
Supplementary information

East-to-west human dispersal into Europe 1.4 million years ago

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Supplementary Information for “East-to-west human dispersal into Europe 1.4-million-years-ago” Garba et al.

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1.0 Background on the archaeology of Korolevo

1.1 Archaeological excavations

Between 1974 and 2017, more than 50 sondages, excavations and profiles were carried out in the area of three archaeological sites (Fig. S1): Korolevo I - Gostry Verkh¹⁻⁵ (Fig. S2), Korolevo I - Beyvar⁶, and Korolevo II^{7,8}. During 1984-88, sondages 14, 18, 26 and excavations XII, X/XIII of the 12 m loess-palaeosol sequence were conducted at Gostry Verkh for archaeological, micromorphological, palaeopedological, palynological, litho-mineralogical, palaeomagnetic, thermoluminescence, palaeomagnetic, and radiocarbon dating studies with lithic artefacts divided into eight cultural levels (CL) based on stratigraphy (Gostry Verkh) and degree of weathering (Beyvar)¹⁻³. Excavation XII at Gostry Verkh was excavated only to a depth of 1.5 m (ref. 7). Later, the focused study of excavation XIII reduced the number of CLs to seven^{4,5}. The lowest CL VII with stratigraphically recorded in situ artefacts and pebbles was used for cosmogenic dating (Fig. S4; Tab. S2). The 1998 profile was excavated to a depth of about 12 m and, together with data from sondages 18 and 26, was used to update the litho-stratigraphic sequence of Korolevo I - Gostry Verkh⁴ (Figs. S1 & S2). In 2006, Nawrocki et al. conducted a dedicated palaeomagnetic survey in profile 2006 (ref. 9) (Figs. S1 & S2).

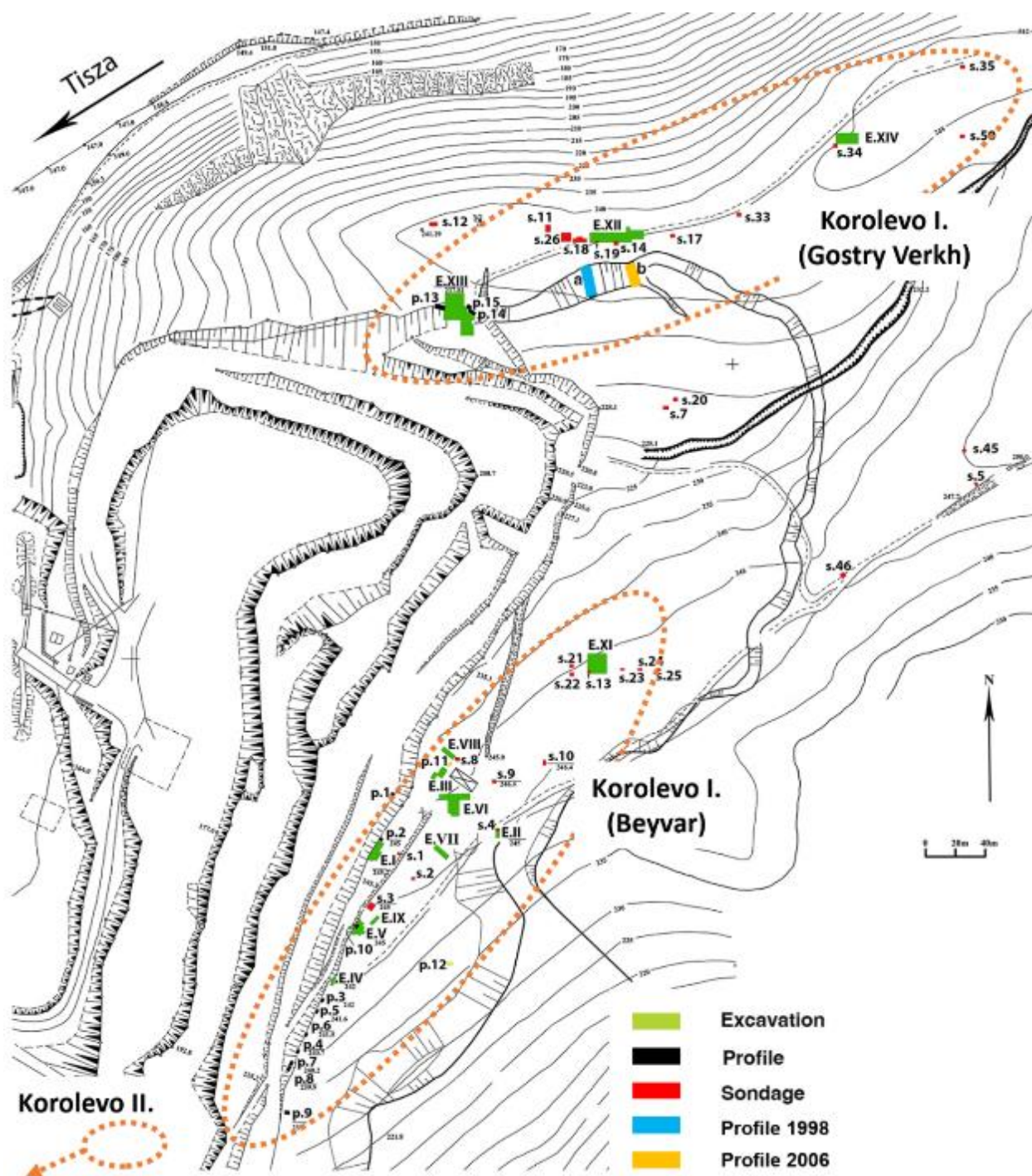


Fig. S1 | Plan of Korolevo excavation sites (brown dotted ovals): archaeological excavations (green), profiles (black), and sondages (red). **a.** Location of litho-pedo-stratigraphic profile 1998 (ref. 4) (light blue). **b.** Location of palaeomagnetic profile 2006 (ref. 9) (orange). Modified and extended⁵.

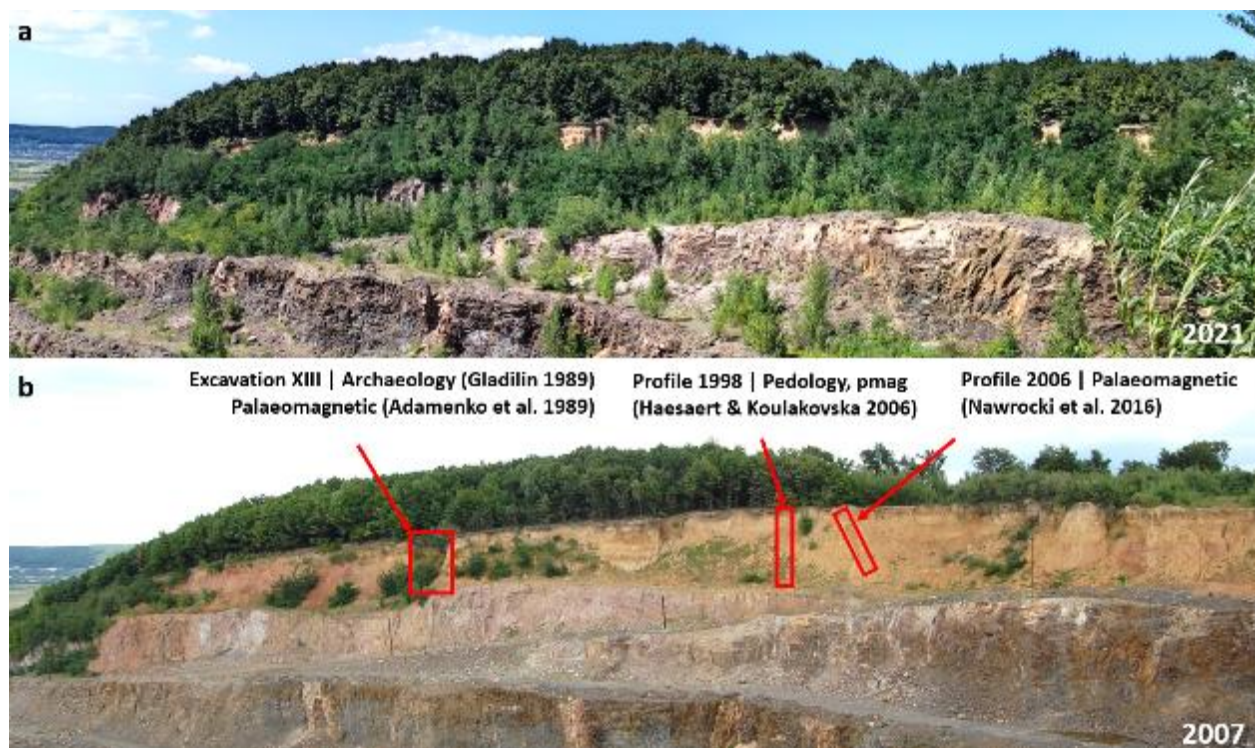


Fig. S2 | Korolevo I, Gostry Verkh: **a.** Recent view of Gostry Verkh from Beyvar hill in 2021. **b.** Gostry Verkh profile from Beyvar hill in 2007 with three main investigations highlighted: archaeological excavation XIII^{1,2,5}; litho-pedo stratigraphic Profile 1998 (ref. 4); palaeomagnetic Profile 2006 (ref. 9).

1.2 Lithostratigraphy

The lithostratigraphy of the Korolevo I site^{2,4,9} comprises alternating loess and palaeosol units, which constitute a subaerial cover on the fluvial deposits at the base of the section. Lithological interpretations are supported by pollen data: pollen assemblages of interglacials and interstadials are identified within the palaeosols, and pollen assemblages of glacials and stadials are identified in the loess layers. Cold climate conditions during the accumulation of the loess layers are also indicated by structures and textures formed by cryogenic processes.

