LETTER

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New cosmogenic burial ages for Sterkfontein Member 2 *Australopithecus* and Member 5 Oldowan

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The cave infills at Sterkfontein contain one of the richest assemblages of *Australopithecus* fossils in the world, including the nearly complete skeleton StW 573 ('Little Foot')[1–4] in its lower section, as well as early stone tools[5–7] in higher sections. However, the chronology of the site remains controversial[8–14] owing to the complex history of cave infilling. Much of the existing chronology based on uranium–lead dating[10,11] and palaeomagnetic stratigraphy[8,12] has recently been called into question by the recognition that dated flowstones fill cavities formed within previously cemented breccias and therefore do not form a stratigraphic sequence[4,14]. Earlier dating with cosmogenic nuclides[9] suffered a high degree of uncertainty and has been questioned on grounds of sediment reworking[10,11,13]. Here we use isochron burial dating with cosmogenic aluminium-26 and beryllium-10 to show that the breccia containing StW 573 did not undergo significant reworking, and that it was deposited 3.67 ± 0.16 million years ago, far earlier than the 2.2 million year flowstones found within it[10,11]. The skeleton is thus coeval with early *Australopithecus afarensis* in eastern Africa[15,16]. We also date the earliest stone tools at Sterkfontein to 2.18 ± 0.21 million years ago, placing them in the Oldowan at a time similar to that found elsewhere in South Africa at Swartkans[17] and Wonderwerk[18].

The cave at Sterkfontein is partly filled with overlapping layers of fossiliferous breccia[19,20] that entered through multiple openings to the surface. The infill was originally divided into six members thought to be in stratigraphic order[19], with Members 1–3 inside the cave and 4–6 now exposed at the surface owing to erosion of the cave roof. Although the complete infill stratigraphy is not exposed in any one place and the temporal relationship between the interior and surface deposits remains debated[11,13], we retain the original nomenclature[19,20] here. We will focus on Member 2 within the Silberberg Grotto (Fig. 1) and on the Oldowan Infill of Member 5 in younger deposits excavated from a higher infill.

Member 2 contains abundant fossils, angular dolomite and chert clasts, and quartz-bearing sand. Several localized flowstones and botryoidal calcite deposits fill cavities that formed after the breccia was cemented and later settled into voids dissolved below (Fig. 1)[4,14]. Fauna was accumulated as a deathtrap assemblage[21] including associated elements, largely of primates and carnivores, with no hominids apart from a single near-complete skeleton of *Australopithecus prometheus* (StW 573; Fig. 2)[1–4,22]. This species was named on the basis of a parieto-occipital fossil from Makapansgat[23]. It has been suggested[22] that several other Sterkfontein and some Makapansgat specimens also belong in this species making *Australopithecus africanus* and *A. prometheus* contemporaries in the assemblages of Makapansgat Member 3 and Sterkfontein Member 4. *A. prometheus* differs from *A. africanus* in features including *Paranthropus*-like larger, bulbous-cusped cheek teeth, a longer, flatter face, incipient supraglabellar hollowing and a more vertical rounded occiput[22]. (Note that we use the term hominid in the traditional sense to include humans and their ancestral relatives but exclude the great apes.)

Dating of Member 2 and StW 573 has been problematic. Flowstones in the vicinity of StW 573 date to about 2.2 million years (Myr)[10,11], but they post-date the breccia and the fossil[4,14]. The only previous date on the breccia itself was cosmogenic ^{26}Al/^{10}Be burial dating of fine-grained quartz[9], which yielded a best-fit age of 4.17 ± 0.35 Myr. This age has been questioned by many[10–13,24] who have suggested that fine sediment could have been reworked from older, higher deposits within the cave, making the burial age of the sediment older than the fossil. To resolve the age of the fossil the breccia must be dated and it must be shown to be a coherent stratigraphic unit, largely free of reworked material. This is now possible owing to improvements in measurement precision and new techniques such as isochron burial dating which can explicitly validate the coeval deposition of the entire unit[24–27].

Member 5 contains both *Homo ergaster* and *Paranthropus* fossils as well as Oldowan and Acheulean stone tools[5–7]. Member 5 East is divided into a lower Oldowan infill, with the first appearance of stone tools and a few fossils of *Paranthropus*, and an overlying early Acheulean infill[5–7]. Faunal comparisons and the *Paranthropus* hominid StW 566 suggested an age estimate of 1.7–2.0 Myr for the Oldowan infill[6,7]. A substantially younger age of 1.32 ± 0.08 Myr (error-weighted mean) has been inferred from electron spin resonance dating of bovid teeth[12]. We use burial dating of a quartz manuport to determine the age of the Oldowan infill.

