Evolutionary Trends in Blank Cutting Edge Efficiency During the Upper Paleolithic of East Asia (Mongolia and China)

By

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DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Anthropology

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Nicolas Zwyns, Chair

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Committee in Charge

2024

Dedication

To my brother, Samson Alexander (Sam), my sister, Catherine Elizabeth (Beth), our mother, and father.

Acknowledgements

First, I would like to thank the sources of funding for this research: The Leakey Foundation, the Wenner-Gren Foundation, the American Center for Mongolian Studies, the Sacramento Archaeology Society, and the UC Davis Anthropology Department, Institute of Social Science, and College of Letters and Science Dean's Office. With their support I was able to spend a little over a year on the ground in Mongolia and China assisting in the excavation of multiple Paleolithic archaeological sites and studying the artifacts from those sites and sites like them. This experience not only involved the thrill of discovery regarding our shared human evolutionary past but also the personal experiences that come with living alongside people day to day in the beautiful and vibrant cultures of those regions. These are the stories I like to tell most: the people I met, the food we ate, the tension, the humor, and the things we shared. On this note I cannot thank my Mongolian and Chinese colleagues enough for all their hospitality and generosity as we worked together over the years and going forward. Many people come to mind – from students to professors – though I am particularly grateful to Fei Peng, Feng Li, and Xing Gao from China, as well as Tsedendorj Bolorbat and Byambaa Gunchinsuren from Mongolia, for all their guidance and support while working abroad with them and their students. I would also like to thank Masami Izuho, Evgeny Rybin, and Arina Khatsenovich for making me feel welcome as veteran Paleolithic field archaeologists working in Mongolia. Back home in Davis I would like to thank the other graduate students in my lab for all their camaraderie, particularly Giulia Gallo, Sara Watson, Peiqi Zhang, and Meredith Carlson. Their scientific curiosity, raw intelligence, creative problem solving, and winning personalities have all been nothing short of inspiring to work alongside, and I look forward to continuing to do so. I want to thank the Paleogroup for being the kind of academic community that I also plan to establish someday. I would also like to thank Mark Grote for all his assistance with the statistics and coding in this manuscript, and for all the helpful professional and personal advice he is always so willing to share upon request. Finally, I'd like to thank my advisor, Nicolas Zwyns, for being a wonderful mentor and colleague, and for helping guide me through one of the most challenging and rewarding periods of my life. It has truly been an honor.

Abstract

Two general lithic technological trends are observed in the Upper Paleolithic archaeological record of East Asia. One initially involved the production of large blades, then subsequently emphasized bladelet, and later microblade production. The other entailed an expedient, flake-based technology that does not seem to have changed much over time. The distribution of archaeological sites falling under these two categories is generally divided along an ecological boundary between the Eurasian Steppe to the north and the Summer Monsoon zone to the south. This dissertation details a research program aimed at diachronically comparing blank cutting edge efficiency between Upper Paleolithic assemblages within the Tolbor Valley in northern Mongolia and Shuidonggou 2 in northern China. Results from the Tolbor assemblages indicate an increase in blank cutting edge efficiency over time associated with small flakes, bladelets, and microblades. Results from Shuidonggou 2 indicate that cutting edge efficiency varied little over time, despite changes in raw material use. These findings reveal ecological and technological aspects of the resettling of East Asia by *Homo sapiens* following their eastward expansion into the region ca. 45,000 years ago.

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Chapter 1: Introduction

Before the arrival of our species in East Asia, the earliest evidence for hominins in the region comes from a small number of incomplete fossils, taxonomically assigned to Early Pleistocene *Homo erectus* s.l. dating to 1.8-1.6 Ma [1-6]. Details surrounding these fossils support the 'Out of Africa 1' hypothesis, which suggests our genus first began expanding into Eurasia ca 1.9 Ma, shortly after its appearance in Africa [7-11]. Populations of *H. erectus* then persisted in regions of East Asia well into the Middle Pleistocene, up until around 400 ka [12-20; though see 21]. After this period, the Paleoanthropological record documents an ever growing number of hominin fossils whose taxonomic status is less clear [22-32]. Historically, these individuals have been interpreted as exhibiting some combination of archaic and derived features which disqualify them as belonging to *H. erectus* yet are not fully in agreement with the taxonomic definitions of other coeval Middle Pleistocene *Homo* sp. known from Africa and Eurasia, such as *Homo heidelbergensis, Homo neanderthalensis*, and *Homo sapiens* [33].

Recently, proteomic analysis of one such Middle Pleistocene fossil, the Xiahe mandible recovered from the Tibetan plateau, indicates a close relationship with a metapopulation of Middle and Late Pleistocene hominins known as Denisovans [29]. Originally defined using aDNA extracted from highly fragmented fossils (and later archaeological sediment) recovered from the eponymous Denisova Cave in the Altai Mountains [34-36], Denisovans represent multiple divergent genetic hominin lineages which split from *H. sapiens* ca. 700-500 ka while still sharing a lineage with Neandertals, from which they then subsequently split again ca. 450-350 ka [37-40]. Proteomic and genetic studies indicate that Denisovans arrived in East Asia as early as ca. 160 ka and persisted until ca. 30 ka, and possibly later in Southeast Asia [29,37,41-45]. Such studies also suggest that some of the enigmatic hominin fossils in East Asia post-dating ca. 400 ka may be related to one or more Denisovan lineages, though aDNA from more completely preserved fossil individuals for comparison with the rest of the fossil record are still needed to clarify this issue.

The Paleolithic archaeological record pre-dating the arrival of *H. sapiens* in East Asia also begins in the Early Pleistocene, with a handful of lithic assemblages dating before [46,47] and between ca 2.0-1.0 Ma that exhibit technological strategies which emphasized non-descript, unprepared flake production [48-54; though see 55-58]. With the onset of the Middle Pleistocene, ca. 780 ka, derived technological behaviors appear in the region such as Acheulean tool types and fire technology [12,59-64]. Additionally, sparse but growing evidence indicates that prepared flake production strategies began to sporadically appear in East Asia after ca. 300 ka [65-67]. Other derived Middle Pleistocene and early Late Pleistocene technological behaviors include possible evidence of bone technologies, pressure flaking, and symbolic behaviors [67-69]. However, despite all these potential technological developments in the Middle Pleistocene and early Late Pleistocene, unprepared flake assemblages continued to be widely used by archaic hominins in East Asia during this time [70-73].

The Late Pleistocene record finally marks the arrival of our species, *H. sapiens*, in East Asia, though there is evidence for two major migration routes into the region circumventing the Himalayas, a northern route and a southern route. Archaeological and fossil evidence from southern East Asia, Southeast Asia, and Sahul point to an eastward expansion of *H. sapiens* populations out of East Africa/West Asia along the southern route ca. 120-65 ka [74-85]. This southern expansion may have been part of similar expansions of *H. sapiens* into West Asia and southeastern Europe documented before ca. 90 ka [86-91]. Evidence for a geneflow event between our species and Neandertals between ca. 300-100 ka [38, 92] further indicates that such early expansions by *H. sapiens* out of northern Africa and into Eurasia, while perhaps at times truncated, may not have been uncommon during the Middle and Late Pleistocene. However, several critical issues remain to be clarified regarding the fossil, genetic, and archaeological evidence along this southern route [93-97].

Fossil and genetic evidence for the northern route is better documented and more temporally constrained, indicating that *H. sapiens* began expanding out of West Asia, across North-Central Asia, and into northern

East Asia during Marine Isotope Stage 3 (MIS 3), ca. 50-45 ka [98-102]. The expansion of *H. sapiens* into East Asia along this route is generally thought to have coincided with the eastward expansion of the Initial Upper Paleolithic (IUP) techno-complex into the region [103-110] - mirroring the coeval expansion of *H. sapiens* and the IUP into Europe [111-114]. Evidence for geneflow from one or more extirpated East Asian Denisovan lineages into our own ca. 45 ka [41-45] and the subsequent development of Early (EUP) and Late Upper Paleolithic (LUP) techno-cultural traditions in the region [115-121] further indicates that after the arrival of *H. sapiens* in northern East Asia ca. 45-40 ka the region became a permanent extension of the geographic distribution of our species for the remainder of the Pleistocene.

This period during MIS 3 and MIS 2 that documents the arrival of the IUP and *H. sapiens* into northern East Asia, and the subsequent period of Upper Paleolithic technological development in the region, is the main topic of this dissertation. This work builds on over a century of archaeological research which indicates that lithic technology in East Asia developed along two major trajectories between ca. 45-20 ka. The first is geographically limited to the steppe region to the north, around Lake Baikal and its tributaries, and involved a succession of lithic technological turnovers from the IUP to the EUP to the LUP [106,108-110,118,119,121]. The second was mainly situated in the Yellow and Hai River basin regions, annually affected by the East Asian summer monsoon, and is characterized by lithic assemblages emphasizing non-descript, unprepared flake production – that in some areas initially coexisted with southern extensions of the IUP from the steppe [120,121-125].

The thesis of this work is that the processes which caused this pattern of technological development within and between these two regions in northern East Asia, while remarkable, were not fundamentally unique. As such, their evolutionary details can be further revealed using methods that account for these processes. Somewhat recently, Režek et al. proposed that parameters of lithic "evolutionary efficiency", which measure the degree to which Pleistocene hominins adapted their lithic technologies to past environments, can be used to explain behavioral and anatomical changes observed within the

Paleoanthropological record [126]. One such parameter underlying the evolutionary efficiency of lithic toolkits, thought to have had direct consequences for changes observed in hominin physiology and technological behavior since the Pliocene [127,128], is blank cutting edge efficiency [126,129-132].

Blank cutting edge efficiency is essentially a measure of how efficiently Paleolithic toolmakers produced sharp edges in the form of flakes, blades, bladelets, and microblades for use in subsistence based cutting tasks. This parameter along with other aspects of lithic evolutionary efficiency, such as lithic recycling, blank productivity, and artifact transportability, can together be conceived of as a critical component of the positive feedback loop proposed by Antón and Snodgrass which hypothetically drove hominin evolutionary ecology during the Pleistocene (Fig. 1) [133]. Because the two trajectories of lithic technological development in East Asia during MIS 3 and MIS 2 seem to correspond to distinct ecological settings, i.e. the steppe region to the north and a monsoon zone to the south, this dissertation frames blank cutting edge efficiency as an ecologically sensitive parameter of lithic toolkits, where changes in cutting edge efficiency reflect changes in the adaptive technological behaviors of toolmakers in response to changing paleoecological conditions.

Previous research has shown that cutting edge efficiency, and variability around this parameter, gradually increased across the Pleistocene, peaking in association with *H. sapiens* ca. 50-20 ka during the Upper Paleolithic [126,129,131,132]. However, this previous work has exclusively focused on the Pleistocene lithic archaeological record from Africa, West Asia, and Europe. This dissertation offers one of the first, if not the first, studies on blank cutting edge efficiency involving Pleistocene lithic assemblages from East Asia. It is the hope of the author that it will not be the last, and that similar studies will follow so that a comprehensive super-regional picture, as illustrated by Režek et al. for East Africa, West Asia, and Europe [126], can someday be comparatively drawn for the Pleistocene lithic archaeological record of East Asia.