Loess and palaeosol units at Korolevo I follow the Quaternary Stratigraphical Framework of Ukraine¹⁰. According to this framework, the lowermost soil of the Korolevo I succession, below the Matuyama-Brunhes boundary (unit 23), is assigned to the last soil unit of the Early Pleistocene—the Shyrokinio. Shyrokinian times are correlated with MIS 21–31 (ref. 11). In stratigraphically complete sequences, the Shyrokinio unit consists of several palaeosols. The presence of only one Shyrokinio palaeosol at Korolevo I is consistent with an erosional break observed at the base of this soil. The significant intensity of erosional processes is indicated by the presence of pebble-size debris, which is absent in the less pronounced erosional levels higher in the sequence (Fig. 2).

The fluvial deposits at Korolevo I consist of three lithological units (25, 26, and 27). The lowermost (27) is represented by a basal bed consisting of pebbles cemented by red-coloured clays. It is overlain by light-grey sands of floodplain facies (unit 26), with multiple yellow and bright-red spots. The latter indicates enrichment in iron oxides that can be typical for sediments formed under a warm interglacial climate. According to the pollen data³, this bed, with cultural layer VII, also was formed in an interglacial. In its pollen data, palynomorphs of broad-leaved temperate-climate trees: *Ulmus* (elm) and *Carpinus* (hornbeam) dominate, and small pollen values of highly thermophilous *Pterocarya* (wingnut) are present, as well as moisture-loving *Picea* (spruce). The fluvial origin of the sediment is evidenced by spores of aquatic ferns (*Azolla* sp.) and other water plants/algae such as *Pennales* and *Pediastrum*^{1,4}. Unit 27 is composed of floodplain silts, with the upper part having a monotonous light-grey colour. Its pollen indicates a cool period with dominant boreal trees: pine, birch and spruce. In Korolevo excavation XIII, an erosional break is observed between the alluvial units 26 and 25.

A two-part sequence of fluvial deposits is typical for alluvial terraces in Ukraine¹⁰. It had been shown that a lower alluvial unit (with a basal layer) was formed potentially during an interglacial, and an upper unit during a subsequent glacial. The upper unit, in turn, is overlain by a subaerial soil formed during the subsequent interglacial. An upper alluvial unit was accumulated during a glacial that preceded a time of subaerial interglacial soil formation. The lower alluvial unit is one interglacial older than that represented by the subaerial interglacial soil.

In the Ukrainian Quaternary framework, the Illichivian cold interval followed the Kryzhanivian interglacial and preceded Shyrokinian interglacial times. Thus, fluvial beds at Korolevo I were formed during Kryzhanivian (units 27–26) and Illichivian (unit 25) times. The Illichivian cold time is correlated with MIS 32–36, whereas the Kryzhanivian interglacial period included MIS 43–47 and terminated with MIS 37 (ref. 11). Thus, the stratigraphical assignment of the lower alluvial suite fits well with the cosmogenic burial age of the artefacts revealed in it, corresponding to MIS 43–47.

The fluvial beds at Korolevo I have formerly been assigned to the Shyrokinian unit^{2,9}. This was because the Taman faunal complex had been found in correlative alluvial beds at a nearby site. The Taman faunal assemblage had formerly been related to the period 1.3–0.85 Ma; though later studies demonstrated that this time span should be expanded back to 1.55 Ma (ref. 12), i.e., to the Kryzhanivian age. The other former argument in support of an early Shyrokinian age for the alluvia was the identification of a palaeomagnetic excursion, taken to be the Jaramillo revealed in the red-orange clayey silt with scattered river gravel at the base of the sequence⁹. An erosional break separates the single Shyrokinian soil from the alluvial beds, and, thus, this palaeomagnetic event might be assignable to an older palaeomagnetic event than the Jaramillo.

The Shyrokin Vertisols and Luvisols in western Ukraine (and in Transcarpathia) do not have red colour shades, whereas a typical feature of the Kryzhanivka soils is their intense red or ochre-brown colouration, which points to formation in a very warm climate; and that is also confirmed by pollen^{10,13}. At Korolevo I, pollen from the Kryzhanivka alluvium (unit 26) indicates that the highly thermophilous tree *Pterocarya* grew here during its accumulation, whereas it was absent during Shyrokinian times (unit 23). Thus, the litho- and biostratigraphic data provide support for the assignment of unit 26 to the very warm Kryzhanivian interglacial, and this is in agreement with the burial age derived from cosmogenic nuclides.

1.3 Contextualization of previous thermoluminescence dating & magnetostratigraphy

The burial age derived from cosmogenic nuclides allows a new view on the interpretation of magnetostratigraphic data, especially for the base of the stratigraphic sequence. The reversed Matuyama polarity of the lower sediments correlates with the new burial age.

The initial thermoluminescence (TL) results¹ generally agree with the stratigraphy, except for the age of 850 ± 100 ka obtained for level VII. Aside from being implausibly old to resolve with TL, this age is inconsistent with identification of a normal polarity zone, originally interpreted as the Jaramillo subchron (1.07–0.99 Ma) above level VII. The TL age of 850 ± 100 ka can be traced back to a compilation by Adamenko and Grodetskaya (1987)¹⁴, which was not subject to international peer review. We consider the 850 ± 100 ka TL age to be unreliable because (1) the measurement was made in the 1980s when the method was still under development, (2) the low likelihood of adequate bleaching of basal fluvial sediments¹⁵, and (3) the absence of any documentation of laboratory procedures. Furthermore, more recent evaluations of luminescence dating techniques indicate an upper age limit < 850 ka^{16,17}, suggesting that an age of 850 ± 100 ka should be considered as a minimum age. Apart from inadequate bleaching in fluvial sediments, the TL sensitivity changes, and anomalous fading are reasons for significant age underestimates for older TL samples¹⁸ and such issues are only partially addressed by preheating and sensitivity corrections, which can still yield only minimum age estimates¹⁸. Other TL results for the site⁹ are also dubious for the reasons outlined above. TL conducted on unheated material is generally not a reliable method and has been replaced by the more robust OSL/TT-OSL optical luminescence method¹⁵.

The normal polarity identified at the base of the profile⁹ may indicate an older magnetic anomaly than originally attributed to the Jaramillo subchron. The spacing of the inclination and declination peaks is somewhat consistent with magnetic excursions at Buenos Aires, Bjorn, Cobb Mountain and Punaruu between 1.31 and 1.13 Ma¹⁹. However, the magnetic susceptibility spike indicates a change in mineralogy that could confound the palaeomagnetic results. The erosional unconformities of unknown time-length may also affect interpretation. The basal units 25–27 (Fig. 2) with layer VII artefacts are defined very differently from the upper soil layers and represent a probably much older unit with a hiatus. This may explain why the Jaramillo subchron is missing

and not found by Gladilin²⁰, or why the period of reversed polarity between the Matuyama-Brunhes boundary and Jaramillo (including the Jaramillo normal polarity subchron itself) might have been partially eroded from the sedimentary sequence. Two samples with normal magnetic polarity have been identified at the bottom of the profile studied by Nawrocki et al. and could instead belong to the older Cobb Mountain subchron. Units 26–27 of the revised chronostratigraphic sequence correlates with the Kryzhanivian interglacial period that overlap with MIS 47–43 (1.45–1.34 Ma) according to the Quaternary-Ukrainian loess stage division¹¹ and are in agreement with the burial age based on cosmogenic nuclides.

1.4 Lithic artefacts, Korolevo I level VII

All artefacts made of hyalodacite show heavy surface weathering, but no evidence of damage or polishing by rolling or abrasion during fluvial transport, which suggests they were buried relatively rapidly. In addition to the lithic assemblage from level VII (selected lithic artefacts shown in Figs. 3 & S3), the pebbles embedded in the same cultural level VII (n = 20; depth 10.03–12.05 m) above the basal pebble layer were recorded, collected and stored with the artefacts as part of the museum collection. These pebbles were the source of the samples selected for cosmogenic nuclide burial dating (Table S2, Fig. S4). Table S1 provides a tentative overview of the lithic technocomplexes from very early hominin sites in Europe and western Asia.

