Timing of archaic hominin occupation of Denisova Cave in southern Siberia

Zenobia Jacobs^{a,b,*}, Bo Li^{a,b,*}, Michael V. Shunkov^{c,d}, Maxim B. Kozlikin^{c,e}, Nataliya S. Bolikhovskaya^{c,f}, Alexander K. Agadjanian^{c,g}, Vladimir A. Uliyanov^{c,f}, Sergei K. Vasiliev^{c,d}, Kieran O’Gorman^a, Anatoly P. Derevianko^{c,e}, Richard G. Roberts^{a,b}

^a Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, New South Wales 2522, Australia

^b Australian Research Council (ARC) Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, Wollongong, New South Wales 2522, Australia

^c Institute of Archaeology and Ethnography, Russian Academy of Sciences, Siberian Branch, Novosibirsk 630090, Russia

^d Novosibirsk State University, Novosibirsk 630090, Russia

^e Altai State University, Barnaul 656049, Russia

^f Lomonosov Moscow State University, Moscow 119991, Russia

^g Borissiak Paleontological Institute, Russian Academy of Sciences, Moscow 117979, Russia

* These authors contributed equally to this work

The Altai region of Siberia was inhabited for parts of the Pleistocene by at least two archaic hominin groups—Denisovans and Neanderthals. Denisova Cave uniquely contains stratified deposits with the skeletal and genetic remains of both hominins, artefacts made from stone and other materials, and a range of animal and plant remains. The previous site chronology is based largely on radiocarbon ages for fragments of bone and charcoal up to 50,000 years old, with older ages of equivocal reliability estimated from thermoluminescence and palaeomagnetic analyses of sediments and genetic analyses of hominin DNA. Here we describe the stratigraphic sequences in Denisova Cave, establish a chronology for the Pleistocene deposits and associated remains from optical dating of the cave sediments, and reconstruct the environmental context to hominin occupation from around 300,000 to 20,000 years ago.

The period of existence and geographical distribution of Neanderthals and their sister group, dubbed the Denisovans^{1,2}, are key unresolved issues in the study of human evolution and dispersal. Denisovan remains are known only from the type locality of Denisova Cave, which is located in the foothills of the Altai Mountains in southern Siberia (51°23’51.3’’N, 84°40’34.3’’E; Fig. 1a). Neanderthal remains have also been recovered from the cave deposits.

The cave consists chiefly of three large chambers, Main, East and South (Fig. 1b), each containing several meters of deposit. The stratified sequences are numbered by layer, but layers with the same number in the different chambers are not necessarily equivalent in age². Excavations have yielded Middle Palaeolithic (MP) stone artefacts and a variety of Upper Palaeolithic (UP) artefacts, as well as the remains of fauna and flora^{3–7}. The fragmentary remains of four Denisovans, two Neanderthals and the daughter of Neanderthal and Denisovan parents have also been recovered^{8–10} and had their genomes sequenced^{1,2,11–16}, along with DNA extracted from the Pleistocene sediments¹⁷.

The time of deposition of the youngest Pleistocene layers in the cave is currently constrained by radiocarbon (¹⁴C) ages for charcoal fragments and bone collagen. However, many of these ages approach or exceed the limit of ¹⁴C dating (~50 thousand years ago, kyr) and the large spread in ages is consistent with field observations of post-depositional disturbance in some parts of the site (e.g., layers 11.1 and 11.2 in East Chamber)². Using a light-sensitive thermoluminescence (TL) signal¹⁸, seven ages have been reported for quartz grains extracted from the deeper deposits in Main Chamber^{3,19}, ranging from 282 ± 56 kyr (lower part of layer 22.2) to 69 ± 17 kyr (layer 14.1). While questions remain about some of the methodological aspects²⁰, these ages broadly agree with the biostratigraphic data for the cave deposits³. Geomagnetic excursions recorded in layers 22.1 and 22.2 (Main Chamber)²¹ were attributed to two events that are no longer supported^{22,23}. DNA-based methods have been used to infer the ages of the hominin remains^{11–13,16,24}. The genetically oldest

and youngest Denisovan fossils—*Denisova 2* (layer 22.1, Main Chamber) and *Denisova 3* (layer 11.2, East Chamber), respectively—appear to differ in age by 54,200–99,400 years¹³, with *Denisova 3* tentatively dated to 85 ± 8 kyr (95.4% confidence interval)²⁴. DNA-based ages have also been estimated for the ‘Altai Neanderthal’ (*Denisova 5*, 123 ± 7 kyr)²⁴ and the Neanderthal–Denisovan offspring (*Denisova 11*, ~90 kyr or younger)¹⁶, the latter dated by ¹⁴C to >50 kyr (ref. 15). Details are given in Supplementary Information.

Collectively, these ages suggest that hominins have inhabited Denisova Cave intermittently since the mid-Middle Pleistocene. However, accurate and more precise chronologies and a higher density of ages are required to address issues of site formation, hominin occupation and environmental conditions in the vicinity of the cave. Here we present details of the stratigraphy and report more than 100 new ages for the Pleistocene sequences in all three chambers, using optical dating of sediments^{25–28} to construct a common timeline for the cultural remains, hominin fossils and palaeoecological records.

Stratigraphy and site formation

Denisova Cave is formed in Silurian limestone and covers a total area of ~270 m². Main Chamber is ~10 m high and contains ~6 m of deposits, which were first excavated 40 years ago. East and South Chambers are narrow (<3 m wide) and extend away from Main Chamber (Fig. 1b and Extended Data Fig. 1a); their deposits have been excavated to depths of about 7 and 4.5 m, respectively. The upper 1.5–2 m of deposit in each chamber (layers 0–8) are Holocene in age. The underlying Pleistocene deposits consist of clay, silt and sand grains (that were blown or washed into the cave, or were reworked from pre-existing cave sediments) interstratified with coarser, angular limestone debris (gravel-size and larger) spalled from the floor, walls and roof of the cave due to physical and chemical weathering of the bedrock.

The Pleistocene sequences (Fig. 2) are complex and include laterally discontinuous layers and unconformities between layers (due to erosional events or depositional gaps), as well as evidence of post-depositional modifications due to chemical diagenesis and freeze–thaw processes, subsidence and slumping, animal burrowing and anthropogenic activities (Supplementary Tables 16–18). The layers cannot be traced stratigraphically between the chambers, but field observations of sedimentary characteristics and morphological features permit correlation of some Pleistocene layers (e.g., 22).

The Pleistocene deposits in Main Chamber comprise layers 9–22 and their subdivisions (Fig. 2a and Extended Data Figs 2 and 5a,b). Most of the layers are composed of a poorly sorted, sandy silt matrix with abundant angular clasts of spalled bedrock. Some layers (e.g., 9 and 21) have fewer coarse clasts. Many of the layer boundaries are indistinct and transitional. Layer 22.1 forms a peak-shaped feature in the southeast profile and incorporates many vertically tilted gravel clasts. The two overlying layers (21 and 20) follow the same topography. There is no evidence for significant mixing of sediments between these three layers. Layer 12 marks the start of the sub-horizontal stratigraphy in this chamber. Parts of some layers show signs of animal burrowing (e.g., 9 and 13), freeze–thaw processes (e.g., 11 and 22.1), phosphatisation (layer 9 in particular), manganese staining and other diagenetic alterations.

In East Chamber, the basal 2 m (layer 17.2) consists mainly of fine-grained sediments (silty clay) deposited in a former phreatic tube (Fig. 2b and Extended Data Figs 3 and 5c–e). The overlying layer (17.1) has a similar composition and is, in turn, overlain by a thin band of organic-rich sediment (layer 16); both layers follow the undulating topography of the narrow bedrock shelf that separates the phreatic tube from the chamber above. The remaining Pleistocene sequence (layers 15 to 9) is characterised by poorly sorted sediments composed of sandy silts with occasional to abundant angular clasts of limestone. Layers 17.1 to 11.1 dip inwards from the walls and sag towards the base of the chamber due to post-depositional subsidence and possibly some slumping; carnivore coprolites (cave hyenas) are common in these layers. Parts of layers 11 and 9 are heavily

phosphatised²⁹ and show signs of disturbance (lack of bedding), especially from animal burrowing activities. Sediment mixing may also have occurred close to the chamber walls, where fissures are evident and the stratigraphy is complex.

Excavations in South Chamber are currently limited to the entrance area, where layers 9–22 are tentatively recognised (Fig. 2c and Extended Data Fig. 4). The lowest excavated unit is provisionally identified as layer 22, based on its similar colour and texture to layer 22 in Main Chamber and its unconformable contact with the overlying unit, tentatively identified as layer 20. The latter is overlain by layers 19–9, which consist of poorly sorted sediments (silty sand with scattered to abundant clasts of spalled bedrock), and are commonly separated by indistinct and transitional boundaries. Layer 9 contains few coarse clasts, but is extensively phosphatised and burrowed in places (Extended Data Fig. 4d).

Pleistocene chronologies

We constructed numerical chronologies for the Pleistocene sequences in all three chambers from optical dating^{25–28} of 103 sediment samples collected over four excavation seasons; 92 samples were dated from measurements of more than 280,000 individual grains of quartz and potassium-rich feldspar (K-feldspar), and 11 samples were dated using multi-grain aliquots of K-feldspar. Optical ages were determined using four methods of equivalent dose (D_e) estimation (see Methods) and were used to develop a Bayesian model for the depositional chronology in each chamber, connect their stratigraphic sequences, and provide a composite age and environmental framework for hominin occupation of the site (Figs 3 and 4). We also compared these ages with the ^{14}C ages published previously^{2,15} for nine animal bones, a fragment of charcoal and a piece of Neanderthal bone from layers 11 and 12; no Denisovan remains have been dated directly. Details of sediment sample locations and collection, preparation, measurement and data-analysis procedures are given in Supplementary Information, together with the measured and modelled ages and related data.

Fifty-five sediment samples have been dated from Main Chamber (Extended Data Figs 2 and 5a,b). The optical ages are mostly in stratigraphic order and show that the deposits have accumulated episodically since the mid-Middle Pleistocene (Fig. 3 and Extended Data Fig. 6). Finite ages for the deeper deposits (layers 22–13) could be obtained only using the K-feldspar post-infrared infrared stimulated luminescence (pIRIR) signal, because the quartz optically stimulated luminescence (OSL) signal was saturated. The wide spread in ages for layer 13 (175–102 kyr at 95.4% probability; Supplementary Table 7) is consistent with disturbance by burrowing animals³, so these ages were omitted from the Bayesian model. Layer 22 accumulated before 287 ± 41 kyr, followed by deposition of layers 21 and 20 between 250 ± 44 and 170 ± 19 kyr, and layers 19–14 between 151 ± 17 and 97 ± 11 kyr; here and below we cite the modelled age estimates and total uncertainties at 95.4% probability. Layer 12 was deposited between 70 ± 8 and 58 ± 6 kyr, before accumulation of layer 11 between 44 ± 5 and 38 ± 3 kyr. The final Pleistocene deposits are represented by layer 9, which unconformably overlies layer 11 and has start and end ages of 36 ± 4 and 21 ± 8 kyr, respectively. There is some uncertainty about layer assignments where stratigraphic boundaries are indistinct and transitional, and small-scale mixing of parts of some layers is indicated by scatter in the single-grain D_e distributions and optical ages.

Thirty-seven sediment samples have been dated from East Chamber (Extended Data Figs 3 and 5c–e). The deposits in layers 17–12 have a stratigraphically coherent chronology (Fig. 3 and Extended Data Fig. 7), limited age variation within any particular layer and D_e distributions that show minimal evidence for mixing, which we attribute to the lack of significant post-depositional disturbance. Layer 17 accumulated before 284 ± 32 kyr (saturation of the pIRIR signal prevented estimation of a finite age for the deepest sample), followed by deposition of layers 16–12.2 between 259 ± 28 and 129 ± 11 kyr. Layers 12.1 and 11.4–11.1 were deposited between 120 ± 11 and 38 ± 9 kyr. None of the samples collected from layers 11.4 or 11.3 show evidence of mixing. Five of 10 samples from layers 11.2 and 11.1 also show good integrity and give age ranges of 63 ± 6 to 55 ± 6 kyr and 49 ± 6 to 38 ± 9 kyr, respectively. The other five samples, and those from layers 9 and 8 in

the southeast profile, have layer assignments that are uncertain or produced scattered D_e distributions from which reliable optical ages could not be determined (see Supplementary Information). We attribute these D_e distributions to disturbance of the deposit by hyenas and other burrowing animals, resulting in mixing of grains—and presumably also artefacts and fossils—of various ages, consistent with the wide spread in ^{14}C ages (>50 to ~ 19 kyr cal. BP) obtained for the upper part of layer 11 in this chamber².

Eleven sediment samples were dated from South Chamber (Extended Data Fig. 4). The lowest sampled unit (layer 22) accumulated before 269 ± 97 kyr, followed by a lengthy time gap before deposition of layers 19 and 14 between 136 ± 26 and 101 ± 19 kyr (Fig. 3 and Extended Data Fig. 8a). Layer 12 was deposited between 64 ± 9 and 47 ± 8 kyr, consistent with ^{14}C ages of ~ 52 and >50 kyr cal. BP for bones from layer 11.2 (ref. 2).

We also compared the OSL and pIRIR ages for 47 samples dated using both quartz and K-feldspar grains as an internal test of consistency (Extended Data Fig. 8b). The mean age-ratio is 1.00 ± 0.01 (standard error of the mean) and the mean ratio for each chamber is also consistent with unity. This implies that the cave sediments were bleached sufficiently at deposition to reset both dating signals (at least over the time span of this comparison), as OSL traps are emptied more rapidly and completely than are pIRIR traps^{30,31}. Collectively, the three chambers contain a near-complete sequence of Pleistocene deposits (with some noticeable gaps in sedimentation) and hominin occupation extending from ~ 300 to ~ 20 kyr (Figs 3 and 4).

History of hominin occupation

The oldest hominin fossil is a Denisovan molar (*Denisova 2*) recovered in 1984 from the top of layer 22.1 in Main Chamber ($328\text{--}246$ kyr), but its exact provenance cannot now be established definitively. Denisovan DNA was retrieved from layer 15 sediments in East Chamber ($217\text{--}185$ kyr) and from hominin remains in East Chamber (*Denisova 8*: $132\text{--}93$ kyr; *Denisova 3*: $69\text{--}48$ kyr) and South Chamber (*Denisova 4*: less than 47 ± 8 kyr). Neanderthal DNA was retrieved from sediments deposited $168\text{--}86$ kyr in Main Chamber (layers 19, 17 and 14) and $205\text{--}172$ kyr in East Chamber (layer 14) and from hominin remains in East Chamber (*Denisova 9*: $150\text{--}118$ kyr; *Denisova 5*: $132\text{--}93$ kyr); the age range for *Denisova 9* applies also to *Denisova 11*. Figures 3 and 4 show the association between the hominin fossils, sedimentary DNA remains and stratigraphic layers in each chamber. The DNA-based ages^{13,24} for *Denisova 5* and *Denisova 8* are consistent with the optical ages for the associated layers, but the estimates for *Denisova 3* and *Denisova 4* are older than expected based on their stratigraphic positions, while the ages for *Denisova 11* and *Denisova 2* are younger than expected. The omission of uncertainties associated with population size, mutation rate and generation interval in the genetic estimates^{16,24} may account for some of these discrepancies, as might the re-deposition of these isolated and fragmentary fossils.

Four main artefact phases have been identified for Pleistocene hominin occupation of Denisova Cave: early MP, middle MP, Initial UP (IUP) and UP (examples of each in Extended Data Fig. 9). Figure 3 and Extended Data Table 1 show the association between the artefact phases and layers in each chamber; Supplementary Table 1 lists the number of artefacts recovered from each layer in Main and East Chambers. Early MP stone tools have been recovered from sediments deposited in Main and South Chambers before 287 ± 41 and 269 ± 97 kyr, respectively, with the further development of early MP assemblages up to 170 ± 19 and 187 ± 14 kyr in Main and East Chambers, respectively. In general, early MP stone tools are characterised by discoidal and Kombewa cores, the presence of Levallois cores for manufacturing flakes, and include various types of scrapers, denticulates and notched tools (Extended Data Fig. 9d). The overlying middle MP layers were deposited between 156 ± 15 and 58 ± 6 kyr in Main and East Chambers, and between 136 ± 26 and 47 ± 8 kyr in South Chamber. Primary flaking is characterised by the use of flat, discoidal and Levallois cores, with isolated sub-prismatic cores also identified. Scrapers dominate the tool assemblage, notched-denticulate pieces are well represented, and end-scrapers, burins, chisel-like tools and truncated flakes are also present (Extended Data Fig. 9c).

Deposition of the IUP layers started before 44 ± 5 and 63 ± 6 kyr in Main and East Chambers, respectively, and after 47 ± 8 kyr in South Chamber; we note that the earliest artefacts were recovered from layer 11.2 in East Chamber, which has been disturbed in places. The IUP assemblages include variants of parallel and radial flaking, narrow-faced cores for blade production and Levallois flaking (Extended Data Fig. 9b). Scrapers dominate the stone artefacts and various UP-type tools represent a large proportion of the assemblage, which also yielded a rich collection of bone tools and ornaments made from animal teeth and bones, ivory and gem stone. Accumulation of UP assemblages (Extended Data Fig. 9a) started in Main Chamber 36 ± 4 kyr, with a well-developed stone bladelet technology and a UP component distinct from the background of prevailing scrapers.

The archaeological, fossil hominin and sedimentary DNA evidence currently suggests, therefore, that the cave was occupied by Denisovans from 287 ± 41 kyr (or, conservatively, from 203 ± 14 kyr) to 55 ± 6 kyr or later, if *Denisova 3* and *Denisova 4* are not intrusive. Neanderthals were also present between 193 ± 12 and 97 ± 11 kyr.

Environmental context

We have reconstructed the Pleistocene environments in the vicinity of Denisova Cave over the last ~350 kyr from the remains of animals and plants in Main and East Chambers^{3–7} (Fig. 3 and Supplementary Information). Inferred conditions are relative to the current moderately continental climate (average January and July temperatures outside the cave of -16°C and 18°C , respectively). Reconstructions are based on analyses of the remains of 27 species of large mammals, more than 100 species of small vertebrates (40 species of small mammals, 66 taxa of birds and bones of fish, reptiles and amphibians) and pollen records for 30 species of tree, 36 shrub and grass taxa, and 6 species of spore-bearing plants.

Deposits accumulated in late Marine Isotope Stage (MIS) 9 under fairly warm and moderately humid conditions with forests dominated by pine and birch and a significant admixture of broad-leaved species. The subsequent period of moderate cooling in early MIS 8 was marked by a reduction in forest cover, followed by an interval of relatively stable climate accompanied by the maximum spread of forest. Subsequent sedimentation in MIS 8 took place in a relatively cold and moderately humid climate, when mountain tundra and forest-tundra landscapes developed in the vicinity of the cave. During MIS 7, and possibly early MIS 6, sediments were deposited under warm and relatively dry conditions, accompanied by the widespread emergence of pine-birch forests and broad-leaved species. Steppe and meadow-steppe communities flourished during the cold and dry periglacial conditions of terminal MIS 6.

Conditions were unstable during MIS 5, incorporating environments that were variously drier, warmer, cooler and milder than at the present day. Climatic deterioration during MIS 4 was accompanied by multiple turnovers of plant associations under alternating dry and wet cold conditions; steppe and meadow-steppe communities expanded significantly, whereas birch, alder and broad-leaved species disappeared. During MIS 3, dark coniferous forests and meadow associations expanded when conditions were cool and humid, while mixed-grass communities and forest (including broad-leaved species) spread when conditions were warmer. In the subsequent millennia leading up to the last glacial maximum (~20 kyr), climate fluctuated between moderately cold (dominated by spruce forests) and cold and dry (dominated by tundra-steppe associations).

There is broad agreement in the interpretation of climatic conditions between the three chambers (linked using the chronological framework established in this study) and with global and other regional records^{32–35} (Fig. 4). The largest anomaly between inferred climate and timing is at ~150 kyr, when the pollen assemblages in East and Main Chambers (layers 13 and 19.3, respectively) indicate the prevalence of hornbeam forest with a mixture of oak and Eurasian linden. This suggests a relatively warm and humid climate, whereas the optical ages place these layers in late MIS 6,

when generally cold conditions are recorded in Lake Baikal^{32,33} (Fig. 4). We caution, however, that climatic conditions may fluctuate greatly within the time resolution of these records (350–1000 years) and of the optical ages, which have uncertainties of several millennia.

Discussion

Combined across all three chambers, the Pleistocene sequences provide a near-continuous record of human and environmental history spanning the past three glacial–interglacial cycles (Figs 3 and 4 and Extended Data Table 1). Many layers show signs of post-depositional subsidence, but the deposits have, by and large, retained their stratigraphic integrity. Disturbance by animal burrowing and other activities is mostly restricted to parts of the uppermost Pleistocene layers, especially close to the cave walls. The timing of the four main artefact phases and the environmental reconstructions are broadly consistent between chambers, taking into account the sampling resolution and uncertainties associated with these records and the optical ages.

The oldest stone artefacts and Denisovan fossil indicate that hominins have occupied the cave since late MIS 9 (~300 kyr), with Denisovan DNA retrieved from sediments deposited during late MIS 7 (~200 kyr). The recovery of Denisovan skeletal and genetic remains in younger deposits implies their presence in the cave until early MIS 3 (~55 kyr) and possibly later. Neanderthals were also present from late MIS 7 or early MIS 6 until MIS 5 (~100 kyr), based on fossil and sedimentary DNA evidence. No such remains of modern humans have yet been recovered to confirm their presence at the site during the Late Pleistocene.

The data presented here and in recent genetic studies^{12–17,24} reveal that the cave was occupied during the last interglacial by Denisovans and two genetically distinct groups of Neanderthals. Denisovans may have survived until at least ~55 kyr, by which time modern humans were present in other parts of Asia^{36–39}. Ongoing investigations at this and other sites in the region may help resolve the timing and possible causes of extinction of archaic hominins in southern Siberia, and the nature of any encounters—including interbreeding—between them and modern humans.

References

1. Krause, J. *et al.* The complete mitochondrial DNA genome of an unknown hominin from southern Siberia. *Nature* **464**, 894–897 (2010).
2. Reich, D. *et al.* Genetic history of an archaic hominin group from Denisova Cave in Siberia. *Nature* **468**, 1053–1060 (2010).
3. Derevianko, A. P. *et al.* *Paleoenvironment and Paleolithic Human Occupation of Gornyy Altai: subsistence and adaptation in the vicinity of Denisova Cave* (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2003).
4. Bolikhovskaya, N. S. & Shunkov, M. V. Pleistocene environments of northwestern Altai: vegetation and climate. *Archaeol. Ethnol. Anthropol. Eurasia* **42/2**, 2–17 (2014).
5. Agadjanian, A. K. & Shunkov, M. V. Evolution of the Quaternary environment in the northwestern Altai. *Archaeol. Ethnol. Anthropol. Eurasia* **37/2**, 2–18 (2009).
6. Bolikhovskaya, N. S., Kozlikin, M. B., Shunkov, M. V., Uliyanov, V. A. & Faustov, S. S. New palynological data from the unique Paleolithic site of Denisova Cave in northwest Altai. *Bull. Moscow Soc. Natural. Biol. Series* **122**, 46–60 (2017).
7. Vasiliev, S. K., Shunkov, M. V. & Kozlikin, M. B. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **23**, 60–64 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2017).
8. Turner, C. G. II. in *Chronostratigraphy of the Paleolithic in North Central, East Asia and America* (ed. Derevianko, A. P.), 239–243 (Institute of History, Philology and Philosophy, Siberian Branch of the USSR Academy of Sciences, Novosibirsk, 1990).
9. Shpakova, E. G. & Derevianko, A. P. The interpretation of odontological features of Pleistocene human remains from the Altai. *Archaeol. Ethnol. Anthropol. Eurasia* **1**, 125–138 (2000).

10. Mednikova, M. B. A proximal pedal phalanx of a Paleolithic hominin from Denisova Cave, Altai. *Archaeol. Ethnol. Anthropol. Eurasia* **39/1**, 129–138 (2011).
11. Meyer, M. *et al.* A high-coverage genome sequence from an archaic Denisovan individual. *Science* **338**, 222–226 (2012).
12. Sawyer, S. *et al.* Nuclear and mitochondrial DNA sequences from two Denisovan individuals. *Proc. Natl Acad. Sci. USA* **112**, 15696–15700 (2015).
13. Slon, V. *et al.* A fourth Denisovan individual. *Sci. Adv.* **3**, e1700186 (2017).
14. Prüfer, K. *et al.* The complete genome sequence of a Neanderthal from the Altai Mountains. *Nature* **505**, 43–49 (2014).
15. Brown, S. *et al.* Identification of a new hominin bone from Denisova Cave, Siberia using collagen fingerprinting and mitochondrial DNA analysis. *Sci. Rep.* **6**, 23559 (2016).
16. Slon, V. *et al.* The genome of the offspring of a Neanderthal mother and a Denisovan father. *Nature* **561**, 113–116 (2018).
17. Slon, V. *et al.* Neandertal and Denisovan DNA from Pleistocene sediments. *Science* **356**, 605–608 (2017).
18. Vlasov, V. K. & Kulikov, O. A. Radiothermoluminescence dating and applications to Pleistocene sediments. *Phys. Chem. Miner.* **16**, 551–558 (1989).
19. Derevianko, A. P., Laukhin, S. A., Kulikov, O. A., Gnibidenko, Z. N. & Shunkov, M. V. First Middle Pleistocene age determinations of the Paleolithic in the Altai Mountains. *Dokl. Akad. Nauk* **326**, 497–501 (1992).
20. Huntley, D. J. Letters: Vlasov & Kulikov's method. *Anc. TL* **10**, 57–58 (1992).
21. Derevianko, A. P., Gnibidenko, Z. N. & Shunkov, M. V. Middle Pleistocene excursions of the geomagnetic field in the strata of Denisova Cave. *Dokl. Akad. Nauk* **360**, 511–513 (1998).
22. Roberts, A. P. Geomagnetic excursions: knowns and unknowns. *Geophys. Res. Lett.* **35**, L17307 (2008).
23. Laj, C. & Channell, J. E. T. in *Treatise on Geophysics* (2nd edition), vol. 5: *Geomagnetism* (ed. Schubert, G.), 343–383 (Elsevier, Amsterdam, 2015).
24. Prüfer, K. *et al.* A high-coverage Neandertal genome from Vindija Cave in Croatia. *Science* **358**, 655–658 (2017).
25. Huntley, D. J., Godfrey-Smith, D. I. & Thewalt, M. L. W. Optical dating of sediments. *Nature* **313**, 105–107 (1985).
26. Hütt, G., Jaek, I. & Tchonka, J. Optical dating: K-feldspars optical response stimulation spectra. *Quat. Sci. Rev.* **7**, 381–385 (1988).
27. Roberts, R. G. *et al.* Optical dating in archaeology: thirty years in retrospect and grand challenges for the future. *J. Archaeol. Sci.* **56**, 41–60 (2015).
28. Athanassas, C. D. & Wagner, G. A. Geochronology beyond radiocarbon: optically stimulated luminescence dating of palaeoenvironments and archaeological sites. *Elements* **12**, 27–32 (2016).
29. Shunkov, M. V. *et al.* The phosphates of Pleistocene–Holocene sediments of the Eastern Gallery of Denisova Cave. *Dokl. Earth Sci.* **478**, 46–50 (2018).
30. Rhodes, E. J. Dating sediments using potassium feldspar single-grain IRSL: initial methodological considerations. *Quat. Internat.* **362**, 14–22 (2015).
31. Smedley, R. K., Duller, G. A. T. & Roberts, H. M. Bleaching of the post-IR IRSL signal from individual grains of K-feldspar: Implications for single-grain dating. *Radiat. Meas.* **79**, 33–42 (2015).
32. Prokopenko, A. A., Hinnov, L. A., Williams, D. F. & Kuzmin, M. I. Orbital forcing of continental climate during the Pleistocene: a complete astronomically tuned climatic record from Lake Baikal, SE Siberia. *Quat. Sci. Rev.* **25**, 3431–3457 (2006).
33. Grygar, T. *et al.* Lake Baikal climatic record between 310 and 50 ky BP: interplay between diatoms, watershed weathering and orbital forcing. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **250**, 50–67 (2007).
34. Melles, M. *et al.* Sedimentary geochemistry of core PG1351 from Lake El'gygytgyn—a sensitive record of climate variability in the East Siberian Arctic during the past three glacial–interglacial cycles. *J. Paleolimnol.* **37**, 89–104 (2007).

35. Frank, U. *et al.* A 350 ka record of climate change from Lake El'gygytyn, Far East Russian Arctic: refining the pattern of climate modes by means of cluster analysis. *Clim. Past* **9**, 1559–1569 (2013).
36. Liu, W. *et al.* The earliest unequivocally modern humans in southern China. *Nature* **526**, 696–699 (2015).
37. Westaway, K. E. *et al.* An early modern human presence in Sumatra 73,000–63,000 years ago. *Nature* **548**, 322–325 (2017).
38. Hershkovitz, I. *et al.* The earliest modern humans outside Africa. *Science* **359**, 456–459 (2018).
39. Groucutt, H. S. *et al.* *Homo sapiens* in Arabia by 85,000 years ago. *Nat. Ecol. Evol.* **2**, 800–809 (2018).
40. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* **20**, PA1003 (2005).

Acknowledgements

This study was funded by the Australian Research Council through fellowships to Z.J. (FT150100138), B.L. (FT140100384) and R.G.R. (FL130100116), the Russian Science Foundation (project 14-50-00036 to A.P.D. and A.K.A.), the Russian Foundation for Basic Research (project 17-29-04206 to M.V.S., M.B.K., V.A.U., N.S.B. and S.K.V.) and the state task of the Ministry of Education and Science of the Russian Federation (project 33.867.2017/4.6 to A.P.D.). We also thank Y. Jafari, T. Lachlan, D. Müller, D. Tanner, V. Vaneev and the Australian Microscopy & Microanalysis Research Facility for assistance, and P. Goldberg for comments on an earlier version of this article.

Author contributions

Z.J., A.P.D. and R.G.R. conceived of this study. M.V.S., M.B.K. and A.P.D. led the excavations and artefact analyses, and Z.J. and B.L. performed the optical dating, with contributions from K.O'G. and R.G.R. The other analyses were led by V.A.U. (stratigraphy and geoarchaeology), N.S.B. (palynology) and A.K.A. and S.K.V. (palaeontology). Z.J., M.V.S., M.B.K. and R.G.R. wrote the main text with contributions from all authors.

Author information

Reprints and permissions information is available at www.nature.com/reprints.

Competing interests The authors declare no competing interests.

Correspondence and requests for materials should be addressed to Z.J. (zenobia@uow.edu.au) and R.G.R. (rgrob@uow.edu.au).

Extended data is available for this paper at

Supplementary information is available for this paper at

FIGURE CAPTIONS

- Figure 1** | **Location of Denisova Cave and site plan.** **a**, Map of southern Siberia and site location. **b**, Plan of cave interior, showing Main, East and South Chambers; the Entrance zone was not investigated in this study.
- Figure 2** | **Stratigraphic sequences exposed in Denisova Cave.** **a**, Main Chamber. **b**, East Chamber. **c**, South Chamber. The southeast profile is shown for each chamber; these profiles were sampled for optical dating in 2012. Numbers denote stratigraphic layers, layer colours are notional, and asterisks indicate areas of mixed deposit.
- Figure 3** | **Chronological summary of hominin and environmental records in all three chambers.** Layers containing skeletal remains and sedimentary DNA of Denisovans and Neanderthals are denoted by circled specimen numbers and by 'DNA', respectively (red, Denisovans; blue, Neanderthals; both colours, mixed ancestry). Artefact assemblages are indicated to the right of the each stratigraphic sequence.

Climatic conditions are inferred from pollen and faunal records (orange, relatively warm; blue, relatively cold; white, no data). Optical ages (in kyr) are the Bayesian model estimates with total uncertainties at 95.4% probability; layer 13 in Main Chamber (labelled 'nm') was not included in the age model. Isochrons (lines of equal age) are used to correlate stratigraphic layers between chambers, with time gaps indicated by wavy lines.

Figure 4 | Comparison of environmental records at Denisova Cave with global and regional climate proxies. **a**, Climatic conditions inferred from pollen and faunal records in Main, East and South Chambers (orange, relatively warm; blue, relatively cold; white, no data) plotted on a calendar-year timescale; the time span of each climatic interval is demarcated by the mean start and end ages for the relevant layers (Fig. 3). Marine Isotope Stage (MIS) boundaries after ref. 40. **b**, Fossils (circled specimen numbers) and sedimentary DNA ('DNA') of Denisovans (red) and Neanderthals (blue) and a fossil of mixed ancestry (both colours). **c**, Composite BDP-96 biogenic silica record of diatom productivity in Lake Baikal³², located ~1600 km east of Denisova Cave; **d**, LR04 stack of marine benthic foraminiferal isotopic ($\delta^{18}\text{O}$) data assembled from 57 globally distributed sites⁴⁰ (VPDB, Vienna Pee Dee Belemnite).

METHODS

Sediment samples for optical dating were collected at Denisova Cave in 2012, 2014, 2016 and 2017. Samples were collected by hand at night using a red-light torch for illumination, and sealed in thick black plastic to prevent light exposure during transport to the University of Wollongong. Optical dating gives an estimate of the time since grains of minerals, such as quartz and potassium-rich feldspar (K-feldspar), were last exposed to sunlight^{25–28}. The time of sediment deposition is estimated by dividing the equivalent dose (D_e , the radiation energy absorbed by grains since deposition) by the environmental dose rate (the rate of supply of ionising radiation to the grains since deposition). The D_e is estimated from laboratory measurements of the optically stimulated luminescence (OSL) from quartz or the post-infrared infrared stimulated luminescence (pIRIR) from K-feldspar. The OSL signal is bleached by light more rapidly and completely than the pIRIR signal^{30,31} (hence, consistent OSL and pIRIR ages suggests prolonged bleaching at deposition), but the latter signal saturates at much higher doses than the OSL signal^{27,28} (hence, finite ages can be obtained for older deposits). The dose rate is estimated from field and laboratory measurements of environmental radioactivity, plus the small contribution from cosmic rays.

We used both quartz and K-feldspar grains to develop a numerical chronology for the Pleistocene sequences in Denisova Cave. The ages of the older samples were determined solely from the K-feldspar pIRIR signal, owing to saturation of the quartz OSL signal. Standard procedures were used to isolate individual grains of quartz (180–212 μm in diameter) and K-feldspar (ranging in size between 90 and 212 μm diameter, depending on availability), and grains were etched in hydrofluoric acid to remove the alpha-irradiated surface layer. D_e values for individual quartz grains were estimated using well-established OSL measurement and data-analysis procedures^{41–43}, and D_e values for individual K-feldspar grains were determined using a two-step (200°C, 275°C) regenerative-dose pIRIR procedure⁴⁴ and a recently developed standardised growth curve approach^{45,46}. We analysed the single-grain pIRIR signals in two ways (Methods A and B) to estimate the final D_e values. A multiple-aliquot regenerative-dose procedure for K-feldspar (Method C) was used to estimate the D_e values for the oldest deposits⁴⁷. Details of sample preparation and D_e determination methods, experimental procedures, quality-assurance criteria and validation tests are given in Supplementary Information.

The environmental dose rate includes contributions from beta particles (measured in the laboratory⁴⁸ on a portion of each sample), gamma rays (measured by *in situ* gamma spectrometry at each sample location), cosmic rays⁴⁹, and radioactive emitters internal to the K-feldspar and quartz

grains. The latter dose rate is commonly trivial for quartz (we assumed a value of 0.032 ± 0.010 Gy kyr⁻¹), but is significant for K-feldspar due to the beta dose from ⁴⁰K; we measured the K contents for a subset of grains by wavelength-dispersive X-ray spectroscopy using an electron microprobe. The measured beta dose rates were corrected for grain-size attenuation, and the beta, gamma and cosmic-ray dose rates were adjusted for water content (based on the measured field values). The sample D_e values were divided by the corresponding total environmental dose rates to calculate the optical ages in calendar years before present; the associated uncertainties are at the 68.2% confidence level and include all known and estimated sources of random and systematic error. Details of dose rate determination and the resulting data are presented in Supplementary Information, together with the age determination and error estimation procedures.

A Bayesian age model was developed separately for Main, East and South Chambers on the OxCal platform^{50,51}. Each age was input as a C_date in calendar years before AD 1950 with an associated uncertainty (the standard error of the mean); we used the weighted mean age for each of the samples with paired OSL and pIRIR ages. The sequence of stratigraphic layers in each chamber was used as prior information, and we also allowed for the probable existence of time gaps (modelled as intervals) in each stratigraphic sequence; the resulting ages, however, are insensitive to the choice of model. Each sequence was modelled as a series of Phases, assuming that (a) the stratigraphically lowest Phase is older than those above, and (b) the measured ages are unordered and uniformly distributed within each Phase. Modelled age estimates were obtained for the start and end of each Phase to facilitate chronological comparisons between the three chambers. Details of the Bayesian modelling and the resulting chronologies are provided in Supplementary Information.

Data availability

All data generated and/or analysed during the current study are available from the corresponding authors on reasonable request.

Code availability

All custom R code used to produce the results presented here are available from the corresponding authors on reasonable request.

41. Jacobs, Z. & Roberts, R. G. Advances in optically stimulated luminescence dating of individual grains of quartz from archeological deposits. *Evol. Anthropol.* **16**, 210–223 (2007).
42. Wood, R. *et al.* Towards an accurate and precise chronology for the colonization of Australia: the example of Riwi, Kimberley, Western Australia. *PLoS ONE* **11**, e0160123 (2016).
43. Clarkson, C. *et al.* Human occupation of northern Australia by 65,000 years ago. *Nature* **547**, 306–310 (2017).
44. Blegen, N. *et al.* 2015. Distal tephras of the eastern Lake Victoria basin, equatorial East Africa: correlations, chronology and a context for early modern humans. *Quat. Sci. Rev.* **122**, 89–111 (2015).
45. Li, B., Jacobs, Z., Roberts, R. G., Galbraith, R. & Peng, J. Variability in quartz OSL signals caused by measurement uncertainties: problems and solutions. *Quat. Geochronol.* **41**, 11–25 (2017).
46. Li, B., Jacobs, Z., Roberts, R. G. & Li, S.-H. Single-grain dating of potassium-rich feldspar grains: towards a global standardised growth curve for the post-IR IRSL signal. *Quat. Geochronol.* **45**, 23–36 (2018).
47. Li, B., Jacobs, Z. & Roberts, R. G. An improved multiple-aliquot regenerative-dose (MAR) procedure for post-IR IRSL dating of K-feldspar. *Anc. TL* **35**, 1–10 (2017).
48. Bøtter-Jensen, L. & Mejdahl, V. Assessment of beta dose-rate using a GM multicounter system. *Nucl. Tracks Radiat. Meas.* **14**, 187–191 (1988).
49. Prescott, J. R. & Hutton, J. T. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term time variations. *Radiat. Meas.* **23**, 497–500 (1994).
50. Bronk Ramsey, C. Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**, 337–360 (2009).