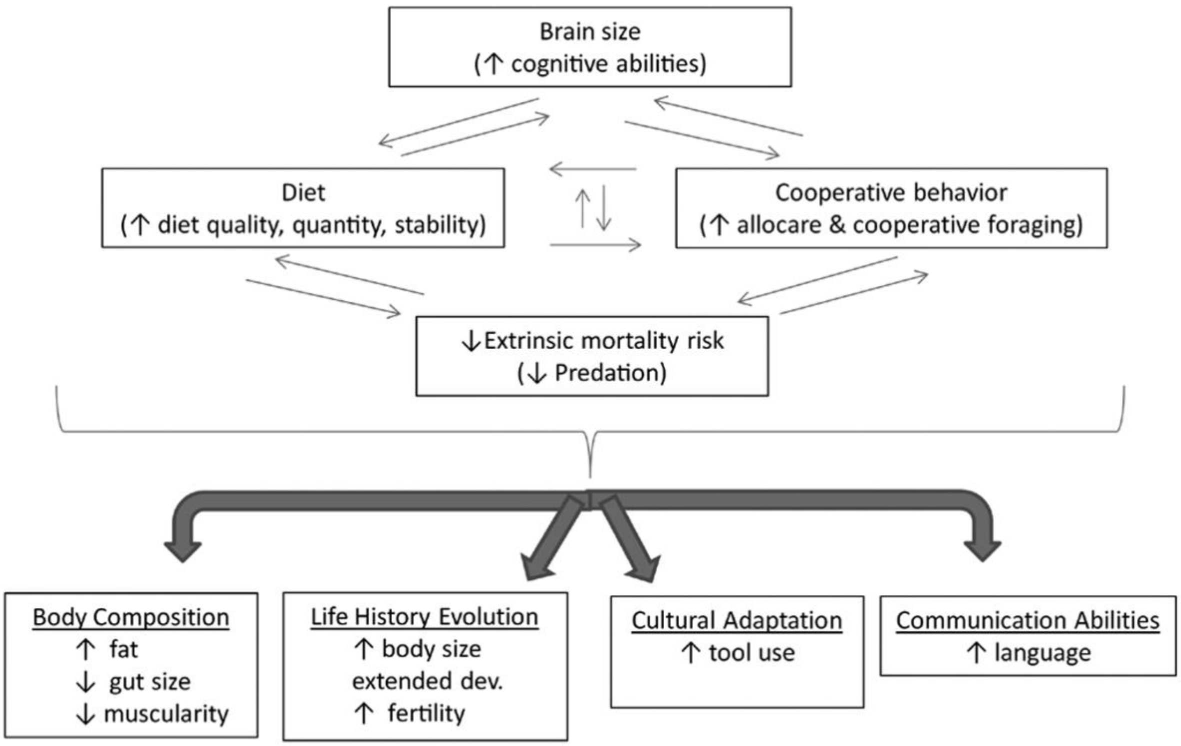

Fig 1. Figure and description from Antón and Snodgrass [133], with emphasis added by the author: "*A positive feedback loop between cooperative behavior (initially in breeding), diet quality and stability, cognitive abilities (brain size), and extrinsic mortality risk drove life history evolution and contributed to cultural change in genus* Homo*. Gradual, self-reinforcing shifts in these central elements had consequences for life history traits including extending the developmental period, increased fertility, and larger body size; body composition including increased adiposity, reduced gut size, and reduced muscularity; communication including eventually the development of language;* ***and cultural change including more complex extractive foraging****. Early* Homo *showed only modest increases in the central elements. The fully modern package of life history and other consequences may not have emerged until recent humans*".

This dissertation is structured into three main chapters, each representing a separate study undertaken by the author and colleagues which statistically models the cutting edge efficiency of nine lithic assemblages dating to MIS 3 and MIS 2 recovered from two site complexes in East Asia, specifically the Tolbor Valley in northern Mongolia and the Shuidonggou site complex in northern China. These chapters are bookended by both this introductory chapter and a concluding chapter, and can be summarized as follows:

Chapter 2 consists of a research paper detailing the primary method of modeling blank cutting edge efficiency used throughout the manuscript, and its application on an EUP and LUP assemblage, which document the appearance of microblade technologies in the Tolbor Valley during MIS 2, as a case study.

Chapter 3 expands upon the previous chapter by including an IUP and an additional EUP assemblage from Tolbor into the model, allowing for greater diachronic coverage regarding the development of Upper Paleolithic technology in the region between ca. 45-20 ka while also elaborating on the baseline model.

Chapter 4 focuses on the coeval, yet distinct, Upper Paleolithic archaeological record at Shuidonggou 2, China, dating between ca. 35-28 ka and documenting the post-IUP appearance of an unprepared flake technology in the region, by further elaborating on the model to account for the influence of lithic raw material selection and blank failure rate on blank cutting edge efficiency.

Finally, Chapter 5 connects the results of the three papers to discuss them in greater evolutionary and archaeological context regarding the resettling of East Asia by *H. sapiens* between ca. 45 and 20 ka, highlighting their implications for the regional record and suggesting pathways for future work.

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Chapter 2: Analyzing blank cutting edge efficiency associated with the adoption of microblade technology: a case study from Tolbor 17, Mongolia

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Abstract

The phenomenon of Late Pleistocene lithic miniaturization at times coincided with increased artifact standardization and cutting edge efficiency – likely reflecting the use of small, sharp artifacts as interchangeable inserts for composite cutting tools and hunting weapons. During Marine Isotope Stage 2, Upper Paleolithic toolmakers in northern East Asia specifically used pressure techniques to make highly standardized lithic artifacts called microblades. However, little is currently known about how microblades affected the cutting edge efficiency of the toolkits they were a part of. We applied three methods of analyzing cutting edge efficiency to two Upper Paleolithic assemblages recently excavated from Tolbor-17, Mongolia, that document the periods before and after the introduction of microblade technology to the Tolbor Valley. A model incorporating allometric relationships between blank cutting edge length and mass suggests no difference in efficiency between the two periods, while two more conventional approaches both indicate a significant increase. The potential for improved cutting edge efficiency is only observed when the microblade sample is artificially inflated via simulation. Our results highlight challenges related to detecting and interpreting archaeological differences in cutting edge efficiency at the assemblage level.

Introduction

Blank production (i.e. the making of lithic flakes, blades, bladelets, etc.) is thought to have initially emerged as an intentional technological behavior within the hominin lineage in large part due to the capacity for a blank to be used in a subsistence based cutting task [1-10]. Subsequent changes in the procedural steps of blank production (methods) and physical means of blank formation (techniques) [11] observed within the lithic archaeological record are at times thought to have resulted in corresponding effects on blank cutting edge efficiency - often defined as the length of a blank's cutting edge relative to its volume [12-18]. From this perspective, as changes in hominin physiology [19-21] and paleoecology

[9,22,23] occurred, blank production methods and techniques which economized the amount of cutting edge available to meet changing energy demands [24] would have represented a fitness benefit to individuals that acquired them [17].

Previous research suggests that blank cutting edge efficiency, and the variability around this parameter, gradually increased throughout the Pleistocene [16-18]. However, it remains unclear exactly how different blank production strategies contributed to this dual condition, as experimental studies find little difference in cutting edge efficiency between generic systems of flake and blade production employed by lithic toolmakers from the Early to Late Pleistocene [13,16,25,26]. Nonetheless, archaeological and experimental results suggest that blank standardization and cutting edge efficiency improved during the Late Pleistocene with the development of methods of blank miniaturization [18,27], and pressure techniques of blank production [16,27,28] - with Late Upper Paleolithic microblade technologies notably representing a unique combination of both of these behaviors [30].

Microblades are small, elongated, very thin blanks often exhibiting a straight lateral profile, narrow, parallel edges, a punctiform platform, and a small compact bulb [30]. These traits are largely the result of the pressure techniques used to produce them [31], which involved the application of a static force to the edge of a core's striking platform using the pointed tip of a pressure crutch, or tine, until detachment via the mechanics of blank formation [32-35]. The small surface area of the tip of the tine would result in a laterally narrow blank platform, which in controlled experiments has been shown to be foundational to the production of narrow blanks [36,37]. Static loading would also allow for precise control over platform depth and angle of force, parameters which have been shown to predetermine blank size and shape [15,38-40]. Finally, methods of microblade core shaping and maintenance [41,42] would have allowed for control over the morphology of the core's flaking surface and exterior platform angle, parameters which have been shown to have important effects on blank shape - particularly blank thickness and elongation [15,38,43].

The development of microblade technology is generally thought to have been driven by adaptive pressures on artifact standardization, utility, and transportability coinciding with the Last Glacial Maximum (LGM) climatic episode of Marine Isotope Stage 2 (MIS 2) [27,44-50]. For humans subsisting in the northern latitudes of East Asia, where microblade technologies first appeared and spread [30], the LGM would have triggered a significant conflict between the availability of food and lithic raw material on the landscape. With the onset of colder climates during the LGM, the density of biomass in these northern environments would have decreased, causing the large-bodied mammals that inhabited them to become more widely distributed [47,50]. This in turn would have required human groups that relied on these animals as sources of food and materials to increase their mobility and regularly operate further away from lithic raw material sources [45-47,48,51].

From this perspective, microblades are thought to have been a technological solution to an ecological dilemma, as methods and techniques underlying microblade production effectively maximized the number of small, standardized blanks that could be made from more easily transportable cores [16,27,44,49,51]. These blanks were possibly used in hand as small cutting tools or inserted into the mortises of composite cutting tools [48] and hunting weapons [27,47,50] - the latter suggested by their high degree of standardization and technological investment [27,52]. However, it is unclear if microblades increased the cutting edge efficiency of the lithic toolkits they were a part of, as little work has attempted to measure their impact on this parameter [though see 44 for a rough comparison with biface cutting edge length; and 16,28 for examples of similar studies using pressure macro-blades]. To address this question, we first selected two lithic assemblages recently excavated from the Upper Paleolithic site of Tolbor-17, Mongolia, which document the periods before and after the adoption of microblade technology in the Tolbor Valley.

Tolbor-17

Tolbor-17 (T17) is an open-air site located in northern Mongolia along a low altitude pass above the Ikh-Tolborin-Gol ('Great Tolbor River' in English); a tributary of the Selenga River basin that flows into Lake Baikal to the north (Fig 1) [53,54]. The site was originally identified by A. Tabarev and S. Gladyshev who conducted the excavation of two test pits in 2010 and suggested a MIS 3 occupation of the site based on the recovered lithic assemblage and an obtained radiocarbon date [55,56]. Full-scale excavation at T17 began in 2017, initially consisting of two new 2x1 m test pits and, as of 2019, the excavated surface has been expanded to ca. 18 m^2. During each stage of excavation archaeological material >2 cm was piece plotted, and excavated sediment was dry sieved using 4 mm and 2 mm mesh screens.