Burial dating is based on the radioactive decay of ^{26}Al and ^{10}Be in quartz. These nuclides build up by exposure to secondary cosmic radiation near the ground surface, and subsequently decay when sediment is buried and cosmogenic nuclide production is attenuated. Because ^{26}Al ($\tau_{26} = 1.021 \pm 0.024$ Myr (ref. 28)) decays faster than ^{10}Be ($\tau_{10} = 2.005 \pm 0.020$ Myr (ref. 29)), the ratio ^{26}Al/^{10}Be decreases over time, with an effective mean-life of $\tau_{bur} = 2.08 \pm 0.10$ Myr. For burial dating to be accurate, three criteria must be met. (1) The quartz must be exposed near the ground surface before burial to accumulate sufficient ^{26}Al and ^{10}Be. (2) It must be buried quickly and deeply enough so that post-burial production is small. The exact depth required depends upon the inherited concentrations, but is usually many metres. (3) It must be buried only once in the past ~10 Myr. If quartz has been reworked from older deposits, or if it has been reworked underground within the cave system, then the burial age will overestimate the true age of the deposit.

An elegant way to test whether the burial dating criteria are met is to construct an isochron[24–27] in which multiple samples are analysed from the same location. Each sample is buried with its own inherited ^{26}Al and ^{10}Be concentrations, but all samples share the same post-burial production history. A plot of ^{26}Al versus ^{10}Be yields a gentle curve with a slope that indicates burial age and an intercept that depends on the amount of post-burial production[24]. The isochron burial dating method accounts for post-burial production without requiring detailed knowledge of

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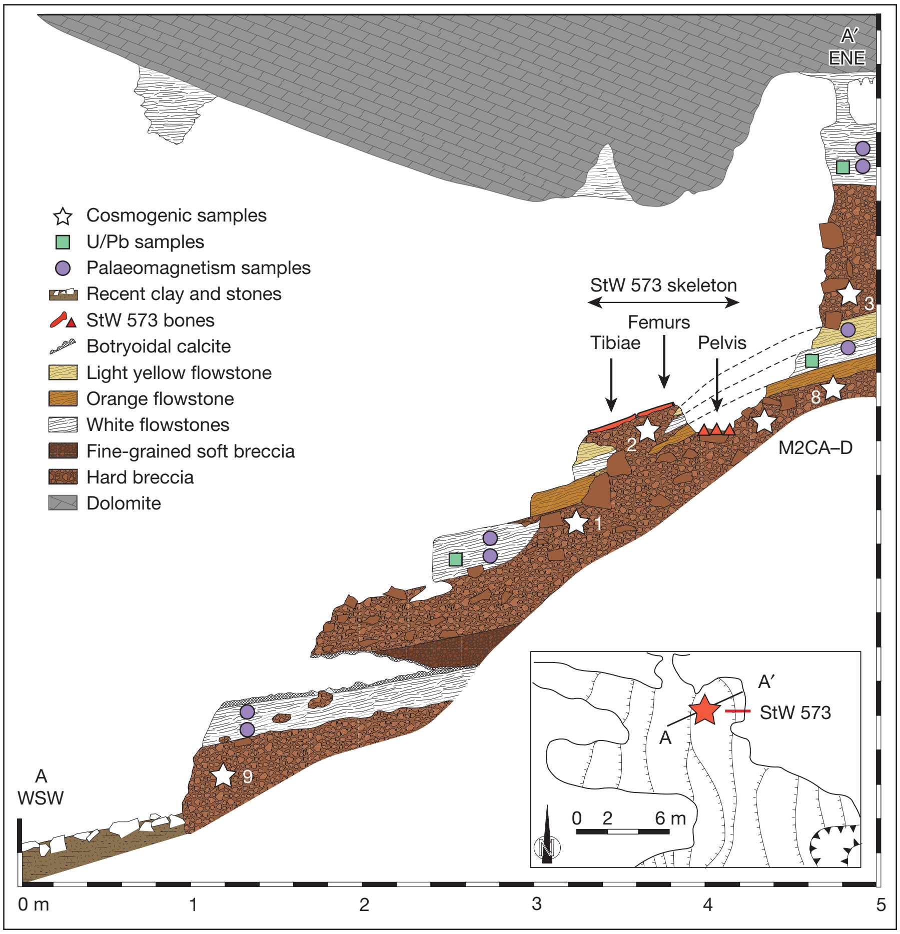

Figure 1 | Stratigraphy and sample locations. Measured stratigraphic section through the Member 2 talus at the location of the StW 573 skeleton showing locations of dated samples, modified from ref 14. Locations of U/Pb samples are estimated from schematic sections of refs 10, 11; palaeomagnetic samples were located from refs 8, 12. Inset locates the cross section in the lower part of the Silberberg Grotto, with approximately 1 m contour intervals for the infill surface.

the burial depth or burial history. It also allows outliers to be identified; reworked samples plot below the isochron, while samples significantly above the isochron are forbidden and indicate issues with either the sample or the laboratory measurements.

