80 m for the two samples) to make subsequent nuclide accumulation negligible, so assuming a single period of burial at constant depth does not have a significant effect on the inferred burial age. Thus, we calculated burial ages for these samples using Equations (1-2) with present burial depths and values of \(P_{10,0w}\) and \(P_{26,0w}\) appropriate for the Gunnison watershed upstream of Cactus Park (following Balco et al. (2008) and Stone (2000), 28 and 189 atoms g⁻¹ yr⁻¹ respectively).

Geological evidence indicates that the other four samples in the borehole were also derived from surface erosion (in the upstream Gunnison catchment for samples at 165-165 m depth and on the nearby canyon walls for samples at 112.7 and 116.6 m). However, they were not buried instantaneously, but rather gradually by accumulation of subaerially deposited alluvial sediment. Given steady accumulation between the time of sample emplacement and the present, ⁹Be and ²⁶Al concentrations are:

\[
N_{10} = \frac{P_{26,0w}}{\lambda_{10} + \lambda_{sp}} e^{-\lambda_{10}t_b} + \frac{P_{10,0w}}{\lambda_{sp}} \left(1 - e^{-\lambda_{10}t_b}\right)
\]

\[
N_{26} = \frac{P_{26,0w}}{\lambda_{26} + \lambda_{sp}} e^{-\lambda_{26}t_b} + \frac{P_{10,0w}}{\lambda_{sp}} \left(1 - e^{-\lambda_{26}t_b}\right)
\]

where: \(N_{10}\) and \(N_{26}\) are ¹⁰Be and ²⁶Al concentrations at the present time (atoms g⁻¹); \(P_{10,0w}\) and \(P_{26,0w}\) are mean surface production rates of ¹⁰Be and ²⁶Al in the watershed from which the sediment is derived (atoms g⁻¹ yr⁻¹); \(P_{10,0w}\) and \(P_{26,0w}\) are production rates of ¹⁰Be and ²⁶Al at the present location and burial depth of the sample (atoms g⁻¹ yr⁻¹); \(\lambda_{10}\) is the ¹⁰Be decay constant (4.99 × 10⁻⁷ yr⁻¹); \(\lambda_{26}\) is the ²⁶Al decay constant (9.83 × 10⁻⁷ yr⁻¹); \(\epsilon\) is the mean erosion rate, at the time of sample burial, in the watershed from which the sediment is derived (g cm⁻² yr⁻¹); \(\lambda_{sp}\) is an effective attenuation length for spallogenic production (g cm⁻²); and \(t_b\) is the burial duration (yr). Granger (2006) describes these equations in additional detail. These equations (as well as Equations 3-4 below) disregard production due to muons during initial exposure of the samples during erosion of the watershed (the first terms in Equations 1 and 2); this introduces a small inaccuracy in the inferred erosion rate prior to burial (see additional discussion in Balco et al., 2008), but as we are interested primarily in the burial age in this work, we accept this tradeoff of accuracy for simplicity. However, in nearly all burial-dating situations, the post-burial nuclide production (the second terms in Equations 1 and 2) is mainly due to muon interactions; we describe how we compute production rates due to muons below.
These cross-sections are: for the CRONUS-Earth project (John Stone, written communication), hole in Beacon Valley, Antarctica, collected as part of the 10Be Heisinger, however, we used cross-sections inferred from the interaction cross-sections determined experimentally by the method of Heisinger et al. (2002b,a). Instead of the muon method, we used source production rates appropriate to the mean elevation of the nearby canyon wall (following Balco et al. 2008)). Table 1 also shows burial ages for these samples calculated using Equations (3-4) (Table 1). For samples in the overlying alluvial section we used source production rates appropriate to the mean elevation of the nearby canyon wall (following Balco et al. 2008)) implies an age of 1.46 ± 0.33 Ma for the Gateway gravels at site 2. In addition to individual clasts, we also analysed a range of grain-size fractions from the sandy matrix at this site (Table 1). Like individual clasts, different sediment grain sizes commonly originate from different sources in the watershed and have different nuclide concentrations (e.g., Balco and Stone, 2005; Brown et al., 1995). As expected from this reasoning, measured 10Be and 26Al concentrations from both clasts and sand grain-size fractions at this site form an isochron in 10Be-26Al space, whose slope is less than the 26Al/10Be production ratio and whose y-intercept is greater than zero. (Figure 5) The isochron slope (computed using the regression scheme of York (1966); see Balco and Rovey (2008)) implies an age of 1.46 ± 0.33 Ma for the Gateway gravels at site 2. The y-intercept is close to zero, indicating that postdepositional nuclide production at this site was relatively small. Thus, in this case, individual burial ages computed from each sample on the assumption of instantaneous, infinite burial (using the MATLAB implementation in Balco et al. (2008) of the Heisinger measurements, and appear to resolve differences between the Heisinger predictions and a variety of geological observations (e.g., Balco et al., 2008;
Equations (1-2); also see Figure 4) closely approximate the isochron age. However, there is no way to know this in advance from geological information.