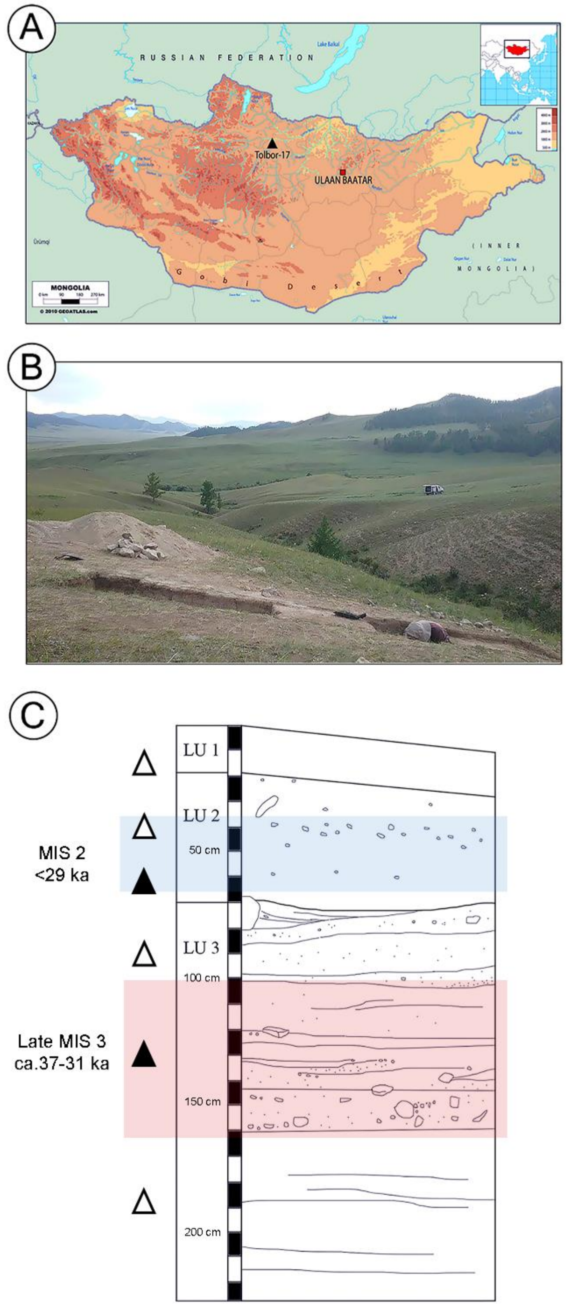

Fig 1. Location and stratigraphy of T17. A) Elevation map showing geographic location of T17 modified after Geo-atlas; B) South facing view of T17 during the 2017 excavation; C) Schematic section drawing of the stratigraphy at T17 with the approximate location of artifact accumulations and denser artifact concentrations indicated by open (△) and closed (▲) triangles, respectively. Colored bands indicate the vertical extent of the lithic assemblages from LU2 and LU3 studied here.

Three main lithological units are identified at T17. These include the LU1 Holocene soil complex, the LU2 loess and loess-like deposits, and the LU3 laminar silt with gravel and cobbles. Our study samples two artifact assemblages, one from LU3 and one from LU2 (Fig 1.C), as these units document the period before and after the appearance of microblade technology in the valley. The LU3 assemblage contains Early Upper Paleolithic (EUP) blade and bladelet technologies as well as diagnostic EUP tool types such as endscrapers and perforators. Previous test excavation at T17 dated a level that corresponds with LU3 to 33-34 ka cal. BP [57,58]. Stratigraphic correlation with other Upper Paleolithic sites in the Tolbor Valley [53,59] also places the material from LU3 in the later period of MIS 3, or ca. 40–30 ka cal. BP. The LU2 assemblage contains microblades and microblade cores characteristic of the Late Upper Paleolithic (LUP). The equivalent unit to LU2 at other Tolbor sites is always younger than ca. 29 ka cal. BP, or yields an MIS 2 age [53,59].

Other Upper Paleolithic sites discovered in the Tolbor Valley besides T17, such as T4, T15, T16, and T21, also document periodic episodes of human occupation in the region, beginning with the Initial Upper Paleolithic (IUP) and continuing to the end of the Pleistocene [53-61]. The appearance of the IUP in the Eurasian steppe coincides with the earliest fossil evidence of *Homo sapiens* in the region, suggesting that the technocomplex documents the expansion of our species eastward across North-Central Asia ca. 45kya [53,62-66]. The persistence of *H. sapiens* in the fossil record of Mongolia [67] coinciding with the archaeological record preserved at T17, further suggests that the Upper Paleolithic assemblages from the site were formed by members of our species as well.

To investigate the cutting edge efficiency of assemblages in the Tolbor Valley during the transition from MIS 3 to MIS 2, we ask: 1) whether the assemblage sampled from LU2 has a higher signature of blank cutting edge efficiency than the LU3 assemblage; and 2) if any difference in cutting edge efficiency observed between the assemblages can be attributed to microblade production.

Measuring blank cutting edge efficiency

There are multiple methods of measuring blank cutting edge efficiency, each with their own built-in assumptions, strengths, and weaknesses [68]. While an assessment of each method used in the literature is beyond the scope of this study, we provide a brief critical review of those that are most relevant.

In many studies concerning blank cutting edge efficiency, ratios of blank perimeter length to mass (as a proxy for volume) are commonly used. For example, the equation:

Perimeter Length/Mass

is in part used by Braun and Harris [12]. Similarly, Mackay [14] proxies blank perimeter using three linear measurements of a blank, producing the form:

(Max Length+Max Width+Max Dimension)/Mass

which has been found to be closely correlated with the variable used by Braun and Harris [see also 68]. Mackay's proxy is the most widely used in the literature as it is easy to measure and calculate, making comparisons between large datasets relatively straightforward [e.g. 10,69-74]. It should be noted however, that both equations use, or proxy, measurements of blank *perimeter* to estimate cutting edge efficiency [12,14], regardless of whether the entire perimeter of said blank is sharp enough to perform a cutting task [75,76].

Sometimes the scaling exponent between blank cutting edge length and mass is assumed to be 1/3, which implies that an increase in blank mass is analogous to an increase in volume (given that the raw material has a uniform density). For example, Stout et al. [77] adjust Braun and Harris' [12] equation with the form:

$$\textit{Cutting edge Length/Mass}^{1/3}$$

to account for the nonlinear relationship between cutting edge and mass. Similarly, Morgan et al. [78] use the form:

$$\textit{Cutting edge Length/Mass}^{1/3} * (1 - \exp[-0.31 * (\textit{Max Dimension} - 1.81)])$$

to also account for the influence of a blank's size on its cutting edge efficiency, rewarding blanks for having high cutting edge efficiency and penalizing them for being small. Stout et al. [77] found that these two equations were highly correlated and produced qualitatively similar results. Notably both equations specifically do use measurements of cutting edge length, rather than the entire perimeter of a blank.

Other times the scaling relationship assumed in cutting edge analyses is not between blank shape and mass. For example, Režek et al. [17] use the dimensionless form:

$$\textit{(Length*Width)/Thickness}^2.$$

In their analysis, blank volume is represented by blank thickness, which is "squared to bring its variance and the variance of blank surface area to the same scale" [17]. Like Mackay's [14] estimate, this approach is attractive for dealing with large data sets from multiple sites, as the measurements used to proxy blank surface area are easy to collect and extract from the literature. Also similar is the fact that Režek et al.'s [17] method uses a proxy for blank perimeter, instead of blank cutting edge length.

An alternative approach to those outlined above does not impose a particular scaling between variables, and instead discovers what the scaling is from the artifacts themselves. For example, blank cutting edge length and mass may be projected into a log-log Cartesian plane [e.g. 12,79]. Such an approach implies an allometric relationship between cutting edge length and mass [68] in the form of a power-law:

$$\text{Cutting edge} = \mu * \text{Mass}^{\beta}.$$

Here there are two free parameters: μ, the allometric coefficient; and β, the allometric exponent [80]; which characterize different aspects of cutting edge efficiency. Braun and Harris [12] hint at an allometric relationship between cutting edge length and mass, as "two measures of size that increase at different rates". The change in allometry presented by Braun and Harris [12: Figs 9 and 10] as an increase in cutting edge efficiency is illustrated here by panels C and C' in Fig 2. As we show in Fig 2, other variations in allometry, also indicating changes in cutting edge efficiency, are possible.

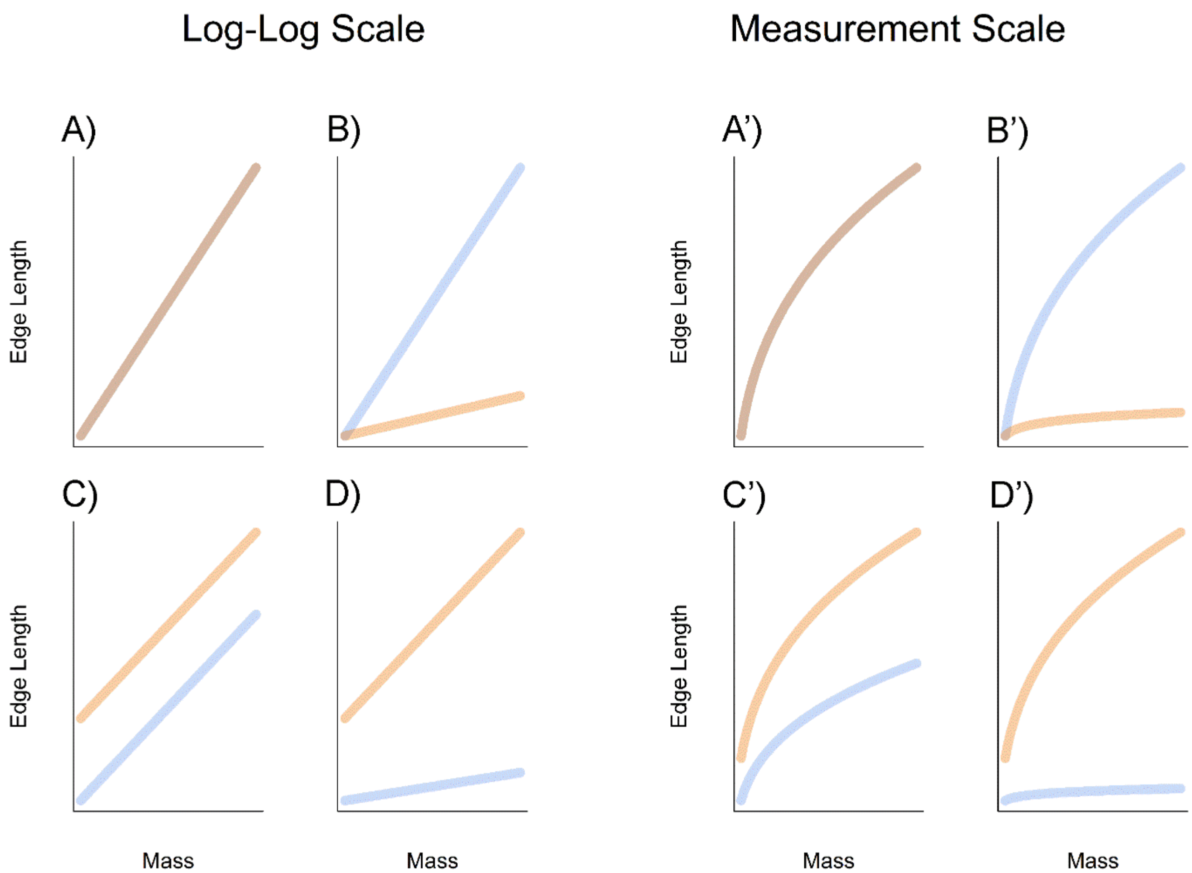

Fig 2. Variations in the allometric relationship between cutting edge length and mass in the measurement scale, expressed as differences in intercepts and/or slopes in the log-log scale. A and A') no differences in slopes or intercepts; B and B') different slopes with shared intercept; C and C') different intercepts with shared slope; D and D') slopes and intercepts both different.