We analysed 11 samples from Member 2 (Table 1), including three previously reported[9]. Effective isochron burial dating requires a wide range of inherited cosmogenic nuclide concentrations. To that end, we selected a suite of samples to maximize variability. Fine quartz sand from multiple samples (ST 1–9) was probably washed in from the surface. In contrast, four blocks of chert were collected from the immediate vicinity of StW 573 (M2CA–D). Two fractions of coarse sand and pebbles were separated (ST M2 Dark and Light). One fraction comprises rounded grains stained with pedogenic iron oxides and washed into the cave from soil at the surface; the second comprises angular unstained grains probably eroded from the walls and ceiling of the cave itself (Extended Data Fig. 1). A previously reported sample from the modern surface[9] was analysed to confirm that material enters the cave with a zero burial age.

From the Oldowan Infill of Member 5 we selected a single quartz manuport—a typical vein quartz cobble with rounding and impact marks characteristic of rocks found in the local river gravels close to Sterkfontein (Extended Data Fig. 2). There is no evidence for reworking of older deposits, as there are no diagnostically younger artefacts within the large Oldowan assemblage of 3,500 pieces[6,7].

^{26}Al and ^{10}Be were measured by accelerator mass spectrometry (AMS). All samples of fine sand and the iron-stained grains have high ^{26}Al and ^{10}Be concentrations, confirming their origin from outside the cave. Light-coloured grains and chert blocks have low concentrations, indicating that they were probably eroded from the walls of the cave within a few metres of the surface. A plot of ^{26}Al versus ^{10}Be (Fig. 3) reveals that all but two of the samples lie on an isochron, consistent with a single episode of deposition. One chert block lies below the isochron, indicating

Figure 2 | Skull of StW 573 ('Little Foot'). The skull, recently extracted from the cave breccia. Photo by Jason Heaton.

Table 1 | Samples and cosmogenic nuclide concentrations

Sample	Location	[^{10}Be] (10^6 atoms per gram)*	[^{26}Al] (10^6 atoms per gram)
ST 1	0.7 m below StW 573	0.493 ± 0.026	0.624 ± 0.053
ST 2	Adjacent to StW 573	0.574 ± 0.025	0.565 ± 0.050
ST 3	0.8 m above StW 573	0.522 ± 0.029	0.562 ± 0.122
ST 7	Surface above cave	1.166 ± 0.020	7.075 ± 0.380
ST 8	0.7 m NW of StW 573	0.685 ± 0.137	0.686 ± 0.074
ST 9	2–2.5 m below StW 573	0.479 ± 0.012	0.550 ± 0.036
ST M2 Dark	From samples ST 1, 2, 8, 9	0.354 ± 0.025	0.412 ± 0.044
ST M2 Light	From samples ST 1, 2	0.118 ± 0.005	0.205 ± 0.015
M2CA	Near StW 573	0.101 ± 0.004	0.099 ± 0.009
M2CB	Near StW 573	0.070 ± 0.004	0.179 ± 0.015
M2CC	Near StW 573	0.043 ± 0.002	0.083 ± 0.012
M2CD	Near StW 573	0.157 ± 0.006	0.955 ± 0.036
Manuport	Oldowan Infill, Member 5	1.623 ± 0.070	3.051 ± 0.295

*All ^{10}Be measurements adjusted to the standard of ref. 30. ST 1–3 are slightly different than reported in ref. 9 owing to inclusion of additional analyses.

that it was reworked from an older deposit within the cave, perhaps from talus of Member 1, nearby. Another chert sample has a ^{26}Al/^{10}Be ratio far into the forbidden zone above the isochron, indicating a problem. Because this was a small sample there is no remaining chert for re-analysis; it is not included in the age determination.