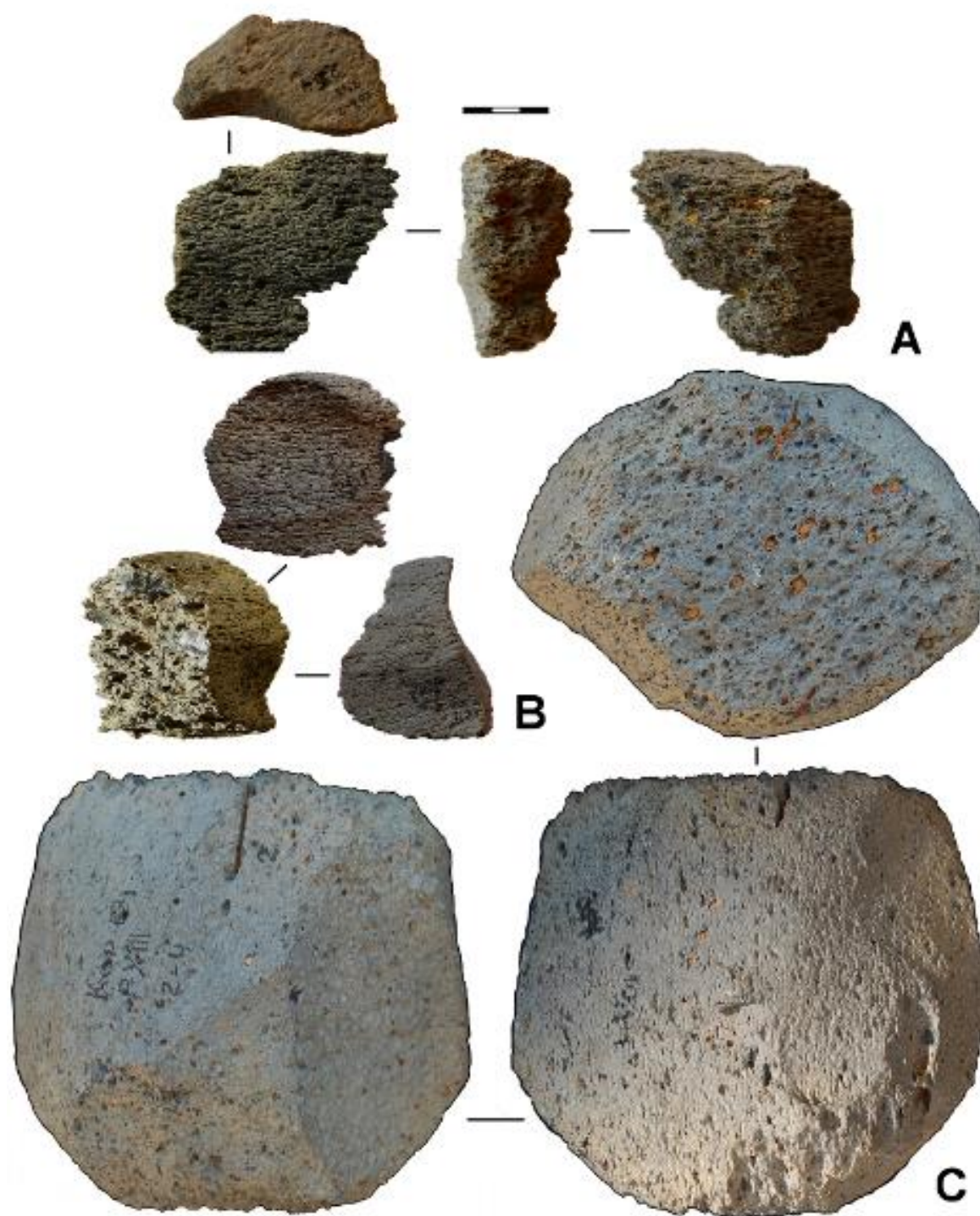


Fig. S3 | Additional lithic artefacts from Korolevo I, excavation XIII, level VII. A. single platform unidirectional core. B. chunk flake. C. polyhedron.

Table S1 | Tentative comparison of lithic technocomplexes with relevant early hominin sites.

SITES	HARD HAMMER REDUCTION	POLYHEDRONS, MANUPOINTS	BIPOLAR REDUCTION	CHOPPERS/ CORES	TOOL ON FLAKES	HANDAXES	COMMENTS
Korolevo	yes	yes	no	yes	yes	no	Unidirectional, parallel unidirectional reduction of flat & multiplatform cores. Kombewa & rare centripetal reduction are present. Choppers & tools on flakes occur.
Atapuerca	yes	?	?	?	?	no	Unidirectional reduction.
Zarqa	yes	?	no	yes	yes	no	Unidirectional (unipolar), parallel uni- & bidirectional, orthogonal exploitation of flat, globular, multiplatform & trifacial cores; centripetal reduction is present. Choppers & tools on flakes occur.
Dmanisi	yes	yes	yes	yes	yes	no	Items (cobbles & fragments) with percussion marks & single scars occur. There are chopper-cores. Unipolar (unidirectional) reduction system is prevailing. Unidirectional, parallel unidirectional, orthogonal, rare bidirectional & radial exploitation of unifacial, bifacial & multiplatform cores. Rare bipolar reduction. Few tools on flakes.
Kozarnika	yes	?	?	no	yes	no	(Levels 13-11c) No chopper-cores or pebble tools occur. Primary flaking characterized by unidirectional, parallel uni- & bidirectional reduction of flat, pyramidal, multiplatform cubic & “spherical” shaped cores.
Vallonnet	yes	?	?	yes	yes	no	Unidirectional, parallel unidirectional reduction of pebbles & chopper-cores. Exploitation of flat faced cores. Tools on flakes are present.
Pirro Nord & Monte Poggiolo	yes	?	yes	?	yes	no	Unidirectional, parallel uni-/bidirectional, convergent, centripetal, & bipolar reduction used for obtaining blanks from flat cores mainly. Traces of usage of bipolar reduction. No choppers or chopper-cores. Tools on flakes are present.
Barranco León & Fuente Nueva 3	yes	yes	yes	yes	yes	no	Uni-/bidirectional, orthogonal, centripetal reduction of flat &, cubic & polyhedral cores. Bipolar or “on anvil” present as well. Tools on flakes occur.

2.0 Chronometry

2.1 Sample preparation for cosmogenic nuclide analysis

Seven cobble-sized samples (Fig. S4) of different lithology (vein quartz, quartzite, fine-grained sandstone), weathering and mass from the lowermost cultural layer (level VII) were taken from the collection of the 1985 Transcarpathian Palaeolithic Expedition housed at the Archaeological Museum of the Institute of Archaeology in Kyiv. Physical sample preparation was carried out at the Czech Geological Survey, and the elemental composition of each sample was analysed by the method of Instrumental Nuclear Activation Analysis²¹. Sample KOR-ISO-06 was excluded from further chemical processing due to its different origin (cf. Table S2).

Table S2 | Cobble-sized clast samples from Korolevo I, excavation XIII, level VII, and cosmogenic nuclide sample qualification process prior to AMS analysis.

SAMPLE ID (KOR-ISO)	Lithology	Excavation square	Depth ⁽¹⁾ [m]	Mass [g]	Sample qualification process			
					Pre- screen	Phys prep	Chem prep	AMS
01	vein quartz	k-10	11.9	1105	✓	✓	✓	✓
02	fine sandstone	h-9	11.65	462	✓	✓	✗ ⁽²⁾	
03	quartzite	k-10	12.00	196	✓	✓	✓	✓
04	fine sandstone	h-9	11.45	204	✓	✓	✓	✓
05	fine sandstone	k-10	12.05	508	✓	✓	✓	✓
06	fine sandstone	b-6	10.03	2059	✗ ⁽³⁾			
07	silicified sandstone	h-9	11.45	545	✓	✓	✓	✓
08	sandstone	h-9	11.40–11.65	354	✓	✓	✓	✓
09	sandstone	h-9	11.10–11.40	522	✓	✓	✓	✓

¹ As per documentation, depth is measured below the Korolevo I reference point used for all excavations.

² Low quartz content.

³ Different spatial location (sector and depth), therefore excluded.



Fig. S4 | The seven clasts used for cosmogenic nuclide analysis (Table S2).

Quartz purification, Be and Al extraction, and accelerator mass spectrometer (AMS) measurements were performed at the Dresden AMS (DREAMS) facility at the Helmholtz-Zentrum, Dresden-Rossendorf^{22,23}. Quartz purification involved processing with a mixture of HCl and H₂SiF₆ followed by leaching in 2–10% HF to etch quartz grains and remove contamination with meteoric ¹⁰Be (ref. 24). Approximately 300 µg of ⁹Be from the Phena EA low-¹⁰Be carrier²⁵ was added to each sample. After dissolution of quartz in HF, an aliquot was taken from each sample for determination of Al concentrations by ICP-MS. Be and Al were separated by ion exchange chromatography and pH-dependent precipitation²⁴. For sample KOR-ISO-07, two grain size fractions (0.5–0.75 mm and 0.75–1.2 mm) were processed as KOR-ISO-07A and KOR-ISO-07B, respectively. Sample KOR-ISO-02 was excluded due to low quartz content (Table S2). Separated Be and Al hydroxides were transferred to quartz crucibles and calcinated at 900°C. The BeO powder was mixed with Nb in Nb:BeO ratios of 2.9 to 6.9, Al₂O₃ was mixed with Ag in Ag:Al₂O₃ ratios of 0.9 to 7.3 (ref. 24). Be and Al isotope ratios were measured at DREAMS. Al and Ti concentrations were measured by ICP-MS. The fine-grained red sandstone samples (KOR-ISO-02, 04, 05, 06) showed a higher content of Al and Ti and required more intensive cleaning processes compared to the quartzite and vein quartz samples. The quality control process applied to the Korolevo samples, including purity control, follow-up AMS mass scans, and discussion of Ti, Al impurities is reported in a dedicated publication²⁴. The extended analytical data for eight measured samples are presented in Table S3. The seven clast samples yielded high and relatively uniform ¹⁰Be concentrations ($1.0\text{--}1.7 \times 10^6$ at g⁻¹) and low ²⁶Al/¹⁰Be ratios of 3.0 to 3.5.

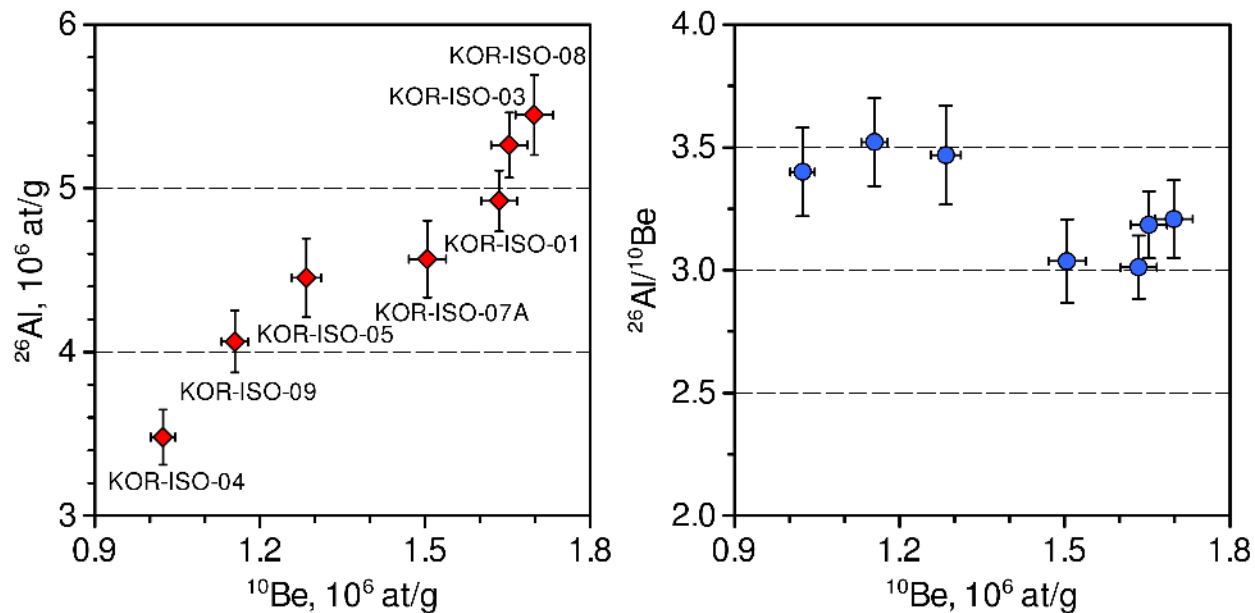


Fig. S5 | ^{26}Al and ^{10}Be concentrations and $^{26}\text{Al}/^{10}\text{Be}$ ratios with $\pm 1\sigma$ uncertainties.

