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Technological innovations and hafted technology in central China ~160,000–72,000 years ago

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Technological innovations in Africa and western Europe in the later part of the Middle Pleistocene signal the behavioural complexity of hominin populations. Yet, at the same time, it has long been believed that hominin technologies in Eastern Asia lack signs of innovation and sophistication. Here, we report on technological innovations occurring at Xigou, in the Danjiangkou Reservoir Region, central China, dating to ~160,000–72,000 years ago. Technological, typological, and functional analyses reveal the presence of advanced technological behaviours spanning over a 90,000-year period. The Xigou hominins used core-on-flake and discoid methods to effectively obtain small dimensional flakes to manufacture a diverse range of tool forms. The identification of the hafted tools provides the earliest evidence for composite tools in Eastern Asia, to our knowledge. Technological innovations revealed at Xigou and other contemporary sites in China correspond with increasing evidence for Late Quaternary hominin morphological variability, including larger brain sizes, such as demonstrated at Lingjing (Xuchang) in central China. The complex technological advancements recorded at Xigou indicate that hominins developed adaptive strategies that enhanced their survivability across fluctuating environments of the late Middle Pleistocene and middle Late Pleistocene in Eastern Asia.

The late Middle Pleistocene to the middle Late Pleistocene, ~300,000–50,000 years ago (ka), was a key period in the evolutionary history of our genus. This period witnessed the rise and development of our species and our interactions with sister taxa, such as the Neanderthals, Denisovans, and perhaps newly reported species, such as *Homo longi* and *H. juluensis*[1–12] (Supplementary Note 1). In Africa and western Eurasia, demographic dynamics are associated with a series of behavioural innovations that typify the Middle Palaeolithic, such as Levallois and other predetermined stone tool reduction methods, hafting technology, formal bone tools, personal ornaments, and pigment use[13–18]. However, cultural developments in Eastern Asia have long been regarded as part of a conservative tradition based primarily on the view that stone tool assemblages were simple, with major technological changes only occurring after ~40 ka[19–24]. Based on these interpretations, a two-stage model, namely, the Early and Late Palaeolithic, was proposed. In recent years, however, archaeological evidence has revealed the presence of a series of technological innovations in lithic assemblages, including complex flake tools and pre-

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determined core preparation methods dating to between ~300 and 50 ka[25–28] (Supplementary Data 1), though our knowledge about the nature of this behavioural complexity remains limited.

Here we report on Xigou, a newly excavated archaeological site in Henan Province of central China, with a stratigraphic sequence dating to between ~160 and 72 ka. Xigou occurs in the Danjiangkou Reservoir Region, along the southern edge of the Qinling Mountain range which serves as the dividing line between temperate northern China and subtropical southern China, and the boundary between the Palaearctic and Oriental biogeographic realms (Fig. 1a and b, Supplementary Note 2). The lithic assemblages at Xigou demonstrate significant technological advancements in comparison to earlier regional technologies, exemplified by well-organised core reduction strategies (core-on-flake and discoid technologies), diverse small flake-based tools, and hafted implements. Xigou shows technological innovations during the late Middle Pleistocene to middle Late Pleistocene, shedding light on technological complexity during a period when large-brained hominins were present in Eastern Asia.

Results

Site setting, stratigraphy, and ages

Xigou (32°56′9.23″N, 111°29′7.83″E, 175–180 m a.s.l., Supplementary Note 2) is situated along the Laoguanhe River which flows into the Danjiang River (now the Danjiangkou Reservoir) around 300 m southwest of the site (Fig. 1b). Xigou was discovered in 2017 and subsequently excavated from 2019–2021. An area of 243 square metres was excavated during the year of 2021 (Fig. 1c), exposing six stratigraphic units labelled Layers 1–6, and further with test trench to 5 m in depth (Fig. 1d). Layers 2–5 are the primary cultural horizons, and the sediments are composed mainly of silty clay with varied colours ranging from yellowish-brown (Layer 2), bright reddish-brown (Layer 3), yellowish-brown with a red tinge (Layer 4), and dark reddish-brown (Layer 5). The sedimentary provenance of the Xigou section primarily comprises far-source and near-source aeolian materials, with a minor contribution from fluvial components (Supplementary Note 2).

Six luminescence dating samples were collected from the Xigou section (Fig. 1d, Supplementary Fig.3). We applied both the single-aliquot regenerative-dose (SAR) optically stimulated luminescence