The burial age for Member 2 is calculated as 3.67 ± 0.16 Myr. The concentration of ^{10}Be produced after burial is calculated as $(21 \pm 3) \times 10^3$ atoms per gram, corresponding to a post-burial production rate of about 0.012 atoms of ^{10}Be per gram per year, a value consistent with deep burial. The burial age of the surface sample is 0.11 ± 0.11 Myr, consistent with zero. Its concentrations indicate a surface erosion rate of 5.5 ± 0.5 m Myr^{-1} for ^{10}Be and 6.0 ± 0.6 m Myr^{-1} for ^{26}Al.

Several factors have contributed to lowering the age of Member 2 from that previously reported for sample ST 2 (4.17 ± 0.35 Myr)[9], even though its ^{10}Be and ^{26}Al concentrations did not change substantially. Since the time of the previous publication the mean-life of ^{10}Be has been re-evaluated and raised from 1.93 Myr to 2.005 Myr (ref. 29), decreasing the burial age. In addition, post-burial production by muons was previously overestimated, making the inferred burial age too old. Although production rates by muons at depth have been revised[27], the isochron method explicitly solves for post-burial production and avoids the need for theoretical production rate calculations, making the method inherently more robust. Finally, rather than relying on a single sample, the new calculations consider nine samples simultaneously; using revised values sample ST 2 alone would yield an age of 3.94 ± 0.20 Myr, older than but well within measurement uncertainty of the joint solution.

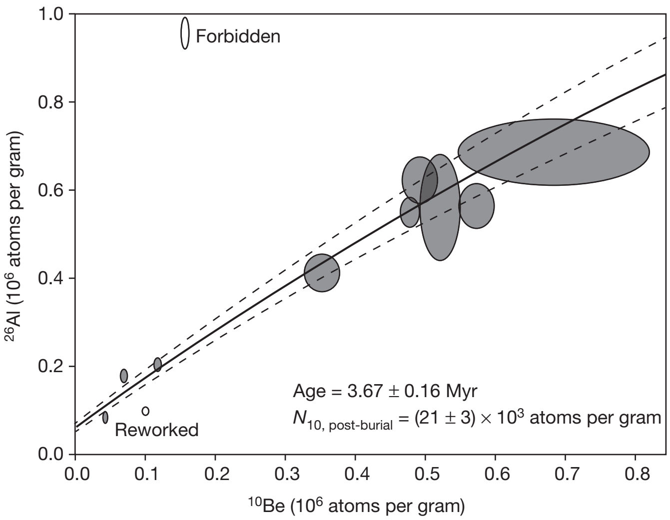

Figure 3 | Burial dating isochron. Cosmogenic ^{26}Al and ^{10}Be concentrations for individual samples from Member 2, shown as 1σ error ellipses. The solid curve shows the error-weighted best fit, and dashed curves illustrate 1σ error bounds. One sample shown as an open symbol lies below the isochron and has been reworked from an older deposit. A single outlier lies far above the line and has been excluded from analysis. The remaining nine samples are all consistent with a single age of deposition at 3.67 ± 0.16 Myr ago.

The new age of the Member 2 breccia and the StW 573 skeleton encased within it is in accordance with stratigraphic and taphonomic data[14] suggesting that they are older than Member 4 with its abundant *Australopithecus* fossils. StW 573 thus represents an earlier individual that is older than similar fossils from Makapansgat and contemporary with some *A. afarensis* fossils such as at Laetoli[15], and a partial skeleton from Woranso-Mille, Ethiopia[16]. The demonstration that *A. prometheus* in South Africa was contemporary with the morphologically very different *A. afarensis* of eastern Africa now raises interesting questions about early hominid diversity and phylogenetic relationships.