The ^{26}Al and ^{10}Be concentrations in quartz of the seven samples studied based on the AMS counting statistics provided in Table S3. Left panel indicates ^{26}Al and ^{10}Be concentrations, right panel shows ratios of ^{26}Al and ^{10}Be concentrations. Error bars represent the full analytical uncertainties ($\pm 1\sigma$) for each value.

Table S3 | Cosmogenic nuclide data⁽¹⁾.

Sample ID (KOR-ISO)	Be Cath.	Al Cath.	Total quartz [g]	⁹ Be added (2) [μg]	²⁷ Al in sample (3) [μg/g]	²⁷ Al in sample (±1s) [μg/g]	¹⁰ Be/ ⁹ Be (4) [10 ⁻¹⁵]	¹⁰ Be/ ⁹ Be (±1s) [10 ⁻¹⁵]	²⁶ Al/ ²⁷ Al (5) [10 ⁻¹⁵]	²⁶ Al/ ²⁷ Al (±1s) [10 ⁻¹⁵]	¹⁰ Be conc. (6) [10 ⁶ at/g]	¹⁰ Be conc. (7) (±1s) [10 ⁶ at/g]	²⁶ Al conc. (6) [10 ⁶ at/g]	²⁶ Al conc. (7) (±1s) [10 ⁶ at/g]
Process blank	B3151	A1061	--	312.3	975 ⁽⁸⁾	29	1.18	0.18	4.4	3.2				
01	B3152	A1062	19.7741	315.1	23.8	0.7	1536	30	9280	210	1.634	0.033	4.92	0.19
03	B3153	A1063	22.1025	313.8	11.9	0.4	1743	34	19750	440	1.653	0.033	5.26	0.20
04	B3158	A1068	13.0314	314.6	137	4	636	13	1139	43	1.024	0.022	3.48	0.17
05	B3159	A1069	12.2181	315.9	249	7	744	15	806	36	1.284	0.027	4.45	0.24
07A	B3160	A1070	16.9697	314.9	314	9	1214	27	655	27	1.504	0.034	4.57	0.23
07B ⁽⁹⁾	B3161	A1071	17.5318	313.9	874	26	1267	26	497	21	1.515	0.032	9.62	0.50
08	B3157	A1067	20.1881	312.1	136	4	1645	32	1794	59	1.698	0.034	5.45	0.24
09	B3156	A1066	19.7449	312.9	112	3	1091	22	1626	57	1.154	0.024	4.06	0.19

¹ Data in this table are updated from Table 1 in ref. 24.

² Gravimetrically added Phena EA carrier (2246 ± 11 μg Be/g [ref. 25, 26]), agreed well with ICP-MS determined Be in dissolved sample aliquot.

³ Determined by ICP-MS on a ~1% aliquot of the dissolved sample.

⁴ Measured against the in-house standard SMD-Be-12 ([1.704 ± 0.030] × 10⁻¹², ¹⁰Be/⁹Be; traceable to NIST 4325 [ref. 27]).

⁵ Measured against the in-house standard SMD-Al-11 ([9.66 ± 0.14] × 10⁻¹², ²⁶Al/²⁷Al [ref. 22]).

⁶ Process blank corrected values.

⁷ Combined uncertainty includes uncertainty of AMS isotope ratio measurement for sample and process blank, uncertainty of stable isotope concentration from carrier added, and uncertainty of ICP-MS measurement for ⁹Be and ²⁷Al, respectively.

⁸ Mass of carrier of ²⁷Al (μg) to process blank.

⁹ Sample with high ²⁷Al concentration indicates inadequate quartz purification (ref. 24).

2.2 Isochron burial dating calculations

The isochron age calculations follow the general approach outlined in Granger (2014)²⁸, which has been used to date the *Australopithecus* fossils at Sterkfontein, South Africa^{29,30}. More specifically, we apply the method used in Granger et al. (2022)³⁰, which relies on the following equation to describe the relationship between ²⁶Al and ¹⁰Be with the assumption that samples derive from a steadily eroding landscape:

$$N_{26} = (N_{10} - N_{10,pb}) [(P_{26}/P_{10})\exp(-t/\tau_{bur}) / (1 + (N_{10} - N_{10,pb})\exp(t/\tau_{10}) / (P_{10} \tau_{bur}))] + N_{26,pb} \quad (\text{Eq. 1}),$$

where N_i denotes the measured concentration of nuclide i , P_i denotes the surface production rate of nuclide i , t is burial age, τ_i is the radioactive meanlife ($\tau = t_{1/2}/\ln[2]$), τ_{bur} is the effective meanlife calculated as $\tau_{bur} = (\tau_{26}^{-1} - \tau_{10}^{-1})^{-1}$; and $N_{i,pb}$ is the inventory of nuclide i that accumulated after burial.

Following Granger et al. (2022)³⁰, we assume constant nuclide production after burial in which case the post-burial concentrations can be calculated as:

$$N_{i,pb} = P_{i,pb} \tau_i (1 - \exp(-t/\tau_i)) \quad (\text{Eq. 2}),$$

where subscript i denotes the nuclides ¹⁰Be and ²⁶Al. The exact values for $N_{i,pb}$ are determined by fitting a York regression to linearized data³⁰. We use a value of 8.4 for the $P_{26,pb}/P_{10,pb}$ production rate ratio at a depth of ~10 m (ref. 31). For the isochron calculations, we use the mean production rate for ¹⁰Be ($\pm 1\sigma$) at the site since 2 Ma based on Lifton et al. (2014). More specifically, the production rate is scaled to catchment mean elevation $\pm 1\sigma$ (330–904 masl), as this is broadly representative of the elevations yielding lithologies included in our sample set. These values and their standard deviations are propagated fully in the calculation of the age uncertainty. The parameters used for isochron burial dating of Korolevo I level VII are summarized in Table S4.

Table S4 | Parameters used in isochron burial dating, Korolevo I level VII.

Parameters	
Latitude	48.1769°N
Longitude	23.1705°E
Source elevation	617 ± 287m asl
SLHL ¹⁰ Be production rate	4.00 at g ⁻¹ yr ⁻¹ (ref. 36)
Surface ²⁶ Al/ ¹⁰ Be production ratio	6.75–7.15
¹⁰ Be half-life	1.387 Ma (refs. 32,33)
²⁶ Al half-life	0.708 Ma (ref. 34)

2.3 Isochron burial dating results, Korolevo I level VII

All seven samples lie on the isochron, suggesting that none of the measured samples experienced substantial reworking (Fig. S6). The mean square weighted deviation (MSWD) of 0.84 is lower

than the expected value of 1, which indicates the data are underdispersed and that the analytical uncertainties may be overestimated. The low MSWD value suggests the data are consistent with the assumptions pertaining to the isochron burial model; i.e., all samples experienced a simple two-stage burial history that included constant exposure under steady erosion followed by burial with little or no reworking of the samples. If the samples had experienced a more complex burial history, it would be very unlikely that they all had the same complex burial history and that they would fall on an isochron with an MSWD value of 0.84. This strongly implies that all samples are consistent with a single burial age.

The linearized data associated with the seven samples yield an isochron with a slope of 3.53 ± 0.42 , which translates to a provisional burial age of $1.42 \text{ Ma} \pm 0.25 \text{ Ma}$ ($\pm 1\sigma$). This is an unexpectedly high (18 %) uncertainty given the low degree of scatter among the samples. However, we attribute this to the high ^{10}Be concentration ($>1.0 \times 10^6 \text{ at g}^{-1}$) in all seven samples, which affects the calculation of the isochron regression slope close to the intercept (Fig. 4B). In addition to the analytical uncertainties, we include an uncertainty on the ^{10}Be production rate ($\pm 1\sigma$) since 2 Ma (Lifton et al., 2014), an uncertainty of 2 % on the decay constants, and we allow the surface $^{26}\text{Al}/^{10}\text{Be}$ production ratio to vary from 6.75 to 7.15 (as a boxcar distribution). This selected range is based on physics-based scaling models fitted to calibration data, which indicate that the $^{26}\text{Al}/^{10}\text{Be}$ surface production ratio may be as high as 7.1 at low elevations³⁵. A value above 7.0 is also supported by the global *Expage* calibration dataset (<https://expage.github.io>)³⁶, which provides a global average of 7.16. A recent study from Greenland³⁷ indicates that the ratio may be as high as 7.3 ± 0.3 in the Arctic. However, the existing global $^{26}\text{Al}/^{10}\text{Be}$ data scatter considerably, and surface production ratios in the range 6.75–7.15 are all consistent with the available data. When all these sources of uncertainty are included by adding them in quadrature, we obtain a total uncertainty of $\pm 0.28 \text{ Ma}$ on the isochron burial age, yielding a final isochron burial age of $1.42 \text{ Ma} \pm 0.28 \text{ Ma}$ ($\pm 1\sigma$).