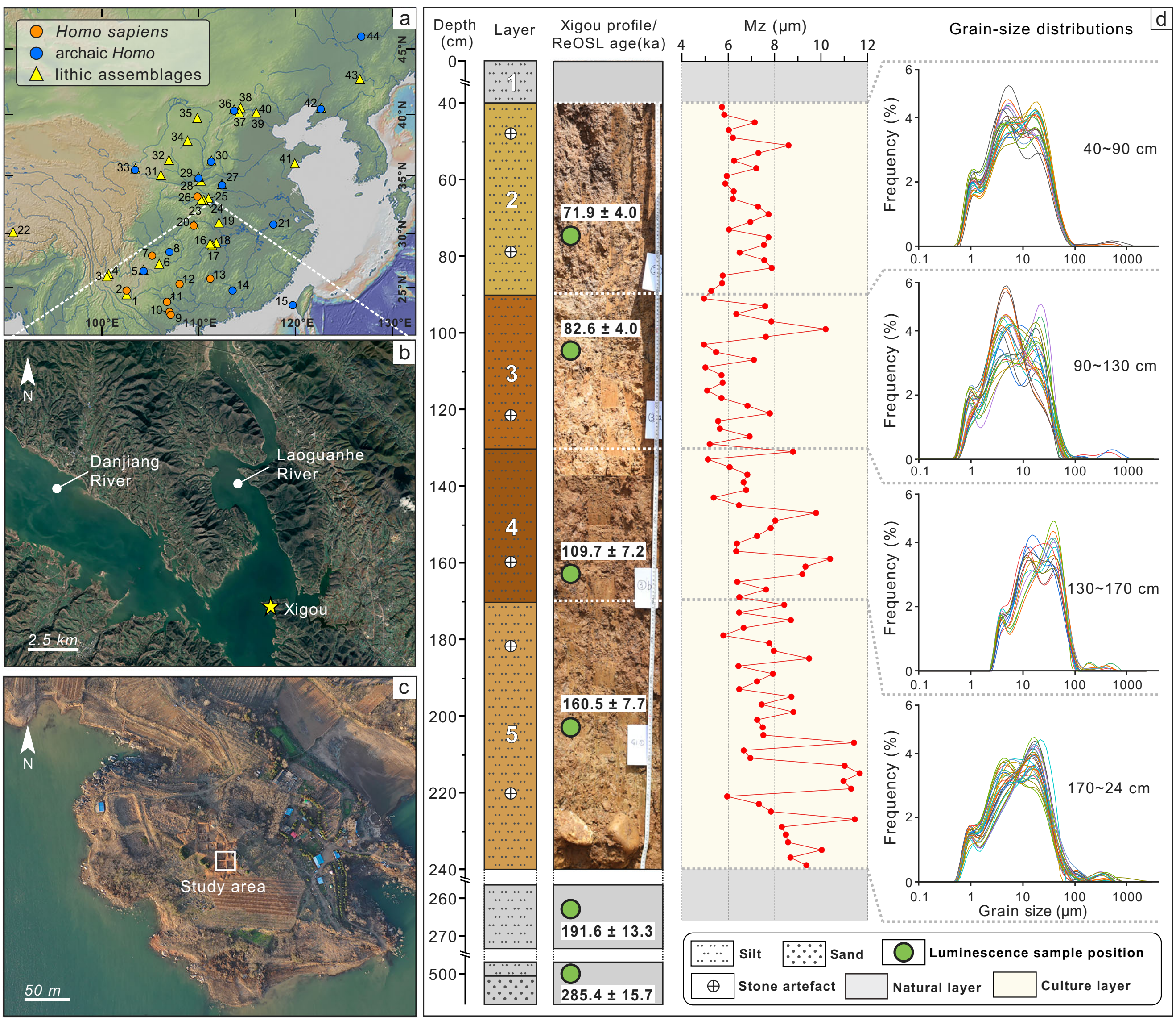

Fig. 1 | Location, stratigraphy and chronology of the Xigou site. a Distribution of key hominin fossil locations and archaeological sites in China between ca. 300–50 ka (See Supplementary Data 1 for site details, made with GeoMapApp[85] (www.geomapapp.org) /C / CC BY). **b** The position of Xigou in the Danjiangkou Reservoir Region. **c** Aerial view of the Xigou site showing excavation location. **d** Lithology, quartz ReOSL ages and mean grain size (Mz) of the Xigou profile at different depth intervals (Supplementary Notes 2 and 3).

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(OSL) and the multiple-aliquot regenerative-dose (MAR) recuperated OSL (ReOSL) dating protocols[29–32] (Supplementary Tables 1–2) to quartz fine-grains (4–11 µm), and the SAR post-infrared infrared stimulated luminescence (post-IR IRSL) dating protocol[33,34] (Supplementary Tables 3) to polymineral fine-grains from all of these samples (Supplementary Note 3). Our dating results show that the quartz ReOSL ages are generally larger than that of quartz OSL for all the six samples, and are systematically smaller than that of polymineral post-IR IRSL for the upper three samples (Supplementary Fig. 20 and Supplementary Data 2). Due to signal saturation, all the quartz OSL ages are believed to be underestimated (Supplementary Note 3.4.2 and Supplementary Fig. 20). Moreover, because of possible large residual doses contributed by near-source aeolian sediments and particularly fluvial components, it is suggested that the post-IR IRSL ages of the upper three samples are possibly overestimated (Supplementary Note 3.4.4 and Supplementary Fig. 20). In contrast, given the good performance of luminescence characteristics of ReOSL signal (e.g., dose-response curves with high saturation levels) (Supplementary Note 3.4.3) and its previous robust dating applications into loess on the CLP[31,32], we recommend the use of ReOSL dating results to constrain the chronology of the Xigou section. The ReOSL dating results indicate that the bottom of the sediment column dates to 285.4 ± 15.7 ka and Layers 2–6, ranging in depth from 2.65 to 0.75 m, accumulated between 191.6 ± 13.3 to 71.9 ± 4.0 ka (Fig. 1d, Supplementary Data 2). The ReOSL chronology dates the cultural horizons (Layers 2–5) between ~160 and 72 ka.

Expedient and well-organised core reduction strategies

The lithic assemblages are composed of 2601 artefacts, including 528 from Layer 2, 550 from layer 3, 1084 from Layer 4, and 439 from Layer 5 (Supplementary Note 4). Most of the artefacts (69.5–78.7%) are smaller than 50 mm. Quartzite and quartz, originating from local riverbeds or gravel layers of the terraces, are the main raw materials (Supplementary Note 4.1). Detached pieces, including flakes, flake fragments, bipolar splinters, and angular fragments and debris dominate the assemblage of each layer (72.4–78.9%), followed by cores, tools, unmodified pieces and hammer stones (Supplementary Table 4).

Freehand hard-hammer percussion (FHHP) constitutes the predominant technique for core reduction across the four phases of Xigou (Supplementary Note 4.2). Both simple and predetermined debitage technologies were employed for the FHHP. Cores of simple debitage without preparation comprise the majority of core types, ranging from 65.2 to 73.7% in Layers 2–5. Among simple debitage cores, unidirectional and multidirectional cores are most common, followed by bidirectional and opposed platform types, along with a few tested and polyhedral types (Supplementary Fig. 22). Predetermined methods are represented by core-on-flake and discoid technologies, both of which show planned technological organisation.