539 51. Bronk Ramsey, C. & Lee, S. Recent and planned developments of the program OxCal.
540 *Radiocarbon* **55**, 720–730 (2013).
541
542
543

EXTENDED DATA CAPTIONS

- Extended Data Figure 1 | Plan maps of Main, East and South Chambers in Denisova Cave.** **a**, Detailed plan of cave interior, showing year of excavation in each of the chambers and at cave entrance. **b**, Photograph of present-day cave entrance, with people on left for scale. **c–e**, Plan maps of Main, South and East Chambers, respectively, with sequence of excavations in each chamber denoted by colour shading: orange (earliest), blue, pink, green, yellow and white (most recent), with unexcavated areas in grey. Crosses denote locations of optical dating samples in each profile.
- Extended Data Figure 2 | Stratigraphic sequences and locations of optical dating samples in Main Chamber.** **a**, Southeast profile after excavations in 1984 and **b**, locations of samples collected from this profile in 2012 (blue) and 2014 (red). **c**, Southeast profile after excavations in 2016 and **d**, locations of samples collected from this profile in 2016 (yellow). The number next to each filled circle represents the sample code (e.g., number 1 next to the blue filled circle in **b** denotes sample DCM12-1).
- Extended Data Figure 3 | Stratigraphic sequences and locations of optical dating samples in East Chamber.** **a**, Southeast profile after excavations in 2012 and **b**, locations of samples collected from this profile in 2012 (blue) and 2014 (red). **c**, Southeast profile after excavations in 2015 and **d**, locations of samples collected from this profile in 2016 (yellow). **e**, Lower section of northwest profile (i.e., below the choke-stone blocking the gap between the middle and lower sections of the hourglass-shaped cave profile) after excavations in 2014 and **f**, locations of samples collected from this profile in 2014. The number next to each filled circle represents the sample code (e.g., number 1 next to the blue filled circle in **b** denotes sample DCE12-1).
- Extended Data Figure 4 | Stratigraphic sequences and locations of optical dating samples in South Chamber.** **a, b**, Southeast profile after excavations in 2003 and **c**, after excavations in 2016, showing locations of samples collected in 2012 (blue) and 2016 (yellow). The number next to each filled circle represents the sample code (e.g., number 1 next to the blue filled circle denotes sample DCS12-1). **d**, Area enclosed by the white square in **c**. Sample DCS16-2 is located ~13 cm below the base of the Holocene deposits and to the left of an infilled animal burrow, and immediately beneath a zone of phosphatisation.
- Extended Data Figure 5 | Additional stratigraphic sequences and sampling locations in Main and East Chambers.** **a**, Upper section of east profile in Main Chamber, showing locations of optical dating samples collected in 2014. **b**, Lower section of east profile in Main Chamber, showing locations of samples collected in 2014. **c**, Upper section of northwest profile in East Chamber, showing locations of samples collected in 2014 (red) and 2016 (yellow). **d**, Middle section of northwest profile in East Chamber, showing locations of samples collected in 2016. The lower section of this profile is shown in Extended Data Fig. 3f. **e**, West profile in East Chamber, showing location of sample DCE14-1.
- Extended Data Figure 6 | Bayesian model of optical ages for deposits in Main Chamber.** Ages (n=43) have been modelled in OxCal version 4.2.4. Only random errors are included in the age model. Pale probability distributions represent the unmodelled ages (likelihoods) and dark grey distributions represent the modelled ages (posterior

598		probabilities). The narrow and wide brackets beneath the distributions
599		represent the 68.2% and 95.4% probability ranges, respectively. Start
600		and end ages have been modelled for each <i>Phase</i> , with age ranges
601		(95.4% confidence interval, random-only errors) given in years and
602		rounded off to the closest decade.
603	Extended Data Figure 7	Bayesian model of optical ages for deposits in East Chamber. Ages
604		(n=28) have been modelled in OxCal version 4.2.4. Only random
605		errors are included in the age model. Pale probability distributions
606		represent the unmodelled ages (likelihoods) and dark grey
607		distributions represent the modelled ages (posterior probabilities). The
608		narrow and wide brackets beneath the distributions represent the
609		68.2% and 95.4% probability ranges, respectively. Start and end ages
610		have been modelled for each <i>Phase</i> , with age ranges (95.4%
611		confidence interval, random-only errors) given in years and rounded
612		off to the closest decade.
613	Extended Data Figure 8	Bayesian model of optical ages for deposits in South Chamber and
614		comparison of OSL and pIRIR ages for all three chambers. a,
615		Ages (n=11) have been modelled in OxCal version 4.2.4. Only
616		random errors are included in the age model. Pale probability
617		distributions represent the unmodelled ages (likelihoods) and dark
618		grey distributions represent the modelled ages (posterior
619		probabilities). The narrow and wide brackets beneath the distributions
620		represent the 68.2% and 95.4% probability ranges, respectively. Start
621		and end ages have been modelled for each <i>Phase</i> , with age ranges
622		(95.4% confidence interval, random-only errors) given in years and
623		rounded off to the closest decade. b, Comparison of single-grain OSL
624		ages for quartz and single-grain pIRIR ages for K-feldspar for 47
625		samples (28, 15 and 4 from Main, East and South Chambers,
626		respectively), with age uncertainties shown at 2σ . The dashed line
627		indicates the 1:1 ratio.
628	Extended Data Figure 9	Palaeolithic artefacts from Main, East and South Chambers. a,
629		Upper Palaeolithic (1–3, bladelets; 4, retouched blade; 5, end-scraper).
630		b, Initial Upper Palaeolithic (1, marble ring; 2, tubular beads; 3, ivory
631		pendant; 4, pendant made of red deer tooth; 5, ivory ring; 6, pendant
632		made of elk tooth; 7, chloritoid bracelet; 8, bone needle; 9, end-
633		scraper; 10, retouched point; 11, biface; 12, pointed blade). c, middle
634		Middle Palaeolithic (1, blade; 2 and 5, Mousterian points; 3, Levallois
635		point; 4, scraper). d, early Middle Palaeolithic (1, core; 2 and 4,
636		scrapers; 3, denticulate tool).
637	Extended Data Table 1	Compilation of modelled start and end ages for Main, East and
638		South Chambers. Modelled mean ages obtained from the Bayesian
639		model results presented in Extended Data Figs 6–8 and their estimated
640		uncertainties ($\pm 2\sigma$) are presented for each layer (or combination of
641		layers) together with their archaeological associations, which have
642		been colour coded to differentiate the four main artefact phases
643		(Middle Palaeolithic, dark and pale green; Upper Palaeolithic, dark
644		and pale orange). Modelled time intervals, representing potential gaps
645		in the stratigraphic sequences, are shaded grey, with their estimated
646		durations ($\pm 2\sigma$) given in thousands of years.
647

[illegible]

a

b

c

d

e

b

d

Archaeology	Main Chamber			East Chamber			South Chamber				
	Layer	Age ± 2σ (kyr)		Layer	Age ± 2 σ (kyr)		Layer	Age ± 2 σ (kyr)			
Upper Palaeolithic	9	end	21 ± 8 36 ± 4	9			9				
Initial Upper Palaeolithic	11	end	38 ± 3	11.1	end	38 ± 9	11				
		start	44 ± 5		start	49 ± 6		end	47 ± 8		
middle Middle Palaeolithic		gap	13 ± 5	11.2	end	55 ± 6	12				
					start	63 ± 6					
	12	end	58 ± 6								
		start	70 ± 8	11.3	end	70 ± 8			start	64 ± 9	
		gap	26 ± 10		start	80 ± 10		gap	39 ± 21		
					gap	25 ± 13					
	14	end	97 ± 11	11.4	end	105 ± 11	14	end	101 ± 19		
		start	112 ± 12								
		gap	13 ± 10	12.1	start	120 ± 11					
	17	end	128 ± 13	12.2	end	129 ± 11					
early Middle Palaeolithic				12.3	start	141 ± 10	19	start	136 ± 26		
					end	146 ± 11					
	19	start	151 ± 17	13	start	156 ± 15					
		gap	16 ± 13		gap	32 ± 18					
	20	end	170 ± 19	14	end	187 ± 14					
					start	193 ± 12					
				15	end	197 ± 12					
					start	203 ± 14					
					gap	36 ± 17					
				16	end	238 ± 20					
	21	start	250 ± 44		start	259 ± 28					
		gap	29 ± 26								
	22.1	end	287 ± 41	17.1	end	284 ± 32	22	end	269 ± 97		
					start	305 ± 37					
sterile	22.3	start	366 ± 43		gap	214 ± 74	22	start	396 ± 121		
				17.2	508 ± 40						

SUPPLEMENTARY INFORMATION

Section 1 | Methods of excavation and analysis of the Pleistocene deposits, fauna and flora

Supplementary Discussion	2
Supplementary Table 1 Number of artefacts—Main & East Chambers	3

Section 2 | Previous chronologies and optical dating

Supplementary Discussion	4
Supplementary Table 2 Previously reported ages—Main, East & South Chambers	29
Supplementary Table 3 Optical dating D_e measurement procedures	30
Supplementary Table 4 Number of quartz grains processed for D_e estimation	31
Supplementary Table 5 Number of K-feldspar grains processed—full SAR	33
Supplementary Table 6 Number of K-feldspar grains processed—SGC and L_nT_n	35
Supplementary Table 7 Dose rates, D_e values and optical ages—Main Chamber	39
Supplementary Table 8 Dose rates, D_e values and optical ages—East Chamber	43
Supplementary Table 9 Dose rates, D_e values and optical ages—South Chamber	46
Supplementary Table 10 Bayesian model age ranges—Main Chamber	47
Supplementary Table 11 Bayesian model age ranges—East Chamber	49
Supplementary Table 12 Bayesian model age ranges—South Chamber	51
Supplementary Table 13 CQL code for Bayesian age model—Main Chamber	52
Supplementary Table 14 CQL code for Bayesian age model—East Chamber	55
Supplementary Table 15 CQL code for Bayesian age model—South Chamber	57
Supplementary Figure 1 Quartz grains—OSL decay and dose-response curves	58
Supplementary Figure 2 K-feldspar grains—pIRIR decay curves	59
Supplementary Figure 3 K-feldspar grains—SGC L_x/T_x ratios and D_e comparisons	60
Supplementary Figure 4 IRSL and MET-pIRIR decay curves and re-normalised ratios	61
Supplementary Figure 5 K-feldspar grains—dose recovery and fading ratios	62
Supplementary Figure 6 T_n threshold plots for SGC D_e values and L_n/T_n ratios	63
Supplementary Figure 7 Quartz grains— D_e distributions	64
Supplementary Figure 8 K-feldspar grains— D_e distributions	65
Supplementary Figure 9 D_e and L_n/T_n distributions—Main Chamber	66
Supplementary Figure 10 D_e and L_n/T_n distributions—East Chamber	71
Supplementary Figure 11 D_e and L_n/T_n distributions—South Chamber	74
Supplementary Figure 12 Re-normalised L_n/T_n ratios from MAR SGC	75
Supplementary Figure 13 D_e values from MAR SGC	76
Supplementary Figure 14 Comparison of D_e values—SGC vs L_nT_n & L_nT_n vs MAR	77
Supplementary Figure 15 Comparison of independent estimates of beta dose rate	78
Supplementary Figure 16 Measurements of K content in individual K-feldspar grains	79

Section 3 | Stratigraphy and sedimentology

Supplementary Table 16 Description of layers and boundaries—Main Chamber	80
Supplementary Table 17 Description of layers and boundaries—East Chamber	83
Supplementary Table 18 Description of layers and boundaries—South Chamber	85

Section 4 | Pleistocene environments, palynology and palaeontology

Supplementary Discussion	86
Supplementary Table 19 Ratios of small vertebrate fauna—Main Chamber	95
Supplementary Table 20 Species composition of vertebrate fauna—Main Chamber	97
Supplementary Table 21 Ratios of small vertebrate fauna—East Chamber	98
Supplementary Table 22 Species composition of vertebrate fauna—East Chamber	99
Supplementary Table 23 Numbers and ratios of diagnostic fauna—East Chamber	100

Supplementary References	101
--------------------------------	-----

SECTION 1 | Methods of excavation and analysis of the Pleistocene deposits, fauna and flora

Supplementary Discussion (Michael V. Shunkov, Maxim B. Kozlikin, Vladimir A. Uliyanov, Nataliya S. Bolikhovskaya and Alexander K. Agadjanian)

To enable a detailed assessment of the Pleistocene archaeological and environmental records at Denisova Cave, we collected and analysed a range of archaeological, geological and biological data using a variety of methods and approaches. The cave deposits were excavated using a rectangular Cartesian coordinate system to provide a location reference for objects and features discovered in the process of excavation. The coordinate axes (X, Y, and Z) refer to a datum point established outside of the excavated areas, with the latter having positive X and Y values. The excavation trenches were divided into 1×1 m squares using electronic, suspended and ground grid systems. A total station was used to correlate the X, Y, and Z data collected by these systems.

Deposits exposed in the excavated sections were separated into lithological units based on differences in granulometric composition and density, colour and tint. Distinctive inclusions, recent formations, textural and structural features, unconformities due to gaps in sedimentation, and traces of biogenic and human activities were also recorded. Visual descriptions of the sections were followed by further analyses to refine the tentatively recognised units on the basis of lithostratigraphy, biostratigraphy and chronostratigraphy.

The positions of the culture-bearing layers in the stratigraphic sections, their spatial organisation and their state of preservation were documented to achieve an integrated analysis of the Pleistocene archaeology. Excavations were conducted by removing sediments from each square to a depth of 2–5 cm within the same lithological unit. For more detailed analysis, squares were divided into 0.5×0.5 m sub-squares. Finds were left *in situ* on the exposed surface of a layer, and the direction of horizontal orientation, vertical angle and depth below datum were recorded for each find. The qualitative and quantitative characteristics of the exposed level were also documented in the field. All sediments removed during the excavations by squares and levels within the same layer were washed through sieves with mesh sizes of 5×5 mm and 1×1 mm; the fill material associated with burrows was removed and washed separately. The cleaned materials retained on the sieves were dried and classified into various categories (e.g., small artefacts and bones) for subsequent lithic, faunal and other analyses. Supplementary Table 1 lists the number of artefacts recovered from Main and East Chambers^{3,52–56}; excavations are ongoing in South Chamber.

Analytical approaches for studying fossils of large- and medium-sized mammals follow standard palaeontological guidelines. All of the bones recovered from the excavated deposits were used to determine the number of identified specimens (NISP) and the minimum number of individuals (MNI) for each species. We also evaluated the degree of bone weathering and traces of the activities of carnivores (tooth marks, coprolites) and humans (indications of fire use, cut marks, bone modifications). The description of each species includes information about its morphological and morphometric features, sex attribution of the dead animal and its age at death, which depends on the extent of tooth wear. Bone measurements were made using established procedures⁵⁷. The small mammal fossils were collected from the washed sediments with the aid of a binocular microscope. The overall species composition of small mammals was determined for each layer, along with the number of bones of each species and their relative abundance, to highlight changes in the taxonomic and ecological diversity of small vertebrate fauna in the vicinity of the cave.

To provide a comprehensive reconstruction of past environmental conditions, we also investigated the structure of the present-day fauna through visual observations, trapping (using standard methods) and the study of food pellets regurgitated by birds of prey. Trap lines (25 traps each) were set up to several kilometres from Denisova Cave to embrace all types of biotopes, from the floodplain of the Anui River in the valley bottom to the alpine meadows and boulder streams scattered along the dominating Bashchelaksky ridge, which attains an elevation of 2,000–2,150 m above sea level.

Spores and pollen were extracted from 50 g samples of sediment from the Pleistocene deposits using a modified separation method developed previously⁵⁸. If the number of pollen grains and spores was insufficient for reliable statistical inference, then additional portions of sediments (50 or 100 g) were prepared for analysis. If necessary, palynological concentrates were purified from large quantities of fine-grained sediments using 40% hydrofluoric acid. For environmental reconstruction, the Pleistocene spore–pollen assemblages were compared to sub-fossil assemblages collected from present-day soils and sub-aqueous deposits in mountainous areas adjacent to the Anui valley covered with vegetation communities typical of alpine tundra and forest-tundra, as well as areas in the valleys of the Anui River and its tributaries that have vegetation communities characteristic of mountain taiga, mountain forest-steppe and mountain steppe belts.

Supplementary Table 1 | Number of artefacts recovered from Main and East Chambers in Denisova Cave, up to the end of the 2017 excavation season. Layers have been colour coded (as in Extended Data Table 1) to differentiate the four main artefact phases: early Middle Palaeolithic, dark green; middle Middle Palaeolithic, pale green; Initial Upper Palaeolithic, dark orange; Upper Palaeolithic, pale orange.

Layer	Number of artefacts	Layer	Number of artefacts
MAIN CHAMBER		EAST CHAMBER	
9	1,583	9	2,902
11	3,214	11.1	1,612
12	2,971	11.2	4,266
13	563	11.3	5,730
14	1,635	11.4	4,367
15	32	12	7,490
16	58	13	1,326
17	223	14	22,308
18	17	15	8,656
19	1,925		
20	1,039		
21	363		
22	360		

SECTION 2 | Previous chronologies and optical dating

Supplementary Discussion (Zenobia Jacobs, Bo Li, Kieran O’Gorman and Richard G. Roberts)

PREVIOUS CHRONOLOGIES

A total of 11 radiocarbon (^{14}C) and seven radiation-induced thermoluminescence (RTL) age determinations have been published previously for Main, East and South Chambers, together with DNA-based age estimates for three hominin fossils (*Denisova 3*, *Denisova 5* and *Denisova 11*) from East Chamber (Supplementary Table 2).

Ten ^{14}C ages have been reported for bone, some of which were humanly modified (e.g., evidence of cut marks), along with one ^{14}C age on charcoal^{2,3,59–62}. All bone samples measured at the Oxford Radiocarbon Accelerator Unit (OxA-) were pretreated using molecular ultrafiltration procedures for bone collagen. This procedure has previously been shown to remove modern carbon contaminants more completely than less rigorous pretreatment methods for collagen. Sample pretreatment information is not published for the other two bone samples, or for the charcoal sample. Only a single ^{14}C age has been reported for layer 11 in Main Chamber, and this estimate is infinite. Six ages were reported for samples from East Chamber. All were from layer 11 and its sub-layers, except for a fragment of bone collected from layer 12.3 (*Denisova 11*). This sample has an infinite ^{14}C age, as did two other samples dated from layers 11.2 and 11.3. The remaining three ^{14}C samples, all humanly modified bones from layer 11, have calibrated ages that range from about 18,830 to 34,580 years cal BP (95.4% confidence interval). These three samples are thought to have originated from disturbed parts of layer 11 in East Chamber², but close to where a Denisovan finger phalanx (*Denisova 3*) was found in layer 11.2. Three of the four ^{14}C samples from South Chamber also gave infinite age estimates. Only the charcoal sample collected from the erosional surface at the boundary of layers 10 and 11 gave a finite age of $29,200 \pm 360$ years BP (32,460–34,085 years cal BP, 95.4% confidence interval). Together, the ^{14}C ages from Denisova Cave suggest that most of the Pleistocene sedimentary deposit and material culture is beyond the effective range of ^{14}C dating, with evidence for mixing in some parts of the deposit.

A considerable antiquity for the sedimentary deposit had been suggested earlier by RTL dating of quartz grains from seven sediment samples collected in Main Chamber^{3,18,19,59–62}. It is unclear exactly what this method entails and how it relates to the more conventional thermoluminescence methods used to estimate the time elapsed since sediments were last exposed to sunlight. Huntley²⁰ provides some insights into the method of Vlasov and Kulikov¹⁸, but the techniques used in their study for determining both the equivalent dose (D_e) and the environmental dose rate have not been verified by others, and the reliability of the RTL age estimates remains uncertain. Five of the seven ages were obtained for sediment samples from layer 22 and range between 282 ± 56 thousand years ago (kyr) for the lowest part of this layer to 171 ± 43 kyr for the uppermost part. Ages were also obtained for layers 21 (155 ± 31 kyr) and 14.1 (69 ± 17 kyr).

Age estimates have also been reported for three hominin fossils—*Denisova 3*, *Denisova 5* (the ‘Altai Neanderthal’ toe phalanx from layer 11.4 in East Chamber) and *Denisova 11* (the daughter of a Neanderthal mother and a Denisovan father)—based on the number of differences in nucleotide substitutions (branch shortening) in their ancient DNA (aDNA) sequences^{11,16,24}. Meyer *et al.*¹¹ were the first to give a tentative age estimate for *Denisova 3* of between 74 and 82 kyr. This estimate was based on an assumed 6.5 million year-old divergence date for chimpanzees and humans and the shortening of the Denisovan branch. They advised, however, that multiple sources of error may affect this estimate. Prüfer *et al.*²⁴ exploited the additional high-coverage genome of a Neanderthal (*Vindija 33.19*) from Vindija Cave in Croatia to further explore the ages of *Denisova 3* and *Denisova 5*. All three of these fossils have high-quality and high-coverage genome sequences that allow for estimation of approximate ages from the number of new nucleotide substitutions relative to present-day humans, when compared to the inferred ancestor shared with apes. Assuming a human–chimpanzee divergence date of 13 million years, Prüfer *et al.* estimated ages of 72 ± 12 kyr for *Denisova 3* and 122 ± 12 kyr for *Denisova 5* based on transversions only, with respective age estimates of 85 ± 8 and 123 ± 7 kyr based on all sites (uncertainties at the 95.4% confidence interval). They cautioned that

many factors make absolute age estimates based on branch shortening of these ancient genomes tentative—including the omission of uncertainties associated with population size, mutation rate and generation time—but similarities obtained with independently dated specimens, such as the ~45,000 years cal BP modern human from Ust'-Ishim⁶³, lend some support to these estimates. Slon *et al.*¹⁶ recently reported a maximum age for *Denisova 11* of ~77 kyr (using transversions only) or ~89 kyr (using all sites), assuming a human–chimpanzee divergence date of 13 million years.

The ages of three Denisovan molars relative to *Denisova 3* have also been estimated, based on differences in their nuclear and mitochondrial aDNA sequences^{12,13}. The most recent of these studies¹³ estimated that *Denisova 2* (from layer 22.1 in Main Chamber), *Denisova 8* (from the interface of layers 12 and 11.4 in East Chamber) and *Denisova 4* (from layer 11 in South Chamber) are 54.2–99.4, 33.6–61.7 and 3.7–6.9 thousand years older than *Denisova 3*, respectively, with the age ranges calculated at the 95.4% confidence interval.

OPTICAL DATING

Optical dating provides a means of determining burial ages for sediments and associated artefacts and fossils^{25–28,41–44,64–66}. The method is based on the time-dependent increase in the number of trapped electrons induced in mineral grains—such as quartz and potassium-rich feldspar (K-feldspar)—by low levels of ionising radiation from the decay of natural uranium, thorium and potassium in the surrounding deposits, from within the mineral grains themselves, and from cosmic rays. The time elapsed since the light-sensitive electron traps were emptied can be determined from measurements of the luminescence signals from quartz (optically stimulated luminescence, OSL) and K-feldspar (infrared stimulated luminescence, IRSL, and post-infrared IRSL⁶⁷, pIRIR)—from which the equivalent dose (D_e) is estimated—together with determinations of the radioactivity of the sample and the material surrounding it to a distance of ~30 cm (the environmental dose rate). The luminescence ‘clock’ is reset by just a few seconds (quartz, OSL) or a few hours (K-feldspar, pIRIR) of exposure to sunlight. The D_e divided by the environmental dose rate gives the burial time of the grains in calendar years ago.

In this study, optical ages for the 11 oldest samples were determined from multi-grain aliquots of K-feldspar using the multiple-aliquot regenerative-dose multiple-elevated-temperature (MET) pIRIR procedure for D_e estimation⁴⁷. For the remaining 92 samples, we measured individual grains of two minerals, quartz or K-feldspar, and two methods of D_e estimation for the K-feldspar grains, to exploit the inherent benefits of single-grain dating. These include the identification and elimination of individual grains that exhibit aberrant luminescence characteristics, and the use of D_e distributions to investigate the potential impact that depositional and post-depositional processes, such as sediment mixing or insufficient exposure to sunlight (partial bleaching), may have on age determination^{27,28,41–44,68,69}. We also measured single grains of both quartz and K-feldspar to obtain D_e values for samples collected from the upper layers. This dual-mineral approach adds further value to this study, for the following reasons:

1. K-feldspar grains are much less affected by differences in the external beta dose rate than are quartz grains, as the internal dose rate derived from radioactive ⁴⁰K and ⁸⁷Rb within the K-feldspar grains makes a much greater contribution to the total dose rate to K-feldspar than it does to quartz. This internal component of the dose rate is not affected by spatial inhomogeneity or temporal variability in the distribution of radioactivity external to the grains, thus reducing the effect that variations in the external beta dose rate may have on the spread in D_e values.
2. The internal dose rate component is also not affected by changes in moisture content or likely to suffer from disequilibrium in the ²³⁸U, ²³⁵U and ²³²Th decay series.
3. The OSL and IRSL/pIRIR signals have different sensitivities to sunlight exposure. Whereas the quartz OSL signal can be reset to zero (or nearly so) within a matter of seconds, the K-feldspar pIRIR signal requires several hours of exposure to sunlight and, even after an extended bleach, a residual signal is commonly observed⁷⁰. Given their contrasting signal

sensitivities to light exposure, agreement between quartz and K-feldspar ages provides strong evidence for adequate bleaching of both minerals during sediment transport prior to burial.

4. Compared to the OSL signal, the IRSL and pIRIR signals usually saturate at much higher doses, enabling much larger finite D_e values (and, thus, older ages) to be measured from K-feldspar grains.

By using this multi-signal approach for D_e and age estimation, we can check that the OSL and pIRIR signals were bleached sufficiently prior to sediment deposition (at least for the upper part of the stratigraphic sequence, which could be dated using both minerals), with the pIRIR signal used to obtain finite age estimates for samples in which the OSL signal is saturated; this corresponds to sedimentary deposits older than ~100 kyr at Denisova Cave.

Sampling strategy and sample descriptions

We have developed numerical chronologies for the Pleistocene deposits in Main, East and South Chambers at Denisova Cave from optical dating of 103 sediment samples collected over four excavations seasons (2012, 2014, 2016 and 2017). All samples were collected at night, using red-light torches for illumination. To remove grains exposed to daylight at each of the sampling locations, the section faces were cleaned at night prior to sample collection. Samples were removed using a trowel or a small coring device (~2 cm diameter) and placed into zip-lock plastic bags. All samples were then packed in light-safe black plastic bags for transport to the luminescence dating laboratory at the University of Wollongong in Australia. A sub-sample of sediment was also collected from the back of each sample hole for measurement of the prevailing moisture content and for laboratory-based measurements of radioactivity. Sample holes were enlarged, if necessary, to insert a 1-inch diameter gamma-ray detector for *in situ* measurements of the gamma dose rates.

Sample codes were assigned to each sample based on the chamber from which it was collected (DCM, Main Chamber; DCE, East Chamber; DCS, South Chamber), the year in which it was collected (2012, 2014, 2016 or 2017) and a sample number. For example, sample DCM12-1 is sample number 1, collected from Main Chamber in 2012. There is no relationship between sample number and stratigraphic position; it reflects only the order in which samples were collected. The sampled profiles are indicated in Extended Data Fig. 1, with individual sample locations shown on the photographs in Extended Data Figs 2–5; samples collected in 2012, 2014, 2016 and 2017 are shown as blue, red, yellow and green filled circles, respectively, with the sample number shown adjacent to the filled circle. The stratigraphic layer from which each sample was collected is provided in Supplementary Tables 7–9. Each sample was collected in consultation with M.B.K. and V.A.U., the site archaeologist and geologist, respectively. Our overall aim was to sample as many of the individual layers and sub-layers identified during excavation of the deposit as was practicable, to match the units of analysis for the other materials (e.g., stone artefacts, bones, pollen).

Main Chamber

Extended Data Fig. 1c shows a plan of Main Chamber, with the profiles sampled for optical dating marked by crosses. The collection locations of individual samples are shown on photographs of the excavated profiles in Extended Data Figs 2b,d and 5a,b. Fifty-five samples were collected from these profiles: 31 samples were collected from the southeast profile of squares E6–E8 (Extended Data Fig. 2b); 15 samples were collected from the southeast profile of squares Ж6–Ж8 (Extended Data Fig. 2d); and nine samples were collected from the east profile of square E9 (Extended Data Fig. 5a,b).

The majority of samples were collected in 2012 from the southeast profile (Extended Data Fig. 2b). It was difficult to clearly discern the different stratigraphic layers because of the complexity of the deposit, the indistinct stratigraphic boundaries and the condition of the section face (i.e., not freshly excavated). New excavations conducted in 2016, extending a further 30 cm into the Ж squares (Extended Data Fig. 2c,d), provided an opportunity to observe the excavation of artefacts and fossils from the freshly exposed sedimentary layers and to assess the stratigraphic assignments of the samples collected in 2012 and 2014; the excavators dug through our original sample holes, so they

could make direct, *in situ* assessments of the sample association with a specific stratigraphic layer. Importantly, this fresh excavation offered a view of the three-dimensional architecture of the deposit.

The 2016 excavation showed the near-horizontal deposition of layers 9–12. So, additional samples were collected from the sub-layers of layers 9 and 11 to best target the Upper Palaeolithic (UP) and Initial Upper Palaeolithic (IUP) deposits containing personal ornaments (made from animal bones and teeth) and to facilitate comparison with ^{14}C ages for these ornaments and charcoal (study conducted by K. Douka and T. Higham). Layer 12 contains the most recent Middle Palaeolithic (MP) artefacts, with a clear contact between blackish layer 11.4 and light brown layer 12.1 (Extended Data Fig. 2d).

The underlying layers are more complex. The 2016 excavation revealed the steep dip of the sediments into the southeast profile. The difference between the sections exposed and sampled in 2012/2014 and in 2016 can be seen in Extended Data Fig. 2 and is particularly important for understanding the integrity of the samples collected in 2012 from layers 14–22. One sample in particular—DCM12-25 from layer 22.1—was found to have cut through layers 22, 21, 20 and 19, due to their steep dip at the sampling location. Layers 13 and 15–17 are not recognised in the new profile (Extended Data Fig. 2c). Layer 20 occurs only as lenses (from which DCM17-1 was collected) on the left-hand side of the peak-shaped sediment cone, whereas to the right of the cone it forms a clear and steeply dipping layer, from where an additional sample was collected (DCM16-9). The thickness of layer 21 varies considerably: on the left-hand side of the cone, it forms a crust a few cm in thickness, thrust up above the peak of the cone, but it is not visible to the right of the cone. Layer 22 is a clearly discernible, yellowish brown sediment layer of considerable thickness and contains the earliest MP in Main Chamber, so it is important to constrain its age.

Samples were also collected from the east profile, for two reasons:

1. To assess the stratigraphic integrity of the upper sedimentary layers (9 and 11) exposed along the east profile of square E9 (Extended Data Fig. 5a). These layers cannot be traced clearly from the exposure in the southeast profile and they overlie a significant post-depositional feature that is thought to be a hyena lair (layer 13).
2. To obtain high-quality and stratigraphically secure samples from layers 19 (DCM14-9), 21 (DCM14-10) and 22.1 (DCM14-11) (Extended Data Fig. 5b). The stratigraphic separation of these layers can be observed clearly and layer 22 is important for determining the start of the MP.

East Chamber

Extended Data Fig. 1e shows a plan of East Chamber, with the profiles sampled for optical dating marked by crosses. The collection locations of individual samples are shown on photographs of the excavated profiles in Extended Data Figs 3b,d,f and 5c–e. Thirty-eight samples were collected from these profiles: 23 samples were collected from the southeast profile of squares E2–E4 and Ж2/Ж3 (Extended Data Fig. 3b,d); 14 samples were collected from the northwest profiles of squares Г3 (lower section: Extended Data Fig. 3f), B2–B4 (middle section: Extended Data Fig. 5d) and A3 and A4 (upper section: Extended Data Fig. 5c); and one sample was collected from the west profile of square A2 (Extended Data Fig. 5e). We could not determine a finite D_e value for the deepest sample (DCE14-6), because the natural pIRIR signal was in saturation.

The first set of samples was collected in 2012 from the southeast profile (blue filled circles in Extended Data Fig. 3b). As was the case in Main Chamber, it proved difficult to clearly discern the different stratigraphic layers because of the complexity of the deposit, the condition of the section face (i.e., not freshly excavated) and restricted access to the upper part of the profile. High-quality samples could be obtained from the lower layers (12–17), but layers 11 and 9 were problematic; the profile was crumbly and access was restricted to the right-hand side, which had clearly been disturbed in places.

New excavations conducted in 2013 and 2014, and the partial collapse of the crumbly 2012 southeast face, provided access to a clean southeast profile for sampling the entire width and depth of deposit; the stratigraphy was much clearer, as can be seen in Extended Data Fig. 3d. High-quality

samples from layer 11 were collected in 2014 from areas identified as undisturbed (red filled circles). Two samples (DCE14-2 and DCE14-3) were also collected from the northwest profile of square A4 (Extended Data Fig. 5c) and one sample (DCE14-1) from the west profile of square A2 (Extended Data Fig. 5e) to help determine whether or not the deposits in these areas—provisionally assigned to layer 11—had been disturbed. The presence of vertical stones in proximity to DCE14-2 and DCE14-3 can be seen in Extended Data Fig. 5c, and bones of a marmot (one of the main burrowing animals) were found in the vicinity of DCE14-1. Four samples were also collected in 2014 from the deeper levels of culturally sterile layer 17, from the northwest profile of the deposit below the choke-stone that blocks the narrow gap separating the lower and middle sections of the hourglass-shaped cave profile (Extended Data Fig. 3f).

Excavations during 2015 and 2016 gave further opportunity to collect samples in 2016. The southeast profile was cleaned back a few cm and samples were again collected from undisturbed areas of layers 11.1, 11.3 and 11.4 (shown as yellow filled circles in Extended Data Fig. 3d), primarily to increase the number of high-quality samples from the layer 11 deposits in this chamber. The main target area, however, was the northwest profile of the freshly excavated squares B2–B4 (Extended Data Fig. 5d), which showed clearly stratified, but deformed, layers 12.3–17.1. Two additional samples were also collected from squares A3 and A4 in the northwest profile (Extended Data Fig. 5c) to further investigate the age and stratigraphic integrity of the deposits in this part of East Chamber, which had provisionally been assigned to layers 9 and 11.

South Chamber

Extended Data Fig. 1d shows a plan of South Chamber, with the profile sampled for optical dating marked by crosses. The locations of the 11 samples collected in 2012 and 2016 from the southeast profile of squares Γ 6 and Γ 7 are shown in Extended Data Fig. 4c, with a close-up of samples DCE16-2 and DCE16-3 in Extended Data Fig. 4d. The first set of five samples was collected in 2012 from layers 12–19 (blue filled circles in Extended Data Fig. 4c), after cleaning back the section exposed by excavations in 2003 (Extended Data Fig. 4a,b). New excavations in 2016 provided the opportunity to collect an additional 6 samples from layers 12–22 (yellow filled circles in Extended Data Fig. 4c), thus extending the depth of deposit sampled in this chamber. Given the limited scale of excavations undertaken thus far in South Chamber, however, the layer assignments should be considered provisional. Further work is ongoing to clarify the stratigraphy and chronology of the deposit in this chamber, including optical dating of 18 and 14 sediment samples collected in 2017 and 2018, respectively, from the southeast profile.

Sample preparation and analytical facilities

All of the samples were prepared using routine optical dating procedures⁶⁴. Samples were first treated with HCl acid and H₂O₂ solution to remove carbonates and organic matter, respectively. The remaining sediment was then dried and sieved to obtain a range of sand-sized grain fractions. Grains of 180–212 μ m in diameter were used for dating of all quartz samples, but grains of between 90 and 212 μ m in diameter were used for dating of K-feldspar, depending on availability. The quartz and K-feldspar grains were separated using sodium polytungstate solutions of densities 2.70, 2.62 and 2.58 g/cm³. The quartz grains were etched using 40% hydrofluoric (HF) acid for 45 min to dissolve any remaining feldspar grains that may be present in the quartz separates, and to remove the alpha-irradiated layer around the surface of each grain. The K-feldspar grains were immersed in 10% HF acid for 40 min to etch the surfaces of the grains and remove the outer, alpha-irradiated portions. Both the HF-etched quartz and feldspar grains were then rinsed in HCl acid to remove any precipitated fluorides and sieved again.

Single-grain OSL measurements of D_e were made for all quartz samples. The D_e values for K-feldspar grains were determined using either single-grain or multiple-aliquot pIRIR measurements. Detailed experimental steps for each of these D_e measurement procedures are summarised in Supplementary Table 2. The OSL and IRSL measurements were made on automated Risø TL-DA-20 luminescence readers equipped with focused green (532 nm) and infrared (830 nm) lasers for

single-grain stimulation, and blue (470 nm) and infrared (870 nm) light-emitting diodes (LEDs) for stimulation of multi-grain aliquots⁷¹. Luminescence emissions were detected using Electron Tubes Ltd 9235QA photomultiplier tubes. The OSL signals were detected through Hoya U-340 filters and the IRSL emissions through Schott BG-39 and Corning 7-59 filters. The single-grain measurements were made using aluminium discs drilled with 100 holes, each 300 µm in diameter and 300 µm deep⁷¹. The multi-grain aliquot measurements were made using 9.8 mm-diameter stainless steel discs, to which grains were affixed to a 5 mm-diameter spot in the centre of each disc using ‘Silkospay’ silicone oil. Irradiations were carried out inside each luminescence reader using ⁹⁰Sr/⁹⁰Y beta sources that have been calibrated using a range of known gamma-irradiated quartz standards for both multi-grain aliquots and individual grain positions. Spatial variations in beta dose rate to individual grain positions were taken into account for D_e determination, based on measurements made using the same gamma-irradiated quartz standards⁷². Solar bleaching tests were conducted using a Dr Hönle solar simulator (model UVACUBE 400).

Single-grain D_e estimation for quartz

All single-grain quartz measurements were made using the single-aliquot regenerative-dose (SAR) procedure^{73,74} and experimental conditions listed in Supplementary Table 3a. The SAR procedure involves measuring the OSL signals from the natural (burial) dose (L_n) and from a series of regenerative doses (L_x) that adequately bracket the D_e value (given in the laboratory by means of the calibrated ⁹⁰Sr/⁹⁰Y beta source). Grains were preheated at 260°C for 10 s prior to optical stimulation by an intense, green (532 nm) laser beam for 2 s at 125°C. A fixed test dose (~9 Gy, preheated at 160°C for 5 s) was given after each natural and regenerative dose, and the induced OSL signals (T_n and T_x) were used to correct for any sensitivity changes during the SAR sequence. A duplicate regenerative dose was included in the sequence to check on the adequacy of this sensitivity correction, and a ‘zero regenerative dose’ (0 Gy) measurement cycle was included to monitor the extent of any ‘recuperation’ induced by the preheat treatment. As a check on possible contamination of the acid-etched quartz grains by other mineral inclusions, we also applied the OSL IR depletion ratio test⁷⁵ to each grain at the end of the SAR sequence, using an infrared exposure of 40 s at 50°C.

A total of 162,400 individual quartz grains were measured from Main Chamber (n = 96,800), East Chamber (n = 58,700) and South Chamber (n = 9,900). Aberrant grains were rejected using quality-assurance criteria similar to, but slightly different from, those employed in previous studies⁶⁸. Grains were rejected for the following reasons:

1. The initial T_n signal is less than 3σ above the corresponding background count, or the relative error on T_n is >25%.
2. The recuperation ratio (i.e., the ratio of the L_x/T_x values for the 0 Gy and maximum regenerative doses) is >5%.
3. The recycling ratio (i.e., the ratio of L_x/T_x values for the duplicate regenerative doses) is not consistent with unity at 2σ.
4. The OSL IR depletion ratio is more than 2σ less than unity.
5. The L_x/T_x ratios are too scattered to be reliably fitted with a curve, or have a large figure-of-merit (FOM) value^{76,77} defined as:

$$FOM(\%) = 100 \times \frac{\sum_{i=1}^n |y_i^o - y_i^f|}{\sum_{i=1}^n y_i^f}$$

where y_i^o and y_i^f denote the i^{th} observed and fitted values, respectively. We set an upper limit of 10% for the FOM value, which has been demonstrated^{46,78} to select satisfactory dose-response curves (DRCs).

6. The D_e value is obtained by extrapolation of the fitted DRC, rather than interpolation among the regenerative-dose signals.
7. The L_n/T_n ratio is statistically consistent with, or higher than, the saturation level of the corresponding DRC, so that a finite D_e value and error estimate could not be obtained.

8. The grain has a negative D_e value consistent with zero; such grains are likely to be modern contaminants introduced during sampling.

Selection of grains based on the above criteria was achieved using the function `calSARED()` provided in the R package *numOSL*^{78–80}. Supplementary Table 4 lists the numbers of individual grains measured, rejected and accepted for D_e determination for each of the samples from the three chambers, and the reasons for grain rejection.

L_n , L_x , T_n and T_x values were estimated from the first 0.22 s of OSL decay, with the mean count recorded over the last 0.3 s subtracted as background. Sensitivity-corrected (L_x/T_x) DRCs were then constructed from the L_x and T_x OSL signals, using a general-order kinetic (GOK) function⁸¹, and the sensitivity-corrected natural OSL signal (L_n/T_n) was projected onto the fitted DRC to estimate the D_e value by interpolation. All data analyses, including curve fitting, D_e and error estimations and statistical analysis of D_e values, were achieved using the functions implemented in two R packages *numOSL*^{78,79} and *Luminescence*⁸².

Supplementary Fig. 1a–c shows a selection of 8–10 OSL decay curves for a representative sample of quartz grains from each chamber (DCM12-29, DCE14-12 and DCS16-2), following a regenerative dose of ~60 Gy and a preheat of 260°C for 10 s. The L_x decay curves represent the range of sensitivities and shapes observed for all samples measured from Denisova Cave. The grains have very low luminescence sensitivities, resulting in large numbers of grains being measured and an average of ~98% rejected across all 50 quartz samples; the vast majority (~97%) of these grains failed criterion (1). The sole exception is DCE12-1, for which ~28% of the measured grains were accepted for D_e determination; we attribute the sensitisation of these grains to heating ~10 kyr, as this sample was located directly below a series of Holocene hearths. The OSL decay curves exhibit a range of shapes, but are generally quite reproducible and decay rapidly to instrumental background, with less than ~5% of the initial signal remaining after 0.3 s of optical stimulation. Supplementary Fig. 1d–f shows the corresponding DRCs for the same grains. The majority of the DRCs have very similar shapes up to a dose of ~60 Gy, after which some of the curves continue to grow with increasing dose while others begin to saturate.

D_e estimation for K-feldspar

We applied three different methods (Methods A, B and C) to determine D_e values for K-feldspar grains. All three methods rely on constructing standardised growth curves (SGCs)^{46,82–86} for the pIRIR signal. Methods A and B are both based on single-grain measurements and use the same single-grain SGC for D_e estimation. Method C is based on a multiple-aliquot regenerative-dose procedure⁴¹ and has its own multiple-elevated-temperature pIRIR SGC.

We also divided the samples into three groups (Groups A, B and C) to relate them to the Method used for D_e determination:

1. Group A contains the youngest set of samples, for which single-grain quartz OSL measurements were also made. The K-feldspar grains from these samples were measured with a single-grain SGC method—Method A.
2. Group B contains samples of intermediate age (i.e., those that are too old to be dated with quartz OSL). The K-feldspar grains from these samples were measured with a single-grain ‘ L_nT_n method’—Method B.
3. Group C contains the oldest samples. The K-feldspar grains from these samples were measured with a multiple-aliquot method—Method C.

Details of the three methods are provided below.

Single-grain D_e estimation and establishment of a SGC

For single-grain measurements of K-feldspars, we applied a two-step SAR pIRIR procedure⁴⁴. The first infrared stimulation was made at 200°C for 200 s using infrared diodes to simultaneously stimulate all 100 grains on a disc, in order to reduce or remove the ‘anomalous fading’ component⁸⁷.

The second infrared stimulation (i.e., the pIRIR measurement) was made at 275°C for 1 s, using the infrared laser to stimulate each grain individually (Supplementary Table 3b); stimulation power was set at 90% for the diodes and laser. Prior to stimulation of the regenerative- and test-dose signals, grains were preheated at 320°C for 60 s. Representative pIRIR decay curves for six grains of K-feldspar from sample DCM12-4 (following a regenerative dose of ~50 Gy and a preheat of 320°C for 60 s) are shown in Supplementary Fig. 2. The pIRIR decay curves exhibit similar shapes, and decay rapidly to a negligible constant background level after 0.5 s of infrared stimulation.

We used the SGC method to measure as many grains as possible from our large collection of samples in the most time-efficient manner. We have demonstrated previously for both multi-grain aliquots⁸⁵ and individual grains⁴⁶ that K-feldspars extracted from samples in different regions of Asia, Europe and Africa share similar pIRIR DRCs, if they are normalised appropriately. To test and construct a SGC for samples from Denisova Cave, we used the single-grain SAR pIRIR procedure to measure 30 samples from Main Chamber, 10 samples from East Chamber and four samples from South Chamber. As with the quartz grains, a series of regenerative doses (including a zero dose and a repeat dose) was given to each K-feldspar grain and the corresponding pIRIR signals were measured to construct single-grain DRCs. The grain-rejection criteria used to select K-feldspar grains suitable for reliable D_e determination are similar to, but differ slightly from, those used for quartz, as listed below:

1. The initial T_n signal is less than 3σ above the corresponding background count, or the relative error on T_n is $>25\%$.
2. The recuperation ratio is $>5\%$.
3. The recycling ratio is outside the range of 0.9–1.1.
4. The FOM value is >10 .
5. The reduced chi-square (RCS) value for the DRC is $>5\%$ (ref. 46).
6. The D_e value is obtained by extrapolation of the fitted DRC, rather than interpolation among the regenerative-dose signals.
7. The relative error on the D_e value is $>50\%$.
8. The L_n/T_n ratio is statistically consistent with, or higher than, the saturation level of the corresponding DRC.

The number of grains measured, rejected and accepted are summarised in Supplementary Table 5 for each of the samples, along with the reasons for grain rejection. Compared to quartz, a much greater proportion of measured K-feldspar grains were accepted, averaging ~18% for all samples, but exhibiting high variability between samples ($<1\%$ to $>40\%$); as with quartz, the vast majority (~93%) of the rejected grains failed criterion (1).

To test whether the grains from Denisova Cave form a SGC, individual DRCs were constructed for each of the grains using a full SAR measurement procedure (Supplementary Table 3b). We rejected grains with poor DRCs based on criteria (1)–(5) prior to application of the least-squares normalisation (re-normalisation) procedure⁸⁵, which was used to compare the DRCs of all accepted grains from all of the samples. A total of 6,549 grains passed these five criteria (Supplementary Table 5), yielding 34,574 sensitivity-corrected pIRIR signals (L_x/T_x ratios). The measured L_x/T_x ratios and re-normalised L_x/T_x ratios for individual grains are displayed in Supplementary Fig. 3a and b, respectively. There is large among-grain variation in the measured L_x/T_x ratios, but all samples share similar re-normalised L_x/T_x ratios that can be fitted well using a GOK function (black line in Supplementary Fig. 3b). The ratios between the individual re-normalised L_x/T_x values and their expected values (based on the best-fit curve) for all the regenerative doses greater than zero are plotted in Supplementary Fig. 3c. This plot shows that ~91% of the ratios are consistent with unity at 2σ , suggesting that the vast majority of grains share a common DRC and, hence, a pIRIR SGC can be established for individual K-feldspar grains from Denisova Cave. If we apply a single saturating exponential function to fit the single-grain pIRIR SGC in this study, the D_0 value is ~500 Gy.

To further confirm the validity of the single-grain pIRIR SGC, we determined D_e values for the same set of grains by projecting their individual re-normalised natural signals (L_n/T_n) onto the SGC (Method A). To select grains for SGC D_e estimation, we applied the rejection criteria related to inherent grain brightness—criterion (1)—and D_e estimation in the saturated region of the DRC—criteria (7) and (8)—but ignored rejection criteria (2)–(6), which involve the L_x/T_x ratios used for SAR DRC construction (Supplementary Table 5). The SGC D_e values for all non-rejected grains are compared to the SAR D_e values obtained from individual DRCs (Supplementary Fig. 3d). The two sets of D_e values are in good agreement, with ~98% of the ratios (SGC D_e /SAR D_e) consistent with unity at 2σ (Supplementary Fig. 3e). The reliability of the SGC D_e estimates is further supported by the observation that the SGC and SAR D_e values for the same sample have similar distributions and yield statistically indistinguishable results; three examples, one from each chamber (DCM12-7, DCE14-1 and DCS12-3), are shown in Supplementary Fig. 3f–h.