The post-burial ^{10}Be production determined from the intercept between the isochron and the post-burial $^{26}\text{Al}/^{10}\text{Be}$ line after correction for radioactive decay is $1.29 \pm 1.17 \times 10^5 \text{ at g}^{-1}$. As the measured concentrations range from 1.15×10^6 to $1.70 \times 10^6 \text{ at g}^{-1}$, the isochron calculations indicate that post-burial production accounts for 0.7–21 % of the total nuclide inventory, which far exceeds the plausible range. However, the precision of this estimate is limited by the intercept and slope of the isochron being so poorly constrained.

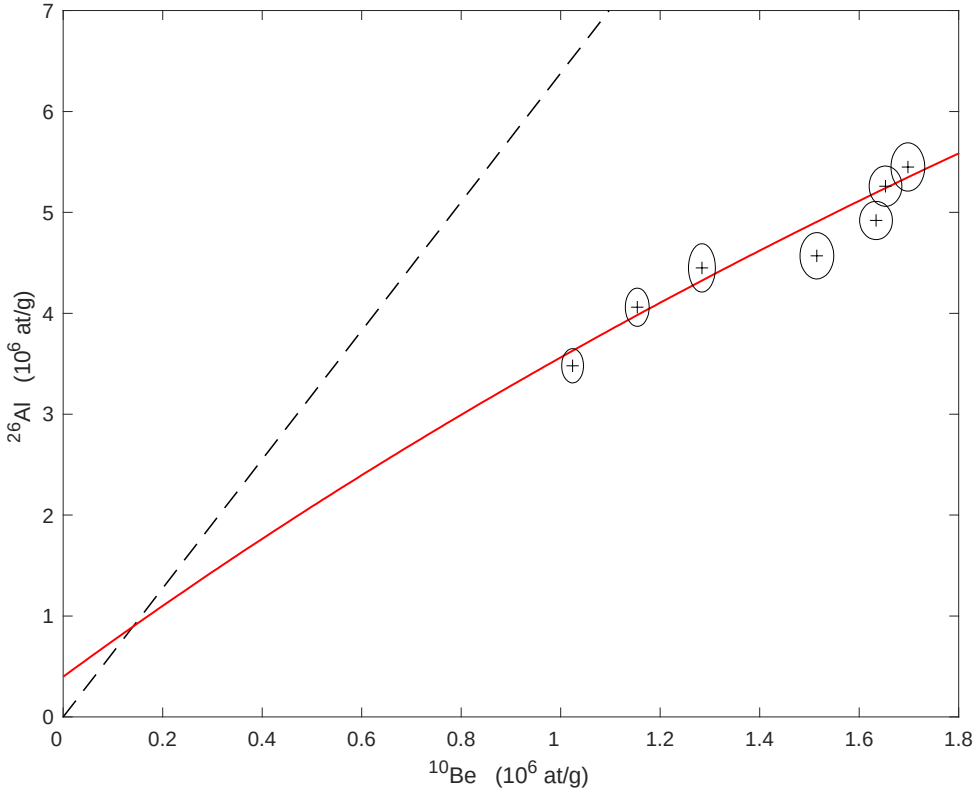


Fig. S6 | Isochron burial dating, Korolevo level VII. The linearized data yield a slope of 3.53 ± 0.42 , which translates to a provisional isochron burial age of $1.42 \text{ Ma} \pm 0.25 \text{ Ma}$ ($\pm 1\sigma$) [the final isochron age is $1.42 \text{ Ma} \pm 0.28 \text{ Ma}$ ($\pm 1\sigma$)]. Shown are the ^{26}Al - ^{10}Be concentrations of the seven samples (plus signs with ellipses indicating $\pm 1\sigma$); the best-fit isochron with $\pm 1\sigma$ uncertainty (red line and shading); and the post-burial $^{26}\text{Al}/^{10}\text{Be}$ production ratio for a depth of ~ 10 m after correction for radioactive decay (black dashed line). Note this plot is the same as Fig. 4B.

2.4 P-PINI burial dating calculations, Korolevo I level VII

In addition to the isochron method, we also use the P-PINI (Particle-Pathway Inversion of Nuclide Inventories) model³⁸ to constrain the burial age of the seven samples from level VII at Korolevo I. P-PINI is distinct from the isochron approach, but it relies on the same ^{10}Be - ^{26}Al data and shares some of the same assumptions—most notably, that samples have experienced a simple two-stage burial history with little or no reworking. And yet, the P-PINI model allows for comparatively greater complexity both during the pre-burial and post-burial phase.

The P-PINI model includes a source-to-sink framework in which detrital particles are produced in the sediment source area via erosion of bedrock (or older sedimentary deposits) and those particles are transported to a sedimentary deposit, or sink zone, where they are sampled³⁴. In the P-PINI model setup, the source zone is the contributing drainage area characterized by a set of model parameters that govern the pre-burial cosmogenic-nuclide inventory of the detrital particles (i.e., ^{10}Be - ^{26}Al production rates, elevation range above sea level, bedrock density, periods of glacial cover, and erosion history). Each of these parameters is allowed to vary within a given range based on the field setting and together they define a range of plausible landscape histories experienced by the samples. The sink zone is defined as the site of permanent burial where samples are collected with the aim of determining their burial age.

For Korolevo, the elevation range applied to the P-PINI source zone model is based on the span of elevations in the Eastern Carpathians draining to the Tysa River from the sample site (232 m asl) up to 90 % of the maximum elevation (Pietrosul Rodnei, 2303 m asl). The erosion rate in the source zone is largely unknown; hence this parameter is allowed to vary widely over 1–1000 m Myr⁻¹. The development of ice masses during the Pleistocene was limited to cirques and alpine valleys spanning <1.6 % (ref. 39) of the ~9300 km² Tysa catchment; hence, we neglect the effect of ice-cover. This portion of the Eastern Carpathians is tectonically quiescent with soil mantled hillslopes and a low frequency of landsliding. We nevertheless include the possibility of some non-steady erosion in the form of bedrock landslides with depths of up to 5 m. The P-PINI source zone model parameters are summarized in Table S5.

The P-PINI sink zone model functions in one of two modes: an erosion mode and an accumulation mode chosen depending on geomorphic considerations and field observations. We selected the accumulation mode given that the level VII cultural layer is topped by a sequence of loess units capped by palaeosols. The post-burial production of ^{10}Be and ^{26}Al is calculated as a function of the time-dependent increase in the burial depth of the samples. We recognize that the true accumulation history was likely more complex than the steady accumulation rate assumed in the sink zone model, but it is not possible to test and resolve such scenarios. We do, however, include a range of linear mass depth accumulation rates in the model that both encompass the Matuyama-Brunhes boundary and the present thickness of the sediment pile. The challenge is that three erosional hiatuses occur between level VII and the Matuyama-Brunhes boundary (Fig. 2); hence, the estimated accumulation rate prior to 0.773 Ma is a minimum value and the true rate may be notably higher.

To accommodate accumulation rate scenarios that are consistent with the stratigraphy, we apply a mass depth range of $300\text{--}2000\text{ g cm}^{-2}\text{ Myr}^{-1}$ in the sink-zone model, which can be converted to accumulation rates by dividing by the bulk density (2.0 g cm^{-3}). The stratigraphic pile is $\sim 8\text{ m}$ thick above our samples, whereas $2000\text{ g cm}^{-2}\text{ Myr}^{-1}$ corresponds to a total thickness of up to 16 m . This is a reasonable maximum limit given that the sample site is close to the top of the Beyvar hill and stands already $\sim 90\text{ m}$ above the modern valley floor that is $3\text{--}5\text{ km}$ wide. The minimum initial depth is set to 400 g cm^{-2} , implying that the stone tools were buried initially within a channel bar deposit at least 2 m in thickness. The observed thickness of this unit shown in Figure 2 is only $1.0\text{--}1.5\text{ m}$, but for initial depths $<1\text{ m}$ the model returns a negative accumulation rate, which is inconsistent with the overall depositional history at the site. We interpret this to be the result of the non-steady nature of cut-and-fill processes that are typical of in-channel fluvial environments. Nevertheless, the burial age, is robust and largely independent of the initial depth. Following channel abandonment (unit 24 and above in Fig. 2), we can assume a fairly steady accumulation of the loess-paleosol sequence above. The P-PINI model parameters used to define the sink zone are summarized in Table S6.

As described in Nørgaard et al. (2023)³⁸, the cosmogenic nuclide production rate is calculated by summing contributions from the three nuclide production-pathways; i.e., spallation associated with high-energy neutrons, negative muon capture, and fast muon interactions^{31,40,41}. The surface nuclide production rate associated with spallation is scaled to latitude, longitude, and elevation above sea level and is incorporated into the model following⁴². The decrease in spallation-induced production with depth below the surface is modelled as an exponential decay with an attenuation length of 160 g cm^{-2} (refs. 43,44). For the muogenic production, we use the muon production parameters calibrated at Beacon Heights, Antarctica³¹, to compute the muon depth profile for Korolevo (Model 1a, $\alpha = 0.75$). For computational efficiency, we fit a multiple-exponential curve to the ^{10}Be and ^{26}Al profiles rather than recalculating the profiles in each run of the Monte Carlo simulations³⁸. The simulated ^{10}Be - ^{26}Al concentrations are accepted using rejection sampling following Mejer et al. (2016)⁴⁵ (Fig. S7).