The burial age for the manuport from the Oldowan infill, calculated for its current burial depth of 7 m and a surface erosion rate of 5 m Myr^{-1} is 2.18 ± 0.21 Myr. The Oldowan at Sterkfontein is now placed at a time compatible with sites elsewhere in Africa, near 2 Myr ago, and with the date of approximately 1.8 Myr ago at Wonderwerk[18]. It is close to the cosmogenic burial age of 2.19 ± 0.08 Myr for a manuport found in the Lower Bank of Member 1 at Swartkrans[17], only about 1 km away. Taken together, these dates show that Oldowan technology was present in South Africa by 2 Myr ago.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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1. Clarke, R. J. & Tobias, P. V. Sterkfontein member 2 foot bones of the oldest South African hominid. *Science* **269,** 521–524 (1995).
2. Clarke, R. J. First ever discovery of a skull and well preserved skeleton of *Australopithecus*. *S. Afr. J. Sci.* **94,** 460–463 (1998).
3. Clarke, R. J. Newly revealed information on the Sterkfontein Member 2 *Australopithecus* skeleton. *S. Afr. J. Sci.* **98,** 523–526 (2002).
4. Clarke, R. J. A deeper understanding of the stratigraphy of Sterkfontein fossil hominid site. *Trans. R. Soc. S. Afr.* **61,** 111–120 (2006).
5. Kuman, K. The archaeology of Sterkfontein: past and present. *J. Hum. Evol.* **27,** 471–495 (1994).
6. Kuman, K. & Clarke, R. J. Stratigraphy, artefact industries, and hominid associations for Sterkfontein Member 5. *J. Hum. Evol.* **38,** 827–847 (2000).
7. Kuman, K. & Field, A. S. in *The Cutting Edge: New Approaches to the Archaeology of Human Origins* (eds Schick, K. & Toth, T.) 151–169 (Stone Age Institute Press, 2009).
8. Partridge, T. C., Shaw, J., Heslop, D. & Clarke, R. J. The new hominid skeleton from Sterkfontein, South Africa: age and preliminary assessment. *J. Quat. Sci.* **14,** 293–298 (1999).
9. Partridge, T. C., Granger, D. E., Caffee, M. W. & Clarke, R. J. Lower Pliocene hominid remains from Sterkfontein. *Science* **300,** 607–612 (2003).
10. Walker, J., Cliff, R. A. & Latham, A. G. U-Pb isotopic age of the StW 573 hominid from Sterkfontein, South Africa. *Science* **314,** 1592–1594 (2006).
11. Pickering, R. & Kramers, J. D. Re-appraisal of the stratigraphy and determination of new U-Pb dates for the Sterkfontein hominin site, South Africa. *J. Hum. Evol.* **59,** 70–86 (2010).
12. Herries, A. I. R. & Shaw, J. Paleomagnetic analysis of the Sterkfontein paleocave deposits: implications for the age of the hominin fossils and stone tool industries. *J. Hum. Evol.* **60,** 523–539 (2011).

13. Herries, A. I. R. *et al.* in *The Paleobiology of Australopithecus* (eds Reed, K. E., Fleagle, J. G. & Leakey, R. E.) 21–40 (Springer, 2013).
14. Bruxelles, L., Clarke, R. J., Maire, R., Ortega, R. & Stratford, D. Stratigraphic analysis of the Sterkfontein StW 573 *Australopithecus* skeleton and implications for its age. *J. Hum. Evol.* **70,** 36–48 (2014).
15. Drake, R. & Curtis, G. H. in *Laetoli: A Pliocene Site in Northern Tanzania* (eds Leakey, M. D. & Harris, J. M.) 48–52 (Clarendon, 1987).
16. Haile-Selassie, Y. *et al.* An early *Australopithecus afarensis* postcranium from Woranso-Mille, Ethiopia. *Proc. Natl Acad. Sci. USA* **107,** 12121–12126 (2010).
17. Gibbon, R. J. *et al.* Cosmogenic nuclide burial dating of hominin-bearing Pleistocene cave deposits at Swartkrans, South Africa. *Quat. Geochronol.* **24,** 10–15 (2014).
18. Chazan, M. D. *et al.* The Oldowan horizon in Wonderwerk Cave (South Africa): archaeological, geological, paleontological, and paleoclimatic evidence. *J. Hum. Evol.* **63,** 859–866 (2012).
19. Partridge, T. C. Re-appraisal of lithostratigraphy of Sterkfontein hominid site. *Nature* **275,** 282–287 (1978).
20. Partridge, T. C. & Watt, I. B. The stratigraphy of the Sterkfontein hominid deposit and its relationship to the underground cave system. *Palaeontol. Afr.* **28,** 35–40 (1991).
21. Pickering, T. R., Clarke, R. J. & Heaton, J. L. The context of StW 573, an early hominid skull and skeleton from Sterkfontein Member 2: taphonomy and paleoenvironment. *J. Hum. Evol.* **46,** 277–295 (2004).
22. Clarke, R. J. in *Integrative Paths to the Past: Essays in Honor of F. Clark Howell* (eds Corruccini, R. S. & Ciochon, R. L.) 205–222 (Prentice Hall, 1994).
23. Dart, R. A. The Makapansgat proto-human *Australopithecus prometheus. Am. J. Phys. Anthropol.* **6,** 259–284 (1948).
24. Granger, D. E. in *Treatise on Geochemistry* 2nd edn (eds Holland, H. D. & Turekian, K. K.) Vol. 14, 81–97 (Elsevier, 2014).
25. Balco, G. & Rovey, C. W. An isochron method for cosmogenic-nuclide dating of buried soils and sediments. *Am. J. Sci.* **308,** 1083–1114 (2008).
26. Erlanger, E. D., Granger, D. E. & Gibbon, R. J. Rock uplift rates in South Africa from isochron burial dating of fluvial and marine terraces. *Geology* **40,** 1019–1022 (2012).
27. Balco, G., Soreghan, G. S., Sweet, D. E., Marra, K. R. & Bierman, P. R. Cosmogenic-nuclide burial ages for Pleistocene sedimentary fill in Unaweep Canyon, Colorado, USA. *Quat. Geochronol.* **18,** 149–157 (2013).
28. Nishiizumi, K. Preparation of ^{26}Al AMS standards. *Nucl. Instrum. Methods B* **223,** 388–392 (2004).
29. Chmeleff, J., von Blanckenburg, F., Kossert, K. & Jakob, D. Determination of the ^{10}Be half-life by multicollector ICP-MS and liquid scintillation counting. *Nucl. Instrum. Methods B* **268,** 192–199 (2010).
30. Nishiizumi, K. *et al.* Absolute calibration of ^{10}Be AMS standards. *Nucl. Instrum. Methods B* **258,** 403–413 (2007).