On the strength of these results, we decided to measure new sets of grains from all of the samples to determine D_e values using this single-grain SGC. This involves just four measurements: the natural signal (L_n), a single regenerative-dose signal (L_x) and the corresponding test-dose signals (T_n and T_x). The regenerative dose was selected to be close to the corresponding natural dose for each sample to minimise the error involved in SGC D_e estimation^{77,84}. Supplementary Table 6 lists the number of individual grains measured, rejected and accepted for D_e determination for each of the samples from the three chambers, and the reasons for grain rejection; it also lists the age Group of each sample and the Method of D_e estimation for single grains—Method A or B. These two methods are identical in terms of the single-grain measurements, and differ only in how these data are then used for D_e determination.

Method A: single-grain SGC

To select grains for D_e estimation using the single-grain SGC, we applied the rejection criteria related to inherent grain brightness—criterion (1)—and D_e estimation in the saturated region of the DRC—criteria (7) and (8) (Supplementary Table 6). Once the SGC function (e.g., $f(x)$) had been established, the sensitivity-corrected natural signal (L_n/T_n) for each grain was multiplied by a re-normalisation factor η determined as:

$$\eta = \frac{f(D_r)}{L_r/T_r}$$

where D_r is the regenerative dose given to each grain and L_r/T_r is the corresponding sensitivity-corrected pIRIR signal. D_e values were estimated for individual grains by projecting the re-normalised natural signal (L_n/T_n) for each grain onto the SGC (solid line in Supplementary Fig. 3b) to obtain a distribution of single-grain D_e values. We then interpreted these distributions and combined the D_e values using an appropriate statistical model. The D_e values for all Group A samples were determined using Method A.

Method B: single-grain L_nT_n

The proportion of accepted K-feldspar grains with saturated natural signals (i.e., L_n/T_n ratios consistent with, or higher than, the saturation level of the corresponding DRCs—criterion (8) in Supplementary Table 6) ranges from nil for some of the younger samples (e.g., DCM14-1, DCE14-1) to ~50% for some of the older samples (e.g., DCE14-5, DCS16-6). Several studies have shown that rejecting large numbers of ‘saturated’ grains may result in significant underestimation of the final D_e value, due to truncation of the full D_e distribution^{86,88–91}. To avoid this problem, we used a method⁴⁵ that involves analysing the distribution of re-normalised L_n/T_n ratios for all grains measured from a particular sample and projecting the weighted mean re-normalised L_n/T_n ratio for those grains onto the SGC to estimate the sample D_e . To distinguish the results obtained using this method from those determined using Method A, we refer to this method here as the L_nT_n method (Method B). With this method, the only rejection criterion applied is that related to inherent brightness—criterion (1) in

Supplementary Table 6—so no grains are rejected because they are ‘saturated’ and, hence, a full (untruncated) distribution of re-normalised L_n/T_n ratios is obtained.

The L_nT_n method is a true single-grain method, but is only applicable if a reliable SGC has been established and the SGC increases monotonically (e.g., Supplementary Fig. 3b). The existence of a common SGC ensures that the re-normalised L_n/T_n ratio for each grain is associated with a unique D_e value. The distribution of single-grain re-normalised L_n/T_n ratios (e.g., for DCM12-21 in Supplementary Fig. 3i) is equivalent, therefore, to the distribution of single-grain D_e values, and can be examined in the same way as conventional single-grain D_e distributions for any evidence of partial bleaching, post-depositional mixing and other factors that can give rise to spread in D_e estimates^{92,93}. Consequently statistical models commonly applied to single-grain D_e values^{73,93} are equally suitable for L_n/T_n ratios⁴⁵. Once the L_n/T_n distribution has been interpreted, the L_n/T_n ratios are combined using an appropriate statistical model and this combined value is projected onto the SGC to estimate the sample D_e —an example (DCM12-21) is provided in Supplementary Fig. 3j. We used the SGC established for K-feldspar grains at Denisova Cave to determine D_e values using Method B for all Group B samples in which the quartz OSL signal was saturated.

Method C: multiple-aliquot SGC

A multiple-aliquot regenerative-dose (MAR) procedure⁴⁷ was used to measure the oldest samples from layer 17 in East Chamber and layer 22 in Main and South Chambers. This procedure utilises the MET-pIRIR signals for D_e estimation (Supplementary Table 3c); these signals appear to be immune from fading^{66,94}. Furthermore, the MAR method has some advantages over the SAR method in overcoming problems associated with inappropriate sensitivity correction of L_n and T_n (refs 47, 94, 95) and, combined with a SGC approach, can also significantly reduce instrument time.

The MAR procedure for K-feldspar grains is based on the establishment of a SGC constructed from the re-normalised L_x/T_x signals from multiple groups of aliquots⁴⁷. To establish a MAR SGC for Denisova Cave, a total of 65 aliquots from eight samples (four aliquots from DCM12-9, eight from DCM12-25, 12 from DCM12-26, 14 from DCM12-27, three from DCM14-1, 12 from DCM14-12, eight from DCE14-5 and four from DCS12-4) were bleached in a solar simulator for ~8 hr. They were then given different regenerative doses, ranging from 0 to ~2900 Gy, followed by a preheat at 320°C for 60 s, before being stimulated by infrared LEDs. The IRSL and pIRIR signals arising from the regenerative and test doses were measured successively at 50, 100, 150, 200 and 275°C (where the signal measured at 50°C corresponds to the conventional IRSL signal). The highest stimulation temperature was set at 275°C, so that the MAR results could be compared directly to the single-grain pIRIR results. At the end of each test-dose measurement, the aliquots were bleached for ~4 hr in a solar simulator, following the ‘pre-dose’ MET-pIRIR procedure^{96–98}. An identical regenerative dose ($D_r = 520$ Gy) was then given to the bleached aliquots for purposes of normalisation, followed by measurement of the regenerative- and test-dose signals (L_r and T_r , respectively).

Supplementary Fig. 4a shows typical natural IRSL 50°C and MET-pIRIR (100 to 275°C) decay curves for a single aliquot of sample DCM12-25. Supplementary Fig. 4b–f shows the re-normalised ratios ($\frac{L_x/T_x}{L_r/T_r}$), plotted as a function of regenerative dose for all eight samples at the five stimulation temperatures. These data show that reliable MAR SGCs can be constructed for our samples using the MET-pIRIR signals. Using these SGCs, we calculated D_e values for 15 samples: 10 samples from Main Chamber, four samples from East Chamber and one sample from South Chamber. For each sample, the natural and corresponding test-dose signals (L_n and T_n) were measured for 5–24 aliquots, after which each aliquot was bleached for ~4 hr in the solar simulator and then given a regenerative dose of 520 Gy (L_r) and a subsequent test dose of 60 Gy (T_r)—the same size doses as those used to establish the MAR SGCs. The individual L_n/T_n ratios were then re-normalised using the corresponding L_r/T_r ratios ($\frac{L_n/T_n}{L_r/T_r}$). The weighted mean re-normalised ratio and associated error were calculated for each sample using the central age model (CAM)^{73,93} and these were projected onto the MAR SGCs (solid lines in Supplementary Fig. 4b–f) to estimate the corresponding D_e values. The errors associated with the weighted mean ratios and with curve-fitting of the SGC

were propagated into the D_e error using the method described by Duller (2007)⁹⁹. The ages were calculated from the D_e values determined at the highest stimulation temperature (275°C).

Performance tests of K-feldspar single-grain methods

Dose recovery tests

The performance of the single-grain pIRIR procedures (Methods A and B) was tested using dose recovery tests⁷³ on seven samples: DCM12-1, DCM12-6 and DCM12-29 from Main Chamber, DCE12-2, DCE12-3 and DCE12-14 from East Chamber, and DCS12-5 from South Chamber. The grains were first bleached for ~4 hr using the solar simulator and then given beta doses of between 100 and 611 Gy as surrogate ‘natural’ doses. For each of the given doses, 200–300 grains were measured using the single-grain pIRIR procedure (Supplementary Table 3b). For grains that were given a dose of 100 Gy, we estimated the measured dose from individual SAR DRCs for those grains that passed all eight rejection criteria. For the grains given larger doses, we estimated the measured doses using the L_nT_n method to avoid any underestimation due to truncation of the dose distribution⁴⁵.

The single-grain dose recovery tests revealed an interesting pattern, in which the average dose recovery ratios (i.e., the ratios of measured dose to given dose) for some samples show a steady increase up to a value consistent with unity for grains with T_n signals brighter than ~200–400 counts per 0.2 s of infrared stimulation (Supplementary Fig. 5a–c); not all samples show this pattern (Supplementary Fig. 5d). We determined a ‘threshold’ T_n intensity for each sample to establish the intensity above which a ‘plateau’ in dose recovery ratios is reached. The dose recovery ratios obtained after applying the T_n threshold are plotted as a function of given dose in Supplementary Fig. 5e. Most ratios are consistent with unity at 2σ and all are consistent with ratios in the range 0.9–1.1, demonstrating that the single-grain pIRIR procedure used here can produce reliable estimates of measured dose over a wide range of applied doses.

To test whether the natural samples exhibit the same pattern, we calculated the weighted mean D_e values (Method A) or re-normalised L_n/T_n ratios (Method B) as a function of T_n intensity for all accepted grains. Example plots for nine samples are shown in Supplementary Fig. 6a–i. About 58% of the samples display a similar trend to that observed in the dose recovery tests, so we determined the threshold T_n intensity for each sample. Many of the samples (~52%) have T_n thresholds of 100–400 cts/0.2 s and a few (~6%) have T_n thresholds of 500–600 cts/0.2 s; the remaining samples (~42%) show no such dependency. This same pattern has also been observed for K-feldspar grains from Chagyrskaya Cave¹⁰⁰, a site located ~70 km to the west of Denisova Cave. For final D_e estimation, we selected only those grains with T_n intensities above their corresponding thresholds. Supplementary Table 6 gives the sample-specific T_n threshold for each sample, together with the number of accepted grains used to estimate the final D_e .

Residual dose tests

We also tested the light sensitivity of the pIRIR signal by measuring the ‘residual doses’ in a relatively young sample (DCM12-1, D_e of ~90 Gy) and an older sample (DCM12-24, D_e of ~700 Gy). Both samples were bleached using a solar simulator for ~5 hr and the residual doses measured using the single-grain pIRIR procedure. The measured doses of 6.6 ± 0.9 and 2.5 ± 1.5 Gy for DCM12-1 ($n = 18$) and DCM12-24 ($n = 22$), respectively, indicate that the pIRIR signals can be bleached to a negligible level. Accordingly, we did not adjust the measured D_e values of the K-feldspar grains for any residual dose. Furthermore, as noted above, the quartz OSL ages provide an additional test of the extent of resetting of the pIRIR signal for samples younger than ~100 kyr: the concordance between the OSL and pIRIR ages (Extended Data Fig. 8b) also suggests that the K-feldspar grains were adequately bleached at the time of deposition, at least over this time span.

Fading tests

To confirm that we have used a pIRIR procedure that minimises the extent of any anomalous (athermal) fading of the dating signal^{166,67}, we also measured the fading rates for individual grains from two of the samples from Main Chamber (DCM12-12 and DCM12-21). It was impractical to use

the single-aliquot fading test procedure¹⁰¹ for our samples, because single-grain pIRIR signal intensities are much weaker than those emitted by multi-grain aliquots, yielding measured fading rates with uncertainties too large to be informative. Instead, we adopted a simple method to estimate the fading rates of individual grains. Following the D_e measurements, four discs (400 grains) of DCM12-12 and eight discs (800 grains) of DCM12-21 were given a final regenerative dose of the same size as that used to determine the recycling ratios (i.e., 100 Gy for DCM12-12 and 300 Gy for DCM12-21). The discs were then preheated and stored in the dark at room temperature for ~3 days before the pIRIR signal was measured again; this corresponds to a time delay of ~2.1 decades compared to that of the prompt measurement of the pIRIR signal made during the SAR sequence. We calculated the ratio of the pIRIR signal measured after delay to that measured immediately (i.e., promptly), which we termed the ‘fading ratio’. If the pIRIR signal faded significantly during storage, then the fading ratio should be significantly smaller than unity. The ratios for individual grains are displayed in Supplementary Fig. 5g,h, which shows that most (> 90%) of the fading ratios are consistent with unity at 2σ ; the weighted mean ratios are 0.99 ± 0.01 (DCM12-12) and 1.00 ± 0.01 (DCM12-21). This result suggests that, on average, the pIRIR signal fades negligibly in the K-feldspar grains from our samples, so we did not apply any fading correction to the calculated ages.

To further check the stability of the MET-pIRIR signals, we also conducted a fading test on 12 aliquots of sample DCM12-12. We adopted a single-aliquot procedure similar to that described in ref. 100, but based on the MET-pIRIR signals. A dose of ~200 Gy was administered using a laboratory beta source, and the irradiated aliquots were then preheated and stored for different periods of time at room temperature (~20°C). Supplementary Fig. 5f shows the fading rates (g-values) for the IRSL and MET-pIRIR signals plotted as a function of stimulation temperature. The g-values have large uncertainties, but a systematic trend can be observed: the 50°C IRSL signal has the highest fading rate (~2% per decade), which decreases as the stimulation temperature is increased, falling to values consistent with zero for the high-temperature (>150°C) pIRIR signals.

D_e and L_n/T_n values and distributions

Information about the number of grains measured and used for D_e determination, the overdispersion (OD) values calculated for the D_e distributions, and the final D_e values $\pm 1\sigma$ uncertainties are presented in Supplementary Tables 7–9 for samples from Main, East and South Chambers, respectively. The OD value is the relative standard deviation (i.e., the coefficient of variation) of the D_e distribution after accounting for the various measurement uncertainties^{92,93}. For each chamber, the samples are arranged by stratigraphic layer within the relevant profile and are colour-coded according to Group: all Group A samples measured with single-grain quartz OSL and single-grain K-feldspar pIRIR (Method A) are shaded blue; all Group B samples measured with single-grain K-feldspar pIRIR (Method B) are shaded red; and all Group C samples measured with multiple-aliquot K-feldspar pIRIR (Method C) are shaded green.

We used the CAM to combine individual D_e values (Group A) or re-normalised L_n/T_n ratios (Groups B and C) and estimate the weighted mean D_e value for age determination. This model^{73,93} assumes that the D_e values or L_n/T_n ratios for all grains are centred on some average value (similar to the median) and the estimated standard error takes account of any overdispersion; hence, the greater the OD, the larger the error. Some of the samples have grains with D_e values or re-normalised L_n/T_n ratios that are clearly significant outliers, with both higher and lower values than those of the majority of grains; these likely represent intrusive grains incorporated in the sample after deposition. These outliers were removed from the data sets before calculating the weighted mean values, to improve the accuracy of the optical ages. We used the normalised median absolute deviation (nMAD) as a means of screening data for outliers^{102–104}. This attaches equal importance to positive and negative deviations from the sample median. After converting the D_e values (in Gy) or re-normalised L_n/T_n ratios to natural logarithms^{73,93}, we calculated the nMAD using 1.4826 as the appropriate correction factor for a normal distribution, and rejected log D_e values or log L_n/T_n ratios with nMADs greater than this value^{42,43,103,105}. We applied the finite mixture model (FMM)^{93,106,107} to two of the quartz D_e distributions (DCE12-4 and DCE14-10) and two of the K-feldspar D_e distributions (DCM12-1 and

DCE14-9) in which discrete D_e components could be clearly identified and were statistically supported, following the procedures described previously^{108–110}.

Some representative single-grain D_e distributions are shown in Supplementary Figs 7 (quartz) and 8 (K-feldspar). For all of the samples from which individual quartz and K-feldspar grains were measured (50 and 100 samples, respectively), the distributions of D_e values (Group A) and re-normalised L_n/T_n ratios (Group B) are presented in Supplementary Figs 9–11 for Main, East and South Chambers, respectively. In each of these figures, the radial plots are arranged by year of collection (starting with samples collected in 2012) and then in numerical order within each year. The grey bands in these plots are centred on the weighted mean (i.e., CAM) D_e values, calculated for some samples after rejecting outliers using nMAD. For the latter samples, the CAM D_e values calculated before outlier rejection are displayed as blue lines, and the numbers of grains accepted and rejected by nMAD are indicated above the radial plots. Supplementary Fig. 12 shows the distributions of re-normalised L_n/T_n ratios for the fifteen K-feldspar samples obtained at a stimulation temperature of 275°C using the MAR SGC procedure, and the corresponding D_e values are presented in Supplementary Fig. 13 as a function of stimulation temperature (50–275°C).

Single-grain quartz OSL D_e values

D_e values for quartz grains could be obtained for 50 samples from layers 9, 11 and 12 in Main Chamber ($n = 28$), layers 8, 9 and 11 in East Chamber ($n = 18$) and layer 12 ($n = 4$) in South Chamber. We expected that the OSL signals for samples collected from deeper layers would be in saturation, and this was confirmed for two samples from layer 12 in East Chamber (DCE12-7 and DCE12-8). Consequently, no OSL measurements were made on any of the remaining samples.

The single-grain D_e distributions for Main Chamber are overdispersed by between $11 \pm 6\%$ (DCM16-3) and $63 \pm 7\%$ (DCM12-4); the latter decreases to $41 \pm 6\%$ after outlier rejection using nMAD. This range of OD values is similar for all three layers (9, 11 and 12; Supplementary Table 7). The radial plots show either (1) tight distributions of D_e values, in which the majority lie within ± 2 standardised estimates of a common value, or (2) D_e distributions that are generally tight, but contain a few significant outliers (shown as open circles in the radial plots), which are identified as such using nMAD. Two examples are shown in Supplementary Fig. 7a,b. DCM12-5 exhibits the first type of D_e distribution (for which the CAM was used to estimate the final D_e value), whereas nMAD identified a few outliers in the D_e distribution of DCM14-5; these were rejected before determining the final D_e using the CAM (denoted ‘nMAD CAM’ in Supplementary Tables 7–9). We interpret the larger-than-expected spread in D_e values for some of these samples to be predominantly the result of micro-scale differences in the beta dose rate received by individual grains¹¹¹. Grains with D_e values that are too small (compared to the majority of values) to be explained by beta microdosimetry are interpreted as intrusive; they are likely due to cryoturbation creating small cracks in the deposit into which younger grains have penetrated, and such features have been observed in the field and microscopically in thin section.

The single-grain D_e distributions for East Chamber have OD values of between $81 \pm 7\%$ (reduced to $13 \pm 2\%$ after outlier rejection) for DCE14-9 and $161 \pm 14\%$ for DCE14-10 (Supplementary Table 8). Samples with the highest OD values are restricted to layers 9 and 11.1 in the southeast profile. Four types of distribution can be seen. The first two (e.g., Supplementary Fig. 7c,d) are the same as the pair in Main Chamber, and the final weighted mean D_e values were calculated using either the CAM or nMAD CAM. The third type of D_e distribution (e.g., Supplementary Fig. 7e) shows a broad, continuous distribution of D_e values; a reliable weighted mean D_e value cannot be obtained from such distributions, which are likely due to substantial bioturbation by cave fauna, either as single or multiple events. The fourth type of D_e distribution (e.g., Supplementary Fig. 7f) shows a mixture of grains consisting of two (in this instance) or three discrete D_e components; this example is for DCE14-10, and the widely bifurcated distribution explains its high OD value. We interpret such distributions to be the result of animal burrows that were intersected during the sampling process.

The four quartz samples from South Chamber have single-grain D_e distributions with OD values of 0% (DCS16-2 and DCS12-3), $20 \pm 7\%$ (DCS12-1) and $37 \pm 8\%$ (DCS16-3) (Supplementary Table 9). Each sample has a tightly clustered D_e distribution to which the CAM was applied to obtain a weighted mean D_e value for age determination; an example (DCS12-1) is shown in Supplementary Fig. 7g. The quartz grains in these samples are relatively dim, resulting in individual D_e values with large measurement errors. The latter explains, at least in part, the zero OD values for two of the samples.

The CAM was used for 27 of the 50 samples measured ($\sim 54\%$), and the CAM with nMAD outlier rejection for a further 19 samples ($\sim 38\%$). So, more than 90% of the quartz samples are thought to have good stratigraphic integrity, from which reliable D_e values can be obtained for age determination. Only four of the samples ($\sim 8\%$) had problematic D_e distributions indicative of significant sediment mixing, and all of them originate from the upper layers (9.3, 11.1 and 11.2) in East Chamber. The D_e components for two of these samples (DCE14-10 and DCE12-4) could be resolved using the FMM, but reliable D_e values could not be determined for the other two samples (DCE12-2 and DCE12-3), so no ages were calculated for the latter pair.

Single-grain K-feldspar pIRIR SGC D_e values: Method A

D_e values for individual K-feldspar grains were estimated using Method A for samples from layers 9–12 in Main Chamber, layers 8–11 in East Chamber, and layer 12 in South Chamber (Supplementary Tables 7–9, respectively).

The single-grain D_e distributions for Main Chamber are overdispersed by between $32 \pm 2\%$ (DCM14-1) and $94 \pm 10\%$ (DCM12-10), with these values decreasing to $18 \pm 2\%$ and $29 \pm 4\%$, respectively, after removing statistically significant outliers using nMAD. The OD values (after outlier rejection) are largest for the samples collected from layer 9 (34–58%) and smaller for layers 11 and deeper. In general, the OD values for K-feldspar grains are larger than those for quartz grains from the same sample, which we attribute mainly to the inclusion of grains with large D_e values in the K-feldspar distributions (e.g., Supplementary Fig. 8e,f); the quartz OSL signals for such grains would be saturated and, thus, fail rejection criterion (7). For age determination, we identified and rejected any D_e outliers using nMAD and then applied the CAM to calculate the final weighted mean D_e values.

The single-grain D_e distributions for East Chamber have OD values of between $14 \pm 13\%$ (DCE14-10; Supplementary Fig. 8c) and $115 \pm 14\%$ (DCE12-1; Supplementary Fig. 8d). Although most samples have D_e distributions clustered around a central value (e.g., Supplementary Fig. 8c), many also contain a small proportion of D_e values identified as outliers (e.g., Supplementary Fig. 8f). A reliable weighted mean D_e value could not be calculated for DCE12-1, from layer 9.2, which has a broad and continuous D_e distribution (Supplementary Fig. 8d). This sample also produced a wide scatter of quartz D_e values (Supplementary Fig. 10), so we observe a similar distribution pattern for both minerals. One sample (DCE14-9) yielded a D_e distribution consistent with two discrete components (Supplementary Fig. 8e), so the FMM was used to determine the weighted mean D_e value for each component.

A notable difference between the K-feldspar and quartz D_e distributions is that the former commonly lack the low- D_e grains observed using quartz from the same sample. For example, only the high- D_e component of the quartz distribution for DCE14-10 (Supplementary Fig. 7f) is detectable in the K-feldspar distribution for this sample (Supplementary Fig. 8c). It seems unlikely that quartz grains would be reworked in preference to K-feldspar grains by burrowing animals. Instead, we propose that for samples with low luminescence sensitivities, such as those from Denisova Cave, K-feldspar is less likely than quartz to yield a detectable luminescence signal. This effect will be enhanced when sediments are heated, as exposure to intense heat (e.g., through burning) has the opposite effect on quartz and K-feldspar grains: quartz is sensitised (i.e., the OSL signal becomes brighter¹¹²), whereas K-feldspar is desensitised (i.e., the pIRIR signal becomes dimmer⁹⁷). If the intrusive grains in DCE14-10 are derived from the overlying Holocene deposits, which have been

intensively burnt, then it is plausible that we could detect OSL signals from quartz grains but not pIRIR signals from K-feldspar grains.

The single-grain D_e distributions from South Chamber are overdispersed by between $53 \pm 4\%$ (DCS12-3) and $62 \pm 5\%$ (DCS16-1), or $27 \pm 3\%$ and $47 \pm 6\%$, respectively, after outlier rejection. Similar to Main Chamber, the K-feldspar results from South Chamber are more overdispersed than the quartz D_e distributions, but the quartz grains in this chamber are relatively dim (as noted above) and few in number, which partly accounts for the low OD values. All the K-feldspar samples have most of their D_e values clustered around a central value (e.g., Supplementary Fig. 8g,h), so the small number of outliers identified using nMAD were rejected before calculating the weighted mean D_e values for age determination.

Single-grain K-feldspar pIRIR L_n/T_n ratios: Method B

D_e values for individual K-feldspar grains were estimated using Method B for samples collected from layers 13–22 in Main Chamber, layers 12–17 in East Chamber and 14–22 in South Chamber. The distributions of re-normalised L_n/T_n ratios are displayed in Supplementary Figs 9–11. The OD values of these distributions range from $8 \pm 1\%$ (DCM14-10) to $22 \pm 2\%$ (DCM12-14), after outlier rejection. These values are, on average, smaller than those of the single-grain SAR and SGC D_e distributions, owing to the non-linear relationship between pIRIR intensity and dose—that is, a small change in the natural signal will produce a large change in D_e in the non-linear range of the DRC. The majority of re-normalised L_n/T_n ratios are typically distributed around a common value, with outliers identified and rejected using nMAD before calculating the weighted mean L_n/T_n ratio for each distribution (e.g., Supplementary Fig. 3j). These ratios were projected onto the SGC for Denisova Cave (Supplementary Fig. 3b) to estimate the final D_e values for age determination.

Multiple-aliquot K-feldspar MET-pIRIR SGC D_e values: Method C

The multiple-aliquot re-normalised L_n/T_n ratios estimated using Method C are displayed in Supplementary Fig. 12 for the pIRIR signals measured at a stimulation temperature of 275°C. Most of the 15 samples have consistent ratios for the separate aliquots (i.e., the ratios cluster for each sample), which suggests that the re-normalisation procedure is effective at overcoming or reducing between-aliquot variation. Sample DCE14-6 appears to have two distinct clusters of ratios, which may indicate a two-component mixture of grains. This inference is supported by the single-grain results (Method B) for this sample, which indicate the presence of some grains with much smaller L_n/T_n ratios (open green circles in Supplementary Fig. 10; note the data point beneath the precision axis). Such grains are likely to be modern contaminants incorporated during sampling.

For each of these samples, the weighted mean re-normalised ratios were calculated and projected onto the MAR SGCs (solid lines in Supplementary Fig. 4b–f) to estimate the D_e values. Supplementary Fig. 13 shows the MAR D_e values and standard errors plotted against stimulation temperature. Six of the 15 samples (DCM12-12, DCM12-21, DCM12-25, DCM14-11, DCM16-7 and DCE14-6) attain a ‘plateau’ in D_e values between 200 and 275°C, which suggests that a non-fading signal has been isolated. All other samples exhibit a systematic increase in D_e with a rise in stimulation temperature. We interpret this trend as indicating that the MET-pIRIR signal measured at 200°C may still be subject to fading. The MET-pIRIR signal measured at 275°C yielded higher D_e values, and three lines of evidence suggest that this signal fades negligibly. First, the single-grain natural pIRIR signal for DCE14-6 (shown as the grey band in Supplementary Fig. 3b) is consistent at 2σ with the saturation level of the single-grain SGC. Second, fading tests on single-grain pIRIR and single-aliquot MET-pIRIR signals indicate negligible fading rates. And third, excellent agreement between single-grain K-feldspar pIRIR, single-grain quartz OSL and ^{14}C ages for samples from the upper layers of the Pleistocene sequence implies negligible fading of the pIRIR signal. We conclude, therefore, that MAR ages based on the 275°C pIRIR signal should be regarded as reliable and finite, and not as minimum age estimates.

K-feldspar D_e comparisons for Methods A, B and C

To test whether the L_nT_n method gives reliable results, we calculated the re-normalised L_n/T_n ratios (Method B) for 51 samples from Group A and compared them to the SGC D_e values (Method A) for these samples. Supplementary Fig. 14a shows that the two methods produce statistically consistent results: the mean ratio is 0.99 ± 0.01 (standard error of the mean), and the corresponding ratios and standard errors for each chamber are 1.00 ± 0.01 (Main, $n = 28$), 0.99 ± 0.01 (East, $n = 17$) and 0.98 ± 0.02 (South, $n = 6$). Most of the individual ratios are consistent with unity at 2σ , and only one sample (DCE16-1) yielded a significantly different ratio.

We also verified our MAR D_e results by comparing the D_e estimates obtained using the single-grain L_nT_n method (Method B) and the MAR SGC procedure (Method C) for 12 samples: one from Group A (DCM16-7), two from Group B (DCM12-12 and DCM12-21) and nine from Group C (DCM12-25, DCM12-26, DCM12-27, DCM16-13, DCM16-14, DCE12-14, DCE14-4, DCE14-5 and DCS16-6). Ten of the samples have paired D_e values that are consistent at 2σ (Supplementary Fig. 14b), while the other two samples (DCM16-4 and DCE14-4) have L_nT_n D_e values slightly smaller than their MAR counterparts.

Environmental dose rate determination

The total environmental dose rate consists of contributions from beta, gamma and cosmic radiation external to the grains, plus a small alpha dose rate due to the radioactive decay of uranium and thorium inclusions inside sand-sized grains of quartz, and potassium (^{40}K) and rubidium (^{87}Rb) inside sand-sized grains of K-feldspar. To calculate the optical ages for both minerals, we have assumed that the present-day radionuclide activities and dose rates have prevailed throughout the period of sample burial. As shown by experiment and modelling, however, most time-dependent disequilibria in the uranium and thorium decay chains are unlikely to give rise to errors in the total dose rate of more than a few percent when emission-counting methods—such as those used in this study—are used to measure the external beta and gamma dose rates^{113,114}.

The dose rate due to K could be affected if the sediments have undergone post-depositional chemical diagenesis, such as phosphatisation^{115,116}. Macroscopic observations and geochemical analyses of the Denisova Cave sediments indicate that phosphatisation is restricted to the interface between the uppermost Pleistocene deposits (layers 11.1 and 9) and the overlying Holocene layers (Extended Data Figs 4d and 5c,e). A recent study of these sediments in East Chamber²⁹ found that phosphatisation is due to the microbial degradation of guano from insectivorous bats that inhabited the cave. The phosphates in layer 9 were identified as predominantly taranakite and those at the top of layer 11.1 as brushite, which crystallises in the reaction rim on limestone fragments. Brushite marks the base of the phosphate profile and the lower boundary of solution leakage²⁹. Neither of these phosphates is found in the underlying deposits (i.e., layers 11.2 and below). While elevated concentrations of K may be associated with taranakite, brushite has no detectable K content and, therefore, will have little or no impact on the environmental dose rate.

External beta dose rates

We estimated the beta dose rates directly by low-level beta counting of dried, homogenised and powdered sediment samples in the laboratory, using a Risø GM-25-5 multi-counter system⁴⁸. We prepared and measured samples, analysed the resulting data, and calculated the beta dose rates and their uncertainties following procedures described and tested previously¹¹⁷; between three and six sub-samples were measured for each sample. For all samples, allowance was made for the effect of sample moisture content, grain size and HF acid etching on beta-dose attenuation^{118–120}. The beta dose rates are provided in Supplementary Tables 7–9 for all samples: they range from 0.65 ± 0.04 (DCM12-9) to 2.63 ± 0.14 (DCM14-1) Gy/kyr in Main Chamber; from 0.49 ± 0.04 (DCE16-3) to 1.80 ± 0.12 (DCE14-4) Gy/kyr in East Chamber; and from 0.80 ± 0.05 (DCS16-1) to 1.49 ± 0.09 (DCS16-6) Gy/kyr in South Chamber.

We also measured the U, Th and K contents of 56 samples collected during the 2014 and 2016 field seasons (26, 24 and 6 samples from Main, East and Chambers, respectively) using a combination of ICP-MS (for U and Th) and ICP-OES (for K). The ICP-MS and ICP-OES measurements were

made independently in a commercial laboratory (Intertek Genalysis). Supplementary Fig. 15 compares the dry and unattenuated beta dose rates calculated from elemental concentrations of U, Th and K by ICP-MS/ICP-OES with the beta dose rates measured directly using a GM-25-5 beta counter. The latter method counts all nuclear disintegrations that emit a beta particle from the U and Th decay chains (and from the decay of ^{40}K), whereas the dose rates obtained from the ICP-MS data are based on measurements of the parental U and Th concentrations and assume secular equilibrium in the decay chains. The vast majority of the paired estimates are consistent with a value of unity at 2σ . The average ratio and standard error for all 56 samples (0.96 ± 0.01) is insensitive to the two conspicuous outliers that lie on either side of the 1:1 line in Supplementary Fig. 15. This result suggests that the beta dose rate measured by GM-25-5 beta counting is systematically smaller, by $\sim 4\%$ on average, than that derived from elemental concentrations of U, Th and K. The underlying cause of this small difference is currently under investigation, but a sensitivity analysis shows that the calculated ages do not depend critically on the method used. The external beta dose rate represents, on average, $\sim 45\%$ of the total dose rate for K-feldspar grains and $\sim 68\%$ for quartz grains. If the beta dose rates are calculated using the ICP-MS/ICP-OES data, therefore, then the K-feldspar and quartz ages will be, on average, $\sim 1.8\%$ and $\sim 2.7\%$ younger, respectively, than those listed in Supplementary Tables 7–9. These differences are well within the total uncertainties on the individual ages.

Gamma dose rates

Gamma dose rates were measured directly by *in situ* gamma spectrometry to take into account any spatial heterogeneity in the gamma radiation field within ~ 30 cm of each sample (as gamma rays can penetrate this distance through most sediments and rocks). The gamma dose rate was measured at every sample location. Counts were collected for 1 hr with a NaI(Tl) detector (1-inch in diameter) and a few samples were measured for longer periods of time. A subset of samples was also measured in different years, as a test of reproducibility. The detectors were calibrated using the concrete blocks at Oxford University¹²¹ and the gamma dose rates were determined using the ‘threshold’ technique¹²². This approach gives an estimate of the combined dose rate from gamma-ray emitters in the U and Th decay chains and from ^{40}K . The gamma dose rates are provided in Supplementary Tables 7–9 for all samples: they range from 0.26 ± 0.02 (DCM12-10) to 0.84 ± 0.05 (DCM16-14) Gy/kyr in Main Chamber; from 0.20 ± 0.01 (DCE14-14) to 0.73 ± 0.05 (DCE12-14) Gy/kyr in East Chamber; and from 0.29 ± 0.02 (DCS16-1) to 0.62 ± 0.04 (DCS16-6) Gy/kyr in South Chamber.

Internal dose rates

K-feldspar also has a significant internal beta dose rate from the radioactive decay of ^{40}K and ^{87}Rb inside the grains, whereas quartz is essentially inert, but may contain trace amounts of U and Th that emit alpha and beta particles^{123,124}. For all of our quartz samples, we assumed an internal dose rate from alpha and beta particles of 0.032 ± 0.010 Gy/kyr (based on U and Th concentrations of 0.15 ± 0.03 and 0.35 ± 0.07 $\mu\text{g/g}$, respectively, and an alpha-efficiency α -value⁶⁴ of 0.04 ± 0.01), which falls within the range of values reported for acid-etched quartz grains⁴¹.

To estimate the internal beta dose rate to K-feldspar grains, K and Rb concentrations of 12.5 ± 0.5 wt% and 400 ± 100 $\mu\text{g/g}$, respectively, have been recommended in the absence of more detailed information^{125,126}. These values may be appropriate for single-aliquot measurements, because the IRSL and pIRIR signals from high-K grains are usually much brighter than those from the low-K feldspars^{126–128}. Individual grains may have a much wider range of K contents, however, with several studies reporting mean K concentrations of 9–14 wt% for single grains emitting detectable luminescence signals^{124,130–134}.

K-feldspar is an end-member of the alkali feldspar group, the other major end-member being albite (Na-feldspar). Pure K-feldspar (orthoclase, KAlSi_3O_8) contains ~ 14 wt% K, while pure albite ($\text{NaAlSi}_3\text{O}_8$) contains no K. In theory, K-feldspar grains are separated from other mineral grains in the < 2.58 g/cm³ fraction using density separation methods⁶⁴. These methods are imperfect, however, as are the minerals. Most alkali feldspars are perthitic—that is, they contain fine intergrowths (lamellae) of albite and K-feldspar that exsolve during cooling of an igneous or metamorphic

rock¹³⁵—leading to grain-to-grain variability in K concentration. In addition, the K concentrations of alkali feldspars in sediments can vary widely across geological regions, because alkali feldspars can be weathered and eroded from many rock types, including igneous, metamorphic and sedimentary rocks. It is important, therefore, to obtain accurate and precise estimates of K concentration for K-feldspar grains that emit detectable luminescence signals to calculate the internal dose rates of the grains used to date a given study site. Ideally, the K content of all grains used for age determination would be measured individually, but this is impractical for this study because of the large number of grains measured. Instead, we measured a subset of grains from two representative samples—DCM16-12 and DCE16-8.

Grains from DCM16-12 and DCE16-8 that produced T_n signals with initial pIRIR intensities >3 times the background count were hand-picked from the single-grain discs after D_e measurement. These grains were then mounted on a glass plate, set in resin, polished and carbon-coated. The stoichiometry of the individual grains was then measured with wavelength-dispersive X-ray spectroscopy (WDS) using a JEOL JXA-8530F Plus electron probe microanalyser housed in the Centre for Advanced Microscopy at the Australian National University. Analyses were made at an accelerating voltage of 15 kV and a current of 20 nA.

The grains had been etched with HF acid during sample preparation for D_e determination. This can cause them to become crumbly and porous, and leave the surfaces of some grains rough, but most areas were suitable for analysis after polishing. Exsolution lamellae were identified using backscattered electron imaging of each grain prior to WDS analysis. Typically each grain was characterised with 2–4 point measurements using a beam size of ~10 μm diameter to incorporate a representative mixture of lamellae. If only a limited flat surface was available for measurement, a beam diameter of ~4 μm was used to avoid rough areas. Point measurements were excluded from analysis if they failed to achieve totals of 99–101, which was usually associated with uneven etched surfaces. Grains for which only a single point measurement was made are not reported here.

Measurements from 32 grains of DCM16-12 and 28 grains of DCE16-8 were included in the final analysis. The measured K content of each grain (in wt%) is plotted as a function of T_n sensitivity in Supplementary Fig. 16. DCM16-12 (open circles) has a tightly clustered distribution, with arithmetic and weighted mean K contents of 13.1 and 13.2 wt%, respectively. DCE16-8 (filled circles) has a slightly broader distribution, with arithmetic and weighted mean K contents of 12.7 and 12.6 wt%, respectively. These results also show that, at least for these samples, grains with detectable T_n signals are predominantly K-rich alkali feldspars, and that there is no clear correlation between T_n sensitivity and K concentration. The two samples combined have arithmetic and weighted mean K contents of 12.9 and 12.8 wt%, respectively. We used the latter value (shown by the dashed line in Supplementary Fig. 16) for all of the K-feldspar samples in this study, and assigned a standard error of ± 0.5 wt%. The 2σ range of 11.8–13.8 wt% incorporates 57 of the 60 K-feldspar grains included in the final analysis of DCM16-12 and DCE16-8, thus capturing the likely variation in mean K concentration between grains.

To calculate the internal beta dose rates for K-feldspar grains of different sizes, we used the above estimate of the K content ($12.8 \pm 0.5\%$) and an assumed Rb concentration of 400 ± 100 $\mu\text{g/g}$. We consider the latter value¹²⁶ appropriate, as K and Rb concentrations are broadly correlated¹³⁶ and the mean K concentration of our samples is similar to that of the K-feldspar samples in ref. 124. We converted these concentrations into dose rates¹³⁷, taking into account corrections for the absorbed dose fraction, which varies depending on grain size. For K-feldspar grains of 180–212 μm and 90–125 μm in diameter, for example, the effective internal beta dose rates are 0.85 ± 0.07 and 0.49 ± 0.05 Gy/kyr, respectively (Supplementary Tables 7–9).

Cosmic-ray dose rates

Account was also taken of the cosmic-ray contribution to the total dose rate⁴⁹, adjusting for site altitude (~670 m), geomagnetic latitude (40.6°), and the density and thickness of rock and sediment overburden. Cosmic-ray dose rates range from 0.038 ± 0.006 Gy/kyr (for the uppermost samples in Main Chamber) to 0.019 ± 0.003 Gy/kyr (for the deepest samples in East Chamber).

Owing to the comparatively high external beta and gamma dose rates, and the significant internal dose rate for K-feldspar grains, the cosmic-ray dose rate forms a trivial fraction of the total dose rate: <2% for quartz grains and <1% for K-feldspar grains, on average.

Moisture content

The external beta, gamma and cosmic-ray dose rates were corrected¹²⁰ for long-term water content. We measured the moisture content for every sample and the field values prevailing at the time of sample collection are listed (in brackets) in Supplementary Tables 7–9. The measured moisture contents are highly variable: 10–36% (Main Chamber), 13–61% (East Chamber) and 22–34% (South Chamber). As some of the section faces had been exposed for several years at the time of sampling, we were concerned that the sediments may have partly dried out in the meantime, resulting in the measured moisture contents significantly underestimating those of the sediments when excavated originally. The moisture values obtained from freshly excavated profiles in 2014 and 2016, however, are consistent with our previous measurements for most layers, so we used the field (measured) values as a guide to the average long-term water content of each sample and applied a relative error of $\pm 20\%$ (at 1σ) to this estimate to accommodate any likely variations over the period of sample burial. Dehydration of the highly organic-rich layers (i.e., 20 and 21 in Main Chamber and 14–16 in East Chamber) had a significant effect on their measured moisture contents, however, so for these samples we used the field values measured for organic-rich layers freshly excavated in 2014 and 2016 in East Chamber. The optical ages are relatively insensitive to variations in the long-term average: the calculated ages increase (or decrease) by only $\sim 1\%$ for each 1% increase (or decrease) in water content for quartz, and about half that for K-feldspar.

Total environmental dose rates

The total dose rates for the quartz and K-feldspar samples from Denisova Cave vary significantly, ranging by a factor of ~ 3 in Main Chamber and a factor of ~ 2 in East and South Chambers. This reflects the variability in the external beta and gamma dose rates, which relate to the sedimentology of the deposits. Samples with the highest dose rates were collected from layers with the greatest silt and clay content (layers 9 and 22 in Main and South Chambers, and layer 17 in East Chamber), whereas samples with lower dose rates were collected from layers composed of coarser-grained sediments with abundant limestone rubble. These spatial differences in external dose rate underscore the importance of making *in situ* measurements of the gamma dose rate, to accurately capture the gamma radiation field at each sample location.

Age estimates and comparisons

The final optical ages for all samples are listed in Supplementary Tables 7–9, together with the supporting D_e and dose rate estimates. Uncertainties on the ages are given at 1σ (the standard error on the mean) and were estimated by combining, in quadrature, all known and estimated sources of random and systematic error. Ages are presented in stratigraphic order, although the order of samples within specific layers or sub-layers is arbitrary, as the relative position of samples between the different profiles is not known. Ages are also presented separately for each chamber and for the different profiles sampled in each chamber. Reliable and finite ages could be obtained for most of the samples measured, ranging from ~ 9 kyr to ~ 500 kyr for the youngest and oldest samples collected from the cave deposits. Each chamber spans a different time range, however, and the basal deposits in East Chamber proved too old for finite age determination, even using the long-range MET-pIRIR 275°C dating signal for K-feldspar. A few samples in each chamber also have ages that are poorly constrained due to:

1. A large spread in individual D_e values, suggestive of extensive mixing of the deposit.
2. The uncertain assignment of samples to specific layers in areas of the deposit with complex stratigraphy.
3. Sampling of more than one layer in a single sample, as a result of inadvertently cross-cutting through adjacent layers when the samples were collected at night. Two samples (DCM12-25

and DCM12-28) were recognised as such after excavating through the sample holes in daylight, and their measured ages are not included in the final chronologies for these chambers.