The P-PINI model yields probability distributions for the accumulation rate and burial age that are quite similar for all seven samples from level VII at Korolevo (Fig. S8). The probability distributions associated with the individual samples are combined as previously described³⁸ to obtain overall distributions for the average accumulation rate and the burial age of level VII (Fig. S9). P-PINI yields a burial age for level VII of $1.42 \pm 0.10\text{ Ma}$ ($\pm 1\sigma$), which includes 2 % uncertainty on the decay constants and a surface $^{26}\text{Al}/^{10}\text{Be}$ production ratio that varies from 6.75 to 7.15 (as for the isochron method). In contrast to the burial age, the accumulation rate is poorly constrained, as expected, due to the post-burial nuclide production accounting for a relatively small fraction of the total nuclide inventory. The accumulation rate was apparently rather slow shortly after burial when the production rate was high, consistent with the location of the Matuyama-Brunhes boundary. Overall, the P-PINI model yields a well-constrained burial age that is relatively insensitive to both the average accumulation rate (Fig. S8) and the imposed initial depth. For

instance, applying an initial depth of 1.5 m (instead of 2 m) yields a burial age of 1.46 ± 0.11 Ma ($\pm 1\sigma$), but as noted above this comes with an accumulation rate that is inconsistent with field observations.

Table S5 | Source zone parameters used in the P-PINI model, Korolevo I level VII.

Parameters	
Latitude	48.1769°N
Longitude	23.1705°E
Elevation	232–2073 m asl
Bulk density	2.5–2.7 g cm ⁻³
Erosion rate	1–1000 m Myr ⁻¹
Plucking depth	0.01–5 m
Duration of ice cover	0 Myr
SLHL ¹⁰ Be production rate	4.00 at g ⁻¹ yr ⁻¹ (ref. 36)
Surface ²⁶ Al/ ¹⁰ Be production ratio	6.75–7.15
¹⁰ Be half-life	1.387 Ma (refs. 32,33)
²⁶ Al half-life	0.708 Ma (ref. 34)

Table S6 | Sink zone parameters used in the P-PINI model, Korolevo I level VII.

Parameters	
Latitude	48.1769°N
Longitude	23.1705°E
Elevation	232 m asl
Accumulation rate	300–2000 g cm ⁻² Myr ⁻¹
Initial mass depth	400 g cm ⁻² Myr ⁻¹
Duration of ice cover	0 Myr
Time in sink zone (burial age)	0–2 Myr
SLHL ¹⁰ Be production rate	4.00 at g ⁻¹ yr ⁻¹ (ref. 36)
Surface ²⁶ Al/ ¹⁰ Be production ratio	6.75–7.15
¹⁰ Be half-life	1.387 Ma (refs. 32,33)
²⁶ Al half-life	0.708 Ma (ref. 34)

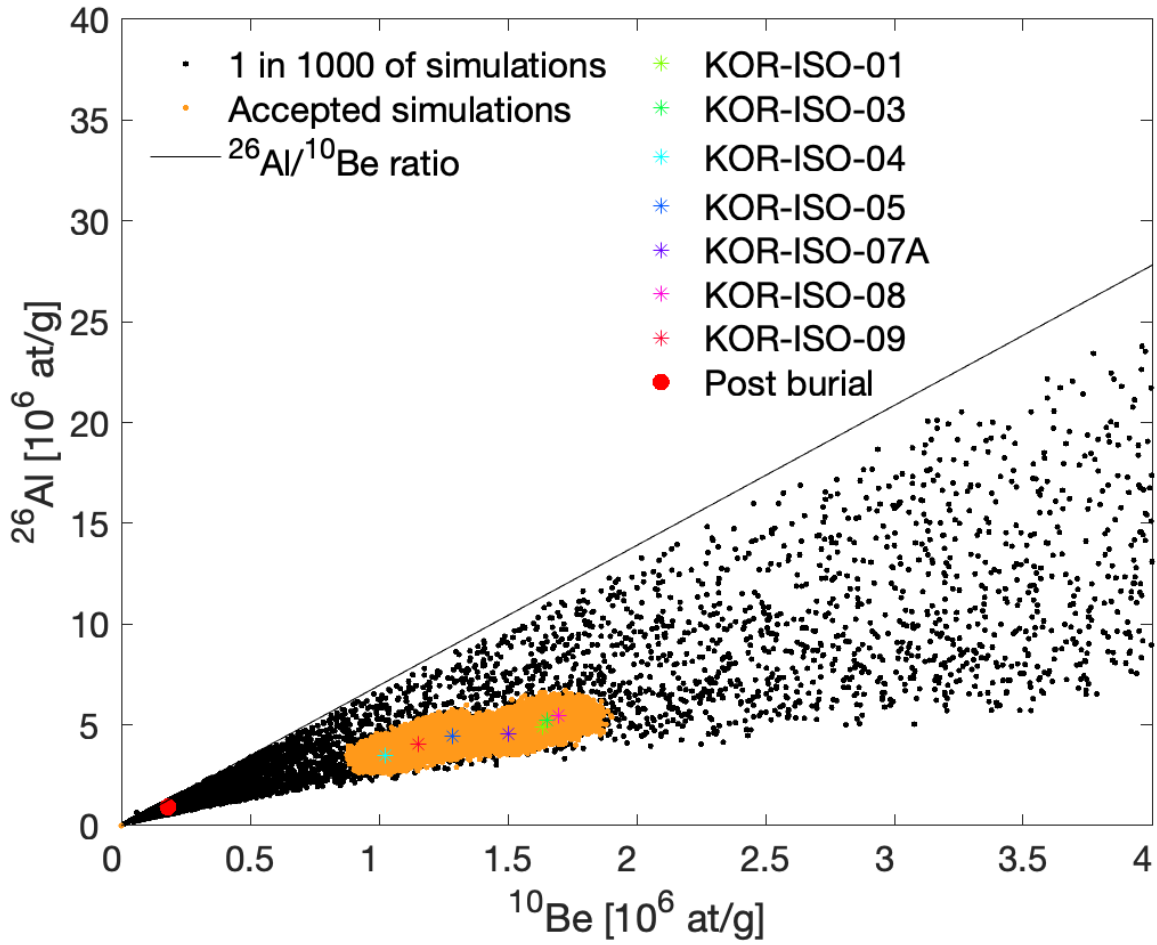


Fig. S7 | Measured and simulated ^{10}Be - ^{26}Al concentrations, Korolevo I level VII. The P-PINI-derived ^{10}Be - ^{26}Al ‘library’ comprises 10 million virtual samples (black dots) simulated for the Korolevo site (only 0.1% are shown here). The 7 Korolevo samples (coloured stars) are shown together with the simulations accepted as having comparable inventories (orange dots). The dimensions of the orange clouds represent the uncertainty of the corresponding samples.

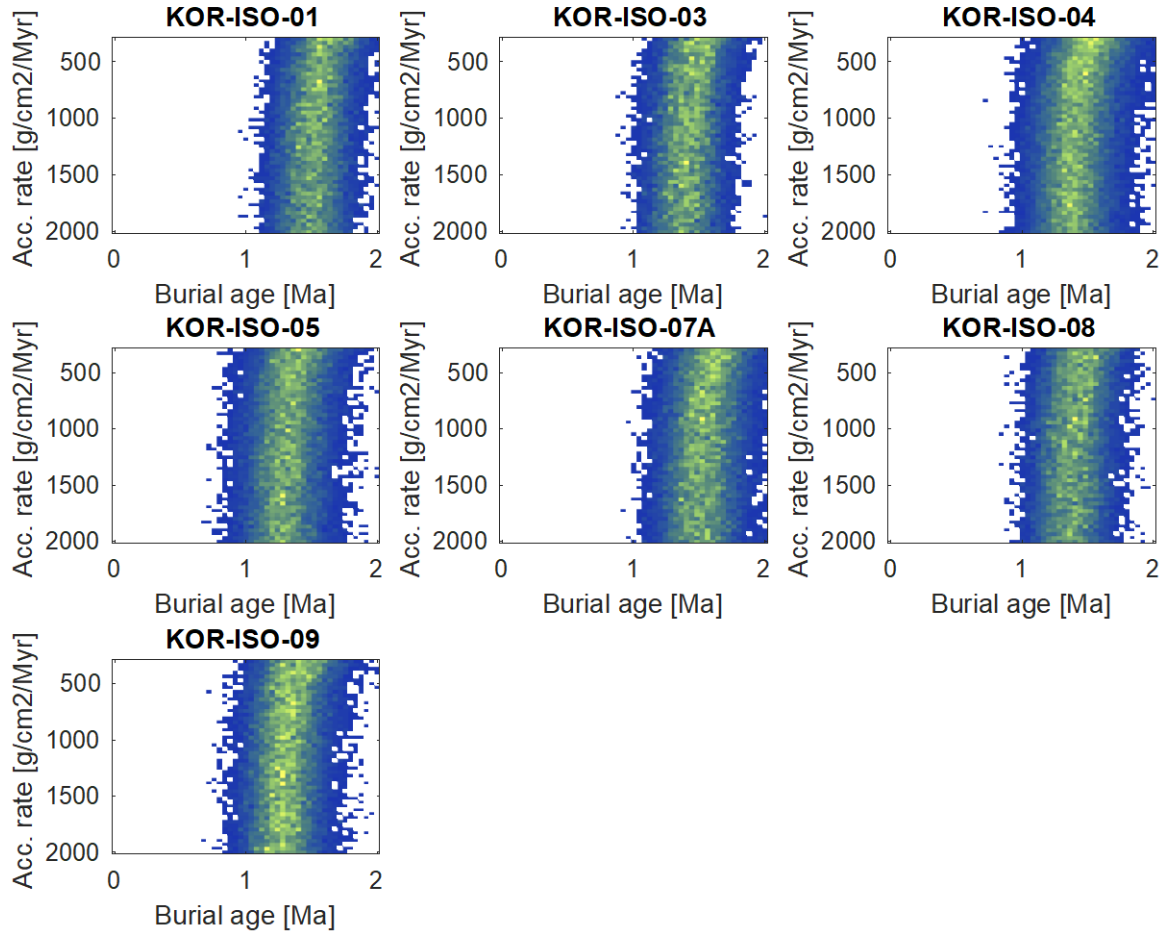


Fig. S8 | P-PINI model results for the 7 individual samples, Korolevo level VII. P-PINI-derived probability plots of sink zone accumulation rate vs burial age generated from the accepted simulations (orange clouds in Fig. S7) for each of the 7 samples. Bright yellow denotes higher density of simulations, while dark blue denotes low density. White colors correspond to negligible or zero probability.