Core-on-flakes play a significant role in the assemblages, with frequencies ranging between 20.8 and 25.8% in each layer. Relatively larger and thicker flake blanks (Mann–Whitney U-test, $p < 0.001$), were selected for these cores, indicating a systematic pattern for initial blank selection. Most of the cores show an exploitation of the dorsal face of flake blank (50.9%), followed by the use of ventral surfaces (41.8%) and the flaking of both dorsal and ventral surfaces (7.3%) (Fig. 2a, Supplementary Fig. 23). The striking platforms are rarely prepared. Two pieces have a facetted platform, and one shows a truncation on one margin of the flake blank, which serves as a platform for the removal of small flakes from the dorsal surface. Considering the high availability of knappable raw materials and the fact that cores-on-flakes are not smaller than other core types (Fig. 2c), the ubiquitous use of this technology likely represents a noteworthy behavioural choice, i.e. a tendency for smaller dimensional flakes with sharp edges.

Discoid cores occur in relatively low frequencies, totalling 19 pieces, while the proportion increased continuously from 2.6% in Layer 5, 8.3% in Layer 4, 10.4% in Layer 3, to 10.8% in Layer 2. Both unifacial and partially bifacial exploitation of discoid cores are present (Fig. 2b, Supplementary Fig. 23). Cobbles are exclusively selected as blanks, and exploitation proceeds by maintaining a stability of the core employing the volumetric concept, with little specific preparation of striking platforms and flaking surfaces (Fig. 2d), resulting in an oval shape and a biconvex asymmetric section of the core. In comparison to simple debitage cores, discoid cores are usually smaller in dimension and negative scar size, while negative numbers (mean = 6.44) are significantly greater, suggesting a higher core reduction degree (Fig. 2c).

Flakes, which occupy a significant portion of the Xigou assemblages through time, are generally small in size, and the metric and techno-typological attributes are consistent with what would be expected based on the nature of the cores (Supplementary Note 4.3). In addition to the FHHP, bipolar percussion on an anvil was applied as a supplementary reduction technique (Supplementary Note 4.4). Generally, the reduction technology employed at Xigou was geared towards the intentional production of small-sized flakes from cobbles and large flake blanks by means of the FHHP. Flexible technical repertoires which range from expedient to well-organised were used for core reduction, with core-on-flake and discoid technologies showing planned organisation and standardised operational schemes, technologically and statistically different from simple debitage.

Diverse toolkits and advanced hafting technology

A diversity of specialised stone tools is present at Xigou across the cultural layers and includes two different sequences of tool production, i.e. retouching and shaping (Supplementary Note 4.5 and 4.6). The former is devoted to turning flakes into tools by retouching working edges (Fig. 3a); the latter is manufacturing tools by sculpting the raw material in line with the desired form, which is represented by the presence of Large Cutting Tools (LCTs), including three handaxes and two picks (Fig. 3b). As would be expected, remarkable disparities in size, weight, raw material and blank selection exist between retouched tools and LCTs (Supplementary Fig. 33).

Retouched tools are predominant in the toolkits (86.8–93.9%) and include scrapers, borers, notches, denticulates, points, basal retouched tools, a burin, and casually retouched pieces (Fig. 3a, Supplementary Table 6). Statistical analysis of metric and technological attributes indicates that the differences in size, raw material, blank selection and retouch pattern are not significant across the four layers (Supplementary Fig. 27). Retouched tools are generally small-sized (mean = 38.1–45.5 mm) and mainly based on flake blanks (73.9–90.9%). The retouch on some tools is elaborate and standardised. Especially for borers, a delicate tip was formed by continuous retouching on the distal and lateral edges mostly by direct retouch from the ventral to dorsal face of flake blanks, and some pieces show comparable shapes (Fig. 3: 1–2 and 7–8, Supplementary Fig. 29).

Alongside artefacts where only the cutting edge was retouched, other tools show more complicated retouching patterns, with clear basal modifications. A total of 22 pieces of basal retouched tools, indicative of potential hafting[35–37], were identified across all five layers, accounting for 8.7% of the toolkits. Among the assemblages, there are 13 tanged or shouldered tools, which are with a projection, or a width-reduced base created by flanking notches or continuous retouch removals (Fig. 3c, Supplementary Fig. 31). In addition, 9 pieces show backing modifications on the proximal end of the artefacts (Fig. 3d, Supplementary Fig. 32), forming an abruptly backed base which could help its handling or even to join a handle or a shaft for use[38]. The cutting edge opposite to the base of tanged and backed tools is usually continuously retouched and shows a pointed, denticulated or straight morphology.

The microwear results obtained on quartz tools resulted in the identification of different functional activities (Supplementary Note 5). Two tanged borers show both boring actions and hafting