Comparison of single-grain optical ages for quartz and K-feldspar

Paired single-grain OSL ages for quartz and single-grain pIRIR ages for K-feldspar were obtained for 47 of the samples (Group A)—close to half the total number of samples dated in this study (Supplementary Tables 7–9). For the remaining three samples (from layers 9.2, 9.3 and 11.1 in the southeast profile of East Chamber), one or other mineral produced a widely scattered D_e distribution from which a reliable age could not be calculated. Although the D_e values for quartz and K-feldspar have largely independent errors, the two minerals have several shared dose rate components and errors. These include the external beta, gamma and cosmic-ray dose rates, and the moisture content correction applied to these dose rate components, which collectively account for 97–99% of the total dose rate to quartz. For the K-feldspar grains, the internal beta dose rate accounts for, on average, around one-third (35%) of the total dose rate, but varies from one-sixth (17%) to almost half (47%). The shared error terms need to be taken into account when comparing the ages obtained from the two minerals for the same sample, and if the ages are then combined^{93,138}. Accordingly, in the comparison of quartz OSL and K-feldspar pIRIR ages described below and in the calculation of their weighted mean age, all shared errors are omitted and only the total random error associated with the D_e values and the error associated with the internal beta dose rate are included.

The 47 pairs of OSL and pIRIR ages are presented in Extended Data Fig. 8b. The mean ratio is 1.00 with a standard deviation of 0.09 and a standard error of the mean of 0.014; the corresponding ratios and standard errors for the separate chambers are 1.01 ± 0.02 (Main, $n = 28$), 1.00 ± 0.03 (East, $n = 15$) and 0.92 ± 0.03 (South, $n = 4$). The ratios are randomly spread around the 1:1 line, suggesting no systematic trend. Only two of the samples (4% of the comparison set) have OSL and pIRIR ages that are statistically significantly different: DCE14-1 and DCE16-1, which are both from known disturbed units in East Chamber (Extended Data Figs 3d and 5e). The overall agreement between the single-grain quartz and K-feldspar ages indicates that the sediments were well bleached when deposited in the cave, given the much longer sunlight exposure time required to empty pIRIR traps compared to OSL traps^{27,28,30,31}. That is, the consistency between the OSL and pIRIR ages suggests that both dating signals were completely reset at the time of sediment deposition and, hence, incomplete bleaching is not an issue at Denisova Cave (at least for those layers with optical ages for both minerals).

For the 45 samples with statistically consistent paired ages, the OSL and pIRIR ages were combined to obtain a single weighted mean age for each sample. To do so, we first determined the shared and unshared components of their errors, and then calculated the pooled mean of each pair of ages, weighted by the inverse square of the unshared errors. We added to this, in quadrature, the average relative shared error for each pair of ages to estimate the total uncertainty on the weighted mean age. The combined weighted mean ages and corresponding total and unshared-only 1σ uncertainties are shown inside the grey bands in Supplementary Tables 7–9; we used these estimates to construct the final chronologies for each chamber.

Bayesian modelling of optical ages

A Bayesian statistical age model was constructed separately for each of the chambers using the OxCal platform (OxCal 4.2.4)^{50,51}. Each age was input as a C_date in calendar years before AD 1950 with an associated 1σ error; these are the so-called likelihood estimates. Only the unshared errors were included in the model¹³⁸; these are shown in brackets in Supplementary Tables 7–9. For samples with both OSL and pIRIR ages, we used the combined ages and random-only errors (shown inside the grey bands in Supplementary Tables 7–9).

In Bayesian analysis, the likelihood estimates are analysed with respect to prior information, and the posterior distributions (i.e., the modelled ages) are estimated. We used the sequence of

stratigraphic layers for each chamber as prior information. Each of these layers (or, in some cases, a combination of layers) was modelled as a *Phase*, in which the measured ages are assumed to be unordered and uniformly distributed, so any mixing within a layer will not influence the model. A *Boundary* was placed at the start and end of each *Phase*. The modelled probability distributions of these *Boundaries* provide estimates for the start and end ages of each *Phase*, which were arranged into a *Sequence* under the assumption that the stratigraphically lowest *Phase* is older than those above.

There is no *a priori* reason to assume that sediments have accumulated continuously in Denisova Cave. Stratigraphic and chronological gaps may exist due to erosional events or periods of little or no sediment deposition. So, where major time gaps were apparent between two layers, we inserted an *Interval* between them and assigned each gap an assumed duration and uncertainty. For the latter estimates, we used the difference between the measured ages for each pair of layers as starting values for the model, which then estimated the likelihood of there being a time interval and incorporated the results in the modelled start and end ages of each *Phase*. The timing of the modelled gaps and their estimated durations are shown inside the grey bands in Extended Data Table 1.

A general t-type outlier model¹³⁹ was used to assess the likelihood of each age being consistent with the fitted model. Each age was assigned a prior outlier probability of 5%. The posterior outlier probability is calculated during the modelling process and the age down-weighted accordingly. For example, if the posterior probability is estimated as 5%, then the age is included in 95% of the model iterations; but an age with a posterior probability of 50% is included in only 50% of the model iterations. We assigned a prior outlier probability of 100% to the ages for samples DCM12-3 and DCM16-3, and 50% to the ages for samples DCM12-6 and DCM16-5, to prevent undue weighting on ages that are known to be problematic for the reasons discussed above.

The Bayesian modelled optical dating chronologies for Main, East and South Chambers are presented in Extended Data Figs 6, 7 and 8a, respectively. The corresponding data for each chamber are provided in Supplementary Tables 10–12 and the CQL codes used to generate these data are listed in Supplementary Tables 13–15. All modelled age ranges were calculated at 68.2% and 95.4% posterior probability. The age likelihood (prior to modelling) and posterior (mathematically modelled) distributions are shown in Extended Data Figs 6–8a using pale and dark shading, respectively. The uncertainties associated with the start and end ages of each *Phase* were calculated using the OxCal platform and are based on the total unshared component of error only. For comparisons with independent chronologies, the total shared component of error should also be included. In our samples, the total shared error is, on average, $3.94 \pm 0.04\%$ (with a median value of 4.00%) of the sample age, thus accounting for ~38% of the total (unshared plus shared) age uncertainty. To estimate the total uncertainties associated with the start and end ages, we combined the total unshared and shared errors in quadrature. In the discussion below, we give ages with two estimates of total uncertainty, both expressed at 95.4% probability and enclosed by brackets: the first estimate is based on propagation of the unshared errors only, while the second also includes propagation of the shared errors and is, therefore, the most appropriate value to use when comparing the optical ages with independent chronologies.

Chronologies for Main, East and South Chambers

The Pleistocene chronologies for all three chambers are summarised and compared in Figs 3 and 4 and in Extended Data Table 1, using the modelled start and end ages with full errors (i.e., both shared and unshared). The corresponding ages for the MP, IUP and UP artefact assemblages are indicated in Fig. 3 and Extended Data Table 1. Ages for the skeletal and genetic remains of Denisovans and Neanderthals are shown in Figs 3 and 4, along with the climatic conditions inferred from pollen and faunal records at Denisova Cave and from diatom records in Lake Baikal^{32,33}.

Main Chamber

Fifty-five samples were collected and dated from Main Chamber. Of these, 12 are excluded from the Bayesian age model in Extended Data Fig. 6. The six samples collected from layers 9 and

11 in the east profile (Extended Data Fig. 5a) are omitted because of uncertainty about their association with specific layers and evidence for post-depositional mixing in some of these samples. The four samples collected from layer 13 (DCM12-11, DCM12-12, DCM12-13 and DCM12-14) were excluded because this layer has been identified as a hyena den. The remaining two samples excluded from the model (DCM12-25 and DCM12-28) were collected from areas identified as disturbed or were found to have cross-cut several layers when collected, as verified after the 2016 excavation. Two samples from layer 11.2 (DCM12-3 and DCM16-3) and two from layer 11.3 (DCM12-6 and DCM16-5) in the southeast profile were included in the model, but with outlier probabilities of 100% and 50%, respectively, because their optical ages (47.3 ± 3.0 to 57.2 ± 3.0 kyr) are inconsistent with those of ~ 40 kyr for other samples from layer 11 in the same profile (Supplementary Table 7) and for a new suite of ^{14}C samples from this layer (study conducted by K. Douka and T. Higham).

The remaining 41 samples show good consistency relative to each other and to the stratigraphic prior applied (Extended Data Fig. 6). In addition to the four samples assigned outlier probabilities of 50% or 100%, the model identified three ages with posterior outlier probabilities of $>10\%$ (Supplementary Table 10). The convergence values for all other posterior distributions, including the timing and duration of each *Phase* and the model as a whole, are good ($>92.7\%$) and provide confidence in the chronology constructed for deposits in Main Chamber.

Layer 22 forms the basal sediments of the stratigraphy in Main Chamber. A few hundred artefacts and a heavily worn Denisovan molar (*Denisova 2*) were recovered from near the top of layer 22.1. The start and end ages for layer 22 are $366.0 \pm (40.3, 42.8)$ and $286.6 \pm (39.8, 41.4)$ kyr, respectively. (Here we report the modelled ages with uncertainties at the 95.4% confidence interval; the first uncertainty is the total unshared-only error and the second is the total uncertainty, which also includes the shared errors.) An erosional unconformity separates layer 22 from the overlying layer 21. Layers 21 and 20 were modelled together and have start and end ages of $249.9 \pm (42.8, 43.9)$ and $169.7 \pm (18.0, 19.2)$ kyr, respectively. Hence, we identify a gap of 29.3 ± 25.9 thousand years (at 95.4% probability) between layers 22.1 and 21 (Extended Data Table 1).

The stratigraphy associated with layers 19–13 is complex: some layers (e.g., 18, 16 and 15) are visible only as discontinuous lenses in the profiles of the 1984 excavation, and layer 13 is a hyena lair. Neanderthal DNA was extracted from three of the sediment samples collected for optical dating: DCM12-20 (layer 19.1), DCM12-18 (layer 17) and DCM12-17 (layer 14.3). Layers 19 and 17 were modelled together and have start and end ages of $151.4 \pm (16.0, 17.1)$ and $127.6 \pm (11.6, 12.6)$ kyr, respectively, while the corresponding modelled ages for layer 14 are $112.3 \pm (10.8, 11.7)$ and $96.5 \pm (10.0, 10.7)$ kyr. These ages suggest deposition of layers 19 and 17 towards the end of Marine Isotope Stage (MIS) 6—the final Middle Pleistocene—and the start of the last interglacial (MIS 5), which marks the onset of the Late Pleistocene. Layer 14 was deposited during the remainder of MIS 5. Evidence of Neanderthals, therefore, extends from at least ~ 150 to ~ 100 kyr in this chamber, based on traces of their ancient DNA in these sediments¹⁷.

Layer 12 is associated with the final MP in Main Chamber. So far, no human remains have been found in this layer and the artefact assemblage shares the same overall features as those in layers 19–14. The modelled start and end ages for layer 12 are $69.6 \pm (7.8, 8.3)$ and $58.3 \pm (5.9, 6.4)$ kyr, indicating sediment deposition and hominin occupation during MIS 4.

There is a clear contact between layer 12.1 and the overlying layer 11.4 (Extended Data Fig. 2d). UP artefacts, including many ornaments, are found throughout layer 11—down to the base of layer 11.4—and the various sub-layers of layer 11 are distinguished mainly on the basis of their colour. Accordingly, we modelled layer 11 as a single layer and obtained start and end ages of $44.1 \pm (4.5, 4.8)$ and $38.4 \pm (2.1, 2.6)$ kyr, which both lie within MIS 3. Layer 9 is the last of the Pleistocene sedimentary layers in this chamber, and is separated from layer 11 by an erosional unconformity (denoted as layer 10), implying a hiatus. We calculated modelled start and end ages of $35.9 \pm (3.5, 3.8)$ and $21.1 \pm (7.6, 7.7)$ kyr for layer 9, indicating sediment deposition from late MIS 3 into MIS 2 (the last glacial maximum). We note, however, that layer 9 has been heavily bioturbated in places

and that two other samples assigned to this layer in the east profile have ages of ~9 kyr (DCM14-1) and ~18 kyr (DCM14-2), which are not included in the Bayesian model.

East Chamber

Thirty-eight samples were collected from East Chamber, but DCE14-6 could not be dated because the natural pIRIR signal was saturated (Supplementary Fig. 3b). Of the remaining 37 samples dated, nine are excluded from the Bayesian age model shown in Extended Data Fig. 7. Four of the samples collected from layers 9 and 11 in the A squares of the northwest and west profiles (Extended Data Fig. 5c,e) are omitted because of their uncertain associations with specific layers; also, DCE14-2 was collected from close to the cave wall and its D_e distribution is suggestive of post-depositional mixing. Likewise, four samples from the upper levels of the southeast profile have scattered D_e distributions consistent with extensive post-depositional mixing—DCE14-9 (layer 8), DCE12-1 and DCE12-2 (both layer 9) and DCE12-3 (layer 11.1)—as does DCE12-4 collected from layer 11.2 in the southeast profile (Extended Data Fig. 3b); mixing is also evident from the macro-stratigraphy. The remaining 26 samples included in the Bayesian model form a chronologically and stratigraphically coherent sequence of ages (Extended Data Fig. 7), which all have posterior probabilities of <5% and convergence values of >88.4% for the posterior distributions (Supplementary Table 11).

The deepest sample in East Chamber that yielded a finite age is DCE14-5, which was collected from layer 17.2, below the choke-stone separating the lower and middle sections of the cave profile (Extended Data Fig. 3f). The age estimate of $508.1 \pm (34.5, 39.9)$ kyr is considerably older than those for two samples from layer 17.1—one above (DCE12-14) and one below (DCE14-4) the choke-stone—which has modelled start and end ages of $304.9 \pm (34.5, 36.5)$ and $283.9 \pm (30.4, 32.4)$ kyr, respectively. Layers 17 and 16—the latter having start and end ages of $259.1 \pm (26.3, 28.2)$ and $237.9 \pm (17.5, 19.9)$ kyr, respectively—are both culturally sterile.

The first evidence of a hominin presence in East Chamber is in layer 15, which has a start age of $203.1 \pm (11.6, 14.1)$ kyr. This layer is rich in stone artefacts—primarily denticulates attributed to the early MP—and Denisovan DNA was also extracted from one of the sediment samples collected from this layer for dating (DCE12-12)¹⁷. These lithic tool types and technologies appear to continue through into layer 14, which has a modelled end age of $186.8 \pm (12.3, 14.4)$ kyr. Neanderthal DNA was extracted from one of the samples collected from this layer (DCE12-11), suggesting that both archaic hominins occupied East Chamber at times during the second half of MIS 7.

A clear lithological change occurs between layers 14 and 13 (Extended Data Fig. 3d,f), which coincides with a change in the biostratigraphy and a shift towards a more blade-based lithic industry. Layer 13 has a start age of $155.8 \pm (14.0, 15.3)$ kyr, with occupation continuing through layers 12.3 and 12.2, which accumulated between $140.5 \pm (8.1, 9.8)$ and $128.6 \pm (9.5, 10.8)$ kyr—around the time of the penultimate glacial maximum during late MIS 6. A fragment of bone (*Denisova 11*) from a young female of mixed ancestry (a Neanderthal mother and a Denisovan father)¹⁶ and a Neanderthal toe phalanx (*Denisova 9*) were excavated from layers 12.3 and 12.2, respectively; collagen from *Denisova 11* yielded a ^{14}C age of >49,900 years BP (ref. 15), which is consistent with the optical ages.

Layer 11 has been divided into four sub-layers and we have obtained reliable ages for each of them. All of the ages are based on single grains of both quartz and K-feldspar, which show good consistency (Extended Data Fig. 8b). The age of layer 11.4 is of particular interest, because of the discovery of two hominin fossils in this deepest sub-layer of layer 11: a toe phalanx of the ‘Altai Neanderthal’ (*Denisova 5*) and a Denisovan molar (*Denisova 8*), which was found at the interface between layers 11.4 and 12 (ref. 12). In addition, Neanderthal DNA was extracted from one of the sediment samples collected from layer 11.4 for dating (DCE14-13)¹⁷. Neither this sample nor the other samples collected from this layer (DCE14-15 and DCE16-3) show any evidence for post-depositional mixing. Ages from layers 12.1 and 11.4 were modelled together, resulting in start and end ages of $120.3 \pm (10.2, 11.3)$ and $104.6 \pm (10.4, 11.1)$ kyr, indicating accumulation during early to mid MIS 5.

No hominin remains have been discovered in layer 11.3 thus far, but the age of this layer is important for constraining the time of deposition of layer 11.2, from which the celebrated Denisovan finger bone (*Denisova 3*) was found^{1,2,11}. The modelled start and end ages for layer 11.3 are $80.4 \pm (9.2, 9.7)$ and $70.1 \pm (7.4, 7.9)$ kyr, respectively, and the corresponding ages for layer 11.2 are $62.9 \pm (6.0, 6.5)$ and $54.8 \pm (5.7, 6.1)$ kyr; these two time intervals span the MIS 5/4 and MIS 4/3 transitions, respectively. The three samples included in the model age estimate for layer 11.2 each have D_e distributions indicative of good stratigraphic integrity, whereas DCE12-4 (also from this layer, but omitted from the model) has a quartz D_e distribution consisting of three discrete components centred on ages of about 15, 29 and 75 kyr (Supplementary Table 8). These ages are consistent with the range of ^{14}C ages ($\sim 19,000$ to $>50,000$ years cal BP) obtained for bones from layer 11 (Supplementary Table 2), which suggests that some parts of this layer have been reworked; this is also clear from the macro-stratigraphy of the deposit.

Bioturbation is particularly evident in the D_e distributions of samples collected from layers 11.1 (e.g., Supplementary Fig. 7e) and 9 (e.g., Supplementary Fig. 8d). The D_e distributions of only two samples from layer 11.1 were considered suitable for reliable age determination (DCE14-10 and DCE16-1): these gave modelled start and end ages of $49.2 \pm (5.9, 6.2)$ and $38.2 \pm (9.7, 9.8)$ kyr, respectively, which lie within MIS 3. None of the samples from layer 9 were included in the age model, as none could be dated with certainty; the D_e distributions show clear signs of sediment disturbance by burrowing animals. DCE16-4 and DCE14-2 were collected from an area of the deposit where the provisional stratigraphic assignments (layers 9 and 11.1, respectively) were in question; the ages of 50–70 kyr for these samples align most closely with that of layer 11.2. A sample (DCE14-9) collected from layer 8—a culturally sterile unit—was deposited ~ 10 kyr, consistent with the basal ages of the overlying Holocene deposits.

South Chamber

All samples collected and dated from South Chamber (Extended Data Fig. 4c) are included in the Bayesian age model (Extended Data Fig. 8a). The ages form a coherent chronostratigraphic series, with posterior probabilities of $<5\%$ for all ages (Supplementary Table 12) and convergence values of $>90.7\%$ for the posterior distributions. We caution that few ages have so far been obtained for South Chamber and that the layer assignments of the samples are tentative. New excavations in South Chamber commenced in 2017, which revealed the complex stratigraphy of these deposits. We have since collected 32 new sediment samples to strengthen chronological control of the stratigraphic sequence in this chamber.

Our provisional chronology for South Chamber suggests deposition of layer 22—which contains the first evidence for human occupation—before or during MIS 8. This layer is overlain unconformably by layer 19 that currently has a single-grain pIRIR age estimate of 125.5 ± 8.1 kyr (1σ uncertainty). We refrain from using the modelled start and end ages for layers 22 and 19, because the two age estimates suggest a significant hiatus between these layers (135.8 ± 105.8 thousand years). The modelled start age for layer 19 and end age for layer 14 are $136.5 \pm (25.3, 25.9)$ and $101.1 \pm (19.0, 19.4)$ kyr, respectively, which are indistinguishable from the MIS 5 age for layer 19. The corresponding ages for layer 12 are $63.7 \pm (9.4, 9.8)$ and $46.8 \pm (7.7, 7.9)$ kyr. This time interval is consistent with published ^{14}C ages of $\sim 52,000$ years cal BP and older for bones from layer 11 in South Chamber (Supplementary Table 2), from which a Denisovan molar (*Denisova 4*) was also recovered.

Supplementary Table 2 | Previously reported ages for samples from Main, East and South Chambers in Denisova Cave. Radiocarbon (^{14}C) ages are listed in years before present (BP, where the present is defined as AD 1950), and ages based on radiothermoluminescence (RTL) dating and ancient DNA (aDNA) analyses are given in thousands of calendar years ago (kyr).

Lab number / specimen ID	Material	Method	Layer	Age (yr BP, ¹⁴ C; kyr, RTL & DNA) ^a	Reference(s)
MAIN CHAMBER					
SOAN-2504	Unidentified bone	¹⁴ C	11	>37,235	3, 59–62
RTL-611	Sediment	RTL	14.1	69 ± 17	3, 59–62
RTL-546	Sediment	RTL	21	155 ± 31	3, 59–62
RTL-737	Sediment	RTL	22.1	171 ± 43	3, 59–62
RTL-738	Sediment	RTL	22.1	182 ± 45	3, 59–62
RTL-739	Sediment	RTL	22.2 (upper part)	223 ± 55	3, 59–62
RTL-547	Sediment	RTL	22.2 (upper part)	224 ± 45	3, 59–62
RTL-548	Sediment	RTL	22.2 (lower part)	282 ± 56	3, 59–62
EAST CHAMBER					
OxA-V-2359-15	Ovis / Carpa bone with cut marks	¹⁴ C	11	15,740 ± 65	2
OxA-V-2359-20	Rib with regular incisions	¹⁴ C	11	30,100 ± 210	2
OxA-V-2359-21	Bone tool blank	¹⁴ C	11	23,170 ± 110	2
OxA-V-2359-16	Ovis / Carpa bone	¹⁴ C	11.2	>50,000	2
<i>Denisova 3</i>	Denisovan finger bone	aDNA	11.2	74–82	11
				72 ± 12 ^b	24
				85 ± 8 ^c	24
OxA-V-2359-14	Bison bone with cut marks	¹⁴ C	11.3	>50,000	2
<i>Denisova 5</i>	Neanderthal toe bone	aDNA	11.4	122 ± 12 ^b	24
				123 ± 7 ^c	24
OxA-32241 (<i>Denisova 11</i>)	Bone of Neanderthal / Denisovan offspring	¹⁴ C	12.3	> 49,900	15
		aDNA		~77 ^b	16
				~89 ^c	16
SOUTH CHAMBER					
AA-35321 ^d	Charcoal	¹⁴ C	10 / 11	29,200 ± 360	59–62
KIA-25285	Hyena bone	¹⁴ C	11.2	48,650 ⁺²³⁸⁰ _{–1840}	59–62
OxA-V-2359-17	Ovis / Carpa bone	¹⁴ C	11.2	>50,000	2
OxA-V-2359-18	Bison bone	¹⁴ C	11.2	>50,000	2

^a Uncertainties at 68.2% confidence interval (^{14}C and RTL) or 95.4% confidence interval (aDNA).

^b Branch-shortening estimate based on transversions only. The estimate for *Denisova 11* is a maximum age¹⁶.

^c Branch-shortening estimate based on all sites. The estimate for *Denisova 11* is a maximum age¹⁶.

^d Misattributed to Main Chamber in ref. 2 (Table S12.1).

Supplementary Table 3 | D_e measurement procedures for **a**, single-grain quartz; **b**, single-grain K-feldspar; and **c**, multiple-aliquot K-feldspar.

Step	a, Single-grain quartz OSL	b, Single-grain K-feldspar pIRIR	c, Multiple-aliquot K-feldspar MET-pIRIR
1	Give regenerative dose, D_i^a	Give regenerative dose, D_i^a	Give regenerative dose, D_i^a
2	Preheat at 260°C for 10 s	Preheat at 320°C for 60 s	Preheat at 320°C for 60 s
3	Single-grain green laser stimulation (2 s) at 125 °C	IR diodes stimulation at 200°C for 200 s	IRSL measurement at 50°C for 100 s
4	Give test dose, D_t	Single-grain IR laser stimulation (1 s) at 275°C	pIRIR measurement at 100°C for 100 s
5	Preheat at 160°C for 5 s	Give test dose, D_t	pIRIR measurement at 150°C for 100 s
6	Single-grain green laser stimulation (2 s) at 125 °C	Preheat at 320°C for 60 s	pIRIR measurement at 200°C for 100 s
7		IR diodes stimulation at 200°C for 200 s	pIRIR measurement at 275°C for 200 s
8		Single-grain IR laser stimulation (1 s) at 275°C	Give test dose, 60 Gy
9		IR bleaching at 325°C for 100 s	Preheat at 320°C for 60 s
10		Return to step 1	IRSL measurement at 50°C for 100 s
11			pIRIR measurement at 100°C for 100 s
12			pIRIR measurement at 150°C for 100 s
13			pIRIR measurement at 200°C for 100 s
14			pIRIR measurement at 275°C for 200 s
15			Solar simulator bleach for 4 hr
16			Give normalisation dose, D_r^b
17			Preheat at 320°C for 60 s
18			IRSL measurement at 50°C for 100 s
19			pIRIR measurement at 100°C for 100 s
20			pIRIR measurement at 150°C for 100 s
21			pIRIR measurement at 200°C for 100 s
22			pIRIR measurement at 275°C for 200 s
23			Give test dose, 60 Gy
24			Preheat at 320°C for 60 s
25			IRSL measurement at 50°C for 100 s
26			pIRIR measurement at 100°C for 100 s
27			pIRIR measurement at 150°C for 100 s
28			pIRIR measurement at 200°C for 100 s
29			pIRIR measurement at 275°C for 200 s

^a For the natural samples, $D_i = 0$ Gy.

^b The same D_r (520 Gy) is applied to all of the aliquots in the different groups.

Supplementary Table 4 | Number of individual quartz grains measured, rejected and accepted for each sample from Main, East and South Chambers, together with the reasons for grain rejection.

Sample	No. of grains measured	Rejection criteria (see footnotes)								Sum of grains rejected	No. of grains accepted
		1	2	3	4	5	6	7	8		
MAIN CHAMBER											
DCM12-1	4000	3814	5	23	31	55	2	5	6	3941	59
DCM14-1	3500	3114	3	101	19	80	0	3	2	3322	178
DCM16-1	2900	2767	1	24	0	42	5	9	5	2853	47
DCM12-2	4000	3807	7	23	26	44	0	4	16	3927	73
DCM14-2	5500	5259	1	51	28	48	0	7	10	5404	96
DCM16-2	2900	2800	0	8	14	22	3	8	4	2859	41
DCM12-3	3400	3258	5	6	25	30	8	9	0	3341	59
DCM14-3	3800	3661	3	31	15	28	1	4	6	3749	51
DCM16-3	2700	2589	2	26	13	21	5	8	7	2671	29
DCM12-4	3400	3262	5	6	27	30	0	4	9	3343	57
DCM14-4	3700	3551	1	28	2	28	9	15	5	3660	40
DCM16-4	2900	2801	1	14	12	24	0	2	3	2857	43
DCM12-5	4000	3768	5	30	55	57	2	8	3	3928	72
DCM14-5	3000	2817	4	14	15	18	21	24	21	2934	66
DCM16-5	2900	2819	2	15	14	12	0	4	0	2866	34
DCM12-6	4000	3787	3	35	33	41	1	7	1	3908	92
DCM14-6	3600	3462	1	26	14	22	3	11	0	3539	61
DCM16-6	2900	2663	1	44	13	38	2	6	4	2771	129
DCM12-7	4000	3734	1	52	111	37	0	3	4	3942	58
DCM14-7	3000	2823	3	35	56	38	0	7	5	2967	33
DCM16-7	2900	2769	3	17	13	14	5	15	5	2841	59
DCM14-8	3800	3587	3	46	30	56	1	5	4	3732	68
DCM12-9	3900	3693	2	33	15	71	3	3	3	3823	77
DCM12-10	3900	3576	7	38	124	56	2	7	10	3820	80
DCM16-10	2900	2735	2	25	12	25	4	5	2	2810	90
DCM16-11	2500	2356	1	30	10	27	0	4	2	2430	70
DCM16-12	3000	2873	1	18	25	20	0	5	6	2948	52
DCM12-29	3800	3494	3	65	23	57	3	9	3	3657	143

EAST CHAMBER											
DCE12-1	1000	592	1	52	16	51	2	7	0	721	279
DCE14-1	5700	5515	1	25	23	49	2	8	6	5629	71
DCE16-1	3000	2869	2	20	20	26	0	3	7	2947	53
DCE12-2	1000	909	1	5	4	16	0	1	8	944	56
DCE14-2	6000	5791	8	33	20	55	4	12	5	5928	72
DCE16-2	3000	2868	5	15	21	23	5	9	3	2949	51
DCE12-3	2000	1826	5	32	13	19	2	7	7	1911	89
DCE14-3	5400	5185	2	28	30	54	6	16	4	5325	75
DCE16-3	3000	2894	2	13	20	19	1	9	3	2961	39
DCE12-4	2000	1814	3	27	53	23	8	14	11	1953	47
DCE16-4	2800	2688	1	19	16	23	3	9	16	2775	25
DCE16-5	2900	2784	0	13	16	26	0	6	10	2855	45
DCE14-9	2000	1852	0	36	13	24	0	1	3	1929	71
DCE14-10	3000	2827	4	72	4	11	3	5	0	2926	74
DCE14-11	4000	3857	1	21	17	41	1	7	5	3950	50
DCE14-12	4000	3782	2	28	30	54	9	8	3	3916	84
DCE14-13	4000	3869	3	22	13	34	4	8	10	3963	37
DCE14-14	3900	3764	3	33	15	38	0	5	4	3862	38
SOUTH CHAMBER											
DCS12-1	3000	2894	2	13	6	22	6	11	10	2965	35
DCS12-3	1000	948	0	7	17	14	2	4	1	993	7
DCS16-2	2900	2829	5	8	7	17	1	4	7	2878	22
DCS16-3	3000	2900	2	14	12	26	3	3	3	2957	37

- 1 Initial T_n signal $<3\sigma$ above corresponding background count, or relative standard error on $T_n >25\%$.
- 2 Recuperation ratio $>5\%$.
- 3 Recycling ratio inconsistent with unity at 2σ .
- 4 OSL IR depletion ratio more than 2σ below unity.
- 5 Figure-of-merit (FOM) value for L_x/T_x ratio $>10\%$.
- 6 D_e value obtained by extrapolation of dose-response curve beyond the largest regenerative dose.
- 7 L_n/T_n ratio statistically consistent with or higher than the saturation limit of the dose-response curve.
- 8 Negative D_e values consistent with zero.

Supplementary Table 5 | Number of individual K-feldspar grains measured for each sample from Main, East and South Chambers using a full SAR pIRIR procedure, together with the number of grains rejected and accepted, and the reasons for their rejection. All grains that passed criteria 1–5 were used to construct the standardised growth curve (SGC) in Supplementary Fig. 3b.

Sample	Method of measurement	No. of grains measured	Rejection criteria (see footnotes)								Sum of grains rejected	No. of grains accepted
			1	2	3	4	5	6	7	8		
MAIN CHAMBER												
DCM12-1	SAR	600	483	0	0	11	3	4	5	2	508	92
DCM12-2	SAR	600	391	9	0	32	NA	2	7	2	443	157
DCM12-3	SAR	600	371	4	1	31	1	6	18	5	437	163
DCM12-4	SAR	600	356	4	0	41	4	1	7	2	415	185
DCM12-29	SAR	600	293	8	0	30	NA	0	8	1	340	260
DCM12-5	SAR	800	502	0	0	35	5	2	7	2	553	247
DCM12-6	SAR	500	328	3	0	17	2	2	4	0	356	144
DCM12-7	SAR	600	445	5	0	45	1	2	13	3	514	86
DCM12-9	SAR	600	382	4	0	49	2	0	6	1	444	156
DCM12-10	SAR	500	431	1	0	13	0	0	2	2	449	51
DCM12-11	SAR	600	382	17	1	47	23	3	7	10	490	110
DCM12-12	SAR	900	500	5	0	44	4	3	17	9	582	318
DCM12-13	SAR	1100	779	4	1	72	2	17	19	28	922	178
DCM12-14	SAR	600	323	4	0	39	10	2	5	10	393	207
DCM12-15	SAR	600	389	1	3	53	3	6	7	4	466	134
DCM12-16	SAR	600	492	3	0	23	0	0	5	0	523	77
DCM12-17	SAR	600	385	7	0	36	2	1	11	5	447	153
DCM12-18	SAR	900	551	4	1	64	4	0	19	7	650	250
DCM12-19	SAR	400	228	13	0	45	9	6	2	7	310	90
DCM12-20	SAR	600	321	7	0	59	3	9	6	10	415	185
DCM12-22	SAR	400	373	0	0	11	1	1	1	0	387	13
DCM12-21	SAR	600	444	3	0	30	4	3	3	10	497	103
DCM12-23	SAR	600	531	3	0	17	1	6	3	5	566	34
DCM12-24	SAR	600	472	3	0	21	2	7	6	12	523	77
DCM12-28	SAR	600	490	3	2	17	5	4	4	5	530	70
DCM12-25	SAR	1200	1071	4	0	38	2	22	5	13	1155	45
DCM12-26	SAR	600	501	NA	0	13	NA	25	2	9	550	50
DCM12-27	SAR	600	504	NA	0	10	NA	18	3	24	559	41
DCM14-9	SAR	600	345	3	0	6	NA	83	1	0	438	162
DCM14-10	SAR	600	447	2	2	11	NA	42	6	3	513	87

EAST CHAMBER												
DCE12-1	SAR	300	276	0	1	11	1	0	5	0	294	6
DCE12-2	SAR	600	520	6	0	14	NA	1	10	1	552	48
DCE12-3	SAR	600	315	NA	0	24	NA	38	4	3	384	216
DCE12-4	SAR	600	303	4	2	51	NA	21	8	5	394	206
DCE12-7	SAR	500	335	5	2	22	NA	2	2	2	370	130
DCE12-8	SAR	600	345	2	3	26	13	20	20	13	442	158
DCE12-9	SAR	500	292	6	0	15	NA	6	11	7	337	163
DCE12-11	SAR	1100	900	3	0	19	3	22	1	17	965	135
DCE12-13	SAR	1100	1050	2	0	5	NA	1	4	6	1068	32
DCE12-14	SAR	600	552	0	0	6	NA	5	1	5	569	31
SOUTH CHAMBER												
DCS12-1	SAR	600	566	0	0	4	0	2	0	2	574	26
DCS12-3	SAR	500	307	1	1	10	NA	5	5	2	331	169
DCS12-4	SAR	600	374	7	0	29	NA	10	6	14	440	160
DCS12-5	SAR	600	380	11	0	29	NA	6	8	8	442	158

- 1 Initial T_n signal $<3\sigma$ above corresponding background count, or relative standard error on $T_n >25\%$.
- 2 Recycling ratio lies outside the range 0.9–1.1.
- 3 Recuperation ratio $>5\%$.
- 4 Figure-of-merit (FOM) value for L_x/T_x ratio $>10\%$.
- 5 Reduced-chi-square value for L_x/T_x ratios $>5\%$.
- 6 D_e value obtained by extrapolation of dose-response curve beyond the largest regeneration dose.
- 7 Relative standard error on D_e value $>50\%$.
- 8 L_n/T_n ratio statistically consistent with or higher than the saturation limit of the dose-response curve.

Supplementary Table 6 | Number of individual K-feldspar grains measured for each sample from Main, East and South Chambers using an abbreviated pIRIR procedure that included measurements of only the natural signal, a single regenerative-dose signal and their corresponding test-dose signals. Also listed are the number of grains rejected and accepted, and the reasons for their rejection. Accepted grains are included in D_e estimation using the standardised growth curve (SGC) and L_nT_n methods. Rejection criteria related to dose-response curves (criteria 2–6) are not available for grains measured using this abbreviated pIRIR procedure. Grains rejected by criterion 8 are accepted for D_e estimation using the L_nT_n method. ‘ T_n threshold’ is the T_n signal intensity in counts/0.2 s of infrared stimulation above which a ‘plateau’ in D_e values or re-normalised L_n/T_n ratios is reached (see Supplementary Discussion for details).

Sample	Group	Method of D _e estimation	No. of grains measured	Rejection criteria (see footnotes)			Sum of grains rejected	No. of grains accepted	T _n threshold	No. of grains accepted after T _n threshold
				1	7	8				
MAIN CHAMBER										
DCM12-1	A	SGC	800	675	7	2	684	116	0	116
DCM16-1	A	SGC	2000	1815	17	3	1835	165	200	90
DCM14-7	A	SGC	800	497	9	8	514	286	0	286
DCM12-2	A	SGC	600	400	13	2	415	185	300	68
DCM16-2	A	SGC	1000	851	9	2	862	138	200	66
DCM14-8	A	SGC	800	629	6	1	636	164	0	164
DCM16-3	A	SGC	1600	1355	20	5	1380	220	200	90
DCM12-3	A	SGC	700	463	17	1	481	219	200	138
DCM16-4	A	SGC	900	771	11	1	783	117	150	56
DCM16-5	A	SGC	900	748	11	3	762	138	350	31
DCM12-4	A	SGC	600	345	14	1	360	240	300	78
DCM12-29	A	SGC	800	475	13	1	489	311	300	111
DCM16-10	A	SGC	800	615	11	1	627	173	250	45
DCM12-5	A	SGC	800	531	21	0	552	248	200	159
DCM12-6	A	SGC	500	331	7	1	339	161	400	56
DCM16-6	A	SGC	800	490	15	5	510	290	200	160
DCM16-11	A	SGC	800	644	12	1	657	143	250	45
DCM12-7	A	SGC	500	324	14	1	339	161	400	43
DCM16-12	A	SGC	1800	1660	10	2	1672	128	0	128
DCM12-9	A	SGC	1300	981	29	3	1013	287	300	56
DCM16-7	A	SGC	900	720	12	2	734	166	250	46
DCM12-10	A	SGC	900	730	41	2	773	127	200	64
DCM12-11	B	L _n T _n	700	482	27	12	482	218	0	218

DCM12-12	B	L _n T _n	700	435	28	7	435	265	200	145
DCM12-13	B	L _n T _n	700	460	45	11	460	240	200	107
DCM12-14	B	L _n T _n	800	512	32	9	512	288	400	106
DCM12-15	B	L _n T _n	500	352	18	3	352	148	400	42
DCM16-8	B	L _n T _n	1800	1606	25	14	1606	194	0	194
DCM12-16	B	L _n T _n	1100	911	10	4	911	189	400	59
DCM12-17	B	L _n T _n	700	455	18	0	455	245	300	98
DCM12-18	B	L _n T _n	800	565	27	5	565	235	600	42
DCM12-19	B	L _n T _n	700	467	18	2	467	233	500	53
DCM12-20	B	L _n T _n	800	505	35	6	505	295	400	106
DCM12-22	B	L _n T _n	2600	2486	11	15	2486	114	200	35
DCM12-21	B	L _n T _n	300	215	9	4	215	85	0	85
DCM12-23	B	L _n T _n	1700	1479	53	20	1479	221	0	221
DCM16-9	B	L _n T _n	1000	737	62	32	737	263	0	263
DCM17-1	B	L _n T _n	500	333	18	13	333	167	600	136
DCM12-24	B	L _n T _n	800	662	43	19	662	138	200	67
DCM12-28	B	L _n T _n	1000	910	20	4	910	90	0	90
DCM16-13	C	L _n T _n	1000	798	55	53	798	202	0	202
DCM12-25	B	L _n T _n	800	704	15	12	704	96	0	96
DCM12-26	C	L _n T _n	800	722	11	14	722	78	0	78
DCM16-14	C	L _n T _n	1000	855	44	28	855	145	0	145
DCM12-27	C	L _n T _n	700	596	14	7	596	104	500	51
DCM14-1	A	SGC	700	347	50	0	397	303	0	303
DCM14-2	A	SGC	700	566	10	0	576	124	0	124
DCM14-3	A	SGC	800	674	15	1	690	110	150	59
DCM14-4	A	SGC	800	610	5	2	617	183	0	183
DCM14-5	A	SGC	700	475	15	5	495	205	0	205
DCM14-6	A	SGC	700	542	4	4	550	150	0	150
DCM14-9	B	L _n T _n	600	345	15	5	345	255	500	140
DCM14-10	B	L _n T _n	600	447	14	8	447	153	200	131

EAST CHAMBER

DCE14-9	A	SGC	600	356	32	5	393	207	200	178
DCE12-1	A	SGC	900	835	27	2	864	36	0	36
DCE12-2	A	SGC	600	544	9	1	554	46	0	46
DCE12-3	A	SGC	700	367	14	7	388	312	200	164

DCE14-10	A	SGC	2500	2483	4	1	2488	12	0	12
DCE16-1	A	SGC	900	607	22	7	636	264	200	111
DCE12-4	A	SGC	800	474	23	6	503	297	200	169
DCE14-11	A	SGC	5600	5463	7	20	5490	110	200	53
DCE14-14	A	SGC	4000	3864	8	14	3886	114	0	114
DCE14-12	A	SGC	4000	3885	7	27	3919	81	0	81
DCE16-2	A	SGC	800	659	11	1	671	129	200	62
DCE14-13	A	SGC	2700	2580	9	3	2592	108	150	59
DCE16-3	A	SGC	3000	2765	15	7	2787	213	200	97
DCE14-15	B	L _n T _n	100	74	0	0	36	24	0	24
DCE12-7	B	L _n T _n	800	576	16	9	576	224	200	143
DCE12-8	B	L _n T _n	800	442	54	25	442	358	0	358
DCE12-9	B	L _n T _n	800	503	37	17	503	297	400	99
DCE14-8	B	L _n T _n	2500	2082	36	17	2082	418	300	197
DCE12-10	B	L _n T _n	800	537	26	8	537	263	500	86
DCE12-11	B	L _n T _n	1700	1381	55	24	1381	319	0	319
DCE12-12	B	L _n T _n	1800	1624	34	14	1624	176	0	176
DCE12-13	B	L _n T _n	1800	1693	19	13	1693	107	0	107
DCE12-14	C	L _n T _n	700	656	12	9	656	44	0	44
DCE16-4	A	SGC	900	782	7	2	791	109	200	53
DCE14-2	A	SGC	800	628	13	3	644	156	200	62
DCE14-3	A	SGC	700	515	8	4	527	173	200	104
DCE16-5 (125–150 µm)	A	SGC	300	204	5	1	210	90	0	90
DCE16-5 (150–180 µm)	A	SGC	500	351	11	7	369	131	0	131
DCE16-6	B	L _n T _n	900	657	27	9	657	243	0	243
DCE16-7	B	L _n T _n	1000	717	34	13	717	283	400	55
DCE16-8	B	L _n T _n	1000	832	28	14	832	168	300	46
DCE16-9	B	L _n T _n	1000	881	20	12	881	119	0	119
DCE16-10	B	L _n T _n	1000	857	19	20	857	143	0	143
DCE16-11	B	L _n T _n	1000	825	27	13	825	175	0	175
DCE16-12	B	L _n T _n	1000	835	24	19	835	165	0	165
DCE14-4	C	L _n T _n	600	566	9	4	566	34	0	34
DCE14-5	C	L _n T _n	900	876	7	8	876	24	0	24
DCE14-6	C	L _n T _n	200	188	6	4	188	12	0	12
DCE14-1	A	SGC	800	594	30	0	624	176	0	176

SOUTH CHAMBER										
DCS16-2	A	SGC	4000	3730	21	2	3753	247	150	86
DCS12-1	A	SGC	700	662	3	1	666	34	0	34
DCS16-1	A	SGC	4000	3871	9	2	3882	118	200	46
DCS12-2	A	SGC	1000	659	17	10	686	314	250	121
DCS12-3	A	SGC	800	493	15	4	512	288	400	88
DCS16-3	A	SGC	3800	3637	16	8	3661	139	150	58
DCS12-4	B	L _n T _n	800	549	22	14	549	251	400	84
DCS16-4	B	L _n T _n	2800	2555	34	20	2555	245	200	96
DCS16-5	B	L _n T _n	1000	851	14	4	851	149	200	81
DCS12-5	B	L _n T _n	800	525	30	21	525	275	200	160
DCS16-6	C	L _n T _n	1000	928	27	23	928	72	0	72

1 Initial T_n signal <3σ above corresponding background count, or relative standard error on T_n >25%.

7 Relative standard error on D_e value >50%.

8 L_n/T_n ratio statistically consistent with or higher than the saturation limit of the dose-response curve.

Supplementary Table 7 | Dose rate data, equivalent dose (D_e) and overdispersion (OD) values, and optical ages for quartz (Q) and K-feldspar (KF) samples from the **a**, southeast and **b**, east profiles in Main Chamber. For each sample, the measured water content value is shown in brackets after the value ($\pm 1\sigma$ uncertainty) used for dose rate and age determination. The total dose rates include a cosmic-ray contribution of 0.02–0.04 Gy/kyr for all samples and an internal dose rate of 0.03 Gy/kyr for quartz grains (see Supplementary Discussion for details). The number of grains refers to those accepted for D_e determination after application of the grain-rejection criteria. The D_e and OD values were calculated using the central age model (CAM), after rejecting any statistical outliers identified using the normalised median absolute deviation (nMAD CAM). The finite mixture model (FMM) was applied to the K-feldspar D_e distribution of sample DCM12-1, with the age for the main D_e component highlighted in bold and italics. Samples highlighted in blue, red and green represent Group A, B and C samples, respectively (see Supplementary Discussion for details). The age uncertainties shown in brackets are the random-only errors, while those shown after the $\pm$ symbol represent the total (random plus systematic) uncertainties at 1σ ; the latter includes a systematic error of 2% to allow for any bias associated with calibration of the laboratory beta source. Ages shown in bold within the grey bands are the weighted mean ages and the total (unshared plus shared) uncertainties at 1σ for the combined quartz and K-feldspar age estimates; the values shown in brackets are the total unshared-only errors.