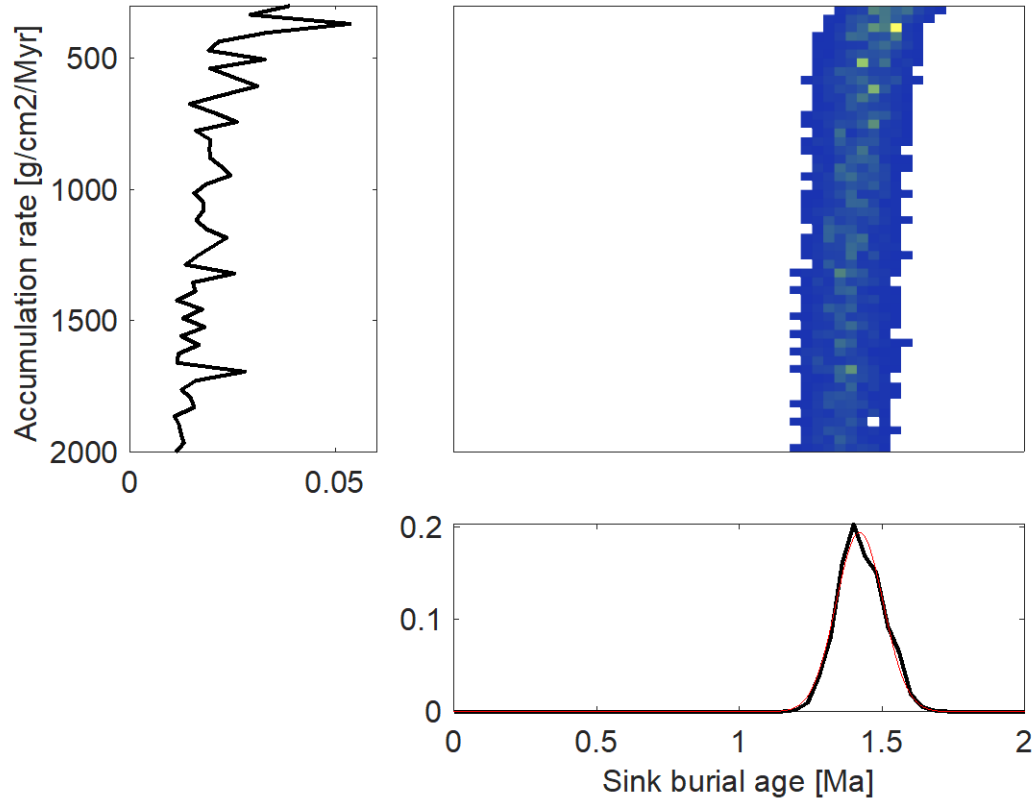


Fig. S9 | Overall P-PINI model results, Korolevo level VII. Central panel shows the merged probability distribution (yellow to blue is high to low density, white is zero), which is the product of all sample distributions. Left panel shows the accumulation rate distribution (independent of burial age) calculated by summing along the x-axis in the central panel. Lower panel shows the burial age distribution (independent of accumulation rate) as a black line with best-fit Gaussian (red line) that defines the burial age reported in Figure 4A.

2.5 A note on the two burial dating approaches: isochron method vs P-PINI

The isochron burial dating method^{28–30} is an elegant approach to dating buried sediments that also makes it possible to detect whether some of the samples have experienced reworking. Nevertheless, the isochron burial dating relies on a set of assumptions that in some settings render the method less versatile than P-PINI. The P-PINI model readily allows for (1) non-steady erosion in the sediment source area, (2) catchments with elevation-dependent $^{26}\text{Al}/^{10}\text{Be}$ ratios, (3) sample-specific source elevations, and (4) changing burial depths in the sink zone due to either erosion or accumulation of sediment over time. The inclusion of these properties exerts small but systematic influences on the resulting burial age for Korolevo I level VII.

The accommodation of non-steady erosion in the sediment source area tends to lower the resulting burial age, but this effect is small at Korolevo because the measured nuclide concentrations are very high, which in the model suppresses the simulation of potential plucking/landsliding in the source area. Having samples derive from varying elevations in the source area, and the possibility that they were sourced from higher elevations than the site elevation, tends to increase the resulting burial age. The effect is smaller for P-PINI, however, because in the P-PINI model setup the samples derive from different source elevations. The inclusion of depth-dependent post-burial nuclide production that, for the Korolevo site, is controlled by the accumulation rate also tends to increase the burial age (compared to constant post-burial production). This is because the post-burial production is higher in the early phase of burial when the samples are less deep. These points bring great versatility to P-PINI and enable it to simulate the physics of erosion and deposition more realistically, which helps constrain the post-burial production in cases where all samples have high nuclide concentrations.

Direct comparison of the two burial methods is confounded by the very different ways in which the post-burial nuclide production is calculated. P-PINI uses the fundamental nuclide production equations to calculate the post-burial production with changing depth over time, whereas the isochron method uses the intersection between the isochron and the $^{26}\text{Al}/^{10}\text{Be}$ post-burial production ratio. If we set up the P-PINI model to resemble the scenario in the isochron method, including constant depth in the sink zone (i.e., constant post-burial production rate), we obtain a total post-burial concentration of $\sim 2.6 \times 10^4$ at g^{-1} , as opposed to $1.29 \pm 1.17 \times 10^5$ at g^{-1} with the isochron method. Manually calculating the post-burial production for a constant depth of 8–10 m yields $\sim 2.5 \times 10^4$ at g^{-1} . This is close to the value obtained with P-PINI (it falls within 1σ uncertainty) but is considerably lower than the central estimate obtained with the isochron method. The post-burial production estimates obtained with the two different methods are consistent, nevertheless, because the uncertainty associated with the isochron estimate is large. This large uncertainty is the product of a sample set with consistently high nuclide concentrations, which affects the spread of isochron slopes towards the intercept (as shown in Fig. S6).

2.6 P-PINI burial age of the cultural layer at Sima del Elefante, Spain

Prior to calculating the burial age of layers TE7 and TE9 at Sima del Elefante using the P-PINI model, we recalculated the ^{10}Be concentrations of the two samples from this site reported in Carbonell et al. (2008) (ref. 46). The original AMS measurements were performed at PRIME Lab (Purdue University). Samples TE9b and TE7 were measured against the ICN standards (2001 dilution series), which were calibrated by decay counting. The nominal $^{10}\text{Be}/^9\text{Be}$ values of these standards must be revised⁴⁷, because an inaccurate ^{10}Be half-life of 1.5 Myr was applied. In this study, we blank-corrected and re-normalized the ^{10}Be concentrations by a factor of 0.9042 to account for changes in the estimate of the ^{10}Be half-life. This changes the ^{10}Be concentrations by 2.6 % compared to those originally reported⁴⁵. There was no need to recalculate the ^{26}Al concentrations from Sima del Elefante, so we used the previously reported values.

The P-PINI approach to re-calculating the burial age of samples TE9b (from the artefact/fossil-bearing layer) and TE7 was generally analogous to that described for Korolevo with the important difference that we applied the P-PINI model to the two samples separately, as they derive from different stratigraphic layers in the cave. We note that it is impossible to test the basic assumption of simple two-stage burial history where there is only one sample from each of the two layers. The basal layer TE7 clearly predates layer TE9⁴⁵, and they have distinct lithologies. We applied the stratigraphic superposition of layer TE9 as a Bayesian constraint on the burial age. The source and sink zone parameters were tuned to the site at Sima del Elefante, whereas the remaining parameter settings were similar to those used for Korolevo (Tables S6 and S7). P-PINI was run in the accumulation mode, as the site has experienced net accumulation since deposition of layers TE7 and TE9. The initial burial depth is uncertain for both samples because the sediments were shielded by the roof of the cave throughout the burial period, in addition to the shielding provided by the sediment pile. We applied an initial depth of $3000 \text{ g cm}^{-2} \text{ Myr}^{-1}$, which corresponds to an overlying sediment pile of 15 m with an average density of 2.0 g cm^{-3} , although the resulting burial ages are largely insensitive to the choice of initial burial depth.

For samples TE9b (Fig. S10) and TE7 (Fig. S11), we obtain P-PINI burial ages of $1.24 \pm 0.19 \text{ Ma}$ ($\pm 1\sigma$) and $1.15 \pm 0.22 \text{ Ma}$ ($\pm 1\sigma$), respectively. The two burial ages are indistinguishable at the 1σ level but based on their stratigraphic positions we impose the Bayesian constraint that layer TE9 must be younger than layer TE7. This is done by randomly resampling the two Gaussian distributions for samples TE9b and TE7 100,000 times, while accepting only ages that obey the Bayesian constraint. This yields a burial age of $1.12 \pm 0.16 \text{ Ma}$ ($\pm 1\sigma$) for layer TE9b, which stands as the most likely age of the artefact/fossil-bearing layer at Sima del Elefante when all available ^{26}Al - ^{10}Be data and stratigraphic information are considered.

Table S7 | Source zone parameters used in the P-PINI model, Sima del Elefante.

Parameters	
Latitude	42.35°N
Longitude	3.5194°W
Elevation	993–2245 m asl
Bulk density	2.5–2.7 g cm ⁻³
Erosion rate	1–1000 m Myr ⁻¹
Plucking depth	0.01–5 m
Duration of ice cover	0 Myr
SLHL ¹⁰ Be production rate	4.00 at g ⁻¹ yr ⁻¹ (ref. 36)
Surface ²⁶ Al/ ¹⁰ Be production ratio	6.75–7.15
¹⁰ Be half-life	1.387 Ma (refs. 32,33)
²⁶ Al half-life	0.708 Ma (ref. 34)

Table S8 | Sink zone parameters used in the P-PINI model, Sima del Elefante.