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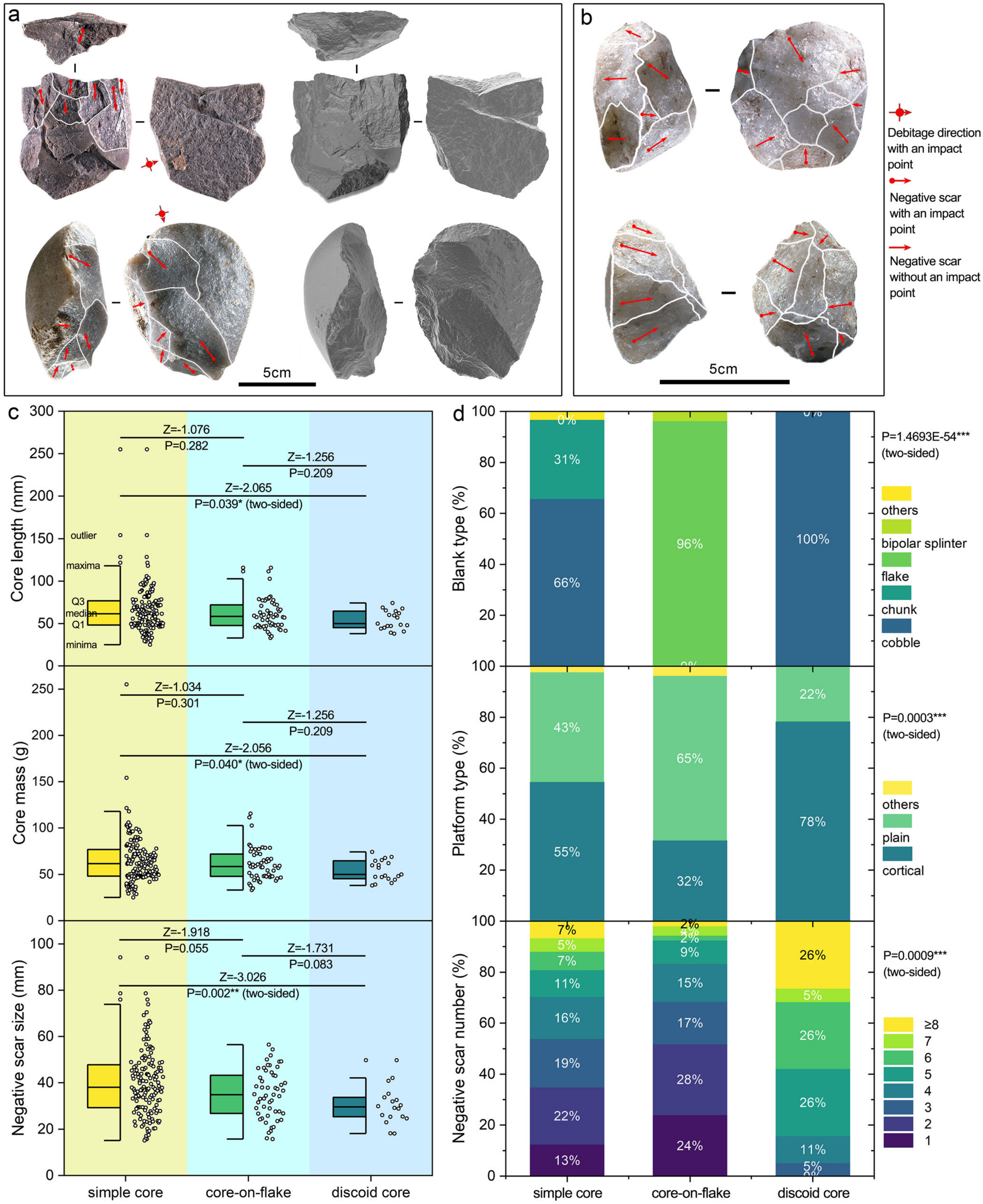

Fig. 2 | Core metric and techno-typological variables. a Cores on flakes. **b** Discoid cores. **c** Core length, mass and negative scar size by core type, showing the Mann–Whitney U-test results. **d** Blank type, platform type and negative scar number by core type, showing the Fisher's exact test results.

evidence. In the first case, the wear marks are concentrated at the tip (Fig. 3c, Supplementary Fig. 35), and include edge macro and micro scars with a distribution consistent with a rotational movement, likely on a hard plant material. The scarring is accompanied by pronounced edge rounding, abundant striations in the form of transverse fine furrows, and a well-developed smooth polish restricted to the crystal ridges at the tip. Such a combination of wear features has been experimentally reproduced on a boring action on