With these details in mind, we adapted Braun and Harris' [12; see also 79] log-log approach into a statistical model (described below) to test for changes in cutting edge efficiency corresponding with the appearance of microblades at T17. We then compared the results with those of the more widely used methods published by Mackay [14] and Režek et al [17].

Materials and methods

Qualitative and quantitative data collection

Lithic data collected from the LU3 and LU2 sample assemblages for this study included: 1) blank completeness; 2) blank length, width, thickness, and mass; 3) blank production method and technique; 4) the presence or absence of retouch; and 5) cutting edge length [81]. All complete, unretouched blanks were included in this study given that incomplete or retouched blanks are missing part of their initial mass and cutting edge length. Complete blanks are defined here as those blanks that preserve a distal termination, mesial edges, and proximal portion including the platform. Blanks were not disqualified from our analysis due to their role within a reduction sequence, whether predetermined or predetermining [81], as any blank with a cutting edge could potentially have been used in a subsistence based cutting task [15,18,77,82]. The total sample consisted of 433 blanks from LU3, and 156 blanks from LU2 - including 10 microblades (Fig 3; Table A in Chapter S1). All artifacts studied are curated at the Institute of Archaeology branch of the Mongolian Academy of Sciences in Ulaanbaatar.

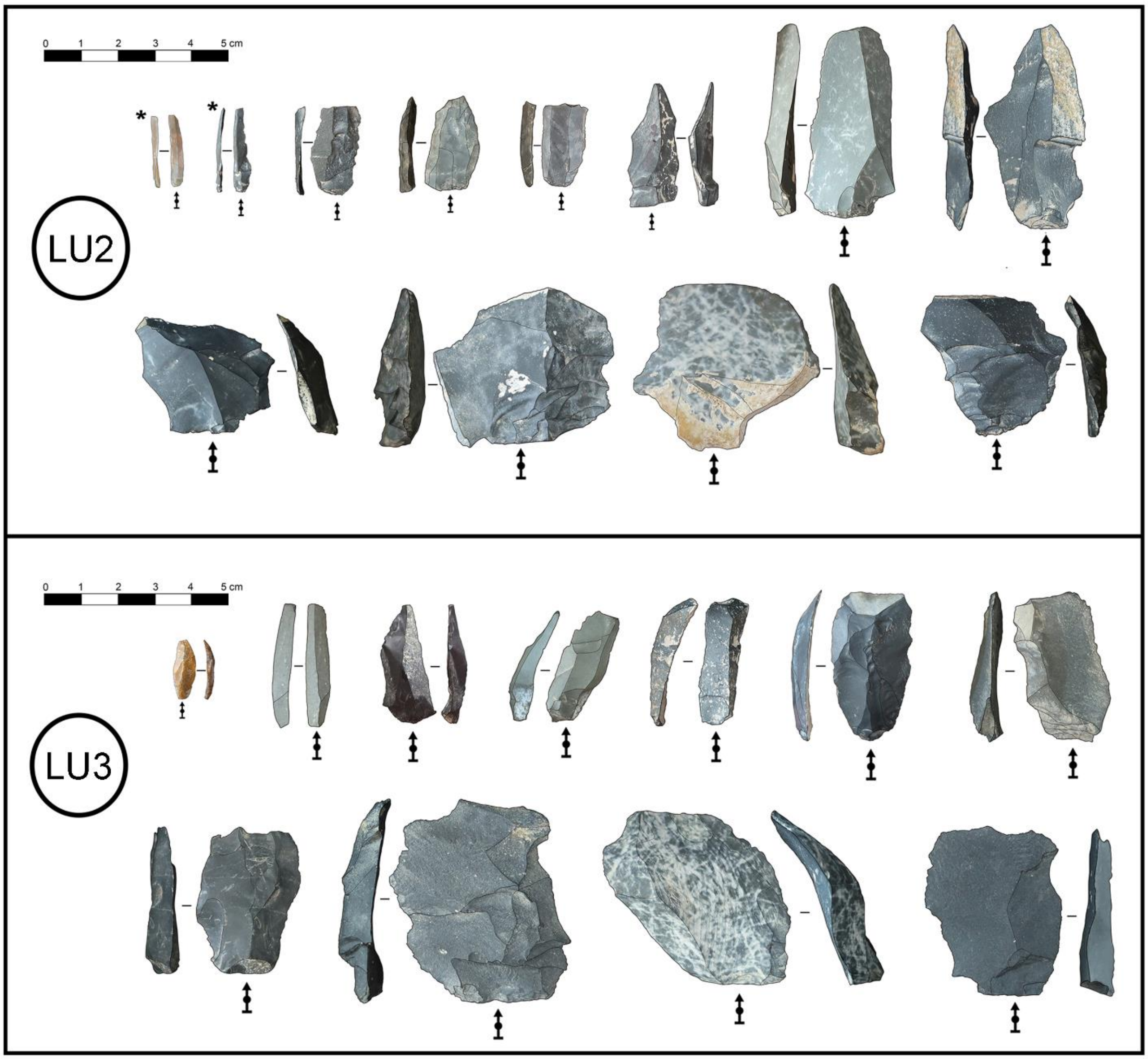

Fig 3. Examples of blanks from LU2 and LU3 used in the study. Asterix denotes microblades.

Metric data for the length and width of each blank were collected using the 'box method' as described by Dogandžić et al [68: Fig 3b], which records the length and width dimensions of a blank relative to its axis of percussion, or technological axis. These measurements also allow for a comparison of the results of our model as described below with the more commonly used methods of analyzing cutting edge efficiency developed by Mackay [14] and Režek et al. [17]. We note here that we risk tautological reasoning if we compare blank cutting edge efficiency across blank type categories defined by different length to width relationships, such as blades and flakes [81]. For example, idealized elliptically shaped blanks, having different length to width ratios, will have deterministically different perimeter lengths, and therefore potentially more cutting edge, per area (Fig 4). More elongated (i.e. blade-like) blanks will have greater perimeter per area than less elongated (i.e. flake-like) blanks [see also 26]. Naïve comparison of cutting edge length solely between blades and flakes may therefore fail to account for these "built in" differences. Some studies presumably combine all blank types in cutting edge analyses for this reason when more than one blank type exists in the sample [e.g. 14,17], and we also follow this approach here.

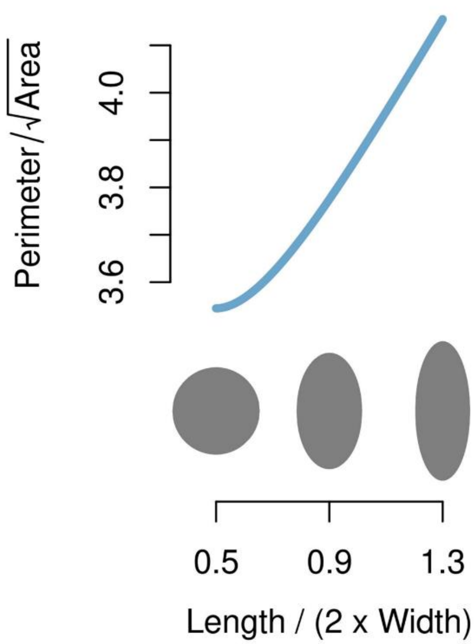

Fig 4. Relationship between the perimeter of an elliptical flake and the ratio Length / (2 x Width). The perimeter is given by Ramanujan's second approximation [83: equation 50] and is scaled by the square-root of the ellipse's area. The ellipses shown in grey have identical areas and correspond to Length / (2 x Width) ratios 0.5, 0.9, and 1.3 as depicted below the curve. The scaled perimeter increases as the ellipse becomes more elongated, suggesting greater cutting edge length per area for more blade-like blanks.

As in some studies [e.g. 25,77,78,84,85], but contra to others [10,12,14,17,69-74], our definition of cutting edge length only included the segments of a blank's perimeter that exhibit a sharp edge between its dorsal and ventral surface, that being an edge angle of <50° for blanks that are <40 mm, and an angle that that is <70° for blanks that are >40 mm. This definition of what constitutes a viable cutting edge is based on what has been experimentally observed as the threshold of a stone artifact edge to optimally cut through organic material [75,76].

All relevant data were collected into an E4-MSAccess database (oldstoneage.com). For metric data, a standard digital caliper, digital scale, and a metric sewing tape measure were used. The sewing tape measure was used to record the length of a blank's cutting edge to the nearest 5 mm to minimize precision error following the logic laid out by Dibble and Bernard [86].

Statistical modeling

We test for differences in cutting edge efficiency between the LU3 and LU2 lithic assemblages using a statistical model which compares all blanks within the two assemblages. We fit linear regression models for Log10 cutting edge length, the dependent variable, with Log10 mass and assemblage (LU3 or LU2) as independent variables, like Braun and Harris [12] and Braun [79]. A factorial 'Analysis of Covariance' model allows for the possibility that slopes and intercepts are unique for each group of blanks. Therefore, for blank *b*, in assemblage *a*, the model has the form:

$$\log_{10} \textit{Cutting edge Length}_{b,a} \sim \log_{10} \textit{Mass}_{b,a} * \textit{Assemblage}_{a} + \varepsilon_{b,a}. \quad (1)$$

Because heavier, and therefore larger, blanks offer the potential for greater variability in cutting edge length, we apply regression weights of the form:

$$w_{b,a} = 1/\log_{10} Mass_{b,a} \quad (2)$$

implying that the variance of ε is proportional to $\log_{10}$ *Mass* [87: Section 5.1.1].

Some complete, unretouched blanks included in this study did not have any segment of useful cutting edge and were consequentially recorded as having 0 mm of useful cutting edge length. Blanks with zero cutting edge length are shown in graphical displays but are not included in the statistical models because of their small sample size (n=10 across both assemblages) and unsuitability for log transformation. Larger numbers of blanks having zero cutting edge length could, in principle, allow for a model that compares both failure rate and cutting edge efficiency across levels [e.g. 88: the "Hurdle Model"].

For comparison with the statistical model, we also applied the approaches used by Mackay [14] and Režek et al. [17] to test for significant differences in cutting edge efficiency between the assemblages. In response to a reviewer's feedback, we carried out additional sensitivity checks to explore more fully the consequences of using direct or proxy measurements of blank cutting edge length, in combination with inferred or imposed allometry (Chapter S1).

Simulated microblade sample

Although the microblade sample from T17 is relatively small (n=10), the additional presence of diagnostic microblade fragments and microblade cores within the LU2 assemblage indicates that microblade production was one of the primary technological activities taking place on site. This potential recovery-bias of microblades at T17 may be due to several factors, including:

- The currently exposed area of the excavation relative to the true extent of the site, and the possibility of a structured use of space by its residents

- The preferential washing away of microblades during site formation due to their small size and light weight
- The preferential transport of microblades away from T17 by people living at the site for use elsewhere in and around the Tolbor Valley

For this reason, we simulated microblades for comparison with the non-microblade archaeological sample from T17. The simulations proceeded as follows: 1) we fit a log-log model of cutting edge length per unit of mass, similar to equations 1 and 2, to the archaeological microblade sample from LU2 (n=10); 2) we simulated microblade mass by generating Normally-distributed variables having a mean equal to the average of the observed microblade mass after log10 transformation; 3) we simulated cutting edge lengths for the virtual samples from the fitted microblade model; and 4) we varied the number of simulated microblades based on frequencies reported from three other sites in East Asia dating to the MIS 2.