Parameters	
Latitude	42.35°N
Longitude	3.5194°W
Elevation	993 m asl
Accumulation rate	0–10000 g cm ⁻² Myr ⁻¹
Initial mass depth	3000 g cm ⁻² Myr ⁻¹
Duration of ice cover	0 Myr
Time in sink zone (burial age)	0–2 Myr
SLHL ¹⁰ Be production rate	4.00 at g ⁻¹ yr ⁻¹ (ref. 36)
Surface ²⁶ Al/ ¹⁰ Be production ratio	6.75–7.15
¹⁰ Be half-life	1.387 Ma (refs. 32,33)
²⁶ Al half-life	0.708 Ma (ref. 34)

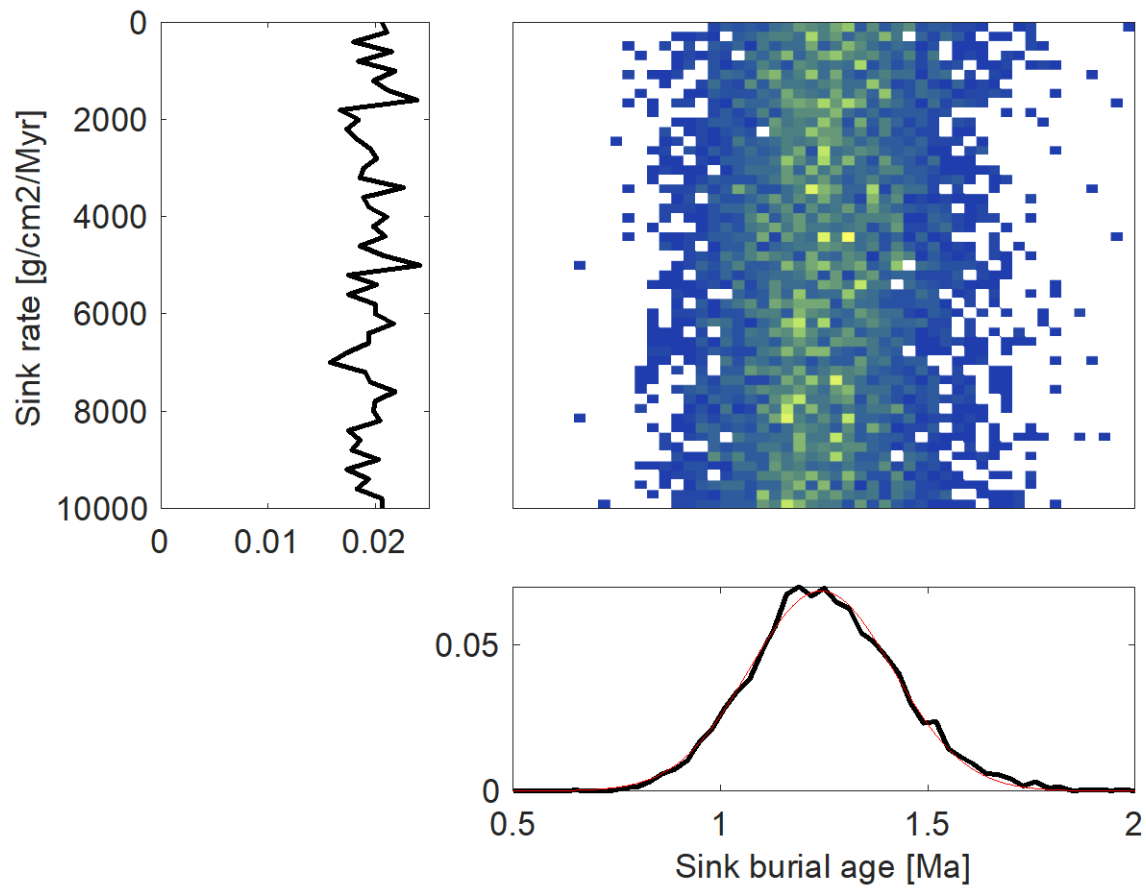


Fig. S10 | P-PINI model results for sample TE9b, Sima del Elefante. Central panel shows the merged probability distribution (yellow to blue is high to low, white is zero), which is the product of all sample distributions. Left panel shows the accumulation rate distribution (independent of burial age) calculated by summing along the x-axis in the central panel. Lower panel shows the burial age distribution (independent of accumulation rate) as a black line with best-fit Gaussian (red line) that defines the burial ages reported in section 2.6.

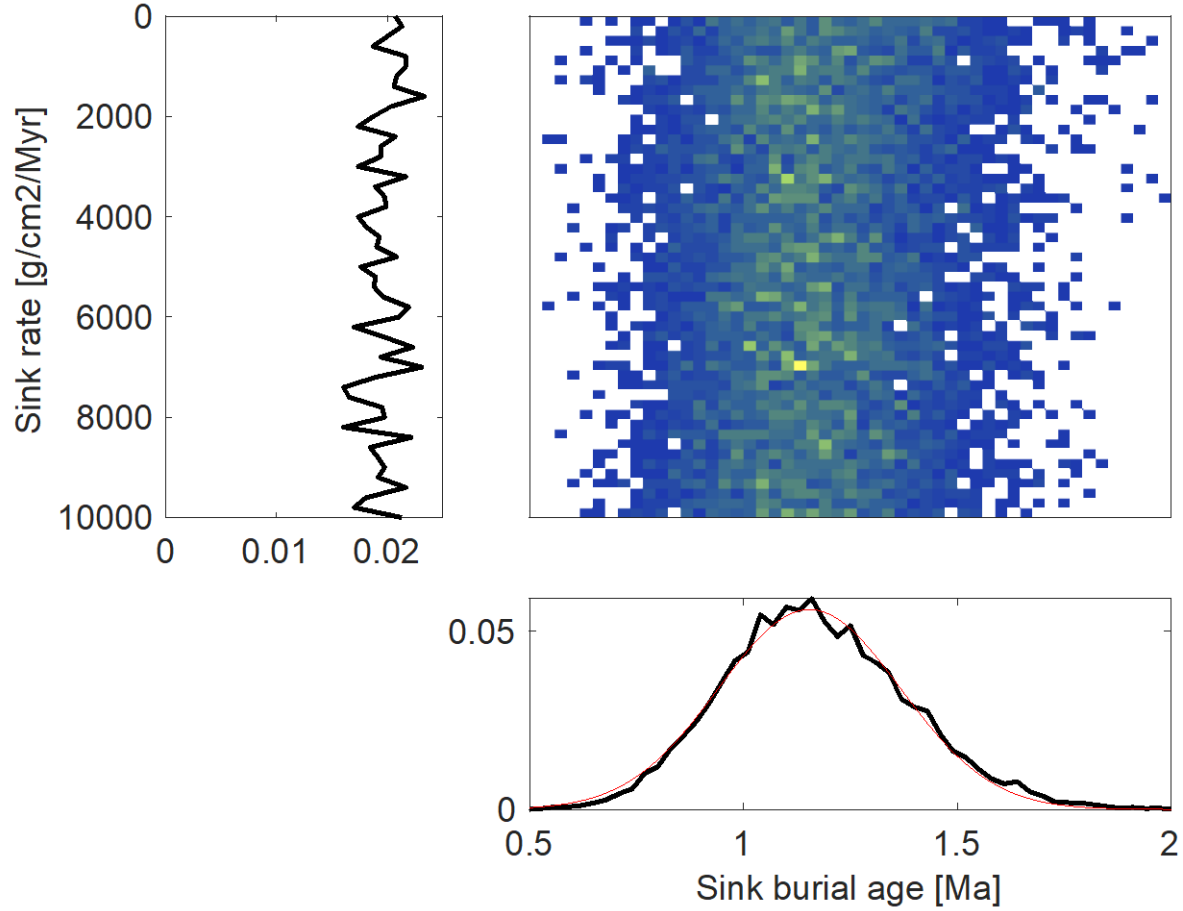


Fig. S11 | P-PINI model results for sample TE7, Sima del Elefante. Central panel shows the merged probability distribution (yellow to blue is high to low, white is zero), which is the product of all sample distributions. Left panel shows the accumulation rate distribution (independent of burial age) calculated by summing along the x-axis in the central panel. Lower panel shows the burial age distribution (independent of accumulation rate) as a black line with best-fit Gaussian (red line) that defines the burial ages reported in section 2.6.

2.7 Burial age of the cultural layer at Kocabaş, Turkey

As reported in Lebatard et al. (2014) (ref. 48), the fossil-bearing Upper Travertine layer at Kocabaş, Turkey, is dated via a combination of magnetostratigraphy and $^{26}\text{Al}/^{10}\text{Be}$ data from the Denizli conglomerates that bound the Upper Travertine. A total of thirteen $^{26}\text{Al}/^{10}\text{Be}$ pairs were reported from three sections: four from the Lower Conglomerates and nine from the Upper Conglomerates. The simple burial ages associated with the individual samples are notably scattered (Fig. 4 in ref. 48) within both the Upper and Lower Conglomerates. Test runs with P-PINI clearly suggest that the scatter cannot be attributed to non-steady erosion or elevation-dependent surface $^{26}\text{Al}/^{10}\text{Be}$ production ratios in the catchment. The data scatter is most likely explained by the samples being subjected to multiple durations of burial and reworking prior to their deposition in the sections where they were sampled. In other words, these samples appear to violate the key premise of burial dating: a simple two-stage burial history. For this reason, we did not to recalculate the burial ages with the P-PINI model, as the resulting outputs would reflect the average amount of reworking associated with the samples. Instead, we cite the originally reported⁴⁸ age estimate of >1.1 Ma, which is guided by a combination of the magnetostratigraphy and $^{26}\text{Al}/^{10}\text{Be}$ data available from the site.

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4.0 Computer code availability

The MATLAB code used to generate burial ages with P-PINI and the isochron method (as shown in Figs. 4 and S6–S11) are shared on <https://github.com/CosmoAarhus/Korolevo>