The same geological constraints apply at our other sample site in the Gateway gravels (site 1; Table 1; Figures 1, 2). However, at this site we only analyzed a single sample of agglomerated pebbles, so we cannot compute an isochron age. Assuming instantaneous, infinite burial yields a burial age of 1.36 ± 0.12 Ma. If the burial history at this site was similar to that at site 2, this is most likely a close approximation of the true emplacement age, and, in fact, it agrees with the isochron age at site 2. However, lacking geological constraints on the burial history, this is a minimum age for the gravels at this site.

5. Discussion

Our best estimate of the age of the Gateway gravels is the isochron age of 1.46 ± 0.33 Ma from sample site 2; this must predate canyon abandonment. Burial ages on the lacustrine unit in the borehole of 1.33 ± 0.18 and 1.69 ± 0.44 must postdate canyon abandonment. These ages all agree within their respective uncertainties and imply canyon abandonment near 1.4 Ma. The rest of the burial ages from higher up in the borehole are consistent, within uncertainties, with their stratigraphic order (Figure 6).

To derive a summary age model and uncertainty estimate for the data set as a whole, we assumed the following: i) our isochron age for the lowest Gateway gravels represents the time of canyon abandonment; ii) the lower lacustrine unit in the borehole accumulated at a constant accumulation rate; and iii) the upper colluvial unit in the borehole accumulated at a constant rate between the time of lake filling and the present. This implies an age model with two free parameters: i) the age of canyon abandonment and beginning of lacustrine sediment accumulation; and ii) the age of lake filling and transition from lacustrine to subaerial sediment accumulation (Figure 6). Fitting this age model to the Gateway gravels isochron age and all seven burial ages from the borehole yields best-fitting ages for canyon abandonment and lake infilling of 1.41 and 1.34 Ma, respectively. The data fit this age model with a reduced chi-squared statistic of 0.6, indicating that the scatter of the data is consistent with measurement uncertainties, and also that a more complex age model is not required or justified by the observations. A Monte Carlo uncertainty analysis including measurement uncertainties only indicates uncertainties in the canyon abandonment and lake filling ages of 0.17 and 0.10 Myr, respectively. Including decay constant uncertainties increases these to 0.19 and 0.13 Ma, respectively.

To summarize, we conclude that the canyon-blocking landslide, that apparently initiated lacustrine sedimentation and presumably also caused diversion of the paleo-Gunnison River into its present course, took place 1.41 ± 0.19 Ma. Complete filling of the lake and commencement of subaerial sediment accumulation at the borehole site took place 1.34 ± 0.13 Ma. As discussed above, in calculating this we assumed that the youngest Gateway gravels were active at the time of canyon blockage. If we relaxed this assumption and fit the age model only to burial ages from the borehole, we would obtain a basal age for the borehole of 1.37 ± 0.22 Ma (measurement uncertainties only), which is indistinguishable from the isochron age for the Gateway gravels. Thus, our observations are consistent with the hypothesis that the youngest Gateway gravels represent the active river channel immediately before with canyon abandonment.

There are several independent constraints on the age of canyon abandonment and the sedimentary section in the borehole that we can use to evaluate these conclusions. First, Aslan et al. (2008a) obtained a single burial age of 1.06 ± 0.38 from the lowest Cactus Park gravels at the east end of Unaweep Canyon (Figures 1, 2). Although Aslan et al. (2008a) did not describe their calculations in detail, they interpreted it as an age for abandonment of Unaweep Canyon by the Gunnison River. This age estimate and our age estimate for the same event agree within uncertainties, which is consistent with the hypothesis that the Gateway and Cactus Park gravels are correlative and represent the course of the Gunnison River prior to canyon abandonment.

Second, the burial ages from the borehole imply a rate of lake infilling that we can compare with the expected sediment delivery from the upstream Gunnison basin. If we approximate the lacustrine sediment section in Unaweep Canyon as an (inverted) irregular pyramid with length ~35 km (Figure 2), width ~3 km (Figure 1), and thickness 230 m (Figure 2), this implies a sediment volume of ~4 km³. The area of the Gunnison watershed upstream of Cactus Park is 9500 km², so given rock and sediment densities of 2.7 and 2.2 g cm⁻³, respectively, and complete trapping of sediment, the lacustrine sediment infill in the canyon would represent ~0.4 m erosion of the watershed. Basin-scale erosion rates inferred from nuclide concentrations in the lacustrine sediment section (Table 1) are 26-29 m Myr⁻¹, at which rate erosion of 0.4 m would require 15,000 yr. Thus, the expected sediment production from the Gunnison watershed is an order of magnitude greater than required to fill the lake basin in the approximately 0.1 Myr implied by our best-fitting age model, and therefore does not contradict the age model. The duration of lake sediment accumulation inferred from the age model is substantially less than the uncertainties in the age model, so we can only conclude that this duration was less than ca. ~0.1-0.2 Myr. It is possible that the lake filled in substantially less than 100,000 years.