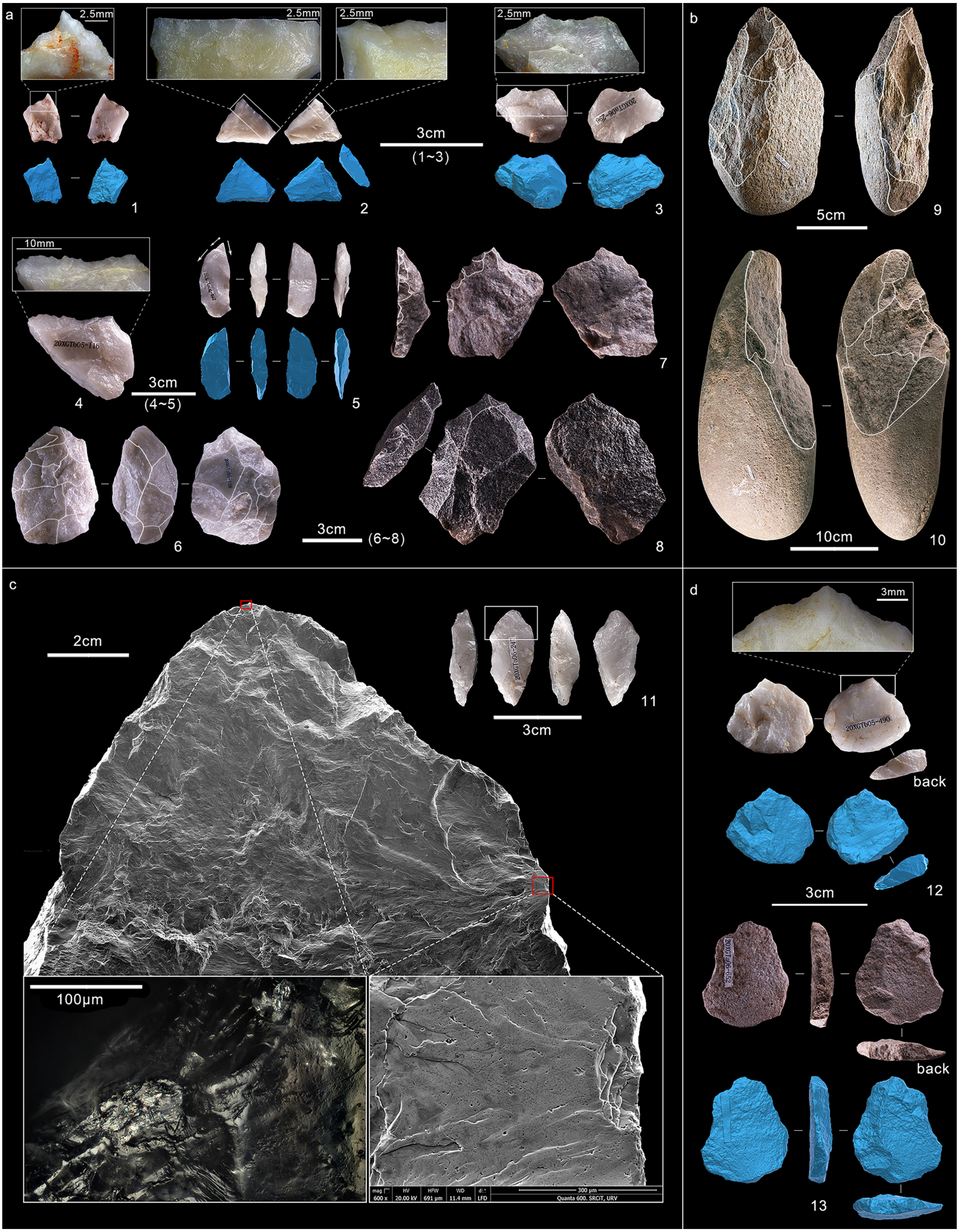

Fig. 3 | Stone tools from Xigou including use-wear observations. a Formal retouched tools: 1, 2, 7 and 8 borer, 3 notch, 4 denticulate, 5 burin, 6 bifacial pointed tool. **b** LCTs. **c** Image of the active part of the tanged borer (SEM micrograph) showing macro- and micro-scarring, intense edge polishing at the tip (optical microscope, 50x lens), and a fracture, edge rounding and furrow-like striations on the side (scanning electron microscope) consistent with a rotational movement. **d** Backed borers. (4 & 9 from Layer 2; 1, 3, 6, 11 & 12 from Layer 3; 7, 8 & 10 from Layer 4; 2, 5 & 13 from Layer 5).

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reed (Supplementary Figs. 49 and 50). Its proximal end shows a large bending fracture and a generally fresher surface, but on the mesial part there is evidence of hafting in the form of slight modifications by retouching and linear friction marks (furrows), together with patches of well-developed polish and isolated striations in the interior of the piece (Supplementary Figs. 36 and 51). Consequently, the hypothesised mode of hafting involves covering of the proximal and medial thirds of the piece. The second one is a flake with backing of both laterals in a kind of tang arrangement. Microtraces of hard-hammer retouching are visible from the proximal end to 2/3 of its length (Supplementary Fig. 37). Use-wear is concentrated on the tip of the tool, with a wear pattern similar to the former one, with more pronounced scarring, striations and polish (Supplementary Fig. 38). While in the first case the type of hafting could imply the insertion of the piece into a haft, i.e. a male terminal hafting[39], the second piece suggests a juxtaposed terminal haft, with part of the lateral scarring possibly related to the binding, as we reproduced experimentally (Supplementary Fig. 49).

Among the actions, boring activities stand out, including examples where plant material (probably wood or reed) has been identified. Piercing actions on an unidentified soft material were also identified. There are 2 pieces that show more than one activity and in both cases plant material is involved. The first is a burin; its tip was used for engraving, and the lateral natural plane was used for whittling (Supplementary Figs. 45 and 46). The second is a pointed piece, classified as a borer, that was used to saw what was probably reed, combining a rotary movement on its distal part portion, accompanied by complementary whittling actions on both mesial edges (Supplementary Figs. 42–44).

In summary, small flake tools were the primary targeted products of the reduction sequence. The tool types are specialised and diverse, and the significant component consists of tanged and backed tools that were produced for the purpose of hafting. Two different handle types: juxtaposed and male, were documented in the traceological analysis. The functional results provide support the hypothesis of an advanced technological management of quartz, a raw material that is widely used but still evokes certain negative connotations with regard to the production of stone tools[40]. Also noteworthy is the versatility of pointed morphologies, which can perform a variety of actions such as piercing, sawing, cutting, perforating, etc.

Discussion

Early technological innovations from the Middle to Late Pleistocene in China

Though stone tool technologies in China have long been regarded as simple and conservative, recent years have witnessed profound changes in our view of the Pleistocene record. Early and Middle Pleistocene lithic assemblages are now known to have prepared core technologies[41], innovative retouched tools[42], and LCTs[43,44]. Consequently, lithic classifications which tend to categorise Pleistocene stone-tool assemblages using terms such as simple core-and-flake industries, Oldowan-like and Mode 1 technologies, are questionable. A re-assessment of Pleistocene assemblages based on technological and functional analysis is therefore required.

Considering the complexities of the sedimentary history and the limitations of ReOSL dating caused by multiple factors during equivalent dose and environmental dose rate determination at Xigou (Supplementary Notes 2 and 3), our ReOSL ages represent the best available estimate to frame the appearance of technological innovations, despite their uncertainties. Xigou therefore documents the appearance of technological innovations dating between ~160–72 ka (Fig. 4a). The frequent application of core-on-flake and discoid methods reveals advanced technological organisation and constitutes a noticeable behavioural choice to produce small-sized flakes. The toolkits show a diversity of tool types, and a high degree of standardisation and complexity especially represented by basal modified tools. Elaborate mental templates, flexible technical repertoires and high level of manual precision are indicated throughout the stone tool reduction sequence. Such a technical system was either unknown or exceedingly rare at earlier archaeological sites in the Danjiangkou Reservoir Region[45–47]. In particular, hafting technology, demonstrated by technological and use-wear approaches from Xigou, to our knowledge, provides the earliest known evidence of this kind for stone tool assemblages in Eastern Asia.