The sites we used to inform our simulated microblade samples were selected to show three different scenarios of preservation frequency. To this end, we used the frequency of complete microblades and proximal fragments (which together represent a minimum number of individual artifacts) reported from: 1) Kovrizhka IV (Level 6; squares 21, 16, and 11) located in northern Cisbaikal, Russia (n=33) [89]; 2) Xishahe (Layer 3A) located in northern China (n=107) [90]; and 3) the Kashiwadai 1 site located in Hokkaido, Japan (n= 275) [91].

Data analysis was performed in R [92] with the addition of the libraries Epi [93] and Scales [94].

Results

Our statistical model found little difference in cutting edge efficiency between the lithic assemblages of LU3 and LU2 (Fig 5). Cutting edge length increases with blank mass in a predictable way in both samples, however a difference in cutting edge efficiency between the two levels, which would be indicated in the log-log plot by differences in intercepts, slopes, or both (Fig 2), is not supported. Though the LU2 central line is slightly above that for LU3, suggesting a slight increase in efficiency, their lines are closely spaced and parallel, and their confidence bands substantially overlap. A cone shaped scatter, widening as blank mass increases, affirms that the variance in cutting edge length also increases with blank mass.

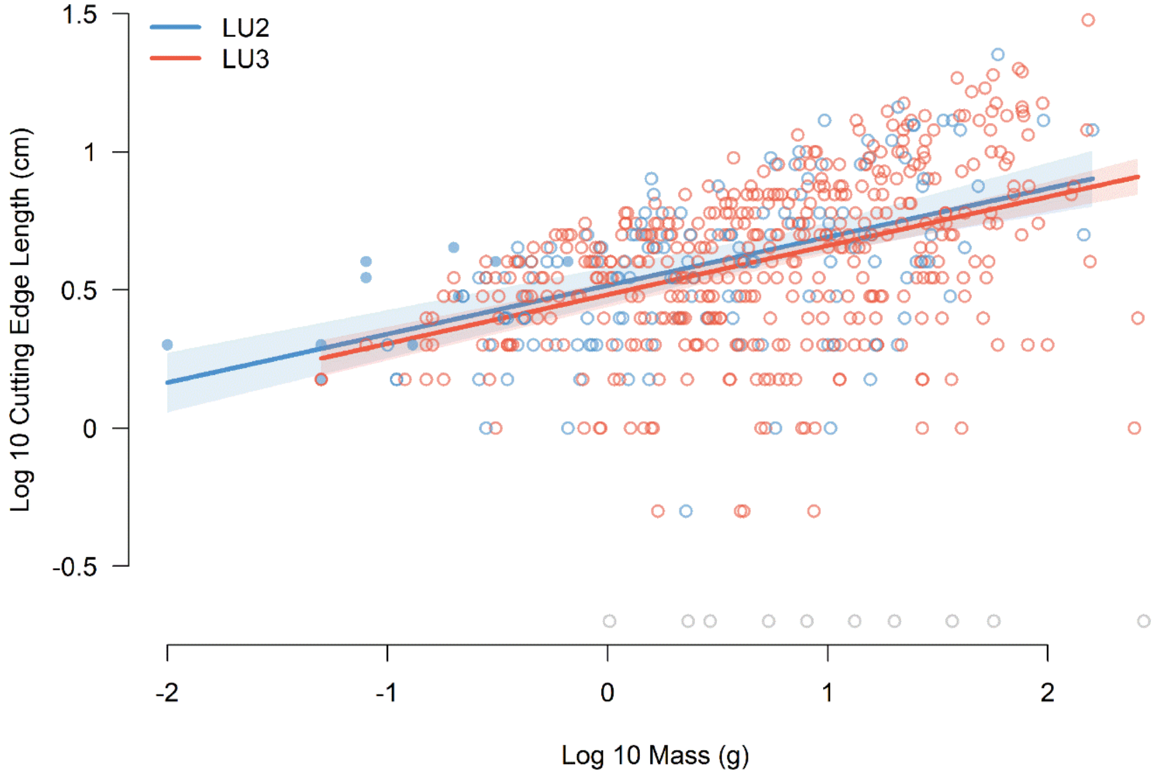

Fig 5. Graphical display of the fitted model comparing all complete blanks from LU3 and LU2.

Blanks with zero-cutting edge are shown in grey and are positioned along the lower edge of the scatter plot, just above their Log 10 mass. Microblades from LU2 are indicated by closed circles (●).

The estimated slopes from these models, reflecting the allometry exponents for the LU3 and LU2 samples [80], are typically less than 1/3. A slope of 1/3 is what would be expected from a purely geometric relationship of a blank's cutting edge (a linear measurement) with its mass (a volumetric measurement) [77,78]. The slopes for the LU2 and LU3 lines of central tendency are each 0.18, and neither of their 95% confidence intervals contains the value 1/3.

Comparisons of cutting edge efficiency based on variables published by Mackay [14] and Režek et al. [17] suggest significant differences between the LU3 and LU2 assemblages. A Wilcoxon ranked sum test based on Mackay's [14] equation using all blank types in each sample returns the test statistic $W = 40020$ and a p-value of <0.001 (Fig 6), indicating that the blanks in LU2 are more efficient than the blanks in LU3. Similarly, a Wilcoxon rank sum test based on Režek et al.'s [17] equation returns the test statistic $W = 38614$ and a p-value of <0.001 (Fig 7), also indicating that the blanks in LU2 are more efficient. We applied the rank sum test in both cases for standardization purposes, although a two sample t test is suggested originally by Mackay [14].

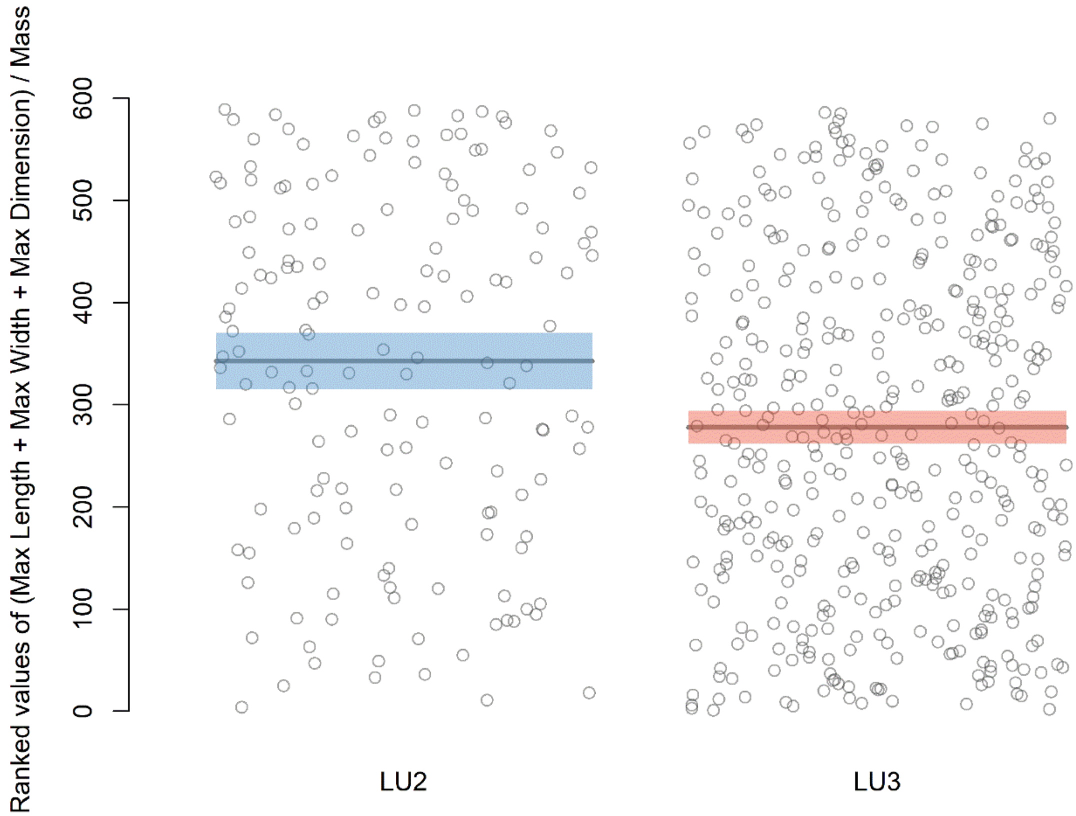

Fig 6. Graphical display of ranked values of the cutting edge efficiency statistic in Mackay [14] for each blank in the LU2 and LU3 assemblages. Means of ranked values are shown as horizontal lines, with shaded bands indicating two standard-error intervals around the means. Means and standard errors are shown here only for visualization purposes and do not reflect the calculation of the Wilcoxon statistic explicitly.

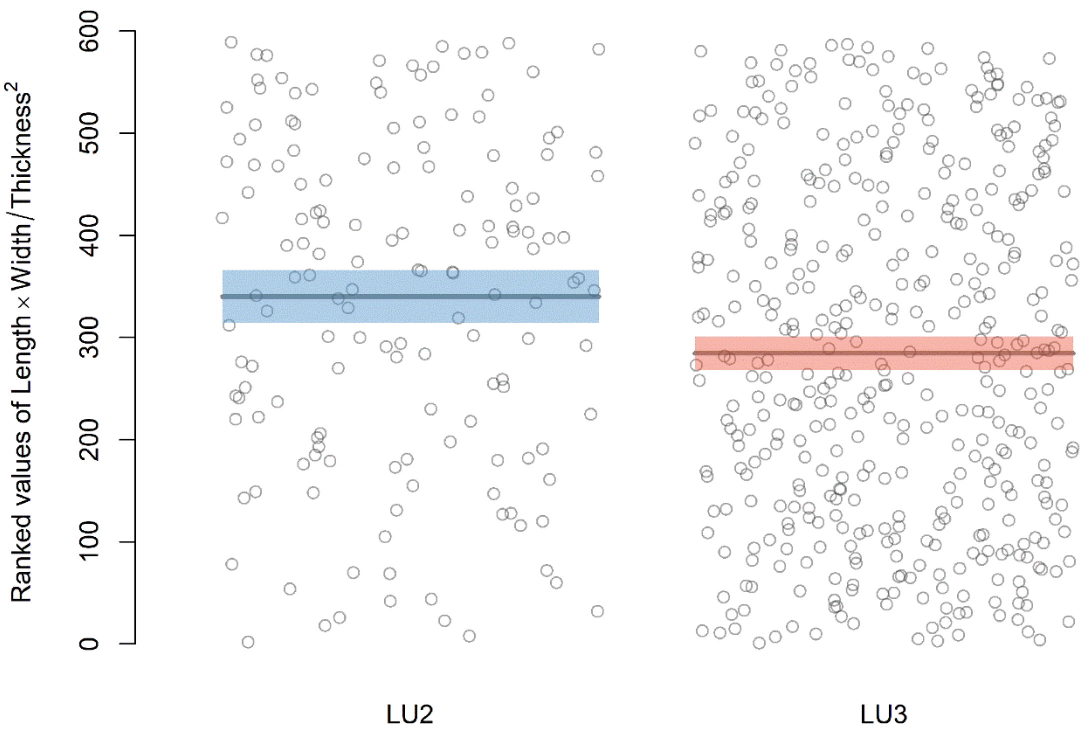

Fig 7. Graphical display of the ranked values of the cutting edge efficiency statistic in Režek et al. [17] for each blank in the LU2 and LU3 assemblages. Means of ranked values are shown as horizontal lines, with shaded bands indicating two standard-error intervals around the means. Means and standard errors are shown here only for visualization purposes and do not reflect the calculation of the Wilcoxon statistic explicitly.