MAIN CHAMBER																	
Sample	Layer	Mineral	Grain size	Water content (%)	External dose rate (Gy/kyr)		Internal dose rate (Gy/kyr)	Total dose rate (Gy/kyr)	No. of grains	D _e (Gy)	OD (%)	Age model	Optical age (kyr)				
					Beta	Gamma											
a, Southeast profile																	
DCM12-1	9.1	Q	180-212	12 ± 2 (12)	1.84 ± 0.08	0.64 ± 0.03	0.85 ± 0.07	2.55 ± 0.09	59	70.6 ± 3.7	26.8 ± 4.7	CAM	27.7 ± 1.8 (1.5)				
		KF															
DCM16-1	9.1	Q	180-212	12 ± 2 (13)	1.90 ± 0.08	0.78 ± 0.03	0.72 ± 0.06	2.75 ± 0.08	47	60.1 ± 3.0	19.6 ± 4.8	nMAD CAM	21.9 ± 1.3 (1.2)				
		KF	150-180		1.94 ± 0.08			3.48 ± 0.11	90	83.3 ± 5.0	45.4 ± 4.1	nMAD CAM	23.9 ± 1.7 (1.5)				
DCM14-7	9.2	Q	180-212	12 ± 2 (11)	1.39 ± 0.06	0.62 ± 0.03	0.85 ± 0.07	2.08 ± 0.06	33	56.9 ± 2.4	13.9 ± 4.3	nMAD CAM	27.4 ± 1.5 (1.2)				
		KF															
DCM12-2	9.2	Q	180-212	15 ± 3 (15)	1.63 ± 0.08	0.57 ± 0.03	0.85 ± 0.07	2.27 ± 0.08	73	73.0 ± 4.0	33.8 ± 4.5	nMAD CAM	32.2 ± 2.2 (1.8)				
		KF															
DCM16-2	9.3	Q	180-212	15 ± 3 (16)	1.27 ± 0.06	0.63 ± 0.03	0.72 ± 0.06	1.97 ± 0.06	41	75.9 ± 4.5	29.2 ± 5.1	CAM	38.6 ± 2.7 (2.4)				
		KF	150-180		1.29 ± 0.06			2.69 ± 0.09	66	94.3 ± 5.7	57.5 ± 5.4	nMAD CAM	35.1 ± 2.5 (2.2)				

DCM14-8	9.3	Q KF	180-212	10 ± 2 (10)	1.49 ± 0.06	0.48 ± 0.02		2.04 ± 0.06	68	63.4 ± 3.2	33.5 ± 4.5	CAM	31.1 ± 1.9 (1.7)
							0.85 ± 0.07	2.86 ± 0.09	164	82.8 ± 2.8	33.9 ± 2.6	nMAD CAM	29.0 ± 1.5 (1.1)
							29.8 ± 1.4 (1.0)						
DCM16-3	11.2	Q KF	180-212 150-180	20 ± 4 (23)	1.06 ± 0.05 1.09 ± 0.05	0.49 ± 0.03		1.62 ± 0.06	29	86.1 ± 4.0	10.7 ± 6.1	CAM	53.3 ± 3.4 (2.4)
							0.72 ± 0.06	2.33 ± 0.09	90	140.7 ± 5.7	31.2 ± 3.2	nMAD CAM	60.4 ± 3.5 (2.4)
							57.2 ± 3.0 (1.7)						
DCM12-3	11.2	Q KF	180-212	17 ± 3 (17)	1.10 ± 0.05	0.37 ± 0.02		1.54 ± 0.06	59	87.0 ± 4.5	27.3 ± 4.6	nMAD CAM	56.3 ± 3.7 (3.1)
							0.85 ± 0.07	2.36 ± 0.09	138	133.0 ± 3.7	26.2 ± 2.2	nMAD CAM	56.4 ± 2.9 (2.4)
							56.4 ± 2.7 (1.8)						
DCM16-4	11.2	Q KF	180-212 150-180	20 ± 4 (21)	0.94 ± 0.05 0.96 ± 0.05	0.36 ± 0.02		1.36 ± 0.05	43	58.8 ± 3.1	25.2 ± 4.5	CAM	43.1 ± 2.9 (2.4)
							0.72 ± 0.06	2.08 ± 0.08	56	79.9 ± 5.4	27.7 ± 4.1	nMAD CAM	38.5 ± 3.1 (2.7)
							41.3 ± 2.3 (1.8)						
DCM16-5	11.3	Q KF	180-212 150-180	18 ± 4 (18)	0.97 ± 0.05 0.99 ± 0.05	0.45 ± 0.02		1.49 ± 0.05	34	72.9 ± 4.7	29.4 ± 6.0	nMAD CAM	49.0 ± 3.7 (3.4)
							0.72 ± 0.06	2.20 ± 0.08	31	98.7 ± 8.0	36.2 ± 5.6	nMAD CAM	44.8 ± 4.1 (3.7)
							47.3 ± 3.0 (2.4)						
DCM12-4	11.4	Q KF	180-212	13 ± 3 (13)	1.08 ± 0.05	0.37 ± 0.02		1.52 ± 0.05	57	57.8 ± 3.9	41.4 ± 5.5	CAM	37.9 ± 2.9 (2.6)
							0.85 ± 0.07	2.34 ± 0.09	78	95.2 ± 3.4	20.3 ± 2.5	nMAD CAM	40.7 ± 2.2 (1.6)
							39.7 ± 2.0 (1.5)						
DCM12-29	11.3	Q KF	180-212	17 ± 3 (17)	1.23 ± 0.06	0.45 ± 0.02		1.75 ± 0.06	143	72.9 ± 1.9	22.5 ± 2.3	CAM	41.6 ± 2.0 (1.3)
							0.85 ± 0.07	2.57 ± 0.09	111	99.7 ± 4.1	30.9 ± 2.5	nMAD CAM	38.8 ± 2.3 (1.8)
							41.0 ± 1.7 (0.9)						
DCM16-10	11.3	Q KF	180-212 150-180	17 ± 3 (17)	1.06 ± 0.05 1.08 ± 0.05	0.42 ± 0.02		1.55 ± 0.06	90	66.1 ± 2.3	23.4 ± 3.2	CAM	42.6 ± 2.3 (1.7)
							0.72 ± 0.06	2.26 ± 0.08	45	88.3 ± 7.5	39.8 ± 5.0	nMAD CAM	39.0 ± 3.7 (3.4)
							42.0 ± 2.1 (1.4)						
DCM12-5	11.3	Q KF	180-212	18 ± 4 (18)	1.32 ± 0.06	0.42 ± 0.02		1.81 ± 0.07	72	70.6 ± 3.6	35.2 ± 4.1	CAM	39.1 ± 2.6 (2.1)
							0.85 ± 0.07	2.62 ± 0.10	159	104.1 ± 3.4	34.0 ± 2.5	nMAD CAM	39.7 ± 2.1 (1.5)
							39.4 ± 1.9 (1.3)						
DCM12-6	11.3	Q KF	180-212	18 ± 4 (18)	0.93 ± 0.05	0.36 ± 0.02		1.37 ± 0.06	92	67.3 ± 2.7	29.1 ± 3.5	CAM	49.1 ± 2.8 (2.2)
							0.85 ± 0.07	2.19 ± 0.09	56	112.6 ± 6.3	38.8 ± 4.1	nMAD CAM	51.5 ± 3.7 (3.1)
							49.7 ± 2.5 (1.7)						
DCM16-6	11.4	Q KF	180-212 150-180	17 ± 3 (15)	1.15 ± 0.05 1.17 ± 0.05	0.33 ± 0.02		1.38 ± 0.05	129	52.1 ± 1.6	26.3 ± 2.7	CAM	37.9 ± 2.0 (1.4)
							0.72 ± 0.06	2.09 ± 0.08	160	81.9 ± 2.9	39.1 ± 2.7	nMAD CAM	39.2 ± 2.2 (1.6)
							38.2 ± 1.6 (1.0)						
DCM16-11	11.4	Q KF	180-212 150-180	17 ± 3 (15)	0.93 ± 0.04 0.95 ± 0.05	0.36 ± 0.02		1.36 ± 0.05	70	52.8 ± 1.8	19.6 ± 3.2	CAM	38.8 ± 2.1 (1.6)
							0.72 ± 0.06	2.07 ± 0.08	45	76.2 ± 3.6	23.9 ± 3.4	nMAD CAM	36.8 ± 2.4 (1.9)
							38.1 ± 1.8 (1.2)						

DCM12-7	11.5	Q	180-212	18 ± 4 (18)	0.85 ± 0.04	0.45 ± 0.02		1.37 ± 0.05	58	62.7 ± 3.9	37.7 ± 5.1	CAM	45.8 ± 3.4 (3.0)
		KF	180-212				0.85 ± 0.07	2.18 ± 0.09	43	98.5 ± 11.7	31.8 ± 4.2	nMAD CAM	45.1 ± 5.7 (5.4)
45.7 ± 3.0 (2.6)													
DCM16-12	12.1	Q	180-212	30 ± 6 (21)	0.73 ± 0.05	0.31 ± 0.02		1.11 ± 0.05	52	69.6 ± 4.4	36.2 ± 5.2	nMAD CAM	62.8 ± 5.1 (3.9)
		KF	150-180		0.74 ± 0.05		0.72 ± 0.06	1.81 ± 0.08	128	98.4 ± 3.4	29.4 ± 2.9	nMAD CAM	54.2 ± 3.2 (2.2)
56.6 ± 3.3 (2.1)													
DCM12-9	12.2	Q	180-212	30 ± 6 (26)	0.65 ± 0.04	0.37 ± 0.02		1.08 ± 0.05	77	76.5 ± 28	23.6 ± 3.2	nMAD CAM	70.7 ± 4.3 (3.2)
		KF				0.85 ± 0.07	1.90 ± 0.09	56	121.6 ± 5.4	30.5 ± 3.5	nMAD CAM	64.1 ± 4.3 (3.2)	
67.8 ± 3.5 (2.4)													
DCM16-7	12.3	Q	180-212	30 ± 6 (33)	0.87 ± 0.05	0.38 ± 0.02		1.31 ± 0.06	59	81.9 ± 2.8	15.6 ± 3.5	CAM	62.4 ± 3.8 (2.7)
		KF	150-180		0.88 ± 0.06		0.72 ± 0.06	2.02 ± 0.09	46	131.5 ± 6.3	27.1 ± 3.8	nMAD CAM	65.0 ± 4.4 (3.4)
63.1 ± 3.2 (2.1)													
DCM12-10	12.3	Q	180-212	30 ± 6 (27)	0.81 ± 0.05	0.26 ± 0.02		1.13 ± 0.06	80	72.0 ± 2.9	25.8 ± 3.6	CAM	63.6 ± 4.2 (3.1)
		KF				0.85 ± 0.07	1.95 ± 0.09	64	119.1 ± 7.6	29.2 ± 4.3	nMAD CAM	61.1 ± 5.0 (4.2)	
63.0 ± 3.5 (2.3)													
DCM12-11	13	KF	180-212	25 ± 5 (25)	0.98 ± 0.06	0.38 ± 0.02	0.85 ± 0.07	2.24 ± 0.09	218	353.1 ± 11.3	16.3 ± 1.1	nMAD CAM	157.4 ± 8.8 (6.0)
DCM12-12	13	KF	180-212	25 ± 5 (24)	1.19 ± 0.07	0.49 ± 0.03	0.85 ± 0.07	2.56 ± 0.10	145	292.7 ± 8.8	12.2 ± 1.1	nMAD CAM	114.5 ± 6.1 (4.1)
DCM12-13	13	KF	180-212	25 ± 5 (24)	1.07 ± 0.06	0.45 ± 0.03	0.85 ± 0.07	2.38 ± 0.10	107	340.5 ± 14.0	15.0 ± 1.4	nMAD CAM	143.3 ± 8.7 (6.6)
DCM12-14	13	KF	180-212	25 ± 5 (18)	0.84 ± 0.05	0.39 ± 0.02	0.85 ± 0.07	2.11 ± 0.09	106	267.6 ± 11.4	21.9 ± 1.8	nMAD CAM	127.1 ± 8.0 (6.1)
DCM12-15	14	KF	180-212	30 ± 6 (20)	0.87 ± 0.05	0.38 ± 0.02	0.85 ± 0.07	2.13 ± 0.09	42	236.0 ± 14.5	20.9 ± 2.7	nMAD CAM	111.1 ± 8.6 (7.2)
DCM16-8	14	KF	150-180	30 ± 6 (25)	1.06 ± 0.07	0.33 ± 0.02	0.72 ± 0.06	2.14 ± 0.09	194	238.0 ± 8.9	20.2 ± 1.7	nMAD CAM	111.2 ± 6.7 (4.8)
DCM12-16	14	KF	180-212	30 ± 6 (18)	0.72 ± 0.05	0.35 ± 0.02	0.85 ± 0.07	1.96 ± 0.09	59	202.3 ± 7.3	11.8 ± 1.7	nMAD CAM	103.4 ± 6.3 (4.4)
DCM12-17	14	KF	180-212	30 ± 6 (21)	0.88 ± 0.05	0.34 ± 0.02	0.85 ± 0.07	2.09 ± 0.09	98	205.1 ± 6.3	13.3 ± 1.4	nMAD CAM	98.0 ± 5.6 (3.7)
DCM12-18	17	KF	180-212	30 ± 6 (21)	0.80 ± 0.05	0.34 ± 0.02	0.85 ± 0.07	2.01 ± 0.09	42	277.6 ± 15.5	12.8 ± 1.8	nMAD CAM	137.8 ± 10.2 (8.3)
DCM12-19	19	KF	180-212	30 ± 6 (27)	0.80 ± 0.05	0.37 ± 0.02	0.85 ± 0.07	2.05 ± 0.09	53	269.2 ± 13.8	14.9 ± 1.8	nMAD CAM	131.1 ± 9.2 (7.5)
DCM12-20	19.1	KF	180-212	30 ± 6 (25)	1.10 ± 0.07	0.42 ± 0.03	0.85 ± 0.07	2.40 ± 0.10	106	308.0 ± 9.9	12.6 ± 1.2	nMAD CAM	128.6 ± 7.3 (4.9)
DCM12-22	19.3	KF	180-212	30 ± 6 (25)	1.05 ± 0.07	0.40 ± 0.03	0.85 ± 0.07	2.33 ± 0.10	35	376.4 ± 27.1	13.5 ± 2.2	nMAD CAM	161.5 ± 13.9 (12.1)
DCM12-23	20	KF	180-212	50 ± 10 (26)	1.20 ± 0.10	0.52 ± 0.04	0.85 ± 0.07	2.59 ± 0.12	221	465.7 ± 21.2	16.2 ± 1.5	nMAD CAM	179.8 ± 12.6 (9.3)
DCM12-21	20	KF	180-212	50 ± 10 (22)	0.80 ± 0.07	0.32 ± 0.03	0.85 ± 0.07	2.00 ± 0.10	85	371.4 ± 17.5	14.1 ± 1.7	nMAD CAM	185.4 ± 13.3 (9.9)
DCM16-9	20	KF	150-180	50 ± 10 (26)	1.29 ± 0.11	0.63 ± 0.05	0.72 ± 0.06	2.67 ± 0.13	263	503.7 ± 19.9	17.1 ± 1.2	nMAD CAM	188.5 ± 12.6 (8.8)
DCM17-1	20-21	KF	180-212	50 ± 10 (27)	0.87 ± 0.07	0.44 ± 0.04	0.85 ± 0.07	2.18 ± 0.11	136	493.7 ± 36.4	13.1 ± 1.6	nMAD CAM	226.6 ± 20.5 (17.6)
DCM12-24	21	KF	180-212	50 ± 10 (27)	1.26 ± 0.10	0.61 ± 0.05	0.85 ± 0.07	2.75 ± 0.13	67	698.9 ± 58.6	15.8 ± 1.9	nMAD CAM	254.6 ± 25.2 (22.2)
DCM12-28	19-22	KF	180-212	35 ± 7 (36)	0.87 ± 0.06	0.50 ± 0.03	0.85 ± 0.07	2.25 ± 0.10	90	367.0 ± 25.9	13.2 ± 1.9	nMAD CAM	163.0 ± 13.9 (12.1)
DCM12-25	21-22	KF	125-180	30 ± 6 (29)	1.50 ± 0.09	0.62 ± 0.04	0.67 ± 0.08	2.83 ± 0.13	96	559.1 ± 37.2	17.5 ± 1.8	nMAD CAM	197.9 ± 16.3 (14.6)
										663.2 ± 48.7		MAR (275)	234.7 ± 20.7 (18.8)

DCM16-13	22.1	KF	90-150	30 ± 6 (25)	1.38 ± 0.09	0.70 ± 0.04	0.54 ± 0.07	2.66 ± 0.12	202	946.9 ± 55.1	11.1 ± 1.5	nMAD CAM	356.1 ± 27.1 (22.6)
										1011 ± 46		MAR (275)	380.3 ± 25.5 (19.8)
DCM12-26	22.2	KF	125-180	30 ± 6 (25)	1.58 ± 0.10	0.64 ± 0.04	0.67 ± 0.08	2.91 ± 0.13	78	897.6 ± 62.8	13.2 ± 1.6	nMAD CAM	308.5 ± 26.3 (22.6)
										912.6 ± 47.1		MAR (275)	313.2 ± 22.2 (17.6)
DCM16-14	22.2	KF	150-180	30 ± 6 (25)	1.56 ± 0.09	0.80 ± 0.05	0.72 ± 0.06	3.12 ± 0.12	145	831.9 ± 47.9	11.6 ± 1.3	nMAD CAM	266.2 ± 19.4 (16.2)
										1137 ± 47		MAR (275)	364.9 ± 22.0 (16.6)
DCM12-27	22.3	KF	125-180	30 ± 6 (25)	1.58 ± 0.10	0.74 ± 0.05	0.67 ± 0.08	3.01 ± 0.13	51	949.5 ± 80.3	11.1 ± 1.5	nMAD CAM	315.4 ± 30.6 (27.5)
										1068 ± 79		MAR (275)	354.4 ± 31.1 (27.2)
DCM14-12	22.3	KF	125-212	30 ± 6 (21)	1.49 ± 0.09	0.64 ± 0.04	0.74 ± 0.10	2.90 ± 0.14		871.3 ± 39.3		MAR (275)	301.0 ± 21.0 (15.5)

b, East profile													
DCM14-1	9.1	Q	180-212	25 ± 5 (24)	2.63 ± 0.14	0.62 ± 0.04	0.85 ± 0.07	3.32 ± 0.15	178	27.5 ± 0.6	22.7 ± 2.0	CAM	8.3 ± 0.4 (0.3)
		KF						4.13 ± 0.17	303	35.6 ± 0.6	17.8 ± 1.6	nMAD CAM	8.6 ± 0.4 (0.2)
		8.6 ± 0.4 (0.1)											
DCM14-2	9.2	Q	180-212	25 ± 5 (28)	2.26 ± 0.12	0.82 ± 0.05	0.85 ± 0.07	3.14 ± 0.13	96	58.0 ± 2.1	26.8 ± 3.1	nMAD CAM	18.5 ± 1.1 (0.8)
		KF						3.96 ± 0.15	124	65.0 ± 2.5	34.2 ± 3.0	nMAD CAM	16.4 ± 0.9 (0.7)
		17.5 ± 0.9 (0.5)											
DCM14-3	9.3	Q	180-212	25 ± 5 (26)	1.59 ± 0.09	0.76 ± 0.04	0.85 ± 0.07	2.42 ± 0.10	51	62.0 ± 4.2	34.0 ± 5.5	nMAD CAM	25.6 ± 2.1 (1.8)
		KF						3.24 ± 0.12	59	84.6 ± 5.4	43.7 ± 4.9	nMAD CAM	26.1 ± 2.0 (1.7)
		25.9 ± 1.6 (1.2)											
DCM14-4	9.3	Q	180-212	25 ± 5 (27)	1.15 ± 0.06	0.59 ± 0.03	0.85 ± 0.07	1.81 ± 0.07	40	76.1 ± 5.9	33.1 ± 6.9	nMAD CAM	42.0 ± 3.8 (3.4)
		KF						2.63 ± 0.10	183	126.8 ± 3.0	22.8 ± 2.0	nMAD CAM	48.2 ± 2.4 (1.5)
		46.9 ± 2.4 (1.5)											
DCM14-5	11	Q	180-212	20 ± 4 (22)	1.01 ± 0.05	0.56 ± 0.03	0.85 ± 0.07	1.65 ± 0.06	66	74.3 ± 3.4	23.5 ± 4.2	nMAD CAM	45.1 ± 2.8 (2.3)
		KF						2.46 ± 0.09	205	113.3 ± 2.9	27.3 ± 2.1	nMAD CAM	46.0 ± 2.3 (1.5)
		45.7 ± 2.1 (1.3)											
DCM14-6	11.2	Q	180-212	20 ± 4 (22)	0.95 ± 0.05	0.44 ± 0.02	0.85 ± 0.07	1.46 ± 0.06	61	80.3 ± 4.1	29.3 ± 4.5	CAM	55.1 ± 3.6 (3.0)
		KF						2.28 ± 0.09	150	138.7 ± 4.2	26.7 ± 2.5	nMAD CAM	61.0 ± 3.2 (2.2)
		58.2 ± 2.9 (1.9)											
DCM14-9	19	KF	180-212	30 ± 6 (24)	0.94 ± 0.06	0.47 ± 0.03	0.85 ± 0.07	2.28 ± 0.10	140	326.0 ± 8.2	10.9 ± 0.9	nMAD CAM	143.0 ± 7.6 (4.7)
DCM14-10	21	KF	125-212	60 ± 12 (35)	0.84 ± 0.07	0.38 ± 0.03	0.74 ± 0.10	1.99 ± 0.13	131	391.6 ± 10.6	7.8 ± 1.0	nMAD CAM	196.9 ± 14.6 (8.5)
DCM14-11	22.1	KF	125-212	30 ± 6 (23)	1.50 ± 0.09	0.44 ± 0.03	0.74 ± 0.10	2.70 ± 0.14		842.6 ± 42.8		MAR (275)	312.0 ± 23.5 (17.8)

Supplementary Table 8 | Dose rate data, equivalent dose (D_e) and overdispersion (OD) values, and optical ages for quartz (Q) and K-feldspar (KF) samples from the southeast, northwest and west profiles in East Chamber (**a–c**, respectively). Details are the same as for Supplementary Table 7, except that the FMM was applied to the D_e distributions of two quartz samples (DCE14-10 and DCE12-4) and one K-feldspar samples (DCE14-9), with the preferred ages highlighted in bold and italics.

EAST CHAMBER													
Sample	Layer	Mineral	Grain size	Water content (%)	External dose rate (Gy/kyr)		Internal dose rate (Gy/kyr)	Total dose rate (Gy/kyr)	No. of grains	D _e (Gy)	OD (%)	Age model	Optical age (kyr)
					Beta	Gamma							
a, Southeast profile													
DCE14-9	8	Q	180-212	30 ± 6 (28)	1.17 ± 0.08	0.40 ± 0.03	0.85 ± 0.07	1.63 ± 0.08	71	16.8 ± 0.4	12.5 ± 2.4	nMAD CAM	10.3 ± 0.6 (0.4)
		KF						2.44 ± 0.10	180	25.8 ± 1.1	61.7 ± 3.6	FMM-1 (74%)	10.5 ± 0.7 (0.6)
										80.0 ± 6.3		FMM-2 (26%)	27.9 ± 4.5 (4.3)
													10.4 ± 0.5 (0.3)
DCE12-1	9.2	Q	180-212	60 ± 12 (61)	0.87 ± 0.07	0.49 ± 0.04	0.85 ± 0.07	1.42 ± 0.08	279	14.7 ± 0.3	19.9 ± 1.6	nMAD CAM	10.3 ± 0.6 (0.4)
		KF						2.23 ± 0.10	36	–	115.3 ± 14.7	–	–
DCE12-2	9.3	Q	180-212	60 ± 12 (58)	1.18 ± 0.09	0.59 ± 0.05	0.85 ± 0.07	1.83 ± 0.10	56	–	99.4 ± 10.3	–	–
		KF						2.64 ± 0.12	46	36.4 ± 2.7	45.0 ± 6.4	nMAD CAM	13.8 ± 1.2 (1.1)
DCE12-3	11.1	Q	180-212	35 ± 7 (34)	0.53 ± 0.04	0.40 ± 0.03	0.85 ± 0.07	0.99 ± 0.05	89	–	105.8 ± 8.4	–	–
		KF						1.81 ± 0.09	164	112.7 ± 3.5	32.6 ± 2.3	nMAD CAM	62.3 ± 3.8 (2.4)
DCE14-10	11.1	Q	180-212	20 ± 4 (18)	0.95 ± 0.06	0.40 ± 0.02	0.85 ± 0.07	1.42 ± 0.07	74	2.2 ± 0.1	161 ± 14	FMM-1 (73%)	1.6 ± 0.1 (0.1)
										63.0 ± 4.3		FMM-2 (27%)	44.5 ± 3.8 (3.2)
		KF											
													43.1 ± 2.9 (2.5)
DCE16-1	11.1	Q	180-212	20 ± 4 (21)	0.97 ± 0.05	0.41 ± 0.02	0.72 ± 0.06	1.44 ± 0.06	53	58.1 ± 3.7	33.4 ± 5.4	nMAD CAM	40.4 ± 3.1 (2.7)
		KF	150-180		0.99 ± 0.05			2.15 ± 0.08	111	108.1 ± 3.8	28.7 ± 2.7	nMAD CAM	50.3 ± 2.8 (2.0)
													46.2 ± 2.5 (1.7)
DCE12-4	11.2	Q	180-212	20 ± 4 (16)	0.67 ± 0.04	0.39 ± 0.02	0.85 ± 0.07	1.12 ± 0.05	47	17.1 ± 3.3	115 ± 12	FMM-1 (6.2%)	15.3 ± 3.0 (3.0)
										32.0 ± 1.9		FMM-2 (49%)	28.6 ± 2.1 (1.8)
										84.2 ± 6.4		FMM-3 (45%)	75.4 ± 6.6 (6.0)
		KF						1.93 ± 0.08	169	152.7 ± 4.7	30.5 ± 2.2	nMAD CAM	79.0 ± 4.4 (3.0)
													77.9 ± 4.2 (3.2)
DCE14-11	11.2	Q	180-212	20 ± 4 (22)	0.71 ± 0.04	0.33 ± 0.02	0.85 ± 0.07	1.10 ± 0.04	50	65.2 ± 3.4	24.6 ± 4.5	nMAD CAM	59.5 ± 4.0 (3.4)
		KF						1.91 ± 0.08	53	113.1 ± 8.3	34.7 ± 5.7	nMAD CAM	59.1 ± 5.2 (4.5)
													59.9 ± 3.4 (2.6)

DCE14-14	11.2	Q	180-212	20 ± 4 (22)	0.79 ± 0.04	0.20 ± 0.01		1.04 ± 0.05	38	62.7 ± 3.9	26.8 ± 5.3	nMAD CAM	60.3 ± 4.6 (4.0)
		KF	150-180		0.80 ± 0.04				0.72 ± 0.06	1.75 ± 0.08	114	92.7 ± 3.4	25.6 ± 3.1
55.7 ± 3.1 (2.2)													
DCE14-12	11.3	Q	180-212	30 ± 6 (34)	0.79 ± 0.04	0.29 ± 0.02		1.13 ± 0.05	84	79.7 ± 3.1	27.4 ± 3.4	CAM	70.9 ± 4.7 (3.9)
		KF						0.85 ± 0.07	1.94 ± 0.09	81	151.6 ± 7.4	28.3 ± 4.3	nMAD CAM
73.4 ± 3.5 (3.0)													
DCE16-2	11.3	Q	180-212	30 ± 6 (34)	0.80 ± 0.06	0.30 ± 0.02		1.16 ± 0.06	51	85.8 ± 5.0	31.7 ± 5.0	CAM	74.3 ± 6.2 (4.8)
		KF	150-180		0.82 ± 0.06				0.72 ± 0.06	1.86 ± 0.09	62	146.1 ± 7.0	30.7 ± 3.8
76.2 ± 4.9 (3.2)													
DCE14-13	11.4	Q	180-212	30 ± 6 (20)	0.67 ± 0.04	0.28 ± 0.02		1.00 ± 0.05	31	103.0 ± 7.7	31.3 ± 6.6	nMAD CAM	103.2 ± 9.3 (7.8)
		KF	150-180		0.68 ± 0.04				0.72 ± 0.06	1.70 ± 0.08	59	176.6 ± 7.6	29.8 ± 4.0
103.5 ± 6.4 (4.6)													
DCE16-3	11.4	Q	180-212	30 ± 6 (15)	0.49 ± 0.04	0.27 ± 0.02		0.82 ± 0.05	39	103.6 ± 6.1	24.9 ± 5.2	CAM	127.1 ± 10.9 (8.1)
		KF	150-180		0.50 ± 0.05				0.72 ± 0.06	1.52 ± 0.08	97	171.0 ± 6.2	28.0 ± 2.7
118.5 ± 7.7 (4.8)													
DCE14-15	11.4	KF	180-212	30 ± 6 (18)	0.81 ± 0.05	0.29 ± 0.02	0.49 ± 0.05	1.60 ± 0.07	27	197.4 ± 14.4	14.7 ± 3.8	nMAD CAM	123.0 ± 10.9 (9.5)
DCE12-7	12.1	KF	180-212	30 ± 6 (20)	0.76 ± 0.05	0.49 ± 0.03	0.85 ± 0.07	2.13 ± 0.09	143	240.0 ± 8.5	19.9 ± 1.5	nMAD CAM	113.0 ± 6.6 (4.7)
DCE12-8	12.2	KF	180-212	30 ± 6 (28)	1.08 ± 0.07	0.66 ± 0.04	0.85 ± 0.07	2.60 ± 0.11	358	373.0 ± 9.6	15.5 ± 0.9	nMAD CAM	143.3 ± 7.4 (4.7)
DCE12-9	12.3	KF	180-212	30 ± 6 (29)	1.02 ± 0.07	0.61 ± 0.04	0.85 ± 0.07	2.50 ± 0.10	99	320.3 ± 12.7	13.3 ± 1.3	nMAD CAM	128.2 ± 7.6 (5.7)
DCE14-8	12.3	KF	180-212	30 ± 6 (29)	0.76 ± 0.04	0.56 ± 0.03	0.85 ± 0.07	2.19 ± 0.09	197	304.5 ± 8.5	13.0 ± 0.9	nMAD CAM	139.0 ± 7.3 (4.9)
DCE12-10	13	KF	180-212	35 ± 7 (34)	0.70 ± 0.05	0.48 ± 0.03	0.85 ± 0.07	2.05 ± 0.09	86	302.0 ± 15.2	16.6 ± 1.5	nMAD CAM	147.4 ± 10.3 (8.2)
DCE12-11	14	KF	180-212	50 ± 10 (30)	0.83 ± 0.07	0.54 ± 0.04	0.85 ± 0.07	2.24 ± 0.11	319	435.5 ± 13.5	16.6 ± 1.0	nMAD CAM	194.7 ± 11.8 (7.6)
DCE12-12	15	KF	180-212	60 ± 12 (31)	0.74 ± 0.06	0.51 ± 0.05	0.85 ± 0.07	2.12 ± 0.11	176	405.7 ± 17.3	17.4 ± 1.4	nMAD CAM	191.1 ± 13.1 (9.5)
DCE12-13	16	KF	180-212	60 ± 12 (36)	0.79 ± 0.07	0.57 ± 0.05	0.85 ± 0.07	2.23 ± 0.11	107	530.5 ± 32.4	17.1 ± 1.7	nMAD CAM	238.3 ± 19.4 (15.7)
DCE12-14	17.1	KF	180-212	35 ± 7 (30)	1.21 ± 0.08	0.73 ± 0.05	0.85 ± 0.07	2.81 ± 0.12	44	987.3 ± 136.1	17.2 ± 2.4	nMAD CAM	351.3 ± 51.2 (49.1)
										824.8 ± 42.7		MAR (275)	294.1 ± 20.5 (16.5)

b, Northwest profile														
DCE16-4	9?	Q	180-212	20 ± 5 (38)	1.01 ± 0.05	0.56 ± 0.03		1.62 ± 0.06	25	98.2 ± 6.9	21.7 ± 7.1	CAM	60.6 ± 4.9 (4.4)	
		KF	150-180		1.03 ± 0.05			0.72 ± 0.06	2.34 ± 0.09	53	146.3 ± 8.1	34.3 ± 4.1	nMAD CAM	62.6 ± 4.4 (3.7)
													61.7 ± 3.7 (2.8)	
DCE14-2	11?	Q	180-212	20 ± 5 (12)	0.75 ± 0.04	0.27 ± 0.02		1.08 ± 0.05	72	68.0 ± 3.6	34.1 ± 4.5	CAM	63.0 ± 4.4 (3.6)	
		KF			0.85 ± 0.07			1.90 ± 0.08	62	109.8 ± 5.8	35.0 ± 4.0	nMAD CAM	58.0 ± 4.2 (3.3)	
													60.8 ± 3.4 (2.5)	
DCE14-3	11.2	Q	180-212	20 ± 5 (21)	0.86 ± 0.05	0.29 ± 0.02		1.21 ± 0.05	75	83.9 ± 3.7	30.2 ± 3.8	CAM	69.2 ± 4.5 (3.4)	
		KF			0.85 ± 0.07			2.02 ± 0.09	104	131.5 ± 4.2	26.5 ± 2.5	nMAD CAM	64.8 ± 3.7 (2.5)	
													67.2 ± 3.5 (2.2)	
DCE16-5	11.2	Q	180-212	20 ± 5 (20)	0.74 ± 0.04	0.19 ± 0.02		0.99 ± 0.04	45	61.7 ± 3.6	31.8 ± 4.8	CAM	62.3 ± 4.6 (4.0)	
		KF	150-180		0.76 ± 0.05			0.72 ± 0.06	1.69 ± 0.07	131	100.9 ± 4.0	29.3 ± 3.2	nMAD CAM	59.6 ± 3.7 (2.7)
		KF	125-150		0.77 ± 0.04			0.57 ± 0.07	1.55 ± 0.08	90	91.3 ± 3.9	31.7 ± 3.6	nMAD CAM	58.9 ± 4.2 (3.0)
													61.1 ± 2.9 (1.8)	
DCE16-6	12.3	KF	150-180	30 ± 6 (25)	1.00 ± 0.06	0.58 ± 0.04	0.72 ± 0.06	2.33 ± 0.10	243	300.3 ± 9.2	16.5 ± 1.2	nMAD CAM	129.0 ± 7.1 (4.8)	
DCE16-7	13	KF	150-180	35 ± 7 (33)	0.82 ± 0.06	0.41 ± 0.03	0.72 ± 0.06	1.98 ± 0.09	55	292.3 ± 12.6	11.6 ± 1.7	nMAD CAM	147.7 ± 9.6 (7.2)	
DCE16-8	14 upper	KF	150-180	50 ± 10 (19)	0.86 ± 0.07	0.24 ± 0.02	0.72 ± 0.06	1.84 ± 0.10	46	409.0 ± 29.4	15.5 ± 2.1	nMAD CAM	222.1 ± 20.3 (17.0)	
DCE16-9	14 lower	KF	150-180	50 ± 10 (26)	0.98 ± 0.08	0.31 ± 0.04	0.72 ± 0.06	2.03 ± 0.11	119	398.1 ± 21.5	15.1 ± 1.8	nMAD CAM	195.8 ± 15.1 (11.8)	
DCE16-10	15	KF	150-180	60 ± 12 (55)	0.75 ± 0.07	0.37 ± 0.04	0.72 ± 0.06	1.86 ± 0.10	143	354.9 ± 17.3	21.6 ± 1.7	nMAD CAM	191.3 ± 14.2 (10.6)	
DCE16-11	15	KF	150-180	60 ± 12 (60)	0.59 ± 0.06	0.40 ± 0.04	0.72 ± 0.06	1.73 ± 0.09	175	335.9 ± 15.5	20.3 ± 1.6	nMAD CAM	193.8 ± 14.0 (10.3)	
DCE16-12	16	KF	150-180	60 ± 12 (56)	0.70 ± 0.06	0.30 ± 0.03	0.72 ± 0.06	1.75 ± 0.09	165	432.7 ± 24.3	22.9 ± 1.7	nMAD CAM	247.5 ± 19.7 (15.4)	
DCE14-4	17.1	KF	90-125	35 ± 7 (30)	1.80 ± 0.12	0.53 ± 0.04	0.49 ± 0.05	2.84 ± 0.13	34	729.5 ± 90.2	16.7 ± 2.7	nMAD CAM	256.9 ± 34.2 (32.3)	
										951.5 ± 63.9		MAR (275)	334.9 ± 28.3 (23.8)	
DCE14-5	17.2	KF	180-212	30 ± 6 (20)	1.73 ± 0.11	0.63 ± 0.04	0.85 ± 0.07	3.23 ± 0.13	23	1184 ± 360	21.9 ± 4.6	nMAD CAM	378.4 ± 116 (115)	
										1639 ± 105		MAR (275)	508.1 ± 39.9 (34.5)	
DCE14-6	17.2	KF	180-212	—	—	—	—	—	12	2077 ± 437		nMAD CAM	—	
c, West profile														
DCE14-1	11?	Q	180-212	15 ± 4 (16)	1.11 ± 0.06	0.41 ± 0.02		1.59 ± 0.07	71	31.1 ± 1.6	34.6 ± 4.2	nMAD CAM	19.6 ± 1.3 (1.1)	
		KF						0.85 ± 0.07	2.40 ± 0.09	176	58.9 ± 2.3	41.2 ± 3.1	nMAD CAM	24.5 ± 1.4 (1.0)
													22.1 ± 1.0 (0.8)	

Supplementary Table 9 | Dose rate data, equivalent doses (D_e) and overdispersion (OD) values, and optical ages for quartz (Q) and K-feldspar samples from the southeast profile in South Chamber. Details are the same as for Supplementary Table 7, except that the FMM was not applied to any of these samples.

SOUTH CHAMBER													
Sample	Layer	Mineral	Grain size	Water content (%)	External dose rate (Gy/kyr)		Internal dose rate (Gy/kyr)	Total dose rate (Gy/kyr)	No. of grains	D _e (Gy)	OD (%)	Age model	Optical age (kyr)
					Beta	Gamma							
Southeast profile													
DCS16-2	12	Q	180-212	30 ± 6 (34)	1.16 ± 0.07	0.53 ± 0.03	0.72 ± 0.06	1.75 ± 0.08	22	88.4 ± 4.9	0	CAM	50.5 ± 3.7 (3.2)
		KF	150-180		1.19 ± 0.08			2.47 ± 0.10	86	136.6 ± 6.2	27.6 ± 3.0	nMAD CAM	55.4 ± 3.6 (2.8)
													51.7 ± 3.1 (1.4)
DCS12-1	12	Q	180-212	30 ± 6 (29)	1.21 ± 0.07	0.58 ± 0.04	0.85 ± 0.07	1.85 ± 0.08	35	85.9 ± 5.2	20.1 ± 6.5	CAM	46.5 ± 3.6 (3.0)
		KF	180-212					2.67 ± 0.11	34	147.5 ± 11.8	38.0 ± 6.6	nMAD CAM	55.3 ± 5.1 (4.6)
													49.2 ± 3.6 (2.5)
DCS16-1	12	KF	150-180	30 ± 6 (22)	0.80 ± 0.05	0.29 ± 0.02	0.72 ± 0.06	1.84 ± 0.08	46	120.5 ± 10.2	46.6 ± 6.2	nMAD CAM	65.0 ± 6.4 (5.8)
DCS12-2	12	KF	150-180	30 ± 6 (26)	1.21 ± 0.08	0.38 ± 0.02	0.72 ± 0.06	2.34 ± 0.10	121	133.0 ± 3.7	29.8 ± 2.5	nMAD CAM	55.2 ± 3.0 (2.0)
DCS16-3	12	Q	180-212	30 ± 6 (26)	0.98 ± 0.06	0.36 ± 0.02	0.72 ± 0.06	1.40 ± 0.07	37	81.9 ± 7.1	37.0 ± 7.5	nMAD CAM	58.4 ± 5.9 (5.3)
		KF	150-180		1.01 ± 0.06			2.11 ± 0.09	58	131.6 ± 11.7	38.5 ± 4.1	nMAD CAM	62.3 ± 6.3 (5.6)
													58.9 ± 4.5 (2.1)
DCS12-3	12	Q	180-212	30 ± 6 (22)	0.96 ± 0.06	0.33 ± 0.02	0.85 ± 0.07	1.35 ± 0.06	7	74.0 ± 9.4	0	CAM	55.0 ± 7.6 (7.1)
		KF	180-212					2.16 ± 0.10	88	122.3 ± 3.9	26.8 ± 2.5	nMAD CAM	56.6 ± 3.3 (2.2)
													55.8 ± 4.9 (1.9)
DCS12-4	14	KF	180-212	30 ± 6 (28)	0.99 ± 0.06	0.43 ± 0.03	0.85 ± 0.07	2.29 ± 0.10	84	251.1 ± 15.8	24.1 ± 1.0	nMAD CAM	109.8 ± 8.6 (7.3)
DCS16-4	14	KF	150-180	30 ± 6 (29)	1.10 ± 0.07	0.40 ± 0.03	0.72 ± 0.06	2.24 ± 0.10	96	270.7 ± 17.5	28.0 ± 2.3	nMAD CAM	120.8 ± 9.6 (8.2)
DCS16-5	14	KF	150-180	30 ± 6 (30)	0.95 ± 0.06	0.43 ± 0.03	0.72 ± 0.06	2.13 ± 0.09	81	226.1 ± 17.2	32.0 ± 2.8	nMAD CAM	106.2 ± 9.5 (8.4)
DCS12-5	19	KF	180-212	30 ± 6 (28)	1.00 ± 0.06	0.46 ± 0.03	0.85 ± 0.07	2.30 ± 0.10	160	288.9 ± 12.8	23.2 ± 1.6	nMAD CAM	125.5 ± 8.1 (6.2)
DCS16-6	22	KF	150-180	30 ± 6 (30)	1.49 ± 0.09	0.62 ± 0.04	0.72 ± 0.06	2.85 ± 0.12	963.4 ± 66.6		MAR (275)		338.3 ± 28.0 (24.4)
									72	1044 ± 97	9.2 ± 2.2	nMAD CAM	366.4 ± 38.2 (35.0)

Supplementary Table 10 | Optical ages for Main Chamber (shown as ‘Unmodelled age ranges’) and corresponding Bayesian age model estimates (‘Modelled age ranges’), obtained using the OxCal 4.2.4 platform, at 68.2% and 95.4% probabilities. The modelled start and end ages for each stratigraphic layer (or combination of layers) are highlighted in bold and italics within the grey bands. The modelled intervals between stratigraphic layers (where used) are shown in grey and italics. All ages are given in years and rounded off to the closest decade.