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Author Contributions D.E.G. and R.J.G. conceived the project and performed laboratory work and data analysis. K.K. and R.J.C. supervised sample collection and interpretation of the dates. L.B. was responsible for mapping and interpretation of Member 2. M.W.C. supervised AMS measurements and methods development. All authors contributed to writing the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to D.E.G. (dgranger@purdue.edu).

METHODS

No statistical methods were used to predetermine sample size.

Samples of breccia were first treated with acid to dissolve carbonate cement and dolomite blocks. Fine quartz sand (<0.25 mm) was sieved for dating because it contained fewer pieces of dark chert visible by eye. Later, coarse sand and pebbles stained with iron oxides were picked by hand from samples ST 1, 2, 8 and 9. Light-coloured angular sand and pebbles were separated by hand from samples ST 1 and 2 (Extended Data Fig. 1). The manuport (Extended Data Fig. 2) was cleaned and crushed to less than 0.5 mm. Quartz from all samples was purified by repeated leaching in hot agitated 1% HF/HNO_3.

The clean quartz fractions from all samples were dissolved in 5:1 HF/HNO_3 and spiked with ^{9}Be prepared from beryl. Upon dissolution, an aliquot was taken for stable Al determination. The sample was then evaporated and fumed to dryness in H_2SO_4. Be and Al were extracted by ion exchange chromatography. Both elements were precipitated as hydroxides and calcined at approximately 1,100 °C for 1 h following standard procedures.

$^{26}Al/^{27}Al$ and $^{10}Be/^{9}Be$ were measured by AMS at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab), Purdue University. $^{26}Al/^{27}Al$ measurements for samples ST 1–3 originally reported in ref. 9 were performed at Lawrence Livermore National Laboratory; measurements reported here were made at PRIME Lab in 2014 on archived Al_2O_3 from the same samples. Stable Al measurements for samples ST 1–3 were measured by flame atomic absorption spectrophotometry; all others were measured by inductively coupled plasma-optical emission spectrometry (ICP-OES). A conservative uncertainty of 5% was assigned to the atomic absorption spectrophotometry measurements, and 2% to measurements by ICP-OES. All ^{26}Al measurements except three (ST 3, M2CC and Manuport) were made in 2014 using a gas-filled magnet. The gas-filled magnet suppresses isobaric interference from ^{26}Mg and allows injection of the AlO^{-} molecular ion into the AMS, resulting in 10–20 times higher beam current and improved precision.

Because measurements were made over a period spanning more than a decade, there have been changes in the AMS standards that must be accounted for. Measurements reported in ref. 9 were normalized to ^{10}Be standards prepared from a standard solution from the National Institute of Standards and Technology. All others were normalized at the time of measurement to standards prepared in ref. 30. All ^{10}Be values were adjusted to match the currently accepted values of ref. 30. All measurements of $^{26}Al/^{27}Al$ were normalized to standards of ref. 28.