Our sensitivity checks for proxied cutting edge length and inferred allometry are reported in the supplementary materials (Chapter S1). When proxied measurements for blank cutting edge length are used in a log-log model with blank mass as a predictor, allowing the allometry to be inferred, results are variable (Fig A in Chapter S1). Use of the Mackay proxy suggests a significant difference between the assemblages, while the Režek et al. proxy does not. When direct measurements for blank cutting edge length are used in equations that impose a certain allometry (Mackay [14], and Režek et al. [17], respectively), both methods suggest significant differences between assemblages (Figs B and C in Chapter S1).

Finally, when larger groups of microblades are simulated using data from LU2, we see them appear as a distinct population relative to the rest of the archaeological blanks (Fig 8). The cutting edge to mass ratios of these virtual microblades exceed those of the other archaeological blanks of similar size, indicating greater efficiency and a unique scaling of cutting edge to mass.

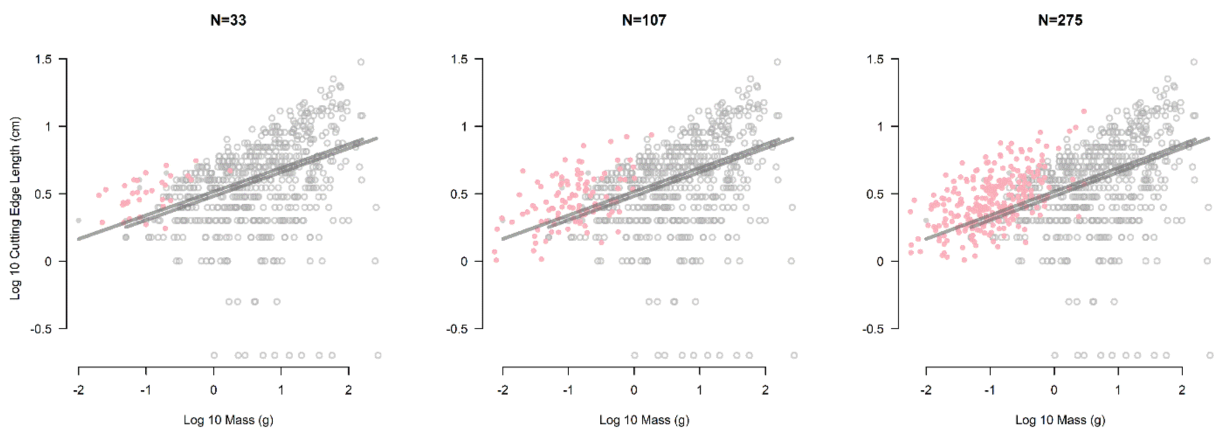

Fig 8. Graphical display of simulation experiments using microblade data from LU2. Simulated sample sizes displayed from left to right are based on microblade frequencies reported from Kovrizhka IV [89], Xishahe [90], and Kashiwadai 1 [91], respectively. In each display, simulated microblades are indicated by pink closed circles (●), and archaeological materials from LU3 and LU2 are shown in grey while following the conventions described in Fig 5. The lines of central tendency for LU2 and LU3 are shown in each panel unmodified from Fig 5: in particular, the central line for LU2 was not re-estimated for the simulated microblades.

Discussion

Scaling relationships matter

While the adoption of methods and techniques underlying microblade production during MIS 2 may have a been an adaptation to selective pressures which in part favored increasing blank standardization [27] and cutting edge efficiency [17,18,28,44], our primary model finds little archaeological evidence for the latter at T17 (Fig 5). Our approach uses two free parameters which characterize cutting edge efficiency [12] (Fig 2). This characterization does not assume a particular scaling relationship between cutting edge length and mass, but instead discovers what the scaling is from the lithics. This is crucial, as the results of our simulations suggest that microblades have a different scaling relationship between cutting edge length and mass than blanks made using percussion techniques (Fig 8) - likely due to the influence that pressure techniques have on blank shape and size [27-29].

Our sensitivity checks found that proxied measurements for cutting edge length following Mackay [14] and Režek et al. [17], substituted for direct measures in our primary model (equation 1), yield conflicting results regarding differences between LU3 and LU2 (Table 1; Fig A in Chapter S1). While it may be tempting to suggest that proxy measurements perform reasonably well, at least in some cases, on principle direct measurements of cutting edge length should be used whenever possible. Finally, we note that proxy measurements of blank cutting edge length are not able to identify blanks which have edges which are too dull to perform a cutting task.

Table 1. Sensitivity of results to different combinations of: 1) the method of cutting edge length measurement (direct, and proxy [14,17]); and 2) statistical approaches that infer, or impose [14,17], allometry between blank edge length and size.

Allometric relationship between blank edge length and size

Measurement of edge length	Inferred	Imposed
Direct	Difference between LU2 and LU3 not supported (**Fig 5**)	LU2 and LU3 significantly different (**Figs B and C in S1 File**)
Proxy	Mackay: LU2 and LU3 significantly different (**Fig A.A in S1 File**) Režek et al.: Difference between LU2 and LU3 not supported (**Fig A.B in S1 File**)	LU2 and LU3 significantly different (**Figs 6 and 7**)

While the primary model found no statistical difference in cutting edge efficiency between the LU3 and LU2 samples, methods which assume particular scaling relationships did (Figs 6 and 7). The latter findings hold whether direct or proxied measurements of cutting edge length are used (Table 1; Figs B and C in Chapter S1). Additionally, we did not find an allometry exponent of 1/3 in our model for either assemblage, implied in other analyses [77,78]. Until we can better understand the cause(s) of these discrepancies we caution against making assumptions about how cutting edge length scales with mass, as doing so will have consequences for accurately characterizing blank cutting edge efficiency when comparing archaeological assemblages that contain blanks of various morphologies (Chapter S1) [see also 68].

At first glance our results seem to subvert expectations of a continuing trend of increasing cutting edge efficiency during the Upper Paleolithic related to the development of novel methods of lithic miniaturization and the use of pressure techniques [16-18,27-29,44]. However, they might be better understood as an example of the increased variability around this parameter also observed during the Late Pleistocene [17]. From this perspective the situation at T17 may be that, within the environmental contexts of the region, selective pressures did not specifically favor technological behaviors which increased cutting edge efficiency at the assemblage level between the EUP and LUP. The appearance of microblade technologies at T17 may therefore reflect selective pressures on other inter-related parameters of technological evolutionary efficiency, such as raw material selection, artifact maintenance, artifact standardization, or artifact transportability [17,27,28].

Assemblage level assumptions

Yet, the apparent fact that cutting edge efficiency did not change at the assemblage level with the adoption of microblade technology at T17 does not necessarily mean that selection pressures on increasing this parameter of efficiency were absent. Selection pressures need not always result in adaptation of the entire lithic assemblage, instead only affecting the efficiency of certain blanks within a reduction system. For example, the development of microblades may be due to selective pressures which favored their improved cutting edge efficiency, yet the impact this had at the assemblage level may be offset by the presence of relatively less efficient technical blanks needed to shape and maintain microblade cores [41,42].

Such a scenario invites a reevaluation of the basic assumptions of blank cutting edge analyses - particularly whether cutting edge efficiency at the assemblage level is a meaningful measure of change in the adaptive behaviors of Plio-Pleistocene hominins. While this may be the case when each blank in a reduction sequence is an end-product, made with the intention of being used in a cutting task [e.g. 12,77], it may not be so for technological systems involving the production of different types of predetermining and predetermined blanks. For example, a core reduction system adapted to produce a blank of a specific shape and size, with a relatively higher cutting edge efficiency, may be equally or even less efficient as other, more generic core reduction systems when all blanks, including byproducts, from each system are considered together [e.g. 16,26].

Without knowing which blanks from a production system were made for cutting tasks, and which were merely byproducts of predetermination or retouch/recycling, our ability to reconstruct the economy of hominin behavior surrounding blank cutting edge production and measure its efficiency is severely limited. Compounding this issue is the fact that most lithic assemblages are palimpsests, in which blanks from numerous different reduction systems are mixed and fragmented via selection for retouch or recycling and/or transportation away from the site. The potential impact of site function and artifact transport on the frequency of blank preservation within an assemblage and its influence on archaeological measures of cutting edge efficiency at T17 is of particular interest.

Interpreting microblade frequency

Although we see a new blank production technology appear at T17 during MIS 2, which perhaps had a more efficient scaling of cutting edge length to mass (Fig 8), the way that the technology was utilized at the site does not seem to have significantly increased the efficiency of the assemblage it was a part of (Fig 5). However, our simulations also suggest that if microblades were discarded at T17 at a frequency seen at other MIS 2 microblade sites in East Asia, a significant increase in cutting edge efficiency would likely be observable at the assemblage level [see also 18 where bladelet frequency seems to echo cutting edge efficiency]. This could mean that microblade technologies might have indeed appeared at T17 in a context where cutting edge efficiency was under selection pressure at the assemblage level, but preservation biases prevent us from observing this. In such a scenario where microblade production was adopted due to the fitness benefit it provided when made at a high enough frequency, how might we explain the preservation of only a handful of complete microblades within the LU2 assemblage?

One explanation may be site excavation extent. As the area excavated at T17 is currently only ca. 18 m^2, the studied sample likely captures only a small part of the total site. The possibility of site structuring, where some spaces of the site may have been preferentially used for microblade related activities, could also mean that evidence for microblade production may be better represented in areas which have not yet been systematically excavated. Future field work will be able to better test this scenario.

A potential recovery bias of microblades at T17 may also be explained by taphonomic processes. Because of their small size, microblades may have been preferentially transported away from the site during erosional, or sheet washing events. However, the preservation of microblades alongside other small artifacts including small flakes, bladelets, lithic fragments, ostrich eggshell beads, etc. suggest that the site is largely *in situ*.

Lastly, site function and preferential artifact transport are possible explanations for recovery bias of microblades at T17. Though microblades could be used in hand for cutting tasks, or as standardized interchangeable tenons for composite cutting tools used in domestic activities on site [48], they also may have been inserted into the mortises of composite hunting weapons used outside of the site [27,44,45,49-51]. In the latter case, these hunting weapons, and the easily transportable microblade cores used to furnish them [46-48,51], would have often been carried away from T17 during logistical hunting forays, meaning a large portion of the production, use, and discard of microblades by people living at the site may have taken place away from the excavated area [95].