Sample	UNMODELLED AGE RANGES (years)				MODELLED AGE RANGES (years)				Outlier probabilities (%)		Convergence values (%)
	68.2% probability		95.4% probability		68.2% probability		95.4% probability		prior	posterior	
	from	to	from	to	from	to	from	to			
<i>End of layer 9</i>					<i>24,000</i>	<i>18,560</i>	<i>28,710</i>	<i>13,420</i>			<i>98.2</i>
DCM12-1	28,920	26,460	30,150	25,240	29,050	26,490	28,710	25,090	5	3	99.3
DCM16-1	23,540	21,660	24,480	20,730	24,200	21,740	30,440	20,460	5	15	98.7
DCM14-7	29,170	27,550	29,980	26,740	29,220	27,550	32,270	26,600	5	3	99.6
DCM12-2	34,240	31,480	35,620	30,110	34,100	31,280	30,170	29,670	5	3	99.3
DCM16-2	38,450	35,210	40,060	33,600	36,830	33,490	35,520	28,220	5	13	98.8
DCM14-8	30,750	28,830	31,710	27,880	30,790	28,800	38,400	27,680	5	3	99.4
<i>Start of layer 9</i>					<i>38,080</i>	<i>34,770</i>	<i>39,430</i>	<i>32,350</i>			<i>99.7</i>
<i>End of layer 11</i>					<i>39,610</i>	<i>37,440</i>	<i>40,510</i>	<i>36,220</i>			<i>99.6</i>
DCM16-3	58,870	55,510	60,540	53,840	42,410	38,960	46,380	37,560	100	100	99.6
DCM16-4	43,100	39,560	44,860	37,800	41,832	39,420	43,590	38,400	5	2	99.8
DCM12-3	58,190	54,570	59,990	52,770	42,350	39,950	46,250	37,550	100	100	99.6
DCM12-5	40,720	38,160	42,000	36,890	40,850	38,930	41,880	37,900	5	2	99.8
DCM12-29	41,950	40,070	42,890	39,140	41,550	39,840	42,550	39,120	5	1	99.6
DCM16-5	49,720	44,840	52,150	42,410	42,670	38,980	46,540	37,790	50	76	99.8
DCM16-10	43,430	40,650	44,820	39,270	42,180	39,220	43,770	39,020	5	2	99.8
DCM12-6	51,420	48,020	53,110	46,330	42,330	38,920	47,130	37,520	50	96	99.5
DCM12-4	41,250	38,210	42,770	36,700	41,100	39,030	42,350	37,900	5	2	99.7
DCM16-6	39,230	37,170	40,260	36,150	40,220	38,390	41,060	37,370	5	4	99.8
DCM16-11	39,350	36,860	40,590	35,620	40,390	38,460	41,270	37,300	5	3	99.7
DCM12-7	48,300	43,040	50,920	40,420	42,900	39,520	46,000	38,600	5	7	99.7
<i>Start of layer 11</i>					<i>44,230</i>	<i>40,310</i>	<i>48,560</i>	<i>39,560</i>			<i>98.3</i>
<i>Interval</i>	<i>14,900</i>	<i>25,100</i>	<i>10,000</i>	<i>30,000</i>	<i>11,800</i>	<i>18,500</i>	<i>8,050</i>	<i>21,650</i>			<i>99.9</i>
<i>End of layer 12</i>					<i>61,070</i>	<i>55,230</i>	<i>64,290</i>	<i>52,400</i>			<i>98.6</i>
DCM16-12	58,730	54,510	60,830	52,410	62,000	56,860	66,170	54,820	5	17	99.1
DCM12-9	70,200	65,400	72,590	63,010	68,120	63,220	70,780	60,860	5	6	99.3
DCM16-7	65,230	61,030	67,320	58,940	65,030	61,190	66,950	59,190	5	3	99.6

DCM12-10	65,250	60,750	67,490	58,510	65,050	61,050	67,100	58,990	5	3	99.6
Start of layer 12					71,100	64,080	77,420	61,740			98.6
Interval	19,800	40,200	10,000	50,000	23,400	35,300	16,100	39,600			100
End of layer 14					103,070	93,470	106,520	86,510			98.4
DCM12-15	118,290	103,910	125,470	96,730	103,070	101,190	116,080	97,420	5	4	99.3
DCM16-8	116,000	106,410	120,780	101,620	110,180	102,600	115,600	99,430	5	5	99.2
DCM12-16	107,800	99,010	112,180	94,620	107,210	100,330	110,960	96,730	5	3	99.4
DCM12-17	101,700	94,310	105,390	90,620	104,730	97,790	108,030	93,860	5	6	99.3
Start of layer 14					115,930	105,010	123,090	101,480			98.4
Interval	9,800	30,200	0	40,000	9,500	23,500	0	43,190			100
End of layer 17					134,530	122,810	139,170	116,010			98.6
DCM12-18	146,090	129,510	154,360	121,240	143,500	132,070	150,190	126,490	5	4	99.2
DCM14-9	147,700	138,310	152,380	133,620	145,420	136,460	150,200	132,520	5	4	99.2
DCM12-19	138,590	123,610	146,070	116,140	140,610	129,840	145,950	124,070	5	4	99.1
DCM12-20	133,500	123,710	138,380	118,820	137,550	128,350	141,770	123,680	5	6	98.9
DCM12-22	173,586	149,420	185,650	137,360	149,860	134,930	160,000	130,000	5	6	98.6
Start of layer 19					156,020	139,760	167,430	135,350			98.0
Interval	9,800	30,200	0	40,000	11,700	29,300	3,500	36,500			100
End of layer 20					180,690	162,460	187,640	151,730			98.8
DCM12-21	194,290	176,710	203,060	167,940	195,200	178,800	203,572	171,480	5	5	97.5
DCM12-23	189,090	170,510	198,360	161,240	191,480	175,110	199,970	167,480	5	5	97.2
DCM16-9	197,290	179,710	206,060	170,940	197,700	180,750	206,270	173,280	5	5	97.5
DCM14-10	205,390	188,410	213,860	179,940	205,640	188,350	213,690	180,390	5	5	97.7
DCM17-1	244,080	209,120	261,520	191,680	237,530	203,780	251,970	188,720	5	5	96.4
DCM12-24	276,770	232,430	298,900	210,300	25,160	212,570	268,650	193,260	5	5	95.1
Start of layer 21					271,910	228,810	292,660	207,150			96.9
Interval	9,600	50,400	0	70,000	19,800	55,200	542	139,450			100
End of layer 22					311,630	272,160	326,460	246,760			96.5
DCM14-11	329,780	294,230	347,520	276,480	332,310	302,030	346,580	287,150	5	5	96.9
DCM16-13	384,180	346,430	403,020	327,590	364,940	331,240	380,690	316,450	5	5	95.8
DCM12-26	330,780	295,630	348,320	278,080	333,180	302,970	347,430	287,760	5	5	97.0
DCM16-14	381,480	348,320	398,030	331,780	365,660	333,930	379,960	318,810	5	6	95.9
DCM12-27	381,860	326,940	409,270	299,530	358,440	319,240	378,300	301,690	5	5	96.6
DCM14-12	316,480	285,520	331,930	270,070	324,270	294,940	336,890	281,970	5	5	96.4
Start of layer 22					384,030	344,750	406,300	325,680			92.7

Supplementary Table 11 | Optical ages for East Chamber (shown as ‘Unmodelled age ranges’) and corresponding Bayesian age model estimates (‘Modelled age ranges’), obtained using the OxCal 4.2.4 platform, at 68.2% and 95.4% probabilities. The modelled start and end ages for each stratigraphic layer are highlighted in bold and italics within the grey bands. The modelled intervals between stratigraphic layers (where used) are shown in grey and italics. All ages are given in years and rounded off to the closest decade.

Sample	UNMODELLED AGE RANGES (years)				MODELLED AGE RANGES (years)				Outlier probabilities (%)		Convergence values (%)
	68.2% probability		95.4% probability		68.2% probability		95.4% probability		prior	posterior	
	from	to	from	to	from	to	from	to			
End of layer 11.1					46,220	39,210	47,820	28,520			97.4
DCE14-10	45,610	40,690	48,060	38,240	46,560	42,520	48,300	40,030	5	5	99.5
DCE16-1	47,850	44,450	49,540	42,760	47,190	44,050	48,800	42,530	5	5	99.5
Start of layer 11.1					50,400	44,730	55,080	43,360			99.1
End of layer 11.2					58,790	53,140	60,260	48,810			99.2
DCE16-5	62,330	58,330	64,320	56,340	61,040	57,640	62,940	56,080	5	5	99.6
DCE14-11	62,500	57,260	65,110	54,650	60,870	57,090	63,140	55,250	5	5	99.6
DCE14-14	57,900	53,480	60,100	51,280	59,530	55,680	61,090	53,380	5	5	99.4
Start of layer 11.2					63,940	58,450	68,860	56,880			99.1
End of layer 11.3					75,260	68,030	77,480	62,640			99.0
DCE14-12	76,450	70,350	79,490	67,320	76,800	71,810	79,250	69,240	5	5	99.5
DCE16-2	79,390	73,070	82,540	69,930	77,770	72,620	80,510	70,140	5	5	99.5
Start of layer 11.3					81,750	73,820	89,640	71,250			98.4
<i>Interval</i>	<i>19,800</i>	<i>40,200</i>	<i>10,000</i>	<i>50,000</i>	<i>20,400</i>	<i>33,400</i>	<i>12,700</i>	<i>38,200</i>			<i>100</i>
End of layer 11.4					111,590	101,000	114,940	94,230			97.6
DCE14-13	108,140	98,870	112,760	94,240	113,470	104,970	116,620	100,440	5	5	98.6
DCE16-3	123,260	113,750	128,000	109,000	118,870	110,790	123,200	107,590	5	5	98.9
DCE14-15	132,490	113,510	141,960	104,050	119,040	109,220	125,220	105,000			99.0
DCE12-7	117,700	108,310	122,380	103,620	116,300	109,000	120,170	105,400	5	5	99.3
Start of layer 12.1					124,410	113,490	130,550	110,100			98.3
End of layer 12.2					135,150	125,300	138,100	119,130			98.4
DCE12-8	148,000	138,610	152,680	133,920	140,580	133,520	144,570	130,580	5	5	99.1
DCE12-9	133,900	122,510	139,580	116,830	137,380	129,600	140,410	124,860	5	5	99.3
DCE14-8	143,900	134,110	148,780	129,220	139,410	132,650	143,200	129,400	5	5	99.4
DCE16-6	133,800	124,210	138,580	119,440	137,030	129,730	139,900	125,280	5	5	99.2
Start of layer 12.3					143,690	135,360	148,640	132,380			98.9

End of layer 13					150,710	140,780	155,660	136,670			98.7
DCE12-10	155,590	139,210	163,760	131,040	154,180	144,250	159,690	140,070	5	5	99.2
DCE16-7	154,890	140,510	162,070	133,330	154,100	144,460	159,230	140,280	5	5	99.2
Start of layer 13					159,440	146,470	169,760	141,820			97.0
Interval	29,600	70,400	10,000	90,000	24,800	42,800	13,400	49,800			100
End of layer 14					194,250	182,300	199,180	174,500			94.5
DCE12-11	202,290	187,110	209,870	179,540	195,660	186,220	200,030	181,330	5	5	99.2
DCE16-8	239,080	205,120	256,020	188,180	195,990	186,190	200,710	180,900	5	5	99.1
DCE16-9	207,590	184,020	219,350	172,260	195,810	185,750	200,360	180,540	5	5	99.2
Start of layer 14					198,030	188,640	202,610	184,020			98.4
End of layer 15					201,520	192,030	206,210	187,560			98.3
DCE12-12	200,590	181,610	210,060	172,150	203,680	194,260	208,530	189,880	5	5	99.2
DCE16-10	201,890	180,720	212,450	170,150	203,770	194,360	208,960	189,900	5	5	99.2
DCE16-11	204,090	183,510	214,350	173,250	203,880	194,360	209,010	190,010	5	5	99.2
Start of layer 15					207,460	195,990	214,740	191,450			94.9
Interval	29,800	50,200	20,000	60,000	27,300	44,300	18,500	52,500			100.0
End of layer 16					247,770	229,400	255,440	220,350			96.8
DCE12-13	253,980	222,620	269,630	206,970	254,580	236,070	264,320	227,710	5	5	98.5
DCE16-12	262,880	232,120	278,230	216,770	255,770	237,060	265,920	228,400	5	5	98.6
Start of layer 16					267,370	241,460	285,460	232,790			96.1
End of layer 17.1					300,740	269,010	314,210	253,490			94.4
DCE12-14	310,580	277,620	327,030	261,180	308,050	278,990	321,010	266,750	5	5	97.6
DCE14-4	358,670	311,130	382,390	287,410	311,750	280,910	328,230	266,900	5	5	97.1
Start of layer 17.1					320,100	284,950	339,390	270,410			88.4
Interval	198,000	402,000	100,000	500,000	175,000	254,000	140,000	287,000			100.0
layer 17.2											
DCE14-5	542,550	473,650	576,940	439,260	547,690	487,340	577,860	458,850	5	5	80.3

Supplementary Table 12 | Optical ages for South Chamber (shown as ‘Unmodelled age ranges’) and corresponding Bayesian age model estimates (‘Modelled age ranges’), obtained using the OxCal 4.2.4 platform, at 68.2% and 95.4% probabilities. The modelled start and end ages for each stratigraphic layer (or combination of layers) are highlighted in bold and italics within the grey bands. The modelled intervals between stratigraphic layers (where used) are shown in grey and italics. All ages are given in years and rounded off to the closest decade.

Sample	UNMODELLED AGE RANGES (years)				MODELLED AGE RANGES (years)				Outlier probabilities (%)		Convergence values (%)
	68.2% probability		95.4% probability		68.2% probability		95.4% probability		prior	posterior	
	from	to	from	to	from	to	from	to			
End of layer 12					52,420	46,250	54,530	39,070			97.4
DCS16-2	53,180	50,300	54,615	48,870	53,580	50,740	55,040	49,320	5	5	99.6
DCS12-1	51,670	46,650	54,170	44,150	53,640	49,040	55,620	46,460	5	5	99.3
DCS12-2	57,220	53,220	59,210	51,230	56,990	53,230	58,890	51,390	5	5	99.5
DCS16-3	61,020	56,840	63,100	54,760	59,980	55,770	62,050	53,760	5	5	99.4
DCS12-3	57,640	53,940	59,481	52,100	57,350	53,820	59,140	52,120	5	5	99.5
DCS16-1	70,720	59,210	76,455	53,470	61,460	53,720	67,190	50,800	5	5	99.2
Start of layer 12					64,710	56,620	73,140	54,290			98.2
<i>Interval</i>	<i>19,600</i>	<i>60,400</i>	<i>0</i>	<i>80,000</i>	<i>32,200</i>	<i>53,000</i>	<i>17,600</i>	<i>60,000</i>			<i>100</i>
End of layer 14					114,900	96,170	120,100	82,130			98.3
DCS12-4	117,090	102,510	124,367	95,230	119,410	107,350	124,550	100,390	5	5	99.1
DCS16-4	128,990	112,610	137,163	104,440	124,490	111,820	131,840	105,930	5	5	99.1
DCS16-5	114,590	97,810	122,962	89,440	119,220	105,610	124,470	97,550	5	5	99.0
DCS12-5	131,690	119,310	137,872	113,130	126,780	114,980	133,240	110,350	5	5	99.0
Start of layer 19					136,200	116,840	161,760	111,140			97.6
<i>Interval</i>	<i>97,000</i>	<i>403,000</i>	<i>-50,000</i>	<i>550,000</i>	<i>111,000</i>	<i>217,500</i>	<i>30,000</i>	<i>241,500</i>			<i>100</i>
End of layer 22					345,400	252,460	366,850	173,670			93.6
DCS16-6	362,670	313,930	386,989	289,610	356,030	303,850	380,500	279,250	5	5	96.4
Start of layer 22					396,600	304,820	515,420	275,950			90.7

Supplementary Table 13 | CQL code for the Bayesian age model used for Main Chamber (Extended Data Fig. 6).

```
Options()
{
  Plot()
  {
    Outlier_Model("General",T(5),U(0,4),"t");
  };
  Sequence()
  {
    Boundary("Start 1");
    Phase("Layer 22")
    {
      C_Date("DCM14-12", calBP(301000), 15500)
      {
        Outlier(0.05);
      };
      C_Date("DCM12-27", calBP(354400), 27500)
      {
        Outlier(0.05);
      };
      C_Date("DCM16-14", calBP(364900), 16600)
      {
        Outlier(0.05);
      };
      C_Date("DCM12-26", calBP(313200), 17600)
      {
        Outlier(0.05);
      };
      C_Date("DCM16-13", calBP(365300), 18900)
      {
        Outlier(0.05);
      };
      C_Date("DCM14-11", calBP(312000), 17800)
      {
        Outlier(0.05);
      };
      Boundary("End 1");
      Difference("difference 1 top and 1 bottom",
"End 1", "Start 1");
      Interval(N(30000,20000));
      Boundary("Start 2");
      Phase("Layer 21-20")
      {
        C_Date("DCM12-24", calBP(254600), 22200)
        {
          Outlier(0.05);
        };
        C_Date("DCM17-1", calBP(226600), 17500)
        {
          Outlier(0.05);
        };
        C_Date("DCM14-10", calBP(196900), 8500)
        {
          Outlier(0.05);
        };
        C_Date("DCM16-9", calBP(188500), 8800)
        {
          Outlier(0.05);
        };
        C_Date("DCM12-23", calBP(179800), 9300)
        {
          Outlier(0.05);
        };
        C_Date("DCM12-21", calBP(185500), 8800)
        {
          Outlier(0.05);
        };
        Boundary("End 2");
        Difference("difference 2 top and 2 bottom",
"End 2", "Start 2");
        Interval(N(20000,10000));
        Boundary("Start 3");
        Phase("Layers 19-17")
        {
          C_Date("DCM12-22", calBP(161500), 12100)
          {
            Outlier(0.05);
          };
          C_Date("DCM12-20", calBP(128600), 4900)
          {
            Outlier(0.05);
          };
          C_Date("DCM12-19", calBP(131100), 7500)
          {
            Outlier(0.05);
          };
          C_Date("DCM14-9", calBP(143000), 4700)
          {
            Outlier(0.05);
          };
          C_Date("DCM12-18", calBP(137800), 8300)
          {
            Outlier(0.05);
          };
          Boundary("End 3");
          Difference("difference 3 top and 3 bottom",
"End 3", "Start 3");
          Interval(N(20000,10000));
          Boundary("Start 4");
        };
      };
    };
  };
};
```

```

Phase("Layer 14")
{
  C_Date("DCM12-17", calBP(98000), 3700)
  {
    Outlier(0.05);
  };
  C_Date("DCM12-16", calBP(103400), 4400)
  {
    Outlier(0.05);
  };
  C_Date("DCM16-8", calBP(111200), 4800)
  {
    Outlier(0.05);
  };
  C_Date("DCM12-15", calBP(111100), 7200)
  {
    Outlier(0.05);
  };
};
Boundary("End 4");
Difference("difference 4 top and 4 bottom",
"End 4", "Start 4");
Interval(N(30000,10000));
Boundary("Start 5");
Phase("Layer 12")
{
  C_Date("DCM12-10", calBP(63000), 2250)
  {
    Outlier(0.05);
  };
  C_Date("DCM16-7", calBP(63130), 2100)
  {
    Outlier(0.05);
  };
  C_Date("DCM12-9", calBP(67800), 2400)
  {
    Outlier(0.05);
  };
  C_Date("DCM16-12", calBP(56620), 2110)
  {
    Outlier(0.05);
  };
};
Boundary("End 5");
Difference("difference 5 top and 5 bottom",
"End 5", "Start 5");
Interval(N(20000,5000));
Boundary("Start 6");
Phase("Layer 11")
{
  C_Date("DCM12-7", calBP(45670), 2630)
  {
    Outlier(0.05);
  };
};

```

```

C_Date("DCM16-11", calBP(38100), 1245)
{
  Outlier(0.05);
};
C_Date("DCM16-6", calBP(38200), 1030)
{
  Outlier(0.05);
};
C_Date("DCM12-4", calBP(39730), 1520)
{
  Outlier(0.05);
};
C_Date("DCM12-6", calBP(49720), 1700)
{
  Outlier(0.5);
};
C_Date("DCM16-10", calBP(42040), 1390)
{
  Outlier(0.05);
};
C_Date("DCM16-5", calBP(47280), 2440)
{
  Outlier(0.5);
};
C_Date("DCM12-29", calBP(41010), 940)
{
  Outlier(0.05);
};
C_Date("DCM12-5", calBP(39440), 1280)
{
  Outlier(0.05);
};
C_Date("DCM12-3", calBP(56380), 1810)
{
  Outlier(1.00);
};
C_Date("DCM16-4", calBP(41330), 1770)
{
  Outlier(0.05);
};
C_Date("DCM16-3", calBP(57190), 1680)
{
  Outlier(1.00);
};
};
Boundary("End 6");
Difference("difference 6 top and 6 bottom",
"End 6", "Start 6");
Boundary("Start 7");
Phase("Layer 9")
{
  C_Date("DCM14-8", calBP(29790), 960)
  {
    Outlier(0.05);
  };
};

```

```

};
C_Date("DCM16-2", calBP(36830), 1620)
{
    Outlier(0.05);
};
C_Date("DCM12-2", calBP(32860), 1380)
{
    Outlier(0.05);
};
C_Date("DCM14-7", calBP(28360), 810)
{
    Outlier(0.05);
};
C_Date("DCM16-1", calBP(22600), 940)
{
    Outlier(0.05);
};
C_Date("DCM12-1", calBP(27690), 1230)
{
    Outlier(0.05);
};
};
Boundary("End 7");
Difference("difference 7 top and 7 bottom",
"End 7", "Start 7");
};
};
Boundary("End 6");
Difference("difference 6 top and 6 bottom",
"End 6", "Start 6");
Boundary("Start 7");
Phase("Layer 9")

```

```

{
    C_Date("DCM14-8", calBP(29790), 960)
    {
        Outlier(0.05);
    };
    C_Date("DCM16-2", calBP(36830), 1620)
    {
        Outlier(0.05);
    };
    C_Date("DCM12-2", calBP(32860), 1380)
    {
        Outlier(0.05);
    };
    C_Date("DCM14-7", calBP(28360), 810)
    {
        Outlier(0.05);
    };
    C_Date("DCM16-1", calBP(22600), 940)
    {
        Outlier(0.05);
    };
    C_Date("DCM12-1", calBP(27690), 1230)
    {
        Outlier(0.05);
    };
    };
    Boundary("End 7");
    Difference("difference 7 top and 7 bottom",
"End 7", "Start 7");
    };
};

```

Supplementary Table 14 | CQL code for the Bayesian age model used for East Chamber
(Extended Data Fig. 7).

```
Options()
{
  Plot()
  {
    Outlier_Model("General",T(5),U(0,4),"t");
  };
  Sequence()
  {
    Phase("Layer 17.2")
    {
      C_Date("DCE14-5", calBP(508100), 34500)
      {
        Outlier(0.05);
      };
    };
    Interval(N(300000,100000));
    Boundary("Start 2");
    Phase("Layer 17.1")
    {
      C_Date("DCE14-4", calBP(334900), 23800)
      {
        Outlier(0.05);
      };
      C_Date("DCE12-14", calBP(294100), 16500)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 2");
    Difference("difference 2 top and 2 bottom",
"End 2", "Start 2");
    Boundary("Start 3");
    Phase("Layer 16")
    {
      C_Date("DCE16-12", calBP(247500), 15400)
      {
        Outlier(0.05);
      };
      C_Date("DCE12-13", calBP(238300), 15700)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 3");
    Difference("difference 3 top and 3 bottom",
"End 3", "Start 3");
    Interval(N(40000,10000));
    Boundary("Start 4");
    Phase("Layer 15")
    {
      C_Date("DCE16-11", calBP(193800), 10300)
      {
        Outlier(0.05);
      };
    };
    C_Date("DCE12-12", calBP(191100), 9500)
    {
      Outlier(0.05);
    };
    Boundary("End 4");
    Difference("difference 4 top and 4 bottom",
"End 4", "Start 4");
    Boundary("Start 5");
    Phase("Layer 14")
    {
      C_Date("DCE16-9", calBP(195800), 11800)
      {
        Outlier(0.05);
      };
      C_Date("DCE16-8", calBP(222100), 17000)
      {
        Outlier(0.05);
      };
      C_Date("DCE12-11", calBP(194700), 7600)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 5");
    Difference("difference 5 top and 5 bottom",
"End 5", "Start 5");
    Interval(N(50000,20000));
    Boundary("Start 6");
    Phase("Layer 13")
    {
      C_Date("DCE16-7", calBP(147700), 7200)
      {
        Outlier(0.05);
      };
      C_Date("DCE12-10", calBP(147400), 8200)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 6");
    Difference("difference 6 top and 6 bottom",
"End 6", "Start 6");
    Boundary("Start 7");
  }
}
```

```

Phase("Layer 12.3-12.2")
{
  C_Date("DCE16-6", calBP(129000), 4800)
  {
    Outlier(0.05);
  };
  C_Date("DCE14-8", calBP(139000), 4900)
  {
    Outlier(0.05);
  };
  C_Date("DCE12-9", calBP(128200), 5700)
  {
    Outlier(0.05);
  };
  C_Date("DCE12-8", calBP(143300), 4700)
  {
    Outlier(0.05);
  };
  Boundary("End 7");
  Difference("difference 7 top and 7 bottom",
"End 7", "Start 7");
  Boundary("Start 8");
  Phase("Layer 12.1/Layer 11.4")
  {
    C_Date("DCE12-7", calBP(113000), 4700)
    {
      Outlier(0.05);
    };
    C_Date("DCE14-15", calBP(123000), 9500)
    {
      Outlier(0.05);
    };
    C_Date("DCE16-3", calBP(118500), 4760)
    {
      Outlier(0.05);
    };
    C_Date("DCE14-13", calBP(103500), 4640)
    {
      Outlier(0.05);
    };
  };
  Boundary("End 8");
  Difference("difference 8 top and 8 bottom",
"End 8", "Start 8");
  Interval(N(30000,10000));
  Boundary("Start 9");
  Phase("Layer 11.3")
  {

```

```

  C_Date("DCE16-2", calBP(76230), 3160)
  {
    Outlier(0.05);
  };
  C_Date("DCE14-12", calBP(73400), 3050)
  {
    Outlier(0.05);
  };
  Boundary("End 9");
  Difference("difference 9 top and 9 bottom",
"End 9", "Start 9");
  Interval(N(10000,10000));
  Boundary("Start 10");
  Phase("Layer 11.2")
  {
    C_Date("DCE14-14", calBP(55690), 2210)
    {
      Outlier(0.05);
    };
    C_Date("DCE14-11", calBP(59880), 2620)
    {
      Outlier(0.05);
    };
    C_Date("DCE16-5", calBP(60330), 2000)
    {
      Outlier(0.05);
    };
  };
  Boundary("End 10");
  Difference("difference 10 top and 10 bottom",
"End 10", "Start 10");
  Boundary("Start 11");
  Phase("Layer 11.1")
  {
    C_Date("DCE16-1", calBP(46150), 1700)
    {
      Outlier(0.05);
    };
    C_Date("DCE14-10", calBP(43150), 2460)
    {
      Outlier(0.05);
    };
  };
  Boundary("End 11");
  Difference("difference 11 top and 11 bottom",
"End 11", "Start 11");
  };
};

```


Supplementary Table 15 | CQL code for the Bayesian age model used for South Chamber (Extended Data Fig. 8a).

```
Options()
{
  Plot()
  {
    Outlier_Model("General",T(5),U(0,4),"t");
  };
  Sequence()
  {
    Boundary("Start 1");
    Phase("Layer 22")
    {
      C_Date("DCS16-6", calBP(338300), 24400)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 1");
    Difference("difference 1 top and 1 bottom",
"End 1", "Start 1");
    Interval(N(250000,150000));
    Boundary("Start 2");
    Phase("Layers 19 and 14")
    {
      C_Date("DCS12-5", calBP(125500), 6200)
      {
        Outlier(0.05);
      };
      C_Date("DCS16-5", calBP(106200), 8400)
      {
        Outlier(0.05);
      };
      C_Date("DCS16-4", calBP(120800), 8200)
      {
        Outlier(0.05);
      };
      C_Date("DCS12-4", calBP(109800), 7300)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 2");
    Difference("difference 2 top and 2 bottom",
"End 2", "Start 2");
    Interval(N(40000,20000));
    Boundary("Start 3");
    Phase("Layer 12")
    {
      C_Date("DCS16-1", calBP(64960), 5760)
      {
        Outlier(0.05);
      };
      C_Date("DCS12-3", calBP(55790), 1850)
      {
        Outlier(0.05);
      };
      C_Date("DCS16-3", calBP(58930), 2090)
      {
        Outlier(0.05);
      };
      C_Date("DCS12-2", calBP(55220), 2000)
      {
        Outlier(0.05);
      };
      C_Date("DCS12-1", calBP(49160), 2510)
      {
        Outlier(0.05);
      };
      C_Date("DCS16-2", calBP(51740), 1440)
      {
        Outlier(0.05);
      };
    };
    Boundary("End 3");
    Difference("difference 3 top and 3 bottom",
"End 3", "Start 3");
  };
};
```

Supplementary Figure 1 | **a–c**, OSL decay curves (initial 1 s of stimulation) for a representative sample of quartz grains from DCM12-29, DCM14-12 and DCS16-2, respectively, spanning the range of observed luminescence sensitivities (i.e., their relative brightness). **d–f**, Corresponding dose-response curves for the grains shown in **a–c**. Each curve in **a–c** or data point in **d–f** represents a single measurement. The error bars in **d–f** are at 1σ .

Supplementary Figure 2 | pIRIR decay curves for 6 grains of K-feldspar from sample DCM12-4. Each curve represents a single measurement.

Supplementary Figure 3 | **a**, Single-grain K-feldspar dose-response curves shown in different colours for each sample. **b**, Least-squares re-normalised standardised growth curve (SGC), based on the data shown in **a**. The grey band represents the natural pIRIR signal for DCE14-6. **c**, Radial plot of the ratios between the measured and expected L_x/T_x values obtained from the SGC in **b**, with the corresponding frequency distribution (kernel density estimate) displayed in the right-hand panel¹⁰⁵. **d**, Comparison of SAR and SGC D_e values. The dashed line represents the 1:1 ratio. **e**, Radial plot of the ratios of the SGC and SAR-derived D_e values. **f–h**, Radial plots of the distributions of SAR and SGC D_e values (black and red circles, respectively) for samples DCM12-7, DCE14-1 and DCS12-3, respectively. **i**, Radial plot of re-normalised L_n/T_n ratios for sample DCM12-21. The rejected outliers (open circles) were determined by the nMAD method. **j**, Same re-normalised L_n/T_n ratios as in **i**, projected onto the single-grain pIRIR SGC in **b**. The accepted and rejected values are the same as in **i**. The nMAD CAM value is shown as a black line and the dashed lines represent the corresponding 1σ errors. Each data point shown in **a–j** is a single observation. All error bars are at 1σ .

Supplementary Figure 4 | **a**, IRSL and MET-pIRIR decay curves for a single aliquot of sample DCM12-25. Each curve represents a single measurement. **b–f**, Re-normalised ratios ($\frac{L_x/T_x}{L_r/T_r}$) plotted as a function of regenerative dose at infrared stimulation temperatures of 50, 100, 150, 200 and 275°C, respectively. The black lines in **b–f** represent the best-fit curves, and the red dashed lines are the 95.4% confidence intervals for the best-fit curves. Each data point in **b–f** is a single observation and all error bars are at 1σ .

Supplementary Figure 5 | **a–d**, Weighted mean ratios of measured to given dose (‘dose recovery ratios’) for single grains of K-feldspar from four samples, plotted as a function of T_n threshold intensity. Error bars are at 1σ and dashed lines indicate a ratio of unity. The number of ratios (n) included in the weighted mean ratio at each T_n threshold intensity from left to right in **a** are 16, 13, 10, 6 and 3, in **b** 132, 106, 79, 53 and 26, in **c** 194, 155, 116, 78 and 39, and in **d** 82, 66, 49, 33 and 16. **e**, Weighted mean dose recovery ratios for single grains of K-feldspar from 7 samples, plotted as a function of given dose. The number of ratios (n) included in the weighted mean ratio for each sample range between 6 (DCE12-2) and 163 (DCM12-6); error bars are at 1σ . **f**, Fading rates (g-values) for single-aliquot MET-pIRIR signals from DCM12-12, plotted against infrared stimulation temperature. Each data point represents the weighted mean fading rate of 12 g-values; error bars are at 1σ . **g, h**, Ratios of delayed to prompt pIRIR signals (‘fading ratios’) for individual grains of K-feldspar from samples DCM12-12 and DCM12-21. Each data point in **g** and **h** represents a single observation.

Supplementary Figure 6 | a–i, Weighted mean SGC D_e values or weighted mean re-normalised L_n/T_n ratios plotted as a function of T_n threshold for 9 samples, three from each chamber; the sample number is shown in each panel. The dashed lines represent the final weighted mean D_e value or weighted mean re-normalised L_n/T_n ratio used to calculate an age for each sample. All error bars are at 1σ .

Supplementary Figure 7 | Representative single-grain quartz D_e distributions for samples from **a, b**, Main Chamber, **c-f**, East Chamber and **g**, South Chamber. The CAM was applied to the distributions in **a, c** and **g** to obtain a weighted mean D_e value for age determination. The D_e distributions in **b** and **d** contain a small number of intrusive grains (open circles) identified using nMAD; these grains were not included in the final weighted mean D_e value calculated using the CAM. The blue lines indicate the CAM D_e values before outlier rejection. Panel **e** shows a widely dispersed and continuous D_e distribution, from which no reliable, combined D_e value could be obtained for age estimation. The D_e distribution in **f** consists of two discrete D_e components, for which weighted mean D_e values were estimated using the FMM.

Supplementary Figure 8 | Representative single-grain K-feldspar D_c distributions for **a, b**, two samples from Main Chamber, **c–f**, four samples from East Chamber and **g, h**, two samples from South Chamber. Five of these samples (**a, b, f–h**) contain a small number of outliers (open circles), with both larger and smaller D_c values than the majority (60–80%) of grains. The outliers were identified using nMAD and are interpreted as intrusive grains, which were not included in the final weighted mean D_c values calculated using the CAM. The blue lines indicate the CAM D_c values before outlier rejection. For the distribution in **c**, the CAM was used to estimate the weighted mean D_c for age determination. A reliable, combined D_c value for age estimation could not be obtained from the widely dispersed and continuous D_c distribution in **d**. The D_c distribution in **e** consists of two discrete D_c components, for which weighted mean D_c values were estimated using the FMM.

Supplementary Figure 9 continued |

Supplementary Figure 9 continued |

Supplementary Figure 9 continued |

Supplementary Figure 9 | Distributions of D_e values and re-normalised L_n/T_n ratios for single grains of quartz and K-feldspar from sediment samples collected from Main Chamber. The grey band in each radial plot is centred on the weighted mean D_e determined using the CAM, after rejecting outliers (open circles). The blue lines indicate the CAM D_e values before outlier rejection. The D_e distribution for K-feldspar grains from DCM12-1 was optimally fitted by two discrete components using the FMM. The age for this sample was estimated from the main D_e component, centred on ~93 Gy and shown in black. The plots are arranged by year (starting with samples collected in 2012) and then in numerical order within each year.

Supplementary Figure 10 continued |

Supplementary Figure 10 continued |

Supplementary Figure 10 | Distributions of D_e values and re-normalised L_n/T_n ratios for single grains of quartz and K-feldspar from sediment samples collected from East Chamber. The grey band in each radial plot is centred on the weighted mean D_e determined using the CAM, after rejecting outliers (open circles). The blue lines indicate the CAM D_e values before outlier rejection. The D_e distributions for K-feldspar grains from DCE14-9 and for quartz grains from DCE14-10 and DCE12-4 were optimally fitted by 2 or 3 discrete components using the FMM. The plots are arranged by year (starting with samples collected in 2012) and then in numerical order within each year.

Supplementary Figure 11 | Distributions of D_e values and re-normalised L_n/T_n ratios for single grains of quartz and K-feldspar from sediment samples collected from South Chamber. The grey band in each radial plot is centred on the weighted mean D_e determined using the CAM, after rejecting outliers (open circles). The blue lines indicate the CAM D_e values before outlier rejection. The plots are arranged by year (starting with samples collected in 2012) and then in numerical order within each year.

Supplementary Figure 12 | Re-normalised L_n/T_n ratios for 15 samples obtained using the MAR SGC procedure at an infrared stimulation temperature of 275°C. The weighted mean ratios (centred on the grey bands) were projected onto the MAR SGC (Supplementary Fig. 3b) to estimate the D_e values used for age determination.

Supplementary Figure 13 | Weighted mean MAR D_e values plotted as a function of infrared stimulation temperature for the same 15 samples as in Supplementary Fig. 12. All error bars are at 1σ .

Supplementary Figure 14 | **a**, Comparison of single-grain D_e values estimated using the standardised growth curve (SGC) and $L_n T_n$ methods for 51 samples from Group A. **b**, Comparison of single-grain $L_n/T_n D_e$ values and MAR SGC D_e values for 12 samples (one from Group A, two from Group B and nine from Group C). Uncertainties are shown at 2σ and the dashed lines indicate the 1:1 ratio.

Supplementary Figure 15 | Beta dose rates for 56 samples estimated from GM-25-5 beta counting and from elemental concentrations of U, Th and K measured by ICP-MS and ICP-OES. Uncertainties are shown at 2σ and the dashed line indicates the 1:1 ratio. The beta dose rate derived from beta counting for each sample is the mean of 3 measurements made on three different sub-samples. The beta dose rate derived from ICP-MS measurements were calculated from a single measurement of U, Th and K for each sample.

Supplementary Figure 16 | K content (wt%) estimated from wavelength-dispersive X-ray spectroscopy (WDS) measurements of 60 individual K-feldspar grains from samples DCM16-12 (open circles) and DCE16-8 (filled circles), plotted as a function of luminescence sensitivity (T_n). The dashed line shows the weighted mean K content.

SECTION 3 | Stratigraphy and sedimentology
(Vladimir A. Uliyanov and Maxim B. Kozlikin)

The summary descriptions given below for Main and East Chambers are based on previous accounts^{3,59,140–144}, most of which are published in Russian.

Supplementary Table 16 | Main Chamber stratigraphy and sedimentology.

Layer	Fill material	Clastic material	Inclusions	Lower boundary	Thickness (m)	Notes
9.1	Light loam, light brown	Fine-grained debris and grus	Recent phosphate formations	Indistinct, notional	0.25	
9.2	Light loam, light brown	Weathered debris and isolated flattened clasts	Recent phosphate formations	Indistinct, blurred	0.30	
9.3	Loam, light brown	Heavily weathered debris	Recent phosphate formations, coprolite and bone fragments	Distinct, straight, contrasting colours	0.10–0.30	Weathered bone fragments
11.1	Light loam, light grey with a slight reddish tint	50–60%, mainly includes medium- and coarse-grained debris	Orange-brown solid animal bone fragments	Indistinct, notional	0.30	Angular debris
11.2	Medium to light loam, grey and light grey	30–50%, debris, isolated boulders and angular clasts	Splintered animal bones and coprolites	Transition zone	0.50	Small charcoal fragments forming thin interbeds. Charred bones
11.3	Light loam, light grey	20–30%, debris	Weathered animal bones, grus composed of schist (schistic grus)	Indistinct, recognised based on changing colour of the fill material	0.10–0.15	
11.4	Light loam, grey with a brown tint	40–50%, mainly includes fine-grained debris	Gravel composed of schist (schistic gravel), animal bone fragments	Distinct	0.05–0.20	Enriched in carbon-bearing inclusions. Isolated fragments of charred bones
11.5	Loam, light brown with a reddish tint	Moderately saturated with medium- and fine-grained clasts		Indistinct	0.15	Recognised as a lens-shaped unit with indistinct boundaries
12.1	Light loam, greyish brown with reddish black stains	20–40%, grus, medium- and fine-grained debris	Schistic gravel and grus. Solid bone fragments covered with a black manganese film	Indistinct, undulating	0.15–0.25	

12.2	Light loam, reddish brown	Mainly includes fine-grained angular debris	Schistic gravel and grus. Solid bone fragments covered with a black manganese film	Indistinct, undulating, transition zone	0.05–0.10	
12.3	Medium loam, sandy, reddish and dark brown	20%, grus and fine-grained debris	Coprolite fragments, small fragile bone fragments	Indistinct	0.15–0.20	
13.1	Light loam, loose with a large percentage of grus, grey-brown	40%, medium- and fine-grained debris	Gravel, grus, coprolites, bones	Indistinct	0.20	Debris show different degrees of weathering
13.2	Light loam with grus, reddish brown	10–40%, fine-grained debris, isolated coarse clasts	Small charcoal fragments, large coprolite fragments, splintered bones	Indistinct	0.30	Deposited as an irregularly shaped stain, 0.4 × 0.3 m in size
13.3	Medium loam, sandy, grey-brown	10%, heavily weathered material consisting of grus and fine-grained debris		Indistinct	0.15	Deposited as a lens-shaped unit
13.4	Medium loam, sandy, reddish brown with rusty ochreous interbeds	30%, grus and partly weathered fine-grained debris	Schistic grus, small charcoal fragments, heavily weathered coprolites, bone fragments covered with a dark film	Indistinct	0.10	Deposited as a lens-shaped unit
14.1	Medium loam, silty, grey with reddish stains	20%, rounded fine-grained debris	Small charcoal fragments, rusty ochre-coloured coprolites and bone detritus	Indistinct, transition zone	0.15	
14.2	Medium loam, silty, grey with a brownish tint	30%, slightly rounded fine-grained debris	Schistic gravel, decomposed bones and coprolites	Indistinct	0.15	
14.3	Medium loam, grey-brown with a reddish tint	Moderately enriched in debris	Bone and coprolite detritus	Distinct, straight	0.20	

17	Loam, grey, sandy	Medium- and fine-grained debris, slightly weathered	Animal bone fragments	Distinct	0.05–0.10	
19.1	Medium loam, reddish brown, sandy	Irregularly (10–40%) enriched in clasts of varying size	High density of bone fragments breaking apart into plates	Indistinct, notional	0.50	Deposited as a tapering unit that is replaced and partly overlain by the deformed sediments
19.2	Heterogeneous loam, reddish brown	Medium-grained debris with isolated boulders	Schistic grus, gravel, fragments of tubular bones and coprolites	Indistinct, notional	0.40	
19.3	Medium loam, reddish brown with a grey tint	Moderately enriched in debris and grus	Fragments of animal bones and coprolites	Indistinct, notional	0.20	Deposited as a concave lens-shaped unit
20	Heavy loam, grey-brown	20%, weathered debris and grus	Bone and small charcoal fragments, crushed coprolites	Distinct	0.15	
21	Sandy loam, dark brown, loose, silty, with black interbeds	Heavily weathered grus	Light yellow and brown coprolite fragments	Distinct	0.03–0.10	No reaction to HCl acid
22.1	Medium loam, heavy, ochreous with a reddish tint	Up to 30%, debris with inclusions of isolated boulders	Finely splintered bones and coprolites	Indistinct, transition zone	0.70	Heavily weathered (ferruginised) isolated clasts of limestone
22.2	Heavy loam, light ochreous (yellow with a greenish tint)	10%, debris	Speleothem and bone fragments. Recent manganese formations	Indistinct, transition zone	0.80	
22.3	Light loam, sandy, light ochreous with a greyish tint		Angular fragments of splintered clay	Bedrock base not reached	0.60	

Supplementary Table 17 | East Chamber stratigraphy and sedimentology.