A derivation of the isochron dating method employed here is provided in detail in ref. 24. It is based on equation (1), which shows that cosmogenic ^{26}Al and ^{10}Be concentrations depend on the decayed inherited concentrations and any accumulation after burial.

$$\left(N_{26}-N_{26,\,\text{post-burial}}\right)/\left(N_{10}-N_{10,\,\text{post-burial}}\right)=N_{26,\,\text{inh}}/N_{10,\,\text{inh}}\exp(-t/\tau_{\text{bur}}) \quad (1)$$

In equation (1) N represents concentration, the numeric subscripts represent ^{26}Al and ^{10}Be, and the subscripts *postburial* and *inh* represent cosmogenic nuclide accumulation that postdates and predates burial. The variable t represents burial age and τ_{bur} is given by ($1/\tau_{bur} = 1/\tau_{26} - 1/\tau_{10}$).

The inherited ratio in equation (1) can be determined by assuming that the rocks being dated were derived from a steadily eroding landscape. In this case, the ratio is governed by equation (2), expressed as a function of N_{10}, where P represents the cosmogenic nuclide production rate at the sediment source area.

$$N_{26,\,\text{inh}}/N_{10,\,\text{inh}}=(P_{26}/P_{10})/[1+N_{10}/(P_{10}\tau_{\text{bur}})] \quad (2)$$

The ratio $N_{26,\text{ post-burial}}/N_{10,\text{ post-burial}}$ can be modelled using equation (3), assuming a constant production rate over the entire burial episode.

$$N_{26,\,\text{post-burial}}/N_{10,\,\text{post-burial}}= [P_{26}\tau_{26}(1-\exp(-t/\tau_{26}))]/[P_{10}\tau_{10}(1-\exp(-t/\tau_{10}))] \quad (3)$$

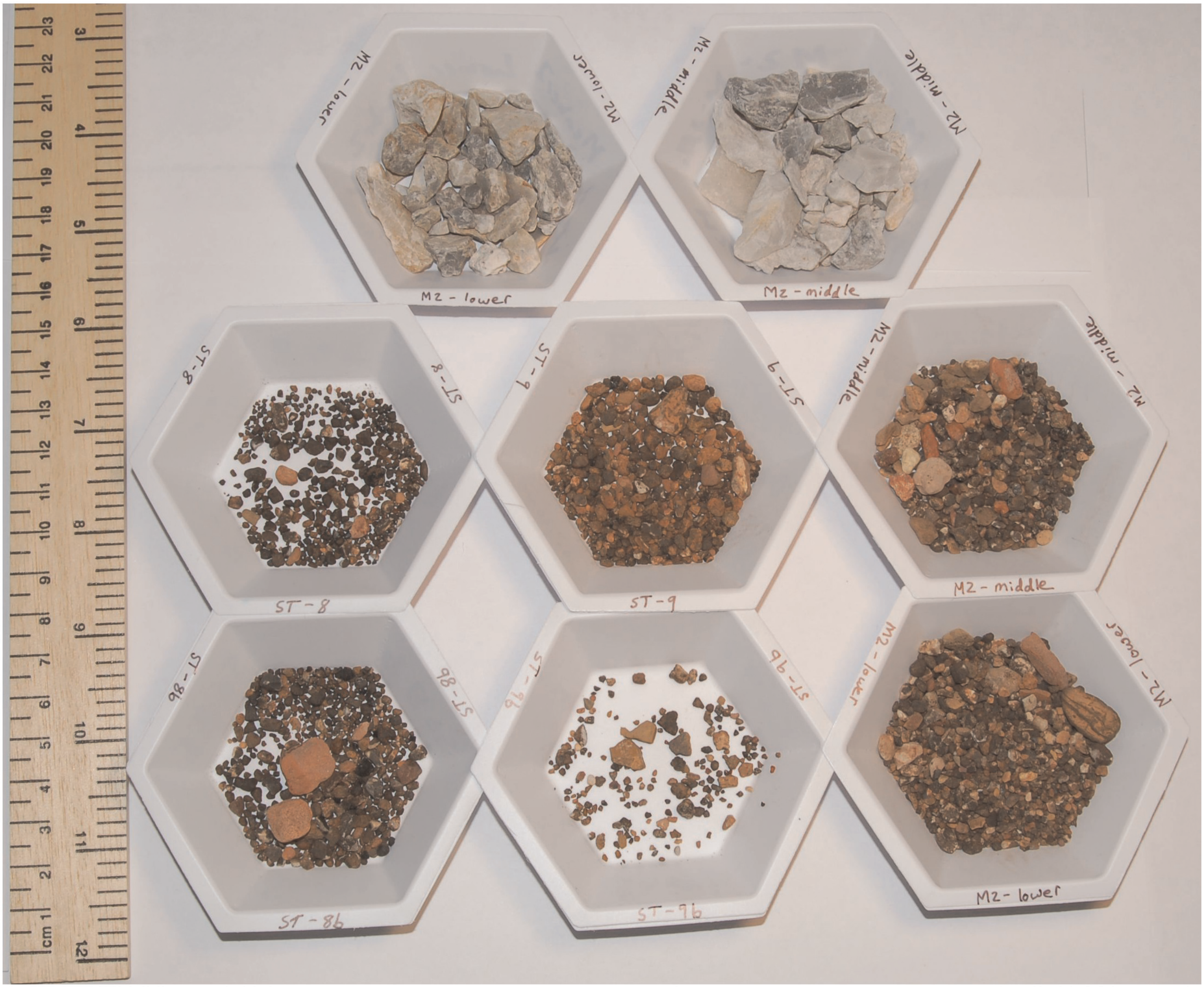
Combining equations (1–3) leads to an expression for an isochron in which N_{26} is a function of N_{10} and only two unknowns: t and $N_{10,\text{ post-burial}}$