To recap, three scenarios concerning the appearance of microblades at T17, and the relationship of this event to parameters of cutting edge efficiency, could have affected our findings. In the first scenario, the lack of difference in efficiency observed at the assemblage level may indicate that the appearance of microblades at the site was not facilitated by selection pressure on increasing cutting edge production, but perhaps on other parameters of lithic evolutionary efficiency and standardization [17,27]. In the second, we posited that selection pressures may have favored the appearance of microblade technology for its cutting edge efficiency, but the assumption that fitness related changes in efficiency are only meaningful at the assemblage level limits our ability to detect them. Lastly, we considered a scenario where the appearance of microblades at T17 was facilitated by selection pressure on increasing cutting edge efficiency at the assemblage level, but preservation bias of microblades related to artifact recovery, site formation, and/or site function also prevents us from detecting this.

While we see no reason to favor any one of these three scenarios over the others, we do think their consideration can help improve future studies of lithic technological change. Investigations that make fewer assumptions about 1) lithic scaling relationships; and 2) how changes in efficiency manifest in the archaeological record, will strengthen regional diachronic studies like ours [e.g. 18], as well as larger-scale diachronic and synchronic studies [e.g. 17]. Human evolutionary history can be characterized as a story about behavioral flexibility. To be able to make sense of the paleoanthropological record, our methods likely need to be flexible as well.

Conclusions

We adapted an approach for analyzing blank cutting edge efficiency which does not make assumptions about the scaling relationship between cutting edge length and mass, but instead discovers what their scaling is from the lithics. We used this approach to test if cutting edge efficiency increased within the Upper Paleolithic record of Tolbor-17 between periods before and after the introduction of microblade technology to the site. Our model found no statistical difference in cutting edge efficiency between the two assemblages, yet more conventional methods which assume a particular scaling did. A signature of improved cutting edge efficiency between the two levels is only observed within our model when microblade frequencies are artificially increased via simulation. Our results highlight the importance of properly identifying scaling relationships underlying blank cutting edge efficiency, and questions current assumptions about how changes in cutting edge efficiency are most dependably detected within the lithic archaeological record.

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Chapter S1: Analyzing blank cutting edge efficiency associated with the adoption of microblade technology: a case study from Tolbor 17, Mongolia

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Supplementary Information for Chapter 2

1. **Assemblage demographics**
2. **Sensitivity to statistical approach**

Assemblage demographics

The number of blanks in the LU2 and LU3 samples and an initial technological categorization made by one of the authors (CLJ) during cutting edge length data collection can be found in the table below (Table A). Blades, bladelets, microblades, and laminar flakes - which show some evidence of being part of blade and bladelet debitage but lack some defining criteria of blades and bladelets [1] - together make up a sizable component of the LU2 (ca. 46%) and LU3 (ca. 30%) samples. Technical blanks with some connection to the production of blades, bladelets and microblades – such as core tablets, crest flakes, outrepassé flakes, debordant blanks, and decortication blanks (blade crests are included in the blade, bladelet, and microblade counts) – make up a small portion of the assemblage, particularly in LU2. Nondescript flakes are the dominate single blank category in both assemblages, with ca. 35% and 47% of all blanks falling under this category in LU2 and LU3, respectively. The low background frequency of preferential flakes such as Kombewa and bifacial thinning flakes, as well as Levallois and non-preferential pseudo-Levallois types likely represent an incidental aspect of the debitage which took place at the site.

Table A. Number of blanks in the LU2 and LU3 samples by blank type.

Blank Type	**LU2**	**LU3**	**Total**
Laminar Flake	30	64	94
Blade	22	27	49
Bladelet	10	39	49
Microblade	10	0	10
Crest Flake	0	2	2
Core Tablet	0	10	10
Outrepassé	3	5	8
Decortication	6	31	37
Debordant	11	18	29
Nondescript Flake	55	204	259
Levallois	2	7	9
Pseudo-Levallois	4	17	21
Kombewa	3	7	10
Bifacial thinning flake	0	2	2
Total	156	433	**589**

Sensitivity to statistical approach

To check the sensitivity of our results to different statistical methods, we contrasted direct or proxy measurements of cutting edge length, in combination with approaches that infer or impose allometry, as in a factorial experiment. The primary analysis in the Chapter 2 uses direct measurements of blank cutting edge length in a model that infers the allometric relationship between cutting edge length and mass to draw conclusion about differences in cutting edge efficiency between levels. For comparative purposes, Chapter 2 also reports analyses, based on the work of Mackay [2] and Režek et al. [3], which use proxy measure of cutting edge length and a statistical test that imposes allometric relationships. At a Reviewer's suggestion we here generate results from the remaining factorial combinations: 1) proxied measures of cutting edge length with inferred allometry; and 2) direct measures of cutting edge length with imposed allometry. Although the proxy measurements can be made even when there is no useful segment of cutting edge length, for standardization purposes these follow up analyses were performed on the same sample used in Chapter 2 (i.e., only blanks with more the 0mm of cutting edge length).

First, we employ a regression model as described by equations 1 and 2 in the Material and Methods section of Chapter 2, though substituting the proxy measurements for perimeter length outlined by Mackay [2] and Režek et al. [3] in place of direct measurement of cutting edge length (Fig A). When the Mackay proxy is used (Fig A.A) there is a slight separation between the confidence bands for the two levels, which can be observed for the smallest blanks, including some microblades (i.e., those blanks less than ca. 0.03g based on the log10 scale). This suggests a difference in cutting edge efficiency between the two levels for blanks of this size. When the Režek et al. proxy is used (Fig A.B) no difference between the levels is observable, as for the primary analysis shown in Fig 5 of Chapter 2.

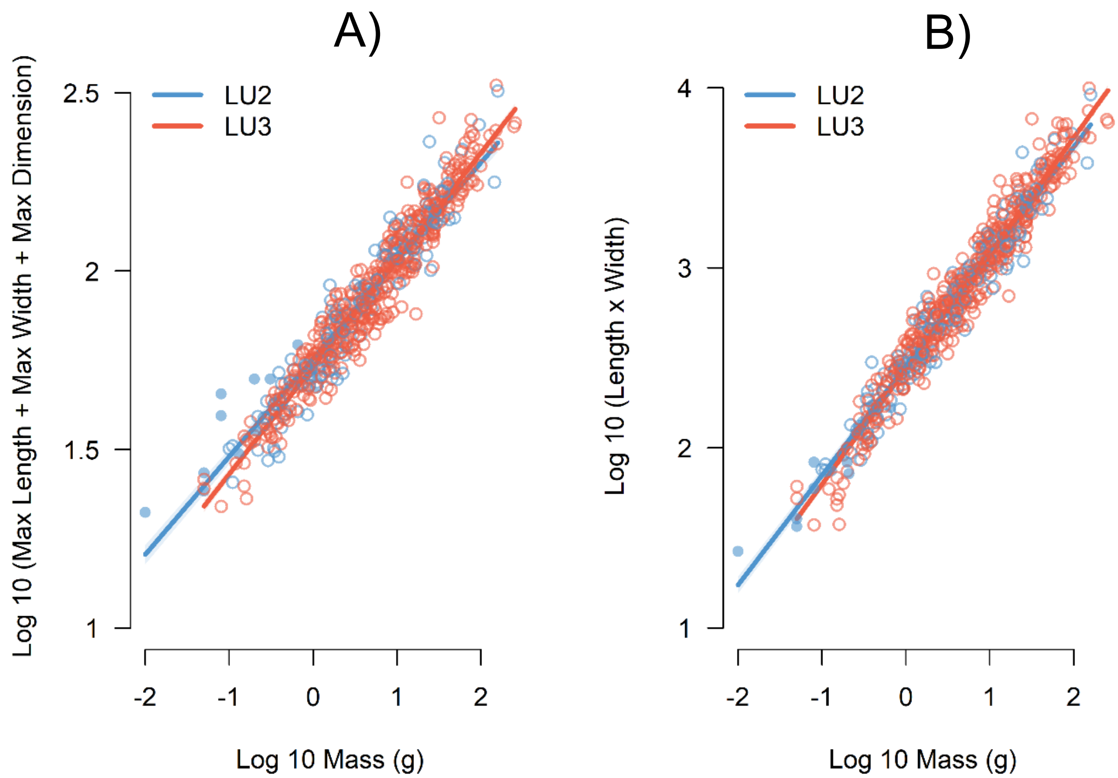

Fig A. Graphical display of the fitted model comparing all complete blanks from LU3 and LU2 using proxy measurement data for cutting edge length. A) Mackay [2] cutting edge length estimate; **B)** Režek et al. [3] cutting edge length estimate. Microblades from LU2 are indicated by closed circles (●).

Moving on to methods that use direct measures of cutting edge length with imposed allometry, we used the blank cutting edge length observations reported in Chapter 2 in the numerator of the Mackay [2] and Režek et al [3] equations, respectively, accepting the implied forms of allometry. We apply Wilcoxon rank sum tests in both cases for comparability (Fig B and C). In both cases significant differences between the levels are suggested (Mackay: $W = 40146$, $p < 0.001$; Režek et al.: $W = 40775$, $p < 0.001$) echoing results obtained when using the methods as originally described (Fig 6 and 7 in Chapter 2).

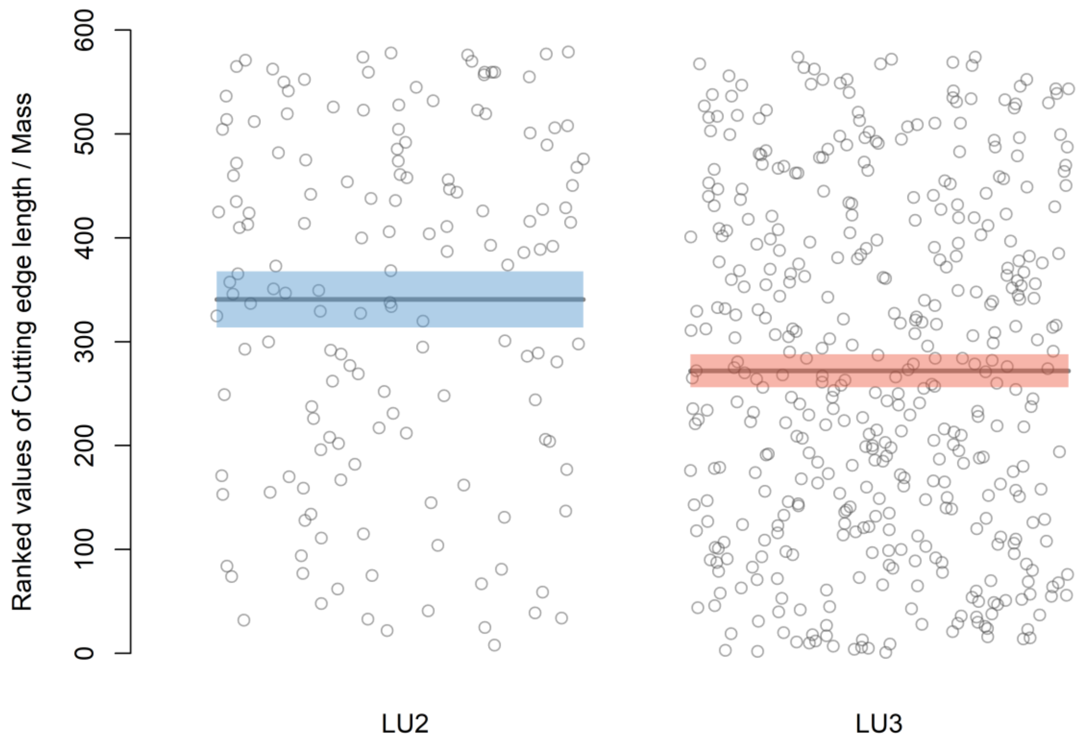

Fig B. Graphical display of ranked values of the cutting edge efficiency statistic in Mackay [2], substituting direct measures of cutting edge length for proxy measures. Means of ranked values are shown as horizontal lines, with shaded bands indicating two standard-error intervals around the means. Means and standard errors are shown here only for visualization purposes and do not reflect the calculation of the Wilcoxon statistic explicitly.