Third, Marra (2008) observed a weathered ash layer at 115 m depth in the borehole. Although the ash was too devitrified by postdepositional chemical alteration to permit either direct dating or geochemical fingerprinting (E. Wan, personal communication, 2008), it is most likely that this ash is one of the Lava Creek (0.62 Ma) or Mesa Falls
(1.2 Ma) ashes from the Yellowstone volcanic center, or the Bishop Ash (0.76 Ma) from Long Valley Caldera. The age model discussed above implies an age of 0.93 ± 0.1 Ma for this depth (Figure 5); although this does not agree exactly with any of the possible ashes, it is closest to the age of the Bishop ash and the precision of the ages is not adequate to reject this possibility. As the Bishop ash occurs nearby (e.g., Colman et al., 1986), it appears most likely that this ash is the Bishop.

6. Conclusions

An age model fit to seven $^{26}\text{Al-}^{10}\text{Be}$ burial ages from sedimentary infill penetrated by a borehole in central Unaweep Canyon, as well as a $^{26}\text{Al-}^{10}\text{Be}$ burial isochron age for the stratigraphically lower Gateway gravels, both indicate that canyon blockage and initiation of lacustrine sediment accumulation took place 1.41 ± 0.19 Ma. Lacustrine sedimentation then ceased 1.34 ± 0.13 Ma. This age model is consistent with all individual ages given their measurement uncertainties, as well as all independent stratigraphic and chronological constraints that we are aware of.

7. Acknowledgements.

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Figures
Figure 1: Shaded-relief map of Unaweep Canyon, showing line of profile in Figure 2 as well as sites mentioned in text. Inset shows simplified geologic map.
Figure 2: Longitudinal section through Unaweep Canyon (see Figure 1 for section line) showing stratigraphy of sedimentary fill. Brackets marked Gateway gravels and Cactus Park gravels show the elevation range of outcrops of these gravel units; filled circles show sites where burial-dating samples were actually collected (also see Figure 1).

Figure 3: Photographs of sample sites in Gateway Gravels. Upper photo, site 1; lower photo, site 2. At both sites, cobble gravels of Gunnison River provenance overlie straths incised into Cutler formation sandstones and siltstones.
Figure 4: Normalized $^{26}$Al and $^{10}$Be concentrations. Nuclide concentrations in samples from the Gateway gravels and below 164 m in the borehole are normalized to mean production rates for the modern Gunnison River watershed upstream of Cactus Park (see text for details). Nuclide concentrations in samples from the colluvial section above 164 m depth in the borehole are normalized to production rates appropriate to the mean elevation of the canyon wall adjacent to the drill site. The numbers adjacent to the ellipses corresponding to borehole samples indicate depths in the borehole (see Table 1). Following common practice for this diagram, isolines of burial age and pre-burial erosion rate are computed on the basis of instantaneous burial at infinite depth. As described in the text, these assumptions are not consistent with the geological context of the samples, so the burial age estimates shown in Table 1, which correctly account for geological constraints, differ from the apparent burial ages inferred from this diagram. The ellipses are 68% confidence regions.