In examining the evidence more widely, lithic technological innovations and behavioural complexity appear to be more apparent in the late Middle Pleistocene to middle Late Pleistocene (ca. 300–50 ka) than heretofore realised (Fig. 4b and c, Supplementary Note 1). The organised reduction methods and tool retouch skills observed at Xigou were particularly well-developed in central and northern China, such as at the sites of Zhoukoudian Loc. 15 (~284–155 ka or 140–110 ka)[48,49], Lingjing (~125–90 ka)[26], Salawusu (~100–90 ka)[27], Banjingzi (~89–80 ka)[50], and Wulanmulun (~65–50 ka)[51]. At Lingjing, for example, biconical discoid cores constitute the most standardised core type and lithic toolkits are featured by discrete small-sized tools (e.g. backed tools, basally retouched points) and the possible use of pressure flaking[26]. The presence of hafting technology has been verified by use-wear analysis at the sites of Salawusu and Wulanmulun back to at least 65–50 ka[27,52]. In southern China, there is a marked decline in the use of LCTs in the Middle Pleistocene and an increase in the production of small flaking technologies in the middle and lower Yangtze River[53]. Lithic assemblages showing some features of Levallois and Quina technologies occur in the Yunnan-Guizhou Plateau[25,28,54]. Simultaneously, bone/antler/wooden tools were used in a variety of activities, including as bone retouchers for pressure flaking[55,56], as billets for soft-hammer flaking[56,57] and as digging equipment for exploiting underground storage organs[57]. Finds from Lingjing also show the presence of ochre residues on an engraved bone dating to ~125–90 ka, providing the earliest evidence of such use behaviours in Eastern Asia[58].

On the whole, a transition towards the use of cores for detaching small flakes with both expedient and well-organised core reduction strategies (i.e. core-on-flake, discoid and Levallois technologies) and the increased presence of diverse and refined small flake tools, including hafted implements, have been documented from the late Middle Pleistocene to middle Late Pleistocene in China. This coincides with a decline in the use of LCTs and the emergence of bone tool technology, symbolic engravings and ochre use (Fig. 4b and c). Though it has been repeatedly asserted that major changes in lithic technologies tended to be clustered at the Upper Palaeolithic in China, after ~40 ka[20,22,23], earlier records, such as the evidence from Xigou, challenge this dominant paradigm and show that hominins in China from the Middle to Late Pleistocene possessed the cognitive and technical abilities to produce complex and diversified items of material culture, compatible with their counterparts from other regions of Africa and Eurasia.

Implications for hominin adaptations in Eastern Asia

Xigou represents a series of precocious behaviours during the late Middle Pleistocene to middle Late Pleistocene of Eastern Asia, including significant changes and innovations in lithic technology between 300 and 50 ka (Fig. 4a–c). The fossil record of China also shows notable changes during this time frame, with the potential presence of multiple species, including the Denisovans, *H. longi, H. juluensis* and *H. sapiens*, with brain sizes ranging from 1200 to 1800 cc[3–12,59] (Fig. 4d and e, Supplementary Note 1). Discoid and core-on-flake technologies can be found throughout the entire 300,000-year time period, indicating that flake technologies were a standard toolkit for multiple hominin species. LCTs technologies lasted for a long time, and then disappeared gradually at around 70–50 ka[44,60],

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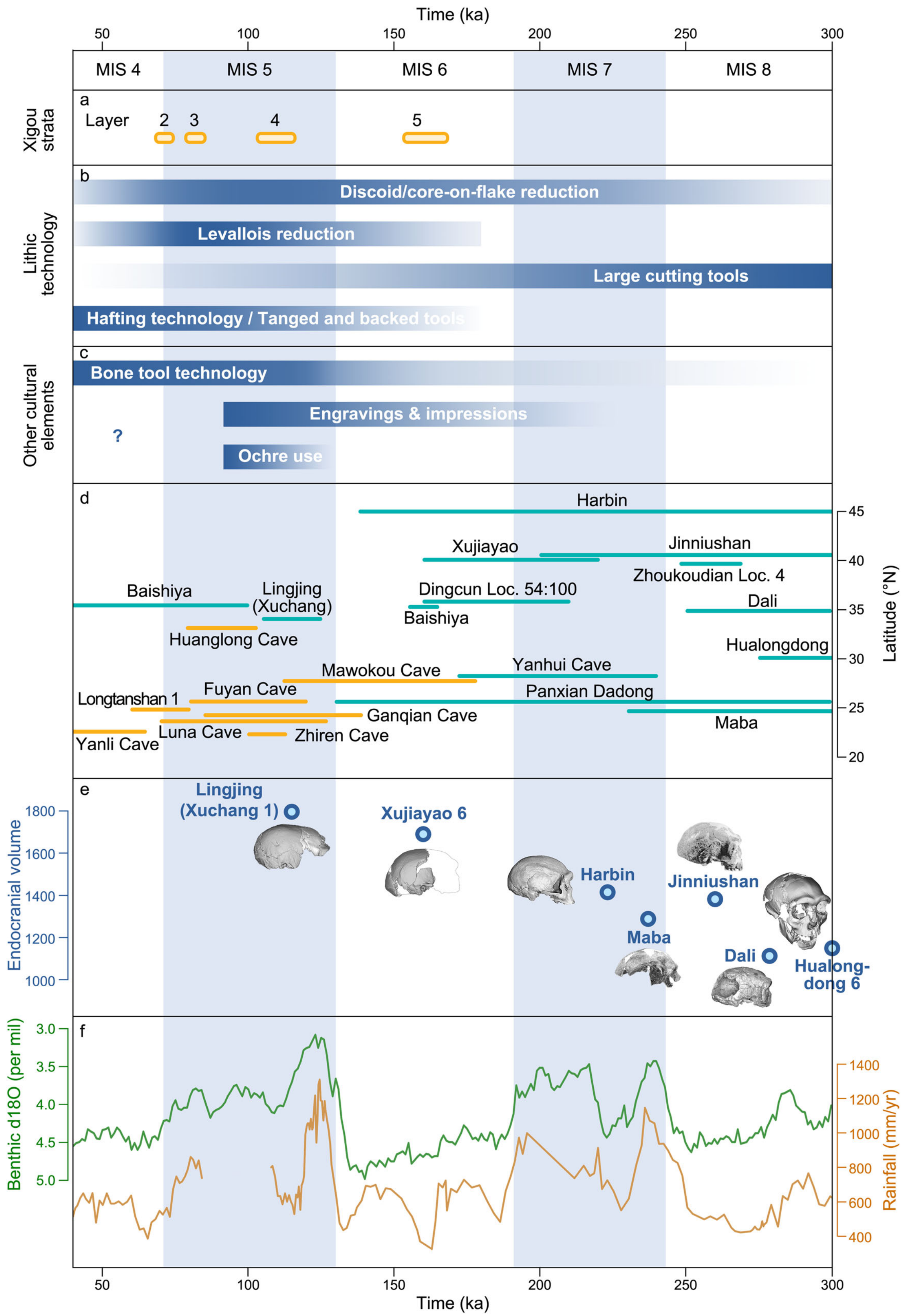