Layer	Fill material	Clastic material	Inclusions	Lower boundary	Thickness (m)	Notes
9	Light loam, silty, reddish brown with black interbeds		Decomposed bones and recent phosphate formations	Distinct, undulating	0.20–0.30	Heavily disturbed by shrews. No reaction to HCl acid
11.1	Light loam, sandy with a large percentage of grus	40%, fine-grained angular debris	Light-coloured bone fragments	Uneven, deformed due to post-depositional subsidence	0.30–0.40	
11.2	Light loam, dark brown with a reddish tint	50%, angular debris	Reddish ochreous bone fragments	Uneven, deformed due to post-depositional subsidence	0.30–0.50	
11.3	Light loam, brown and dark brown	50–60%, angular debris	Rusty ochreous coprolite detritus, solid bone fragments with a reddish surface	Distinct, distinguished by a black lens	0.20–0.30	
11.4	Light loam, grey	50%, angular debris with isolated boulders	Very well preserved, grey-coloured bone fragments	Uneven, undulating and pocket-shaped, transition zone	0.25–0.35	
12.1	Light loam, brown, in parts dark grey with a brown tint	50%, clasts of varying size	Bone fragments with a reddish surface	Distinct, undulating	0.05–0.25	Rounded debris with a thin, whitish weathering fringe resulting from a chemical reaction
12.2	Light loam, brown with a reddish tint	50%, rounded clasts of varying size	Brown ochreous coprolite fragments, bone detritus	Indistinct, transition zone	0.25–0.30	Deposited as a confined lens-shaped unit
12.3	Medium loam, grey-brown	30%, rounded medium- and fine-grained debris	Abundant bright ochreous and reddish coprolite and bone detritus	Distinct, straight, synclinal in form, deformed due to subsidence	0.50–0.60	
13	Light loam, sandy, light brown with a bright ochreous tint	Occasional heavily weathered debris	Abundant bright ochreous and reddish coprolite and bone detritus	Distinct, slight deformations due to subsidence	0.30	

14	Medium loam, sandy with grus, dark brown	20–25%, rounded debris	Solid reddish bone fragments, small charcoal fragments	Notional, transition zone	0.90	Abundant charred limestone and bone fragments
15	Light loam, sandy with grus, black-brown and dark grey	40–50%, rounded medium- and fine-grained clasts	Crushed coprolites and splintered bone fragments of light yellow and ochreous colours	Distinct, subsided due to viscoplastic deformations	0.30–0.35	Abundant charred limestone and bone fragments
16	Sandy loam, loose, silty, dark brown with black interbeds		Isolated fragments of reddish coprolites	Distinct, subsided due to viscoplastic deformations	0.01–0.05	No reaction to HCl acid
17.1	Heavy loam, brownish yellow	Isolated completely weathered clasts and speleothems	Scattered ferromanganese concretions, splintered clays, no reaction to HCl acid. Light yellow bones with Fe-Mn dendrites		0.70–1.0	Stains from secondary ferruginisation
17.2	Heavy loam, light yellow		Large, decalcified concretions	Bedrock base not reached	1.0	

Supplementary Table 18 | South Chamber stratigraphy and sedimentology.

Layer	Fill material	Clastic material	Inclusions	Lower boundary	Thickness (m)	Notes
9	Loam, light yellow and light brown	Sparse weathered debris and grus	Recent phosphate formations. Heavily weathered bone fragments	Distinct, undulating	0.15–0.30	Heavily disturbed by shrews
11	Light loam, grey with an occasional reddish tint	50–60%, medium- and coarse-grained debris with isolated boulders	Light grey and rusty ochreous bone fragments	Indistinct, notional, transition zone	0.50–0.70	
12	Medium loam with grus, light brown	50–60%, slightly rounded medium- and fine-grained debris	Abundant solid bone fragments	Distinct	0.20–0.25	
14	Light loam, light brown	40%, medium- and coarse-grained debris with isolated boulders	Bone and coprolite detritus of reddish ochreous colour	Undulating, notional	0.30–0.40	
19	Medium loam with grus, light brown	10–15%, rounded medium- and coarse-grained debris	Ochreous bone and coprolite fragments	Indistinct, notional, transition zone	0.30–0.50	Heavily weathered isolated limestone fragments
20	Medium loam, greyish brown	Sparse, heavily weathered debris and grus	Yellowish bone and coprolite fragments	Distinct	0.10–0.25	Small charcoal fragments
22.1	Medium loam, yellow ochreous	10–30%, heavily weathered fine-grained debris	Light yellow bone and coprolite fragments	Indistinct, transition zone	0.50–0.70	
22.2	Heavy loam, yellow and light yellow		Splintered clays, decalcified concretions	Bedrock base not reached	0.40–0.50	

SECTION 4 | Pleistocene environments, palynology and palaeontology

Supplementary Discussion (Michael V. Shunkov, Nataliya S. Bolikhovskaya, Alexander K. Agadjanian and Sergei K. Vasiliev)

PLEISTOCENE ENVIRONMENTS—MAIN CHAMBER

Here we summarise the data used to reconstruct the environmental conditions in the vicinity of Denisova Cave during sedimentation of the Pleistocene sequence in Main Chamber, based on the comprehensive lithological and biostratigraphic analyses published previously^{3–5,145}. Summary lists of the composition and number of fossil remains of faunal taxa are given in Supplementary Tables 19 and 20.

Sediments from layer 22 differ markedly from the overlaying deposits in terms of their bright yellow, ochreous colour, their substantially heavier mechanical composition, and the relatively low amount of clastic materials. The textural and structural features of layer 22 indicate that temperature and humidity conditions inside the cave were mostly stable when sedimentation occurred. The associated spore–pollen assemblages are characterised by a predominance of pollen from woody species, a relatively high percentage of pollen from exotic plants (including a great diversity of broad-leaved trees) and a small number of spores. The number of bones of the red-backed vole (*Clethrionomys*), an ecologically diagnostic mammal species, is twice as high as the average in the overlaying layers. Fossils identified as belonging to tree species of the family Sciuridae—such as tree squirrel (*Sciurus vulgaris*), chipmunk (*Eutamias sibiricus*) and flying squirrel (*Pteromys volans*)—occur at significantly higher densities than in the overlaying layers, whereas remains of species characteristic of open landscapes are few in number. For example, bones of the steppe lemming (*Lagurus* sp.) are fewest in this layer, and fossils attributed to the narrow-headed vole (*Stenocranius gregalis*) and Siberian zokor (*Myospalax myospalax*) are only half as numerous as remains of these species recovered from the overlaying layers.

Sediments from layer 22.3 and the lower part of layer 22.2 reflect the earliest phase of sedimentation in Main Chamber. Based on their lithological characteristics, the sediments were transported through internal karst cavities and deposited under hydromorphic conditions. Pollen analysis indicates that pine–birch forests, with a mixture of spruce and Siberian pine (*Pinus sibirica*), prevailed in the Anui River valley during this period. Alder (*Alnus glutinosa*), hazel (*Corylus* spp.), elm (*Ulmus pumila*), Eurasian linden (*Tilia* sp.) and other broad-leaved species were permanent members of the plant community. The composition of small mammals also suggests a considerable expansion of forest vegetation and favourable environmental conditions. These deposits have yielded the greatest number of fossils attributed to bats, a high density of bones of the red-backed vole and a low number of bones of mountain vole (*Alticola*) and narrow-headed vole. Overall, sedimentation of layer 22.3 and the lower part of layer 22.2 occurred under warm and moderately humid climatic conditions.

The upper part of layer 22.2 appears to have formed from water-saturated sediments. The spore–pollen assemblages indicate two events associated with a decrease in the abundance of pollen grains from woody vegetation. A significant reduction of birch in the forest composition occurred at this time, whereas dark coniferous species—spruce (*Picea obovate*) in particular—increased in number. The number of bats and red-backed vole declined, and the mole (*Asioscalops* sp.) disappeared almost completely, whereas the numbers of mountain vole and narrow-headed vole increased significantly.

Layer 22.1 is formed of sub-aerial deposits that have experienced post-sedimentation deformation. The sedimentary matrix includes materials resulting from heavy chemical weathering of rocks transported from the interior areas of the cave. Granulometric features of the deposit suggest slightly increased climatic aridity during sedimentation, marked by the maximum expansion of forest massifs in the vicinity of the cave. Dominant communities comprised birch and pine with a mixture of alder, spruce, Siberian pine, hazel, linden, elm, oak (*Quercus robur*) and other broad-leaved species. The small-mammal populations underwent a substantial growth in the number of the red-backed voles, and the total number of shrews—such as the mole and Siberian zokor—also increased.

These environmental proxies suggest that layer 22.1 was deposited in a period of relatively warm and moderately humid climate.

Sediments from layer 21 were deposited after a long time gap under distinctly different environmental conditions from layer 22. They appear to have formed under sub-aerial conditions, with the accumulation of biogenic material associated with mineral substances derived from the weathering of limestone; lower plants (algae) that covered the cave walls may have been the primary source of organic material. Based on the limited palaeoenvironmental data for this layer, birch was a dominant tree species in the forest cover, the mountain vole dominated the composition of small mammals, and the red-backed vole was present in considerable numbers. Overall, this period of relatively cold and moderately humid climate was characterised by a gradual reduction of forest massifs and an expansion of areas with nival biotopes.

Layers 20–11 include multi-coloured lenticular stratified loam deposits, with large quantities of gravelly material and debris that incorporates isolated blocks of limestone. During this period, environmental conditions inside the cave were influenced to a greater extent by the outside environment than was the case previously. Owing to the more open aspect and enhanced ventilation of the cave, physical weathering would have had a stronger effect, and daily and seasonal fluctuations of temperature and humidity would have been more pronounced. The nature of sedimentation inside the cave changed accordingly. During dry and relatively warm periods, sediments may have been transported episodically from the side chambers, resulting in the formation of irregular micro-relief features on the floor of the cave; these irregularities on the floor surface were infilled during relatively cold periods. More humid phases are characterised by the development of viscoplastic deformations in the underlying deposits. Environmental conditions in the vicinity of the cave also changed significantly, with widespread steppe and nival communities, the expansion of grass meadows and the substantial reduction of forest cover. Spruce and, to a lesser extent, birch dominated the forests; the number of pine decreased considerably and broad-leaved species diminished rapidly in both abundance and diversity. The small mammals were dominated by mountain and narrow-headed voles, with relatively low numbers of red-backed vole.

During sedimentation of layer 20, areas with nival communities decreased significantly in the Anui River valley, whereas meadow and steppe associations expanded. Forests consisted of birch and pine with a mixture of alder, linden and elm. Among the small mammals, remains of mole and Siberian zokor are numerous, whereas the numbers of the mountain vole are much lower. The high proportion of shrews indicates snowy and mild winters. Overall, these data suggest that layer 20 was deposited under relatively warm climatic conditions, but drier than when layer 21 accumulated.

Layer 19 is a complex, polygenetic deposit that formed in two climatic phases. The lower part of this layer was deposited under the same environmental conditions as layer 20, whereas the upper part accumulated in a cooler climate in which the vegetation cover was dominated by motley grass–steppe associations; the forests were dominated by spruce, with some Siberian pine, fir (*Abies*) and larch. Layer 17 is formed of clasts with a loamy matrix that was deposited in relatively dry climatic conditions. The small-mammal fossils indicate the development of steppe and nival landscapes, while the pollen assemblages indicate that the local valley slopes were covered in spruce forests with a mixture of birch, pine and dark coniferous species. Overall, sedimentation of layer 17 took place in a transitional environment characterised by moderate temperatures and humidity.

Faunal data show that meadows with nival and steppe vegetation occurred on slopes adjoining the cave during sedimentation of layer 14. Small forest areas were occupied by spruce and birch–pine stands. These environmental proxies suggest that layer 14 was deposited in a relatively warm climate compared to conditions prevailing before (layer 17) and after (layer 13).

Based on its structural and lithological features, layer 13 is likely of biogenic origin. The layer is rich in coprolites and fractured bones that differ markedly from most of the fossils recovered from the cave deposits. The remains of small mammals show evidence of rapid changes in composition. There is an overall reduction in the number of bones of mole, mountain vole, tundra vole and steppe lemming and a low density of fossils of red-backed vole, together with bone remains of lemmings

(*Lemmus*) and pikas (*Ochotona* sp.). Collectively, these data suggest relatively cold and dry climatic conditions.

The majority of clasts in layer 12 show signs of physical weathering, consistent with a moderately cold environment and episodic deposition. Spores and pollen from the lower part of this layer attest to the recovery of spruce forests with a mixture of pine, Siberian pine, fir and larch. Grass meadows were the dominant vegetation on the wet valley slopes and on the valley floor, whereas nival associations dominated on the dry valley sides. The upper part of layer 12 was deposited under an increasingly arid climate, in which nival associations expanded, meadow biotopes declined, and areas occupied by forest massifs reduced significantly.

There is an apparent gap in sedimentation between layers 12 and 11, with the latter deposited during a period in which the forest vegetation was dominated by dark coniferous forests of spruce and Siberian pine. The overall taxonomic diversity of woody species steadily decreased over this period. Fir and alder almost disappeared from the forests, and birch became rare. Flowering plants Cichorioideae and Caryophyllaceae grew significantly in number, implying increased erosion in the vicinity of the cave. Faunal analysis of small mammals indicates that areas with nival biotopes expanded and meadow associations decreased during the period of deposition of the upper part of layer 11. Overall, this layer accumulated in a moderately warm climate compared to conditions under which the underlying and overlying sediments were deposited.

Layer 9 includes light-brown loams separated from layer 11 by a thin interlayer of iron-manganese compounds (layer 10). Layer 9 contains numerous lenses and isolated inclusions of debris, crushed stone and whitish phosphatic concretions. Weathering of the clasts and the characteristics of the matrix materials suggest that cold and dry conditions prevailed during sedimentation of this layer. The spore–pollen and small-mammal remains indicate that forests retreated in the Anui River valley, while nival and steppe biotopes expanded. Spruce, Siberian pine and some birch remained the dominant species in the small forested areas. The small-mammal populations were dominated by mountain vole and steppe lemming, whereas the number of moles, Siberian zokor and red-backed voles decreased significantly. These environmental indicators show that layer 9 was deposited under the harshest environmental and biotopic conditions to have occurred in the vicinity of the cave during the entire period of sedimentation.

PLEISTOCENE PALYNOSTRATIGRAPHY—EAST CHAMBER

The discussion presented here for East Chamber is summarised from the detailed pollen and spore data reported in Russian⁶. Palynological details for Main Chamber have been published previously in both Russian and English^{3,4}.

The analysed samples collected from layer 17.2—deposited over bedrock at the base of the stratigraphic section in East Chamber—yielded an insufficient amount of pollen and spores to carry out statistical analysis, but all of these samples have a predominance of pollen from shrubs associated with microtherm species (*Betula* sect. *Nanae*, *Alnaster fruticosus* / *Duschekia fruticosa*), indicating cold-climate conditions. In addition to this material, isolated pollen grains from spruce and pine, as well as spores from green moss and fern (Polypodiaceae), have been identified. These data are likely to indicate prevalence of alpine tundra and subalpine tundra cenoses in the vicinity of the cave.

Two phases in the development of vegetation are recognised within the period of deposition of overlaying layer 17.1. Samples collected from the lower part of layer 17.1 yielded representative spore–pollen assemblages reflecting slight amelioration of environmental conditions and the expansion of forest biotopes that mainly included Siberian spruce (*Picea obovata*), Siberian cedar (*Pinus sibirica*), common pine (*P. sylvestris*) and birch (*Betula* sect. *Albae*). Assemblages from these deposits are dominated by pollen from these trees, but also reveal the permanent presence of pollen grains from shrubby species of birch (*Betula* sect. *Nanae*, *B. rotundifolia*), shrubby alder (*Alnaster fruticosus* / *Duschekia fruticosa*) and juniper (*Juniperus*), suggesting that during this time the area under study was confined to a transition zone from subalpine tundra landscapes to the upper part of the mountain taiga belt. The herb–shrub layer of vegetation (stratum) shows predominance of forbs,

mainly members of the sunflower family (Asteraceae) and ferns (Polypodiaceae). The moss stratum was dominated by green mosses.

Sediments constituting the uppermost part of layer 17.1 appear to have been deposited under colder climatic conditions, when bushy tundra with a thick cover of ground birch (*Betula rotundifolia*) dominated in the vicinity of Denisova Cave. The shrub stratum also included shrubby alder (*Alnaster fruticosus* / *Duschekia fruticosa*), dwarf bog birch (*Betula fruticosa*), juniper and, possibly, shrubby willow (*Salix*). The weak development of the herb–shrub stratum, dominated by Ericales and Poaceae plants, may be associated with a high density of ground birch thickets. Horsetail and green mosses were dominant among spore plants.

In contemporary landscapes of the northwest Altai, *Betula rotundifolia* forms extensive thickets above the mountain taiga vegetation line in subalpine and alpine tundra belts. Ground birch is one of the most abundant components of the alpine tundra vegetation developed at the present day in the upper reaches of the Shinok River, a tributary of the Anui River that flows into the latter 1.5 km downstream from Denisova Cave. It currently forms shrub thickets about 1.5–2.0 m high on a high floodplain of the Shinok basin, whereas the low floodplain is covered with thickets composed of its dwarf forms (0.3–0.5 m high).

The sample collected from layer 16 yielded only isolated pollen grains of *Betula* sect. *Nanae*, which may also indicate sediment deposition under cold environmental conditions. These palynological data suggest that layers 17.2, 17.1 and possibly 16—all of which are archaeologically sterile—appear to have been deposited during a cold (glacial) period, when periglacial alpine and subalpine tundra landscapes developed in the vicinity of the cave.

Only a few pollen grains of *Pinus* and Poaceae were recovered from the two samples collected from layer 15. Their presence is consistent with relatively warm conditions, but more data are needed to confidently establish the climatic and vegetation characteristics during the period of deposition of this thin layer.

Sediments from layers 14 and 13 are characterised by palynological assemblages that are representative of an interglacial period, with environmental conditions much warmer than the present-day climate in the study area. Changes in the zonal and formational structure of the vegetation over this interglacial period attest to its duration, with the spore–pollen data indicating four phases of vegetation development. During the first phase, when deposition of the middle part of layer 14 occurred, the area of the Anui valley nearest Denisova Cave harboured broad-leaved forests that comprised heartleaf hornbeam (*Carpinus cordata*), Mongolian oak (*Quercus* cf. *mongolica*), Eurasian linden (*Tilia* sp.), Siberian elm (*Ulmus pumila*), Chinese elm (*U. parvifolia*), Asian hazel (*Corylus heterophylla*), euonymus (*Euonymus*), daphne (*Daphne*) growing in the shrub stratum, and mixed forests that included spruce, pine, birch, alder (*Alnus glutinosa*) and the aforementioned species.

The second phase occurred at the time of accumulation of sediments at the base of layer 13, and indicates a decrease in heat and water availability and predominance of open meadow-steppe landscapes with small tracts of land covered with alder in the vicinity of Denisova Cave. The herb–shrub stratum was dominated by motley grass–grasses associations (e.g., Poaceae, Polemoniaceae, Polygonaceae, Ranunculaceae, Asteraceae).

During the third phase, when the overlying sediments in the lower part of layer 13 were deposited, forest areas increased significantly in warmer and humid climatic conditions. The interglacial forest and forest-steppe landscapes were dominated by birch–hornbeam forests with a mixture of linden and a thick undergrowth of hazel, alder and motley grass–grasses associations.

During the fourth reconstructed phase in the development of vegetation during this interglacial, when deposition of layer 13 occurred, the study area was dominated by forest formations that grew under more humid climatic conditions than existed during the preceding phase. Pollen analysis indicates a dominance of hornbeam forests with a mixture of oak and linden, including heartleaf and European hornbeam (*Carpinus cordata*, *C. betulus*), linden (*Tilia cordata*, *T. sibirica*), European oak (*Quercus robur*) and an undergrowth of hazel (*Corylus* spp.) and alder (*Alnus glutinosa*).

and *A. incana*). Less common were birch–coniferous forests that included such species as silver birch (*Betula pendula*), Siberian spruce (*Picea obovate*) and common pine (*Pinus sylvestris*).

Based on palynological data, deposition of layer 12.3 and the lower part of layer 12.2 occurred in the harsh climatic conditions of a cold glacial period. The spore–pollen assemblages have made it possible to reconstruct six phases in the evolution of the dominantly periglacial landscapes, as inferred from successive changes in the following types of vegetation: periglacial forest-tundra, forest-steppe tundra, periglacial tundra, steppe-tundra, periglacial steppes and steppe-tundra. All of the analysed samples show that the tree and shrub pollen is dominated either by pollen from microtherm shrubs, such as ground birch (*Betula rotundifolia*) and shrubby alder (*Alnaster fruticosus* / *Duschekia fruticosa*), or co-dominated by pollen from *Betula rotundifolia*, *Alnaster fruticosus* / *Duschekia fruticosa*, *Alnaster mandshuricus* / *Duschekia mandshurica* and juniper (*Juniperus*). Changes in their percentage composition in assemblages seem to reflect transformations in the tundra shrub communities. In most of the phases, ericales (Ericales), gramineous plants, wormwood (*Artemisia* s.g. *Euartemisia*, *A.* s.g. *Seriphidium*) and the sunflower family (Asteraceae) dominated the herb–shrub stratum in the reconstructed periglacial vegetation.

Spore–pollen assemblages obtained for samples from the upper part of layer 12.2 and from layer 12.1 suggest that open landscapes with almost omnipresent steppe, meadow-steppe and epilithic herb–shrub communities emerged across a large part of the Anui valley, indicating drier climatic conditions than exist at the present day. The vegetation was dominated by forbs, motley grass–grasses, wormwood and other communities (including *Ephedra*, *Cannabis*, Poaceae, *Artemisia* s.g. *Euartemisia*, *A.* s.g. *Seriphidium*, Chenopodiaceae, Caryophyllaceae, Polygonaceae, *Rumex*, Ranunculaceae, *Delphinium*, Rubiaceae, Fabaceae, Apiaceae, Dipsacaceae, Brassicaceae, Lamiaceae, Valerianaceae, Scrophulariaceae, Alliaceae, Liliaceae, Asteraceae and Cichoriaceae). Birch and alder, as well as the herb–shrub stratum that included ferns (Polypodiaceae), ericales (Ericales), horsetails and aquatic-riparian plants (Alismataceae), grew in small streamside floodplain forest stands.

The analysis of samples from layers 11.4–11.1 and 9.3–9.1 has yielded a detailed palynological record that reflects the complex climate stratigraphy of these lithological units. Most of the layers show changes in the taxonomic components and percentages of spore–pollen assemblages, which reflect climatic fluctuations and vegetation transformations that accompanied sedimentation of these layers, but it cannot be ruled out that, in some instances, the changes may be due to post-depositional disturbance of the enclosing sediments.

Deposition of the lower part of layer 11.4 occurred in environmental conditions warmer than those at the present day. In the vicinity of the cave, the vegetation cover was dominated by elm–alder (*Ulmus pumila*, *Alnus glutinosa*) valley forests with a thick undergrowth of European hazel (*Corylus avellana*), and birch–coniferous (*Betula pendula*, *Pinus sylvestris*) forest formations on the mountain slopes. The herb stratum consists predominantly of ferns from the Polypodiaceae family and gramineous plants, while other species (e.g., moonwort, horsetails) were also abundant.

The upper part of layer 11.4 was deposited during a period of significant cooling. Broad-leaved tree species, alder and birch disappeared and there was possibly a reduction of floodplain forest areas. Tundra communities with *Betula* sect. *Nanae* and *Alnaster fruticosus* and, possibly, alder, willow and dwarf birch shrubby cenoses dominated in the vicinity of the cave during the first phase of cooling. Environmental conditions were milder during the second cooling phase. Valley slopes were covered by forest communities that included larch and Siberian pine (*Pinus sibirica*), and riparian forest stands were dominated by willow. During both phases, the herb–shrub stratum was dominated by Poaceae, *Artemisia*, Asteraceae, Liliaceae and Alliaceae.

The initial stage of sedimentation of layer 11.3 is associated with a subsequent phase of warming, which resulted in the spread of interstadial steppes. Willow and alder–elm forest stands dominated the composition of floodplain forests, and the driest and warmest areas in the valley were covered with oak. Ericales and gramineous plants were abundant in the herb–shrub stratum of the forest cenoses; water plantain grew in riparian biotopes. Herb-rich motley grass–grasses associations (e.g., Asteraceae, Geraniaceae, Ranunculaceae, Brassicaceae, Polygonaceae, Gentianaceae,

Scrophulariaceae, Boraginaceae, Valerianaceae, Polemoniaceae) dominated in areas with steppe and meadow-steppe vegetation. Following this initial warming phase, most of spore–pollen assemblages from layers 11 and 9 consist of pollen from aquatic-riparian and aquatic plants, dominated by water plantain (Alismataceae).

Spore–pollen assemblages from the middle part of layer 11.3 reflect a cold dry climate and the development of tundra-steppe landscapes. Pollen from alder and broad-leaved species disappears and the amount of tree pollen decreases, while pollen from *Betula* sect. *Nanae*, juniper and willow dominates in the group of hardy-shrub species. The composition of herb–shrub plants is dominated by pollen from *Artemisia*, Asteraceae, Poaceae, Ericales, Chenopodiaceae, Caryophyllaceae, Saxifragaceae and Lamiaceae.

The upper part of layer 11.3 was deposited in a cool and more humid climate than that of the preceding phase. Periglacial open spruce–pine woodlands with *Daphne mezereum* in the undergrowth and motley grass–grasses steppes became dominant in the valley. Apart from Poaceae, Asteraceae were the dominant species in the vegetation cover of steppe and meadow-steppe cenoses. The plant cover also included a great number and variety of other species that represent miscellaneous herbs, such as Polygonaceae, Apiaceae, Ranunculaceae, *Thalictrum*, Dipsacaceae, Scrophulariaceae, Lamiaceae, Valerianaceae, Cichoriaceae, Fabaceae, Alliaceae, Campanulaceae and Geraniaceae. The hardy-shrub plants on the floodplain included willows and thickets of currents, with Ericales, Poaceae and *Carex* abundant in the herb–shrub stratum.

Pollen assemblages recognised in layer 11.2 show that pollen from Poaceae, Asteraceae and many different herbs dominates in the group of herb–shrub plants. The lower part of layer 11.2 was deposited during an interstadial period when mountain-steppe landscapes emerged and motley grass–grasses steppes dominated the plant cover. The floodplain forest stands were dominated by silver birch, willow, alder and elm, while ferns from the Polypodiaceae family dominated in the herb stratum. Siberian larch, spruce and Siberian pine (*Pinus sibirica*) grew on the ridge-top slopes in the valley. Sedimentation in the upper part of layer 11.2 occurred during a stadial period of climatic cooling: tree vegetation almost disappeared from the composition of the dominantly periglacial mountain-steppe landscapes, with shrub communities that included shrubby alder (*Alnaster fruticosus*), juniper and daphne (*Daphne mezereum*).

Based on the composition and percentage of pollen taxa in the herb and shrub assemblages obtained from layer 11.1, the vegetation cover included steppe and meadow-steppe associations for most of this period of sedimentation. Data obtained for the lower part of this layer indicate an increase in the amount of pollen from trees and shrubs towards the middle part of layer 11.1, where it reaches a maximum in the pollen spectrum. Sedimentation occurred under warm interstadial conditions that may have closely resembled those of an interglacial climate. Forest areas on the valley slopes and terraces were dominated by broad-leaved species that included European oak, ash and linden, with an undergrowth of European hazel and separated birch stands. The pollen spectrum from the top part of layer 11.1 is dominated by Cichoriaceae, *Artemisia* and Asteraceae, which may indicate a short period of more arid climate.

Three phases are recognised in the development of vegetation cover and environmental conditions during the period of accumulation of layer 9. Deposition of layer 9.3 occurred during an interstadial phase, with a relatively cold climate and predominance of spruce (*Picea obovata*) forests and some Siberian pine. Sedimentation of the upper part of layer 9.2 took place under harsh, cold and dry glacial climatic conditions. Periglacial tundra-steppes developed extensively in the vicinity of the cave; shrubby alder, dwarf bog birch, Ericales, Ephedraceae, *Artemisia* and Poaceae dominated the vegetation. Layer 9.1 was deposited during a period when periglacial interstadial forest-steppes emerged and larch–pine–spruce forests were dominant on the valley slopes, while motley grass–grasses and *Artemisia*–Chenopodiaceae associations dominated the open areas.

PLEISTOCENE VERTEBRATE FAUNA—EAST CHAMBER

The discussion presented here for East Chamber is based on the faunal data reported recently^{7,146} and in earlier articles^{147–149}, all of which are published in Russian. Excavations in East Chamber have yielded more than 177,000 bone remains attributed to over 80 species of large and small mammals (Supplementary Tables 21 and 22). Megafaunal remains are abundant and environmentally informative (Supplementary Table 23) and a large number of bones from rodents, insectivores, birds, bats, amphibians and fish were also recovered.

Small vertebrate fauna

A total of 17,422 bones attributed to small vertebrate fauna have been recovered from the Pleistocene deposits in East Chamber (Supplementary Table 21), of which 2,202 specimens were obtained from layer 17.1. The composition of the small vertebrate fauna in this archaeologically sterile layer indicates a variety of environmental conditions characteristic of a depositional period marked by forest massifs alternating with biotopes consisting of herbaceous and epilithic vegetation. The terminal phase of sedimentation of layer 17.1 occurred during a rapid, relatively strong but brief cooling event, as inferred from the carbonate crust developed on bones and from the pollen analyses.

The faunal collection recovered from layer 15 consists of 975 bones and teeth. The composition of small vertebrate fauna is similar to that typifying the initial phase of sedimentation of layer 17.1. Fossil remains attributed to the genus *Lemmus* are present in the lower part of layer 15, which was deposited during a period of milder environmental conditions that entailed some reduction of forest massifs and a slight expansion of steppe biotopes under a cooling climate.

Layer 14 yielded a total of 5,105 bones. Based on the taxonomic structure of these fossils, sedimentation of this layer took place in a warmer climate compared to the conditions prevailing during deposition of layer 15. The proportion of xerophytic biotopes increased, and forest massifs expanded slightly.

Layer 13 yielded 2,738 bone remains. A reduction in the numbers of red-backed vole (*Clethrionomys*) and an increase in the population of steppe lemming (*Lagurus lagurus*) suggest that this layer was deposited during a period of forest decline and meadow and steppe biotope expansion; the proportion of shrub-dominated rocky habitat remained the same. Pollen analysis indicates a complex three-phase climatic event during this period. We consider it likely, therefore, that the phase changes occurred relatively rapidly, without altering dramatically the structure of the small-mammal communities.

A total of 1,090 specimens were identified for layer 12.3. The fossil record is characterised by little taxonomic diversity of small vertebrates and a decrease in the number of bats (Chiroptera). The bones of Eurasian pygmy shrew (*Sorex minutus*) and moles (*Asioscalops altaica*) are the only remains associated with insectivores. We found no fossils of tree squirrel (*Sciuridae*), marmot (*Marmota* sp.), wood mouse (*Apodemus* (*Alsomys*), hamster (*Cricetus crisetus*) or mole vole (*Ellobius* sp.), and the number of bones attributed to Siberian zokor (*Myospalax myospalax*) and meadow vole declined. These data indicate adverse climatic conditions when this layer accumulated. Based on the presence of *Lemmus*, the area in the vicinity of the cave was occupied largely by open biotopes characteristic of steppe and tundra-steppe. This indicates climatic cooling and increased aridity, although the occurrence of mole and Siberian zokor rules out permanent and deep freezing of the ground.

The fossil assemblage from layer 12.2 consists of 649 bones. Compared to the underlying layer, this assemblage shows an increase in the number of bats and steppe lemmings, an increase in the proportion of ground squirrels, and the appearance of marmot. In contrast, there was a decrease in the numbers of red-backed vole, mountain vole (*Alticola*) and meadow vole (*Microtus*). These data indicate a reduction of forest massifs and an expansion of steppe biotopes with a mixture of gramineous plants. An increase in aridity likely occurred during this period, as inferred also from the pollen analysis.

Layer 12.1 yielded a total of 780 recognisable bones and teeth. Compared to layer 12.2, there was a two-fold increase in the proportion of bones attributed to bats and an increased abundance of

fossils from mountain and meadow voles. The numbers of mole, red-backed vole, ground squirrel (*Spermophilus* sp.) and Siberian zokor decreased, and marmots and steppe lemmings disappear from the fossil record. Remains identified as *Lemmus* were recovered from the lower part of this layer. These indicators suggest a reduction of forest massifs and xerophytic steppe biotopes, together with an increase in the proportion of shrub-dominated rocky biotopes and an expansion of grass meadows. Although the fauna are not diagnostic of exclusively warm or cold conditions, the spore–pollen assemblages indicate the continuation of a drier climate than exists at the present day.

Layer 11.4 yielded a total of 757 vertebrate remains. Bats and other insectivores, including mole and mountain vole, decrease as a proportion of the assemblage from this layer, whereas the numbers of red-backed voles increase and steppe lemmings appear. Meadow voles became numerous at this time, and their taxonomic variety also increased. Remains attributed to *Lemmus* were recovered from the upper part of this layer. The composition of the small fauna that cannot be uniquely defined may imply a complex history of sedimentation. Pollen analysis suggests that the lower part of layer 11.4 was deposited under warmer climate conditions than exist at the present day, whereas the upper part accumulated during a period of significant cooling.

A total of 704 bones were recovered from layer 11.3. The fauna are broadly characteristic of both relatively warm and relatively cold conditions. Relative to the underlying layer, however, the higher proportion of bats and other insectivores, including moles, steppe lemmings and Siberian zokor, may indicate a moderate increase in winter temperature and, possibly, an increase in winter precipitation. Palynological analyses also indicate that layer 11.3 began to accumulate during a warmer phase within a mostly cold period. Remains of ground squirrels that live in areas with grass–forb vegetation increase significantly, whereas the numbers and variety of meadow voles do not change appreciably, and there is a decrease in the number of the red-backed and mountain voles. These trends are consistent with an expansion of open biotopes and a reduction of forest habitats. The two-fold increase in the number of fish bones suggests increased river flow in the vicinity of the cave, which is consistent with the appearance of aquatic-riparian and aquatic plants in the pollen assemblages.

Layer 11.2 yielded a total of 1,350 bones. Compared to layer 11.3, there is a slight decrease in the numbers of bats, other insectivores, red-backed and meadow voles. In contrast, the relative number of fish bones and the remains of mole and steppe lemming increased, as did the taxonomic variety of insectivores. Fossils attributed to chipmunks (*Eutamias* sp.) and flying squirrels (*Pteromys* sp.) were also recovered from this layer, including isolated bones from lemming. This assemblage suggests an expansion of open landscapes, with steppe and meadow associations. Areas with thin stands of grass were also present, based on the recovery of bones of marmot and dipodids (*Allactaga* sp.).

Layer 11.1 produced a total of 821 bones, which show a substantial decrease (more than two-fold) in the number of bats as compared to layer 11.2. The number of shrews, meadow voles and pikas (*Ochotona* sp.) also declined, whereas the numbers of mountain vole increased. The proportion of bones attributed to steppe lemming is by far the greatest of any of the layers in East Chamber (Supplementary Table 21). In general, these data suggest an expansion of steppe and rocky biotopes. Given the relative abundance of bones of fish and frogs, we infer that river flows remained high for much of the period of deposition of this layer.

A total of only 251 bones were identified for layer 9. The increase in the number of bat bones may indicate that human use of the cave became less intensive. Remains of shrews, red-backed and meadow voles also increased in number, whereas there was a reduction in the proportion of bones from steppe lemmings, mountain voles and hamsters (*Cricetus crisetus*, *Crisetulus barabensis*, *Allocricetulus eversmanni*). These faunal changes can be directly linked to environmental conditions associated with an expansion of forests and a reduction of open biotopes. Given the relatively few identifiable bone remains recovered from this layer, however, we consider that the spore–pollen assemblages are a more reliable environmental proxy, and they indicate that the climate was relatively cold at this time.

Overall, the remains of small vertebrate fauna suggest that a high diversity of biotopes persisted in the vicinity of the cave throughout the period of sedimentation of layers 17.1 to 9 in East Chamber. Forest massifs alternated with patches of meadow and steppe vegetation, with the occurrence also of small admixtures of plant associations characteristic of dry steppe and low-shrub tundra. The forest stand included both broad-leaved and dark coniferous species, with green mosses under their canopies. Climatic fluctuations appear to have induced changes in the proportions of different ecosystems.

Large mammal fauna

Past environmental conditions can also be inferred from the remains of large mammal fauna (megafauna). Layer 17.1 yielded only 13 identifiable mammal bones fragments, nine of which are from six species of megafauna. Sedimentation of layers 15 and 14 was accompanied by a significant number and variety of megafauna associated with forest and forest-steppe environments, but few species characteristic of the steppe biotope. For example, bones of roe deer (*Capreolus pygargus*) and Siberian red deer (*Cervus elaphus*) are more numerous than in layer 17.1, and the remains of brown bear (*Ursus arctos*), woolly mammoth (*Mammuthus primigenius*) and *Megaloceros giganteus* (an extinct species of giant deer) appear in the fossil record for the first time (Supplementary Table 22).

The faunal associations for layers 15 and 14 include species typical of interglacial forest-steppe fauna, with bones of roe deer and Siberian red deer accounting for ~19% and ~7% of the large mammal assemblage, respectively (Supplementary Table 23). The full spectrum of megafauna typical of open landscapes (mountain-steppe, forest-steppe and tundra-steppe) are also represented, including two horse species, bison (*Bison priscus*), woolly rhinoceros (*Coelodonta antiquitatis*), Mongolian gazelle (*Gazella guttursza*) and saiga antelope (*Saiga tatarica borealis*). Forest massifs, even at times of greatest expansion during interglacial periods, spread mainly along river valleys, mountain gorges and north-facing slopes, while large areas of meadow and steppe vegetation occurred in drainage basins and on south-facing slopes. Layer 15 yielded too few pollen grains and spores to reliably infer climatic conditions, whereas palynological analyses of layers 14 and 13 indicated deposition during an interglacial period, when climatic conditions were much warmer than at the present day and mixed broad-leaved forests expanded in the vicinity of the cave. These environmental interpretations are consistent with the megafaunal compositions of layers 15 and 14, which are broadly similar.

Mammal communities typical of open landscapes show few differences in the composition and relative abundance of common species during deposition of layer 13 (an interglacial period) and layer 12 (a glacial period). Indeed, open landscapes prevailed for most of the period of accumulation of layers 13–9. Ratios among megafaunal species associated with different biotope groups (steppe, forest-steppe, forest and rocky communities) suggest that environmental conditions remained relatively stable during this period, which was dominated by steppe biotopes (63–68%) and smaller proportions of species associated with forests, forest-steppe and rocky biotopes. For example, the proportion of bones of roe deer is low but stable at 4–5% in layers 13–9, compared to much higher representation (~19%) in layers 15 and 14 (Supplementary Table 23).

There is evidence, however, for fluctuations in climate and vegetation cover in the vicinity of the cave during the period of sedimentation of layers 13–9. For example, bones of Mongolian gazelle and saiga antelope decrease in relative abundance from 14–16% in layers 13 and 12 to ~6% in layers 11 and 9, and the presence of isolated bones of reindeer (*Rangifer tarandus*) in layer 12 supports palynological indications of periglacial conditions and open landscapes.

Supplementary Table 19 | Ratios (in %) of small vertebrates from the Pleistocene deposits in Main Chamber.