Figure 5: $^{26}$Al-$^{10}$Be burial isochron diagram (Balco and Rovey, 2008) for samples from Gateway Gravels at site 2 (Figure 1; Table 1). Ellipses are 68% confidence regions.
Figure 6: Stratigraphic section (adapted from Soreghan et al. (2007)) and summary age model for Unaweep Canyon sedimentary fill. The solid line shows a two-parameter, piecewise-linear age model fit to the isochron burial age for the Gateway gravels at our site 2 and the burial ages from borehole samples (data used for fitting are shown by black symbols here and in bold in Table 1; see text for details). Error bars show 1σ measurement uncertainties. Dashed lines show a 68% confidence estimate based on a Monte Carlo simulation. Apparent burial ages based on single samples from the Gateway gravels at our site 1 (see Table 1) and the Cactus Park gravels (Aslan et al., 2008) are shown in gray. Open triangles show ages of widely distributed western U.S. ashes, plotted at the depth of an unidentified ash in the borehole (see text).
Table 1. Cosmogenic-nuclide concentrations and burial ages. Burial ages shown in bold are those that are consistent with geomorphic and stratigraphic constraints; other ages are calculated using assumptions that are inconsistent with these constraints and are included here as examples to support discussion in the text. Sample names in italics were processed at the University of Vermont; others were processed at the University of Washington.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Depth in core (m)</th>
<th>Grain size (mm)</th>
<th>$^{10}\text{Be}$ (10$^3$ atoms g$^{-1}$)</th>
<th>$^{26}\text{Al}$ (10$^3$ atoms g$^{-1}$)</th>
<th>Burial age (Ma)</th>
<th>Burial erosion rate (m Myr$^{-1}$)</th>
<th>Apparent burial age (Ma)</th>
<th>Apparent burial erosion rate (m Myr$^{-1}$)</th>
<th>Isochron age (Ma)</th>
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<tr>
<td>UNW04-396S-1</td>
<td>112.7</td>
<td>0.25-0.85</td>
<td>111.9 +/- 3.8</td>
<td>496 +/- 142</td>
<td>0.86</td>
<td>87</td>
<td>0.95 +/- 0.65 (0.66)</td>
<td>310 +/- 210 (220)</td>
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<tr>
<td>UNW04-396S-2</td>
<td>112.7</td>
<td>0.25-0.85</td>
<td>114.4 +/- 2.2</td>
<td>462 +/- 38</td>
<td>1.06</td>
<td>77</td>
<td>1.16 +/- 0.19 (0.25)</td>
<td>342 +/- 60 (117)</td>
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<tr>
<td>UNW04-396S-3</td>
<td>110.6</td>
<td>0.25-0.85</td>
<td>150.7 +/- 5.9</td>
<td>720 +/- 50</td>
<td>0.71</td>
<td>70</td>
<td>0.76 +/- 0.17 (0.19)</td>
<td>125 +/- 10 (22)</td>
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<td>UNW04-396S-4</td>
<td>164.3</td>
<td>0.125-0.5</td>
<td>321.7 +/- 8.0</td>
<td>1125 +/- 74</td>
<td>1.34</td>
<td>26</td>
<td>1.37 +/- 0.15 (0.17)</td>
<td>32.7 +/- 2.6 (5.4)</td>
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<tr>
<td>UNW04-396S-5</td>
<td>164.6</td>
<td>0.125-0.5</td>
<td>266.1 +/- 6.1</td>
<td>736 +/- 155</td>
<td>1.69 +/- 0.44 (0.45)</td>
<td>28.7 +/- 6.4 (7.2)</td>
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<td>UNW04-396S-6</td>
<td>202.4</td>
<td>0.25-0.85</td>
<td>348.4 +/- 6.2</td>
<td>1198 +/- 103</td>
<td>2.33 +/- 0.18 (0.22)</td>
<td>25.9 +/- 2.6 (3.7)</td>
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<td>Core samples from Gunnison gravels, site 1</td>
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<tr>
<td>09-GUNN-1-PEBBLES</td>
<td>-</td>
<td>10-40</td>
<td>373.0 +/- 9.3</td>
<td>1287 +/- 72</td>
<td>1.86 +/- 0.12 (0.14)</td>
<td>22.4 +/- 1.7 (3.0)</td>
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<td>Core samples from Gunnison gravels, site 2</td>
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<td>09-GUNN-2-CLAST-C</td>
<td>-</td>
<td>60</td>
<td>167.9 +/- 4.2</td>
<td>582 +/- 53</td>
<td>-</td>
<td>-</td>
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<tr>
<td>09-GUNN-2-CLAST-G</td>
<td>-</td>
<td>55</td>
<td>110.3 +/- 2.8</td>
<td>330 +/- 56</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>09-GUNN-2-CLAST-E</td>
<td>-</td>
<td>70</td>
<td>88.9 +/- 2.3</td>
<td>351 +/- 34</td>
<td>-</td>
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<tr>
<td>09-GUNN-2-MTX-C</td>
<td>-</td>
<td>0.71-1</td>
<td>60.7 +/- 1.9</td>
<td>237 +/- 44</td>
<td>-</td>
<td>-</td>
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<tr>
<td>09-GUNN-2-MTX-M</td>
<td>-</td>
<td>0.5-0.71</td>
<td>62.3 +/- 2.0</td>
<td>189 +/- 48</td>
<td>-</td>
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<tr>
<td>09-GUNN-2-MTX-P</td>
<td>-</td>
<td>0.25-0.5</td>
<td>79.7 +/- 2.3</td>
<td>252 +/- 42</td>
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</tr>
</tbody>
</table>

1 Normalized to the "07KNSTD" Be isotope ratio standard series. See Nishiizumi et al. (2007).
3 Calculated assuming initial equilibrium with steady erosion followed by a single period of burial at the present depth of the samples (Equations (1) in text).
4 Calculated assuming initial equilibrium with steady erosion, followed by slow burial by steady sediment accumulation between the time of sample emplacement and the present (Equations (2) in text).
5 Assumes both instantaneous and infinite burial.