Fig. 4 | Lithic technological change, hominin history and climatic background from the late Middle Pleistocene to middle Late Pleistocene (ca. 300–50 ka) in China. **a** Xigou stratigraphic layers. **b** Lithic technology. **c** Other cultural elements including the bone tools and the symbolic related cultural remains. **d** Fossil hominin site record (orange lines indicate potential *H. sapiens* fossils; green lines indicate other *Homo* species). **e** Hominin fossil endocranial volumes[10,59]. **f** LR04 benthic stack $\delta^{18}O$ records[62] and ^{10}Be-based rainfall for the Baoji loess section in northern China[64].

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corresponding with evidence for *H. sapiens* in southern China. More complex forms of lithic manufacture, including Levallois reduction, occurs by ca. 180 ka in Southwest China, and corresponds with fossil evidence which shares derived features that align with *H. sapiens* such as at Panxian Dadong[61]. Innovations such as bone tool and hafting technologies occur much earlier in the end of Middle Pleistocene than previously understood and may reflect the presence of hominins such as that found at Lingjing (Xuchang)[4], with the largest known brain sizes in China outside of *H. sapiens*.

With respect to climatic variability and hominin behaviours, some broad observations are possible (Fig. 4f). LCTs are introduced by at least the mid-Pleistocene transition in southern China, and they continue to be present in MIS 6–5[43,44]. LCTs decline in MIS 6–5, corresponding with the increased development of discoid and core-on-flake since MIS 7, and later accompanied by Levallois reduction MIS 6. The technological transformation occurs during the transition to MIS 6, potentially related to the harsh glacial climate and the strengthened winter monsoon[62–64]. Overall, the appearance of technological innovations throughout the late Middle Pleistocene to middle Late Pleistocene may signal behavioural responses to ecosystem change[65]. In the more ameliorated warm and humid period of MIS 5, hominin sites tend to occur in higher density along with more in-migrations of early modern humans, and technological diversity is at its greatest, exemplified by the presence of predetermined core reduction strategies, hafting technology, bone tools, deliberate engraving and pigment use.

The archaeological record of Xigou indicates complex technological advancements in China between ~160 and 72 ka. The site occupants aimed at producing small-sized flakes with core reduction strategies ranging from expedient to well-organised (core-on-flake and discoid technologies). The dominant small tool retouching patterns evidence a great degree of technological standardisation and complexity, especially in the early occurrence of hafting technology (tanged and backed tools), indicative of elaborate mental templates and advanced technical abilities among the toolmakers. Xigou and other archaeological sites between 300 and 50 ka demonstrate the complexity and diversity of lithic technologies and challenge the long-standing view of the Chinese Palaeolithic as a conservative entity from the Middle and Late Pleistocene, with cultural advancements only occurring after ~40 ka. The period between 300 and 50 ka also witnesses the presence of multiple large-brained hominin species and an increase of human populations in a fluctuating climate background. Though many of the details of this evolutionary story are yet to be told, and much additional data is required, the picture that is emerging is that changes in technology and behaviour likely reflect taxonomically-linked cognitive changes and responses to strong environmental variability across Eastern Asia.

Methods

All the field excavations and sample extractions were permitted by the National Cultural Heritage Administration. The archaeological excavation of the Xigou Site is one of the cultural preservation and archaeological excavation projects under the South-to-North Water Diversion Water Supply Project in Henan Province, with project number No. B-201807. The research work was permitted by Institute of Vertebrate Palaeontology and Palaeoanthropology(Chinese Academy of Sciences), College of Applied Arts and Science (Beijing Union University), Institute of Earth Environment (Chinese Academy of Sciences) conducted the analysis of the al. Results of this study will be shared with Henan Provincial Institute of Cultural Heritage and Archaeology and Nanyang Institute for the Preservation of Cultural Heritage.