Taxa	Layers																						
	9.1	9.2	9.3	11.1	11.2	11.3	11.4	12.1	12.2	12.3	13	14.1	14.2	14.3	17	19.1	19.2	19.3	20	21	22.1	22.2	22.3
Chiroptera	1.88	-	2.36	1.56	1.96	0.62	1.17	2.74	1.81	0.81	1.23	0.87	1.75	1.96	6.67	2.74	2.86	3.16	3.65	8.19	27.99	41.60	48.51
<i>Erinaceus</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	0.50	-	-	-	-	-	-	-	-	-	-
<i>Sorex roboratus</i>	-	-	-	-	-	-	-	0.22	-	0.16	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Sorex minutus</i>	-	-	-	-	-	-	-	0.07	0.26	0.49	0.15	-	-	-	-	-	-	-	-	-	-	-	0.15
<i>Sorex araneus</i>	0.75	-	0.59	0.59	0.84	0.89	0.33	1.73	1.55	2.11	1.07	1.73	1.25	1.96	0.95	0.60	1.11	0.63	0.52	0.44	0.30	0.84	0.30
<i>Neomys</i> sp.	-	-	-	-	-	-	-	-	-	0.16	-	-	0.25	-	-	-	-	-	-	-	-	-	-
<i>Asioskalops altaica</i>	1.32	1.01	2.24	1.71	2.24	1.96	3.60	1.15	1.55	2.11	1.07	1.16	1.00	-	1.90	1.73	1.43	1.90	5.21	1.44	0.75	0.44	0.15
<i>Sciurus</i>	1.13	-	-	-	-	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-
<i>Pteromys</i>	-	-	-	0.07	-	-	-	-	-	-	-	-	0.25	-	-	0.06	-	-	-	-	0.01	0.12	-
<i>Eutamias</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	-
<i>Spermophilus undulatus</i>	-	1.52	2.24	1.26	1.61	1.87	1.09	1.30	0.78	0.49	0.46	1.16	1.25	-	2.38	0.65	1.43	0.79	-	1.22	0.74	0.52	0.45
<i>Marmota</i> sp.	-	-	0.12	0.07	0.07	-	0.17	0.07	0.26	-	0.46	0.29	0.25	-	-	0.48	0.48	-	1.56	0.66	0.30	0.12	-
<i>Castor</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	1.96	-	-	-	-	-	0.11	-	-	-
<i>Apodemus (Alsomys)</i>	-	-	0.12	-	-	-	-	-	-	-	-	-	-	-	-	-	0.16	-	-	-	-	-	-
<i>Cricetus crisetus</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.06	-	0.16	-	0.22	0.07	-	-
<i>Crisetulus barabensis</i>	0.38	0.76	0.47	0.37	0.28	0.27	0.33	0.72	0.52	0.49	0.31	-	0.25	-	0.48	0.24	0.79	0.47	-	0.22	0.68	0.64	0.60
<i>Allocricetulus eversmanni</i>	0.75	-	1.06	0.74	0.77	0.80	1.34	0.86	0.78	0.81	-	0.29	0.25	-	-	0.24	-	-	-	-	0.22	-	0.15
<i>Sicista</i> sp.	-	0.25	-	-	-	0.09	-	0.07	-	0.16	-	-	-	-	-	-	-	-	-	0.11	-	0.04	-
<i>Allactaga</i> sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.16	-	-	-	0.04	-	-
<i>Ellobius</i> sp.	-	0.25	0.71	0.22	0.14	-	0.33	0.14	0.26	0.49	0.15	0.29	-	-	-	0.12	0.64	-	-	-	0.01	-	-
<i>Clethrionomys rutilus</i>	0.75	-	-	-	0.21	0.09	0.67	0.14	-	1.62	-	0.29	1.25	-	4.29	1.67	0.48	-	-	3.10	0.14	0.28	0.15
<i>Clethrionomys rufocanus</i>	1.51	0.25	0.12	0.82	0.14	0.44	1.25	0.65	0.52	1.30	0.46	3.47	2.76	3.92	0.48	1.96	0.64	1.42	3.65	1.11	0.78	0.84	0.60
<i>Clethrionomys</i> sp.	0.56	2.02	1.41	2.30	0.84	0.98	0.50	0.86	0.78	-	3.68	2.31	1.00	3.92	1.43	1.79	4.29	3.48	-	5.43	5.64	5.25	4.63
<i>Alticola strelzovi</i>	4.33	5.05	1.88	4.53	6.17	2.58	5.77	2.88	3.10	5.19	2.76	1.73	5.76	3.92	5.71	5.30	3.66	4.27	1.04	5.09	1.37	1.20	1.19
<i>Alticola</i> sp.	19.40	11.62	16.02	16.20	10.52	10.67	12.46	12.32	9.56	10.55	8.90	13.29	15.79	5.88	11.90	11.79	14.31	13.61	-	11.74	8.76	9.23	6.57
<i>Lagurus lagurus</i>	4.33	6.06	0.94	0.89	0.70	1.87	1.42	0.50	0.26	0.81	0.15	1.73	1.75	1.96	-	1.90	0.48	0.95	0.52	0.22	0.02	-	0.30
<i>Lagurus</i> sp.	17.33	3.79	2.47	3.12	1.75	3.47	3.09	0.65	0.26	1.30	0.46	2.89	2.76	1.96	2.38	2.26	4.45	2.53	-	0.89	0.16	0.20	-
<i>Lemmus</i> sp.	-	-	-	0.07	0.14	0.27	0.08	0.07	-	-	0.61	0.29	-	-	0.48	-	0.32	0.16	-	-	0.06	0.12	-
<i>Stenocranium gregalis</i>	9.42	9.60	6.95	9.21	8.42	8.09	10.45	8.36	13.44	15.10	13.04	12.43	10.03	13.73	6.19	8.10	6.52	9.49	7.29	5.65	4.22	3.85	2.69
<i>Microtus oeconomus</i>	1.13	0.76	1.06	0.67	0.42	0.62	0.75	0.72	0.78	1.46	0.77	1.45	2.26	5.88	0.48	0.95	0.95	1.11	0.52	0.66	1.54	0.48	0.45
<i>Microtus hyperboreus</i>	1.13	-	-	-	0.21	-	0.17	0.07	-	0.49	0.15	0.29	0.50	-	-	0.36	0.64	0.47	-	-	0.05	0.04	-
<i>Microtus agrestis</i>	-	-	-	-	-	-	0.08	0.14	-	-	0.15	0.29	1.25	-	-	0.12	0.16	0.16	-	-	-	-	-
<i>Microtus arvalis</i>	-	-	-	-	0.14	-	0.17	-	-	-	0.15	-	-	-	-	0.18	-	-	-	-	-	-	-
<i>Microtus</i> sp.	12.05	19.70	20.49	22.51	21.88	29.42	18.65	27.09	26.61	26.14	20.86	24.86	23.06	35.29	23.81	16.01	18.28	20.25	2.60	13.40	23.84	20.66	18.21
<i>Arvicola</i> sp.	-	-	0.12	0.45	0.21	-	0.08	0.07	-	0.16	0.15	0.29	0.75	-	-	0.18	-	-	0.52	0.11	0.05	-	-
<i>Myospalax myospalax</i>	3.20	2.02	4.36	4.90	5.89	3.02	5.52	2.23	3.88	4.06	1.84	4.34	2.26	-	0.95	5.06	5.56	1.74	13.02	4.32	1.87	1.52	0.15
<i>Arvicolidae</i> gen.	16.01	17.17	1.18	7.80	8.20	13.07	9.62	12.97	9.56	12.99	31.29	13.29	9.27	7.84	5.71	8.39	15.26	11.23	10.94	11.30	11.77	6.02	8.81

<i>Ochotona hyperborea</i>	0.19	-	-	0.67	0.21	0.09	1.59	0.29	-	0.16	-	-	0.50	-	0.95	-	-	-	5.21	0.22	0.01	-	-
<i>Ochotona pusilla</i>	-	0.25	-	-	0.07	0.09	-	-	-	-	0.15	-	-	-	-	-	-	-	-	-	-	-	
<i>Ochotona</i> sp.	1.13	1.26	1.06	1.19	1.47	0.71	1.76	1.08	0.52	1.95	1.84	2.02	1.50	-	0.95	2.68	1.43	1.90	-	2.21	2.68	1.32	0.90
<i>Lepus</i> sp.	1.32	0.25	0.35	0.15	0.56	0.27	0.59	-	0.52	-	-	-	0.25	-	-	0.12	0.32	-	-	0.11	0.04	0.16	-
<i>Mustela</i> sp.	-	-	0.35	0.15	0.07	0.09	0.25	0.22	-	0.16	-	-	-	-	0.48	0.18	0.16	-	0.52	0.11	0.17	0.24	0.15
Carnivora	-	0.51	0.12	0.52	0.21	0.18	0.25	0.07	-	0.32	0.15	0.58	0.75	-	0.95	1.19	0.64	1.11	4.69	0.33	0.65	1.40	0.75
Aves	-	1.77	2.71	4.61	8.35	4.18	2.93	3.03	5.17	3.08	4.45	4.34	6.27	-	12.86	8.57	5.88	4.75	19.79	6.42	0.54	0.40	0.30
Reptilia	-	0.25	0.24	-	-	-	0.08	0.07	-	-	-	-	-	-	-	0.06	0.16	-	-	-	-	0.04	-
Amphibia	-	-	-	0.07	0.07	-	-	0.36	-	-	0.15	0.87	1.00	1.96	0.48	2.08	0.79	0.79	5.21	0.11	0.01	0.04	-
Pisces	-	13.89	28.27	12.56	15.22	13.24	13.46	16.07	17.31	4.87	2.91	3.18	2.26	7.84	7.14	12.20	5.56	13.45	13.54	14.84	4.51	2.33	3.88
Total %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total specimens	531	396	849	1346	1426	1125	1196	1388	387	616	652	346	399	51	210	1680	629	632	192	903	8121	2493	670

Supplementary Table 20 | Species composition and number of bones recovered from the Pleistocene deposits in Main Chamber. The ratio of mammal fossils in each layer is shown in %.

Taxa	Layers									
	9	11	12	13	14	17	19	20	21	22
Carnivora	26.67	30.88	34.02	32.81	41.67	33.33	59.76	64.00	67.50	82.56
<i>Alopex lagopus</i>	1.33	0.35	1.03	-	-	-	0.59	-	-	1.91
<i>Vulpes corsac</i>	1.33	-	0.52	-	0.69	-	1.78	-	2.50	1.36
<i>Vilpes vulpes</i>	5.33	5.96	6.19	6.25	4.17	4.17	7.10	12.00	12.50	11.44
<i>Cuon alpinus</i>	1.33	0.35	1.03	-	2.08	-	2.37	4.00	-	1.63
<i>Canis lupus</i>	2.67	8.07	12.89	9.38	12.50	4.17	17.75	16.00	20.00	11.17
<i>Ursus arctos</i>	-	1.05	-	-	2.08	-	1.18	2.00	-	1.36
<i>Ursus rossicus</i>	-	0.70	1.03	-	0.69	-	-	-	2.50	4.09
<i>Ursus arctos/rossicus</i>	2.67	3.51	3.09	3.13	6.94	16.67	8.28	6.00	17.50	43.32
<i>Maries zibellina</i>	-	-	-	-	0.69	-	0.59	-	5.00	0.27
<i>Mustela eversmannii</i>	2.67	0.70	-	-	2.08	-	0.59	2.00	-	0.82
<i>Mustela ermiea</i>	-	-	-	-	-	-	0.59	-	-	0.27
<i>Mustela altaica</i>	1.33	-	-	-	-	-	-	-	-	0.27
<i>Mustela nivalis</i>	-	0.35	-	-	0.69	-	1.18	4.00	-	-
<i>Crocota spelaea</i>	8.00	9.82	8.25	14.06	9.03	8.33	16.57	18.00	7.50	4.09
<i>Panthera spelaea</i>	-	-	-	-	-	-	-	-	-	0.27
<i>Lynx lynx</i>	-	-	-	-	-	-	1.18	-	-	0.27
Proboscidea	-	1.05	2.06	-	8.33	-	2.37	-	5.00	-
<i>Mammuthus primigenius</i>	-	1.05	2.06	-	8.33	-	2.37	-	5.00	-
Perissodactyla	14.67	16.49	15.98	7.81	11.81	20.83	13.61	12.00	2.50	2.72
<i>Coelodonta antiquitatis</i>	1.33	3.51	1.55	-	4.17	8.33	3.55	-	2.50	0.82
<i>Equus hydruntinus</i>	-	1.05	2.58	-	2.78	-	2.96	2.00	-	0.54
<i>Equus ferus</i>	-	0.35	2.06	-	-	-	1.78	-	-	0.27
<i>Equus hydruntinus/ferus</i>	13.33	11.58	9.79	7.81	4.86	12.50	5.33	10.00	-	1.09
Artiodactyla	58.67	51.58	47.94	59.38	38.19	45.83	24.26	24.00	25.00	14.71
<i>Capreolus pygargus</i>	-	1.05	1.03	-	4.17	8.33	0.59	-	2.50	1.91
<i>Cervus elaphus</i>	2.67	2.81	4.12	3.13	3.47	8.33	1.18	-	-	0.27
<i>Poephagus mutus</i>	-	0.35	0.52	-	-	-	-	-	-	-
<i>Bison priscus</i>	-	3.51	4.12	6.25	1.39	4.17	2.96	-	2.50	0.27
<i>Poephagus/Bison</i>	8.00	8.77	7.22	21.88	4.86	-	2.37	2.00	7.50	2.72
<i>Procapra gutturosa</i>	5.33	2.11	2.58	-	2.08	8.33	2.96	4.00	-	0.27
<i>Saiga tatarica</i>	2.67	2.11	5.67	1.56	-	-	0.59	2.00	-	-
<i>Procapra/Saiga</i>	2.67	2.11	2.58	4.69	1.39	-	-	4.00	2.50	1.09
<i>Capra sibirica</i>	13.33	9.47	5.15	4.69	4.86	8.33	4.14	2.00	2.50	3.00
<i>Ovis ammon</i>	4.00	3.86	3.09	7.81	6.94	8.33	3.55	4.00	-	0.27
<i>Capra/Ovis</i>	20.00	15.44	11.86	9.38	9.03	-	5.92	6.00	7.50	4.90
Total %	100	100	100	100	100	100	100	100	100	100
Total definable mammal bones	75	285	194	64	144	24	169	50	40	367
Total indefinable bone fragments	10229	16880	19595	5663	5213	1234	6099	2356	1514	17343

Supplementary Table 21 | Ratios (in %) of small vertebrates from the Pleistocene deposits in East Chamber.

Taxa	Layers											
	9	11.1	11.2	11.3	11.4	12.1	12.2	12.3	13	14	15	17.1
Chiroptera	4.38	0.49	5.03	7.95	5.81	9.49	4.01	2.11	2.82	8.74	12.87	6.18
<i>Crocedura</i> sp.	-	-	0.01	-	-	-	-	-	-	0.03	0.08	0.18
<i>Sorex roboratus</i>	-	-	0.03	0.14	-	-	-	-	-	-	-	-
<i>Sorex minutus</i>	-	-	0.06	-	0.13	-	0.15	0.09	-	0.02	-	-
<i>Sorex araneus</i>	-	-	0.01	0.43	0.13	-	-	-	-	0.04	0.10	0.18
<i>Sorex</i> sp.	2.79	0.37	1.25	1.42	0.92	1.03	0.31	-	0.28	0.30	0.45	0.36
<i>Neomys</i> sp.	-	-	0.03	-	0.13	0.13	-	-	0.03	-	0.04	-
<i>Asioskalops</i> sp.	1.99	2.56	1.72	1.28	0.53	1.15	2.47	3.21	1.46	3.16	2.76	2.72
<i>Eutamias</i> sp.	-	-	0.04	-	-	-	-	-	0.02	0.02	0.11	0.18
<i>Sciurus</i> sp.	-	-	-	-	-	-	-	-	0.07	0.02	-	0.09
<i>Pteromys</i> sp.	-	-	0.09	-	0.13	-	-	-	-	-	-	-
<i>Spermophilus undulatus</i>	2.39	-	0.20	0.85	0.26	-	-	-	0.14	0.18	-	-
<i>Spermophilus</i> sp.	-	1.83	0.80	0.71	0.66	0.51	0.92	0.64	0.48	0.88	0.94	0.91
<i>Marmota</i> sp.	-	-	0.07	-	-	-	0.15	-	0.09	0.27	0.42	0.64
<i>Sicista</i> sp.	-	-	0.07	-	-	-	-	0.09	-	0.05	-	-
<i>Allactaga</i> sp.	-	-	0.01	-	-	-	-	-	-	0.01	-	-
<i>Apodemus (Alsomys)</i>	-	-	0.01	-	-	-	-	-	-	0.04	-	-
<i>Cricetus crisetus</i>	-	0.24	-	-	-	-	-	-	-	0.04	0.04	0.09
<i>Crisetulus barabensis</i>	-	0.73	0.33	-	0.13	0.13	-	0.09	0.31	0.33	0.30	0.45
<i>Allocricetulus eversmanni</i>	1.59	2.56	1.19	0.57	0.26	0.38	0.92	0.37	0.28	0.26	0.42	0.36
<i>Ellobius</i> sp.	-	0.24	0.10	0.14	0.40	0.13	0.15	-	0.07	0.01	-	-
<i>Clethrionomys rutilus</i>	2.39	0.37	1.63	0.43	2.51	1.03	2.00	3.03	1.74	1.93	1.06	1.36
<i>Clethrionomys rufocanus</i>	0.80	-	0.60	0.28	2.25	3.08	-	-	0.95	0.88	0.23	0.27
<i>Clethrionomys</i> sp.	-	0.73	0.30	1.56	2.51	0.90	3.08	5.50	3.30	4.77	5.13	5.72
<i>Alticola macrotis</i>	-	-	0.11	0.57	0.13	0.26	0.15	-	0.03	0.02	-	-
<i>Alticola strelzovi</i>	10.36	6.33	5.30	4.55	4.76	6.03	4.31	4.86	4.77	4.74	4.57	4.72
<i>Alticola</i> sp.	0.80	11.57	8.12	8.52	9.51	13.08	10.63	11.47	11.63	12.50	11.33	11.44
<i>Lagurus lagurus</i>	-	1.46	0.14	-	0.13	-	0.62	0.18	0.10	0.13	0.11	0.18
<i>Lagurus transiens</i>	-	-	0.04	-	-	-	-	-	0.02	-	-	-
<i>Lagurus</i> sp.	0.40	1.71	0.35	0.28	-	-	0.15	-	0.40	0.28	0.26	0.09
<i>Lemmus</i> sp.	-	0.12	0.09	-	0.53	0.13	-	-	0.07	0.01	0.04	0.09
<i>Stenocranius gregalis</i>	6.37	1.10	3.29	3.55	6.34	5.00	6.01	4.22	6.42	6.22	6.08	7.08
<i>Microtus oeconomus</i>	1.99	0.24	0.87	1.14	1.85	0.90	0.77	0.92	0.74	0.70	0.98	1.82
<i>Microtus hyperboreus</i>	5.58	4.87	3.25	6.68	4.23	3.33	1.85	4.04	1.60	1.40	1.09	1.18
<i>Microtus agrestis</i>	-	-	0.70	0.28	0.66	0.26	-	-	0.07	0.10	0.34	0.64
<i>Microtus arvalis</i>	-	0.24	0.30	-	0.53	-	-	-	0.03	0.12	0.15	0.27
<i>Microtus</i> sp.	21.51	20.71	20.76	22.44	20.48	19.36	13.25	16.51	19.24	18.51	22.61	22.89
<i>Microtinae</i> gen.	3.19	3.29	8.63	7.24	6.47	6.15	6.16	2.94	4.80	5.25	3.66	6.18
<i>Arvicola cf. sapidus</i>	-	0.37	0.14	-	0.13	-	0.15	0.09	0.05	0.10	0.26	0.36
<i>Myospalax myospalax</i>	1.59	2.44	2.51	2.84	1.45	1.28	2.00	1.74	2.01	3.22	4.08	4.45
<i>Ochotona hyperborea</i>	-	-	0.20	-	-	-	-	0.09	0.05	0.09	0.23	0.18
<i>Ochotona pusilla</i>	-	-	0.04	-	-	-	-	-	0.03	0.02	0.04	-
<i>Ochotona</i> sp.	0.80	1.10	0.89	0.57	0.26	0.38	0.77	0.46	0.46	1.45	1.32	1.18
<i>Lepus</i> sp.	-	0.12	0.20	-	0.26	-	0.15	0.09	-	-	-	-
<i>Mustela</i> sp.	-	-	0.17	-	0.26	0.26	0.15	-	0.07	0.24	0.23	0.45
<i>Martes</i> sp.	-	-	0.04	-	0.13	-	-	0.09	0.02	0.06	0.08	0.18
Carnivora	-	-	0.41	-	0.26	0.26	0.46	0.37	0.50	0.46	0.34	0.91
Aves	5.98	6.82	10.28	7.39	15.85	9.74	12.02	7.43	6.09	6.83	6.38	6.90
Reptilia	-	-	0.03	-	-	0.13	-	-	-	0.15	0.08	-
Amphibia	-	0.49	0.26	0.43	0.40	1.54	1.54	1.65	2.74	2.03	1.43	1.36
Pisces	25.10	26.92	19.31	17.76	8.59	13.97	24.65	27.71	26.02	13.41	9.44	7.72
Total %	100	100	100	100	100	100	100	100	100	100	100	100
Total specimens	251	821	1350	704	757	780	649	1090	2738	5105	975	2202

Supplementary Table 22 | Species composition and number of bones recovered from the Pleistocene deposits in East Chamber. The ratio of mammal fossils in each layer is shown in %. Numbers of definable mammal bones, bones of fish, amphibians and birds, and indefinable bone fragments of medium and large mammals are indicated as total specimens.

Taxa	Layers									
	9	11.1	11.2	11.3	11.4	12	13	14	15	17.1
<i>Erinaceus auritus</i>	-	-	-	-	-	0.05	-	-	-	-
<i>Asioscalops altaica</i>	5.05	3.48	3.00	2.89	2.37	2.25	2.20	3.08	1.17	-
Chiroptera	1.01	0.25	0.13	-	-	-	0.37	-	-	-
<i>Lepus tanaiticus</i>	1.01	1.99	1.85	1.03	1.48	1.10	0.73	0.65	1.17	-
<i>Lepus tolai</i>	-	1.74	2.17	0.45	0.59	0.38	-	0.19	-	7.69
<i>Ohotona</i> sp.	1.01	1.24	0.57	0.64	0.59	0.38	0.37	0.19	-	-
<i>Pteromys volans</i>	-	-	0.19	-	-	0.05	-	-	-	-
<i>Tamias sibiricus</i>	-	-	-	0.06	-	-	-	-	-	-
<i>Spermophilus</i> sp.	1.01	8.21	4.47	2.06	1.18	1.49	1.47	2.05	1.17	23.08
<i>Marmota baibacina</i>	3.03	1.49	2.68	3.79	3.85	3.74	4.40	7.93	5.45	-
<i>Castor fiber</i>	-	-	0.13	0.58	0.30	-	-	-	0.78	-
<i>Allactaga</i> sp.	-	-	-	-	-	-	-	0.09	-	-
<i>Cricetus</i> sp.	-	-	0.89	0.45	0.15	0.86	-	-	-	-
<i>Myospalax myospalax</i>	15.15	22.89	17.29	14.32	9.91	10.78	11.36	9.79	6.61	-
Rodentia gen. indet.	8.08	16.42	9.76	6.74	3.70	4.22	9.52	6.62	3.89	-
<i>Canis lupus</i>	5.05	2.24	5.23	4.11	6.80	5.75	6.23	6.16	9.34	-
<i>Vulpes vulpes</i>	1.01	2.24	3.13	2.38	4.88	3.64	2.20	1.87	2.72	-
<i>Vulpes corsak</i>	-	-	0.96	0.83	2.07	0.86	1.47	0.75	-	7.69
<i>Cuon alpinus</i>	-	0.50	0.51	1.73	2.51	2.64	3.30	5.04	5.06	7.69
<i>Ursus arctos</i>	-	-	0.13	0.77	-	1.10	0.37	1.87	2.33	-
<i>Ursus (Spelaearctos) savini</i>	-	0.25	0.19	-	-	-	-	-	-	-
<i>Martes zibellina</i>	-	-	-	0.19	-	-	-	-	-	-
<i>Gulo gulo</i>	-	-	0.13	0.06	-	-	-	-	-	-
<i>Mustela erminea</i>	-	-	0.06	0.06	0.30	-	-	-	-	-
<i>Mustela nivalis</i>	-	-	-	0.06	-	0.05	-	-	-	-
<i>Mustela sibirica</i>	-	-	0.06	0.13	-	-	-	-	-	-
<i>Mustela altaica</i>	-	-	0.19	0.06	0.89	0.05	-	0.19	0.39	-
<i>Mustela eversmanni</i>	-	0.25	0.13	-	0.30	0.38	0.37	0.19	-	-
<i>Crocota crocota spelaea</i>	10.10	7.46	6.32	8.54	7.54	8.72	5.13	3.08	1.17	-
<i>Panthera spelaea</i>	-	-	0.19	-	0.30	0.05	-	-	-	-
<i>Uncia uncia</i>	-	-	0.19	0.13	0.15	-	-	-	-	7.69
<i>Lynx lynx</i>	1.01	-	-	-	-	-	-	-	-	-
<i>Felis manul</i>	-	-	-	0.06	-	-	-	-	-	-
<i>Mammuthus primigenius</i>	1.01	0.25	0.19	0.83	1.33	0.91	0.73	0.37	1.56	-
<i>Equus (Equus) ferus</i>	3.03	1.24	0.38	0.51	0.30	0.62	0.37	0.37	-	-
<i>Equus (Sussemionus) ovodovi</i>	1.01	0.50	0.89	2.31	1.92	1.58	0.37	1.03	3.11	-
<i>Equus ovodovi / ferus</i>	2.02	3.98	5.62	6.23	7.25	8.62	9.16	10.54	2.72	-
<i>Coelodonta antiquitatis</i>	2.02	1.49	1.02	2.83	2.81	2.06	5.13	4.94	3.50	-
<i>Cervus elaphus</i>	3.03	0.75	1.72	2.76	4.14	1.44	1.47	2.80	10.12	15.38
<i>Megaloceros giganteus</i>	1.01	-	0.26	0.32	0.74	0.14	-	0.47	1.17	-
<i>Alces cf. alces</i>	-	-	-	0.06	0.15	0.05	-	-	-	-
<i>Capreolus pygargus</i>	2.02	0.25	1.79	2.95	4.29	2.44	2.20	10.17	19.07	15.38
<i>Rangifer tarandus</i>	-	-	0.19	0.06	-	0.19	-	-	-	-
<i>Bison priscus</i>	10.10	5.47	7.40	6.23	7.40	5.89	4.40	4.48	5.06	-
<i>Poëphagus mutus baicalensis</i>	-	-	-	0.06	0.15	0.05	-	-	-	-
<i>Saiga tatarica borealis</i>	-	-	0.13	0.51	-	0.34	-	0.28	-	-
<i>Gazella guttursza</i>	-	-	0.06	3.85	3.25	5.65	7.69	4.29	0.78	-
<i>Gazella / Saiga</i>	-	0.25	0.57	1.35	1.18	2.35	1.10	1.68	1.95	-
<i>Capra sibirica</i>	6.06	6.72	8.93	7.77	6.95	8.15	8.06	5.88	4.28	15.38
<i>Ovis ammon</i>	1.01	3.73	3.06	1.73	1.78	1.53	3.66	0.56	0.39	-
<i>Capra / Ovis</i>	15.15	4.73	7.21	7.45	6.51	9.39	6.23	2.43	5.06	-
<i>Spirocerus kiakhtensis</i>	-	-	-	-	-	0.05	-	-	-	-
Total %	100	100	100	100	100	100	100	100	100	100
Total definable mammal bones	99	402	1567	1557	676	2087	273	1072	257	13
Pisces	-	2	6	5	3	-	5	-	-	-
Amphibia	-	-	2	2	-	3	-	1	-	-
Aves	7	49	194	133	75	137	12	55	5	-
Total indefinable bone fragments	1282	5152	14177	25167	18437	41534	6243	29757	8221	405

Supplementary Table 23 | Number of bones and ratios (in %) of diagnostic species (or species groups) recovered from the Pleistocene deposits in East Chamber.

Taxa	Layers							
	9, 11.1–11.4		12		13		14, 15	
	number	%	number	%	number	%	number	%
Carnivora	814	37.77	485	38.28	52	35.37	259	31.09
<i>Crocota crocuta spelaea</i>	323	14.99	182	14.36	14	9.52	36	4.32
<i>Ursus arctos</i>	14	0.65	23	1.82	1	0.68	26	3.12
Equidae	342	15.87	226	17.84	27	18.37	143	17.17
Cervidae (without <i>Rangifer tarandus</i>)	227	10.53	85	6.71	10	6.80	222	26.65
<i>Capreolus pygargus</i>	106	4.92	51	4.03	6	4.08	158	18.97
<i>Cervus elaphus</i>	104	4.83	30	2.37	4	2.72	56	6.72
<i>Rangifer tarandus</i>	4	0.19	4	0.32	–	–	–	–
<i>Bison priscus</i>	295	13.69	123	9.71	12	8.16	61	7.32
<i>Gazella / Saiga</i>	132	6.13	174	13.73	24	16.33	74	8.88
<i>Capra sibirica</i>	341	15.82	170	13.42	22	14.97	74	8.88
Total large mammal remains	2155	100	1267	100	147	100	833	100

Supplementary References

52. Derevianko, A. P., Shunkov, M. V., Kozlikin, M. B., Uliyanov, V. A. & Chekha, A. M. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **20**, 50–53 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2014).
53. Derevianko, A. P., Shunkov, M. V., Kozlikin, M. B. & Chekha, A. M. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **21**, 71–74 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2015).
54. Derevianko, A. P. *et al.* in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **22**, 60–64 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2016).
55. Kozlikin, M. B. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **22**, 84–88 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2016).
56. Kozlikin, M. B. *The Palaeolithic Complexes from the Eastern Chamber of Denisova Cave*. PhD thesis, Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk (2017).
57. von den Driesch, A. A guide to the measurement of animal bones from archaeological sites. *Peabody Mus. Bull.* **1**, 1–136 (1976).
58. Bolikhovskaya, N. S. *Evolution of the Loess-Palaeosol Formation of Northern Eurasia*. (Moscow University Press, Moscow, 1995).
59. Derevianko, A. P. *et al.* *Archaeology, Geology, and the Pleistocene and Holocene Palaeogeography of the Mountainous Altai* (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 1998).
60. Derev'anko, A. & Markin, S. in *The Paleolithic of Siberia: new discoveries and interpretations* (eds Derev'anko, A. P., Shimkin, D. B. & Powers, W. R.), 88–94 & 160–167 (Univ. Illinois Press, Urbana & Chicago, 1998).
61. Derevianko, A. P., Shunkov, M. V. & Volkov, P. V. A Paleolithic bracelet from Denisova Cave. *Archaeol. Ethnol. Anthropol. Eurasia* **34/2**, 13–25 (2008).
62. Derevianko, A. P. Three scenarios of the Middle to Upper Paleolithic transition – Scenario 1: the Middle to Upper Paleolithic transition in northern Asia. *Archaeol. Ethnol. Anthropol. Eurasia* **38/3**, 2–32 (2010).
63. Fu, Q. *et al.* Genome sequence of a 45,000-year-old modern human from western Siberia. *Nature* **514**, 445–449 (2014).
64. Aitken, M. J. *An Introduction to Optical Dating* (Oxford Univ. Press, Oxford, 1998).
65. Wintle, A. G. in *Treatise on Geochemistry*, 2nd ed. (eds Holland, H. D. & Turekian, K. K.), **14**, 17–35 (Elsevier, Oxford, 2014).
66. Li, B., Jacobs, Z., Roberts, R. G. & Li, S.-H. Review and assessment of the potential of post-IR IRSL dating methods to circumvent the problem of anomalous fading in feldspar luminescence. *Geochronometria* **41**, 178–201 (2014).
67. Thomsen, K. J., Murray, A. S., Jain, M. & Bøtter-Jensen, L. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. *Radiat. Meas.* **43**, 1474–1486 (2008).
68. Jacobs, Z., Duller, G. A. T. & Wintle, A. G. Interpretation of single grain D_e distributions and calculation of D_e . *Radiat. Meas.* **41**, 264–277 (2006).
69. Duller, G. A. T. Single-grain optical dating of Quaternary sediments: why aliquot size matters in luminescence dating. *Boreas* **37**, 589–612 (2008).
70. Li, B., Roberts, R. G. & Jacobs, Z. On the dose dependency of the bleachable and non-bleachable components of IRSL from K-feldspar: improved procedures for luminescence dating of Quaternary sediments. *Quat. Geochronol.* **17**, 1–13 (2013).

71. Bøtter-Jensen, L., Andersen, C. E., Duller, G. A. T. & Murray, A. S. Developments in radiation, stimulation and observation facilities in luminescence measurements. *Radiat. Meas.* **37**, 535–541 (2003).
72. Ballarini, M., Wintle, A. G. & Wallinga, J. Spatial variation of dose rate from beta sources as measured using single grains. *Anc. TL* **24**, 1–8 (2006).
73. Galbraith, R. F., Roberts, R. G., Laslett, G. M., Yoshida, H. & Olley, J. M. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: Part I, experimental design and statistical models. *Archaeometry* **41**, 339–364 (1999).
74. Murray, A. S. & Wintle, A. G. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiat. Meas.* **32**, 57–73 (2000).
75. Duller, G. A. T. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiat. Meas.* **37**, 161–165 (2003).
76. Balian, H. G. & Eddy, N. W. Figure-of-merit (FOM), an improved criterion over the normalized chi-squared test for assessing goodness-of-fit of gamma-ray spectral peaks. *Nucl. Instrum. Meth.* **145**, 389–395 (1977).
77. Peng, J., Pagonis, V. & Li, B. On the intrinsic accuracy and precision of the standardised growth curve (SGC) and global-SGC (gSGC) methods for equivalent dose determination: a simulation study. *Radiat. Meas.* **94**, 53–64 (2016).
78. Peng, J. & Li, B. Single-aliquot regenerative-dose (SAR) and standardised growth curve (SGC) equivalent dose determination in a batch model using the R package ‘numOSL’. *Anc. TL* **35**, 32–53 (2017).
79. Peng, J., Dong, Z., Han, F., Long, H. & Liu, X. R package *numOSL*: numeric routines for optically stimulated luminescence dating. *Anc. TL* **31**, 41–48 (2013).
80. R Core Team. *R: A Language and Environment for Statistical Computing* (Vienna, Austria, 2016).
81. Guralnik, B., Li, B., Jain, M., Chen, R., Paris, R. B., Murray, A. S., Li, S.-H., Pagonis, V., Valla, P. G. & Herman, F. Radiation-induced growth and isothermal decay of infrared-stimulated luminescence from feldspar. *Radiat. Meas.* **81**, 224–231 (2015).
82. Kreutzer, S., Schmidt, C., Fuchs, M.C., Dietze, M., Fischer, M. & Fuchs, M. Introducing an R package for luminescence dating analysis. *Ancient TL* **30**, 1–8 (2012).
83. Roberts, H. M. & Duller, G. A. T. Standardised growth curves for optical dating of sediment using multiple-grain aliquots. *Radiat. Meas.* **38**, 241–252 (2004).
84. Li, B., Roberts, R. G., Jacobs, Z. & Li, S.-H. Potential of establishing a ‘global standardised growth curve’ (gSGC) for optical dating of quartz from sediments. *Quat. Geochronol.* **27**, 94–104 (2015).
85. Li, B., Roberts, R. G., Jacobs, Z., Li, S.-H. & Guo, Y.-J. Construction of a ‘global standardised growth curve’ (gSGC) for infrared stimulated luminescence dating of K-feldspar. *Quat. Geochronol.* **27**, 119–130 (2015).
86. Li, B., Jacobs, Z. & Roberts, R. G. Investigation of the applicability of standardised growth curves for OSL dating of quartz from Haua Fteah cave, Libya. *Quat. Geochronol.* **35**, 1–15 (2016).
87. Li, B. & Li, S.-H. A reply to the comments by Thomsen *et al.* on “Luminescence dating of K-feldspar from sediments: a protocol without anomalous fading correction”. *Quat. Geochronol.* **8**, 49–51 (2012).
88. Duller, G. A. T. Improving the accuracy and precision of equivalent doses determined using the optically stimulated luminescence signal from single grains of quartz. *Radiat. Meas.* **47**, 770–777 (2012).
89. Gliganic, L. A., Jacobs, Z. & Roberts, R. G. Luminescence characteristics and dose distributions for quartz and feldspar grains from Mumba rockshelter, Tanzania. *Archaeol. Anthropol. Sci.* **4**, 115–135 (2012).

90. Thomsen, K. J. *et al.* Testing single-grain quartz OSL methods using sediment samples with independent age control from the Bordes-Fitte rockshelter (Roches d'Abilly site, Central France). *Quat. Geochronol.* **31**, 77–96 (2016).
91. Guo, Y.-J. *et al.* New ages for the Upper Palaeolithic site of Xibaimaying in the Nihewan Basin, northern China: implications for small-tool and microblade industries in north-east Asia during Marine Isotope Stages 2 and 3. *J. Quat. Sci.* **32**, 540–552 (2017).
92. Galbraith, R. F., Roberts, R. G. & Yoshida, H. Error variation in OSL palaeodose estimates from single aliquots of quartz: a factorial experiment. *Radiat. Meas.* **39**, 289–307 (2005).
93. Galbraith, R. F. & Roberts, R. G. Statistical aspects of equivalent dose and error calculation and display in OSL dating: an overview and some recommendations. *Quat. Geochronol.* **11**, 1–27 (2012).
94. Li, B. & Li, S.-H. Luminescence dating of K-feldspar from sediments: a protocol without anomalous fading correction. *Quat. Geochronol.* **6**, 468–479 (2011).
95. Chen, Y., Li, S.-H., Li, B., Hao, Q. & Sun, J. Maximum age limitation in luminescence dating of Chinese loess using the multiple-aliquot MET-pIRIR signals from K-feldspar. *Quat. Geochronol.* **30**, 207–212 (2015).
96. Guo, Y.-J., Li, B., Zhang, J.-F. & Roberts, R.G. Luminescence-based chronologies for Palaeolithic sites in the Nihewan Basin, northern China: first tests using newly developed optical dating procedures for potassium feldspar grains. *J. Archaeol. Sci. Rep.* **3**, 31–40 (2015).
97. Li, B., Jacobs, Z., Roberts, R. G. & Li, S.-H. Extending the age limit of luminescence dating using the dose-dependent sensitivity of MET-pIRIR signals from K-feldspar. *Quat. Geochronol.* **17**, 55–67 (2013).
98. Li, B., Roberts, R. G., Jacobs, Z. & Li, S.-H. A single-aliquot luminescence dating procedure for K-feldspar based on the dose-dependent MET-pIRIR signal sensitivity. *Quat. Geochronol.* **20**, 51–64 (2014).
99. Duller, G. A. T. Assessing the error on equivalent dose estimates derived from single aliquot regenerative dose measurements. *Anc. TL* **25**, 15–24 (2007).
100. Derevianko, A. P. *et al.* *Multidisciplinary Studies of the Chagyrskaya Cave – Middle Paleolithic site in Altai* (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences Press, Novosibirsk, 2018).
101. Auclair, M., Lamothe, M. & Huot, S. Measurement of anomalous fading for feldspar IRSL using SAR. *Radiat. Meas.* **37**, 487–492 (2003).
102. Rousseeuw, P. J. & Croux, C. Alternatives to the median absolute deviation. *J. Am. Stat. Assoc.* **88**, 1273–1283 (1993).
103. Powell, R., Hergt, J. & Woodhead, J. Improving isochron calculations with robust statistics and the bootstrap. *Chem. Geol.* **185**, 191–204 (2002).
104. Rousseeuw, P. J., Debruyne, M., Engelen, S. & Hubert, M. Robustness and outlier detection in chemometrics. *Crit. Rev. Anal. Chem.* **36**, 221–242 (2006).
105. Storey, M., Roberts, R. G. & Saidin, M. Astronomically calibrated $^{40}\text{Ar}/^{39}\text{Ar}$ age for the Toba supereruption and global synchronization of late Quaternary records. *Proc. Natl Acad. Sci. USA* **109**, 18684–18688 (2012).
106. Galbraith, R. F. & Green, P. F. Estimating the component ages in a finite mixture. *Nucl. Tracks Radiat. Meas.* **17**, 197–206 (1990).
107. Roberts, R. G., Galbraith, R. F., Yoshida, H., Laslett, G. M. & Olley, J. M. Distinguishing dose populations in sediment mixtures: a test of single-grain optical dating procedures using mixtures of laboratory-dosed quartz. *Radiat. Meas.* **32**, 459–465 (2000).
108. David, B. *et al.* Sediment mixing at Nonda rock: investigations of stratigraphic integrity at an early archaeological site in northern Australia, and implications for the human colonisation of the continent. *J. Quat. Sci.* **22**, 449–479 (2007).
109. Jacobs, Z., Wintle, A. G., Duller, G. A. T., Roberts, R. G. & Wadley, L. New ages for the post-Howiesons Poort, late and final Middle Stone age at Sibudu, South Africa. *J. Archaeol. Sci.* **35**, 1790–1807 (2008).

110. Jacobs, Z. *et al.* Single-grain OSL dating at La Grotte des Contrebandiers ('Smugglers' Cave'), Morocco: improved age constraints for the Middle Paleolithic levels. *J. Archaeol. Sci.* **38**, 3631–3643 (2011).
111. Jacobs, Z., Wintle, A. G., Roberts, R. G. & Duller, G. A. T. Equivalent dose distributions from single grains of quartz at Sibudu, South Africa: context, causes and consequences for optical dating of archaeological deposits. *J. Archaeol. Sci.* **35**, 1808–1820 (2008).
112. Fleming, S. J. The pre-dose technique: a new thermoluminescence dating method. *Archaeometry* **15**, 13–30 (1973).
113. Olley, J. M., Murray, A. S. & Roberts, R. G. The effects of disequilibria in the uranium and thorium decay chains on burial dose rates in fluvial sediments. *Quat. Sci. Rev.* **15**, 751–760 (1996).
114. Olley, J. M., Roberts, R. G. & Murray, A. S. Disequilibria in the uranium decay series in sedimentary deposits at Allen's Cave, Nullarbor Plain, Australia: implications for dose rate determinations. *Radiat. Meas.* **27**, 433–443 (1997).
115. Mercier, N. *et al.* Thermoluminescence dating and the problem of geochemical evolution of sediments—a case study: the Mousterian levels at Hayonim. *Isr. J. Chem.* **35**, 137–141 (1995).
116. Karkanas, P., Bar-Yosef, O., Goldberg, P. & Weiner, S. Diagenesis in prehistoric caves: the use of minerals that form *in situ* to assess the completeness of the archaeological record. *J. Archaeol. Sci.* **27**, 915–929 (2000).
117. Jacobs, Z. & Roberts, R. G. An improved single grain OSL chronology for the sedimentary deposits from Diepkloof Rockshelter, Western Cape, South Africa. *J. Archaeol. Sci.* **63**, 175–192 (2015).
118. Bell, W. T. & Zimmerman, D. W. The effect of HF acid etching on the morphology of quartz inclusions for thermoluminescence dating. *Archaeometry* **20**, 63–65 (1978).
119. Brennan, B. J. Beta doses to spherical grains. *Radiat. Meas.* **37**, 299–303 (2003).
120. Nathan, R. P. & Mauz, B. On the dose-rate estimate of carbonate-rich sediments for trapped charge dating. *Radiat. Meas.* **43**, 14–25 (2008).
121. Rhodes, E. J. & Schwenninger, J.-L. Dose rates and radioisotope concentrations in the concrete calibration blocks at Oxford. *Anc. TL* **25**, 5–8 (2007).
122. Mercier, N. & Falguères, C. Field gamma dose-rate measurement with a NaI(Tl) detector: re-evaluation of the "threshold" technique. *Anc. TL* **25**, 1–4 (2007).
123. Murray, A. S. & Roberts, R. G. Determining the burial time of single grains of quartz using optically stimulated luminescence. *Earth Planet. Sci. Lett.* **152**, 163–180 (1997).
124. Zhao, H. & Li, S.-H. Internal dose rate to K-feldspar grains from radioactive elements other than potassium. *Radiat. Meas.* **40**, 84–93 (2005).
125. Huntley, D. J. & Baril, M. R. The K content of the K-feldspars being measured in optical dating or in thermoluminescence dating. *Anc. TL* **15**, 11–13 (1997).
126. Huntley, D. J. & Hancock, R. G. V. The Rb contents of the K-feldspars being measured in optical dating. *Anc. TL* **19**, 43–46 (2001).
127. Spooner, N. A. Optical dating: preliminary results on the anomalous fading of luminescence from feldspars. *Quat. Sci. Rev.* **11**, 139–145 (1992).
128. Smedley, R. K., Duller, G. A. T., Pearce, N. J. G. & Roberts, H. M. Determining the K-content of single-grains of feldspar for luminescence dating. *Radiat. Meas.* **47**, 790–796 (2012).
129. Sutikna, T. *et al.* Revised stratigraphy and chronology for *Homo floresiensis* at Liang Bua in Indonesia. *Nature* **532**, 366–369 (2016).
130. Lamothe, M., Balescu, S. & Auclair, M. Natural IRSL intensities and apparent luminescence ages of single feldspar grains extracted from partially bleached sediments. *Radiat. Meas.* **23**, 555–561 (1994).
131. Godfrey-Smith, D. I., Scallion, P. & Clarke, M. L. Beta dosimetry of potassium feldspars in sediment extracts using imaging microprobe analysis and beta counting. *Geochronometria* **24**, 7–12 (2005).

132. Neudorf, C. M., Roberts, R. G. & Jacobs, Z. Sources of overdispersion in a K-rich feldspar sample from north-central India: insights from D_e , K content and IRSL age distributions for individual grains. *Radiat. Meas.* **47**, 696–702 (2012).
133. Gaar, D., Lowick, S. E. & Preusser, F. Performance of different luminescence approaches for the dating of known-age glaciofluvial deposits from northern Switzerland. *Geochronometria* **41**, 65–80 (2014).
134. Trauerstein, M., Lowick, S. E., Preusser, F. & Schlunegger, F. Small aliquot and single grain IRSL and post-IR IRSL dating of fluvial and alluvial sediments from the Pativilca valley, Peru. *Quat. Geochronol.* **22**, 163–174 (2014).
135. Vernon, R. H. *A Practical Guide to Rock Microstructure* (Cambridge Univ. Press, Cambridge, 2004).
136. Mejdahl, V. Internal radioactivity in quartz and feldspar grains. *Anc. TL* **5**, 10–17 (1987).
137. Liritzis, I., Stamoulis, K., Papachristodoulou, C. & Ioannides, K. A re-evaluation of radiation dose-rate conversion factors. *Mediterr. Archaeol. Archaeom.* **13**, 1–15 (2013).
138. Rhodes, E. J. *et al.* Bayesian methods applied to the interpretation of multiple OSL dates: high precision sediment ages from Old Scatness Broch excavations, Shetland Isles. *Quat. Sci. Rev.* **22**, 1231–1244 (2003).
139. Bronk Ramsey, C. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* **51**, 1023–1045 (2009).
140. Derevianko, A. P. *et al.* in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **17**, 48–53 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2011).
141. Derevianko, A. P., Shunkov, M. V., Uliyanov, V. A., Kozlikin, M. B. & Chekha, A. M. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **18**, 78–82 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2012).
142. Uliyanov, V. A. & Shunkov, M. V. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **19**, 159–162 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2013).
143. Uliyanov, V. A., Kozlikin, M. B. & Shunkov, M. V. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **21**, 157–160 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2015).
144. Uliyanov, V. A., Kozlikin, M. B., Belousova, N. E. & Shunkov, M. V. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **22**, 169–172 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2016).
145. Agadjanian, A. K. & Serdyuk, N. V. History of mammalian communities and paleogeography of Altai Mountains in the Paleolithic. *Paleontol. J.* **39**, Suppl. 6, S645–S821 (2005).
146. Agadjanian, A. K., Shunkov, M. V. & Kozlikin, M. B. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **23**, 7–10 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2017).
147. Vasiliev, S. K., Shunkov, M. V. & Tsybankov, A. A. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **14**, 26–31 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2008).
148. Vasiliev, S. K., Shunkov, M. V. & Tsybankov, A. A. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **16**, 28–32 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2010).
149. Vasiliev, S. K., Shunkov, M. V. & Kozlikin, M. B. in *Problems of Archaeology, Ethnography and Anthropology of Siberia and Neighbouring Territories* **19**, 32–38 (Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, 2013).