$$N_{26}=\left(N_{10}-N_{10,\,\text{post-burial}}\right)[P_{26}\exp(-t/\tau_{\text{bur}})/(1+N_{10}\exp(t/\tau_{10})/(P_{10}\tau_{\text{bur}})] + N_{10,\,\text{post-burial}}[P_{26}\tau_{26}(1-\exp(-t/\tau_{26}))]/[P_{10}\tau_{10}(1-\exp(-t/\tau_{10}))] \quad (4)$$

Equation (4) can be used with a suite of samples to solve for both the burial age and the post-burial component of cosmogenic nuclides. We used equation (4) to solve for the age of the Member 2 breccia, with uncertainties determined by Monte Carlo analysis. The best fit age is 3.67 ± 0.16 Myr, and the best fit value for $N_{10,\text{post-burial}}$ is $(21 \pm 3) \times 10^3$ atoms per gram. The solution is shown graphically in Fig. 3.

For the Oldowan Infill, with only one sample, it is not possible to use an isochron. We corrected for post-burial production beneath an eroding surface following ref. 17. Post-burial production rates for a burial depth of 7 m and a bulk density of 2.0 g cm^{-3} were calculated using a multi-exponential profile adjusted for the muon cross sections given in ref. 27. We calculated the burial ages three ways (Extended Data Table 1): a minimum age was calculated that ignored post-burial production completely, and would be correct if erosion rates (ε) at the site were extremely fast; a maximum burial age was calculated by assuming that the burial depth had not changed over time—that is, that erosion rate was zero; finally, an optimum age was calculated using a reasonable value for erosion of the ground surface, which caused the burial depth to change over time. We assume that the ground surface eroded at 5 m per million years, consistent with the value reported here. Cosmogenic nuclide production rates of 10.8 and 73.1 atoms per gram per year at the surface were calculated for a latitude of 26° S and an elevation of 1,500 m, with a $^{26}Al/^{10}Be$ production rate ratio of 6.8. Previous work using this method at Swartkrans nearby[17] has yielded burial ages concordant with U/Pb ages of capping flowstones, supporting its accuracy.

Reported uncertainties are measurement errors only. We do not include uncertainties in cosmogenic nuclide production rates (which are generally minor for burial dating), in the $^{26}Al/^{10}Be$ production rate ratio or in radioactive mean-lives. Accounting for uncertainty in the mean-lives would lead to an additional ~5% systematic uncertainty in the final ages, resulting in ages with total uncertainties of 3.67 ± 0.24 Myr for Member 2 and 2.18 ± 0.24 Myr for the manuport.



Extended Data Figure 1 | Hand-picked samples. Dark-coloured and light-coloured grains separated for samples M2 Dark and M2 Light. Each dish contains grains from the labelled original sample; M2 lower is sample ST 1, and M2 middle is ST 2. Light-coloured angular clasts in the top two dishes were combined into sample M2 Light, while the iron-stained and rounded clasts in the remaining dishes were combined into sample M2 Dark.

Extended Data Figure 2 | Manuport. Quartz manuport analysed from the Oldowan Infill. Maximum dimension is 67 mm. Sample recovered from Square Q57 spit 27′ 8′′–28′ 8′′.

Extended Data Table 1 | Burial ages for Oldowan manuport

Minimum (ε = fast)	Maximum (ε = 0)	Optimum (ε = 5 m/My)
2.09 ± 0.20 My	2.21 ± 0.21 My	2.18 ± 0.21 My

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