Luminescence dating

Luminescence dating samples were collected by hammering stainless steel cylinders, each with a diameter of 5 cm and a length of 20 cm, into freshly cleaned section. A total of six samples were obtained, with one sample located at a depth of 5 m and the other five ones spanning the depth interval of 2.65–0.75 m (Fig. 1d). Considering the silty-clay dominated nature of the Xigou section (Fig. 1d; Supplementary Note 2.3), the fine fraction of quartz and polymineral (4–11 µm) was used for luminescence dating. Details of luminescence dating sample preparation, instruments, and environmental dose rate determination can be found in Supplementary Note 3.1, 3.2, and 3.3, respectively. For cross check, we applied multiple luminescence dating protocols into the Xigou section to obtain equivalent dose, including quartz single-aliquot regenerative-dose (SAR) optically stimulated luminescence (OSL), quartz multiple-aliquot regenerative-dose (MAR) recuperated OSL (ReOSL), and polymineral SAR post-infrared infrared stimulated luminescence (post-IR IRSL).

Lithic techno-typological and functional analysis

A techno-typological approach together with attribute analysis was applied to reconstruct lithic reduction sequences and to investigate debitage and toolmaking strategies[66–69]. From this, raw material procurement, core reduction, and tool production strategies are examined across the four phases of site occupation. Three-dimensional reconstruction with Shining 3D and magnified observation with a Leica DVM6 are applied for more detailed examinations of a selection of retouched tools, which permit a higher level of analytical interactions with the samples.

Use-wear was documented using a multi-technique approach combining the use of optical microscopy (OM), Scanning Electron Microscopy (SEM) and 3D digital microscopy (3D DM). The microwear traces were interpreted using the experimental collection of the Laboratory of Technology of the IPHES-CERCA[70,71], where raw materials from the Danjiangkou Reservoir Region and the Nihewan Basin are currently being included.

Detailed methodology for functional analysis

The approach followed in this preliminary study applies criteria established experimentally[70,72,73] according to a multiscale and multi-technique microscopic approach[74–77]. The artefacts were cleaned and prepared according to the protocols established in previous works[78,79]. This process, once the label on the pieces was removed, involved successive ultrasonic baths in neutral soap, 130-vol hydrogen peroxide, and pure acetone. When necessary, we resorted to a 10% HCL bath.

Microwear was documented with the combined use of optical microscopy (OM), Scanning Electron Microscopy (SEM) and 3D digital microscopy (3D DM). First, a systematic observation was carried out at different magnifications using different 3D digital microscopes. We used a Hirox KH8700, with an MXG-5000REZ dual illumination revolver zoom lens (allowing for magnifications ranging from 35 to 5000x; Horizontal Field of View -HFOV- 8.6 mm–60 µm), a Keyence VHX 7000, with a High- Performance Zoom lens VH-20R (20-200x, HFOV 15.24–1.52 mm), and occasionally a Leica DVM6 (PlanAPO 12.55, up to 675x). Detailed observations of use-wear traces were made using a Wide-Range Zoom Lens VH-Z100 UR (100-1000x, HFV 3.05–300 µm) in the Keyence, and an optical microscope (Zeiss Axioscope A.1, with differential interference contrast -DIC- prisms and a Nomarski interference contrast filter, with 10x oculars and EC Epiplan objectives ranging from 5x/0.13 to 50x/0.5 HD DIC, giving nominal magnifications of 50 to 500x; HOFV 2.9 mm–295 µm).

Some artefacts were subsequently observed using Scanning Electron Microscopes. We mainly used an environmental SEM {FEI Quanta 600 ESEM, with an EDX-EXL System Analytical Oxford energy dispersive X-ray spectrometer, and a combination of Large-field detector (LFD) and Back-scattered electron detector (dual BSD)}. These SEM observations were all made in low vacuum mode, which does not require a conductive coating of the sample. We also observed some samples with high vacuum SEM equipment (a tabletop SEM

COXEM EM-30 and an EMCRAFTS), but with a low voltage (10 Kv) to avoid coating the samples.

To interpret the use-wear traces, apart from existing literature[80,81], we resorted to experimental collection of the Laboratory of Technology at the IPHES-CERCA (TraceoIPHES). The collection includes a wide variety of samples resulting from experiments (i.e., butchery, hide work, woodwork, vegetal tissues, projectiles, hafting, technological traces, etc.) in which the main types of raw material are well represented[70–73,77,82]. For the assessment of post-depositional surface modifications, we considered their distribution on the surface of the artefacts, the results of our own experiments[77,83], as well as others involving different depositional environments[84].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All study data are included in the article and/or Supplementary Information. Data used to generate for Fig. 1 can be found in Supplementary Data 1 and 2; Data for Fig. 2 can be found Supplementary Note 4. All artifacts referred to in this study are curated in the Institute of Vertebrate Palaeontology and Palaeoanthropology, Chinese Academy of Sciences, Beijing, and Nanyang Institute for the Preservation of Cultural Heritage. If anyone what to have access to the original materials (lithics) from this work, please contact Shi-Xia YANG, yangshixia@ivpp.ac.cn.

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Author contributions

S.-X.Y., S.-G.K., and M.P. designed research; G.-D.S., J.-Y.L. Q.-P.Z., Z.-S.S., and B.-T.Q. conducted fieldwork and collected finds for analysis; S.-G.K., P.-X.S., Z.-S.S., and C.-L.D. conducted the stratigraphic and dating studies; Y.-X.Z. and H.-Y.L. analyzed the raw materials; J.-P.Y., S.-X.Y., B.M., A.O., J.L.F.-M., F.-X.H., and M.P. analyzed the stone artefacts; J.-P.Y., S.-X.Y., S.-G.K., and M.P. wrote the main text and supplementary materials with specialist contributions from the other authors.

Competing interests

The authors declare no competing interests.

Additional information

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