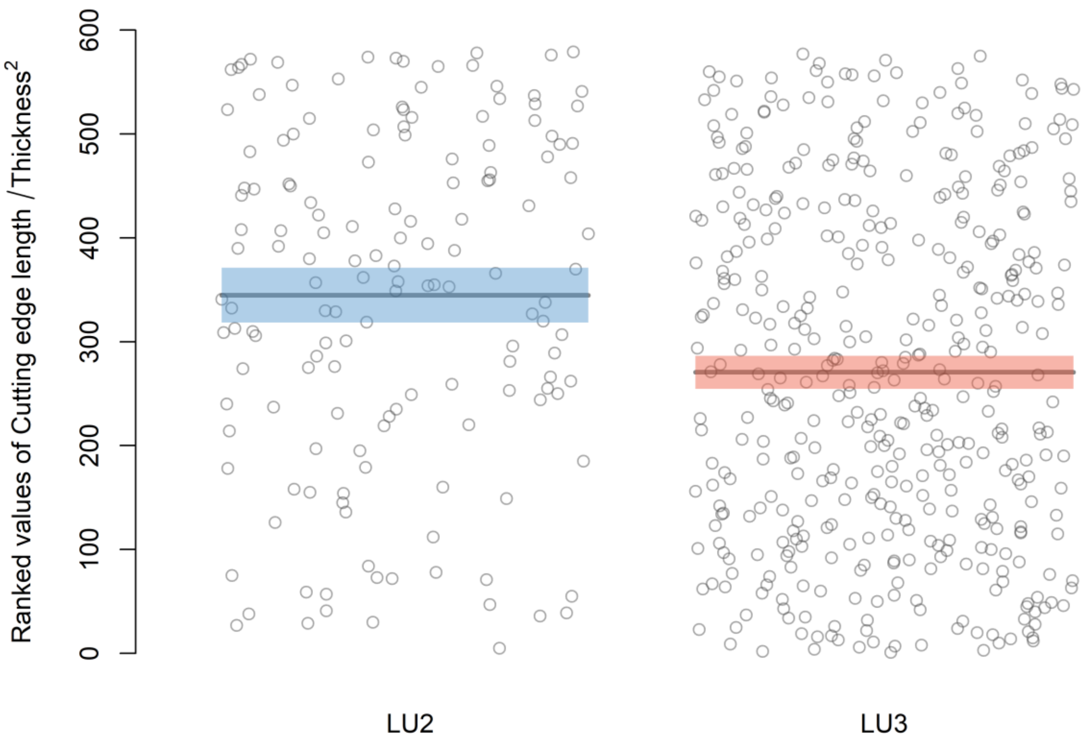

Fig C. Graphical display of ranked values of the cutting edge efficiency statistic in Režek et al [3], substituting direct measures of cutting edge length for proxy measures. Means of ranked values are shown as horizontal lines, with shaded bands indicating two standard-error intervals around the means. Means and standard errors are shown here only for visualization purposes and do not reflect the calculation of the Wilcoxon statistic explicitly.

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Chapter 3: Increases in small blank cutting edge efficiency during the Upper Paleolithic at Tolbor, Mongolia

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Abstract

The shift from large blade production towards an emphasis on bladelets, and later microblades, during the Upper Paleolithic in East Asia denote two major events of lithic miniaturization thought to underly the success and continuity of *Homo sapiens* in the region. Lithic miniaturization is generally thought to have been driven by selection pressures on stone artifact standardization and interchangeability as part of complex composite tools. Here we model a related parameter, blank cutting edge efficiency, from four lithic assemblages recently excavated from the Tolbor Valley in northern Mongolia which document both Initial-to-Early and Early-to-Late Upper Paleolithic technological turnovers. Our results indicate a gradual, or delayed, increase in small blank cutting edge efficiency coinciding with the Early Upper Paleolithic. Notably, both bladelets and small flakes contributed to this pattern. A second increase in cutting edge efficiency is implied by the unique allometry of Late Upper Paleolithic microblades. Our results demonstrate Upper Paleolithic blank cutting edge efficiency at Tolbor developed in a manner echoing the tempo and mode observed from some regions of Europe and West Asia.

Main

The eastward expansion of *Homo sapiens* populations into northern East Asia from North-Central Asia ca. 45 ka coincided with the arrival and development of novel Upper Paleolithic technological and symbolic behaviors [1-15], as well as genetic introgression from Denisovans [16-19]. One of the main archaeological localities which documents the arrival of the Upper Paleolithic in East Asia is the Tolbor Valley of northern Mongolia - named after the Tolbor River (*Ikh-Tolborin-Gol*) which flows northwest from the foothills of the Khangai Mountains and into the Selenge River basin (Fig 1). The Paleolithic archaeological record at Tolbor generally consists of three stages of techno-cultural development, beginning with the Initial Upper Paleolithic (IUP) [4,7,9,10], followed by the Early Upper Paleolithic (EUP) [14,20-23], and finally the Late Upper Paleolithic (LUP) [22,23]. Technologically, the shift from the IUP to the EUP in the valley involved an increased emphasis on systematic bladelet production [21-23], as opposed to large blades made from asymmetrical, volumetric cores typical of the Asian IUP [5,8-10,13,23,24]. Subsequently, the shift to the LUP involved the inclusion of pressure produced microblades into lithic toolkits [22,23], a technology which is often characterized as being even smaller, thinner, and more standardized in shape and size than their bladelet counterparts [25,26].

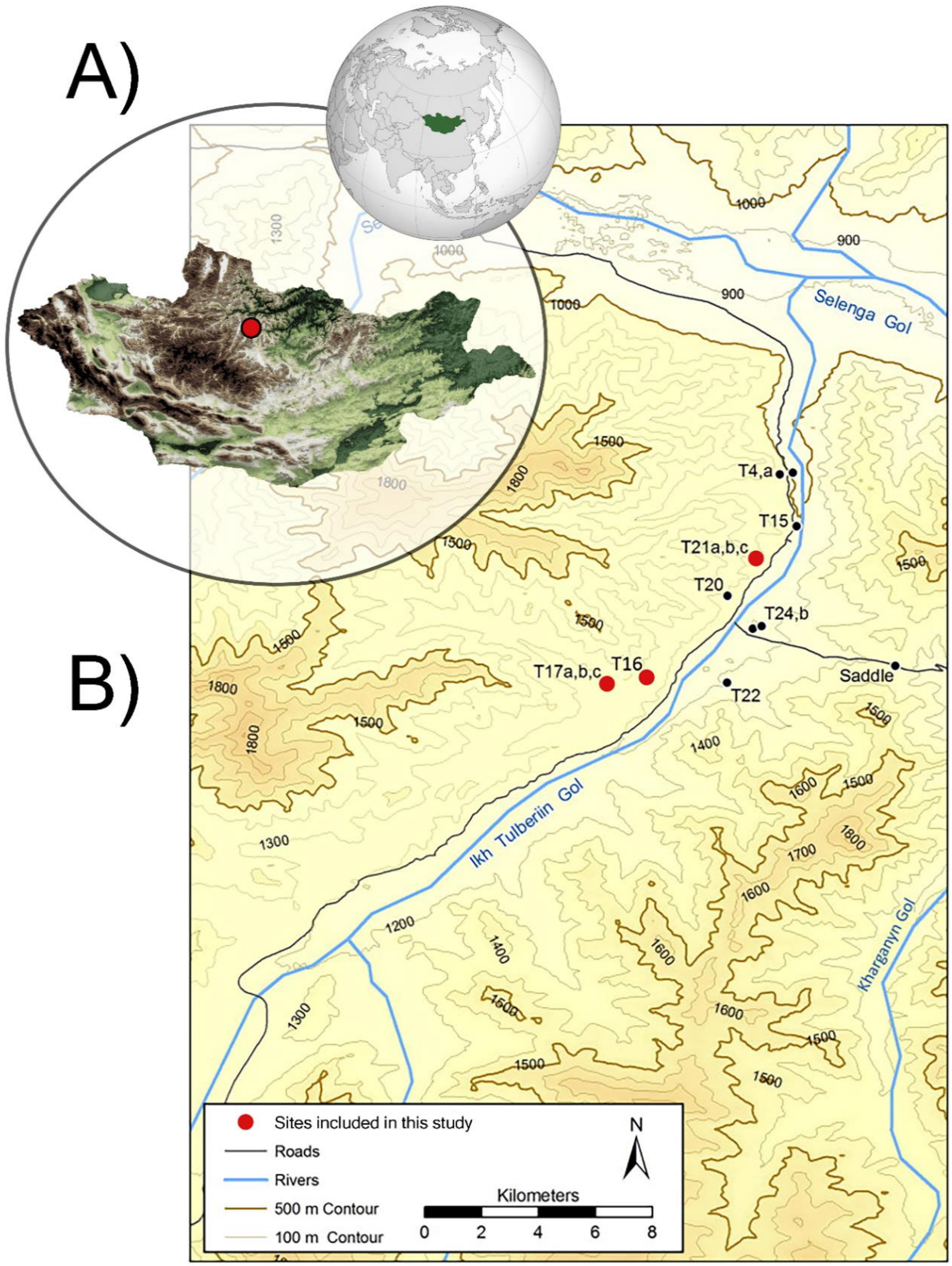

Fig 1. Map of the sites in the Tolbor Valley included in this study. A) Location of the Tolbor Valley in Mongolia. **B)** Location of the sites included in this study. Modified after Zwyns et al. [7].

This diachronic trend observed at Tolbor, of increasingly standardized 'blanks' (a generic term for flakes, blades, bladelets, and microblades) and decreasing blank size, is indicative of a global phenomenon of lithic miniaturization (aka microlithization) widely documented in the Late Pleistocene archaeological records of Africa and Eurasia [26-38]. The evidence for blank miniaturization in different regions is difficult to broadly interpret, as it is characterized by high variability in both systems of manufacture and use, as well as timing of appearance [25-38]. Nonetheless, decreasing blank size is thought to have generally been a solution for improving artifact standardization, being that variation in blank shape has been shown to decrease as blank size decreases [26]. Increased standardization is in turn thought to have been driven by selection pressures on improving the performance of artifacts as interchangeable tips for hafting, or as inserts which could be fit into the mortises of composite cutting tools and hunting weapons [25-39] (Fig 2). The development of pressure techniques for Upper Paleolithic blade and microblade production are also thought to have been driven by a need to increase blank standardization [26,40,41], as such techniques generally provided greater control over key parameters underlying blank formation [40-43]. In the archaeological records of Europe and West Asia, lithic miniaturization is most visible within Upper Paleolithic contexts [25-29,31,32,34-36,38,39; but see 37], where the phenomenon is also notably associated with an increase in blank cutting edge efficiency [44,45].

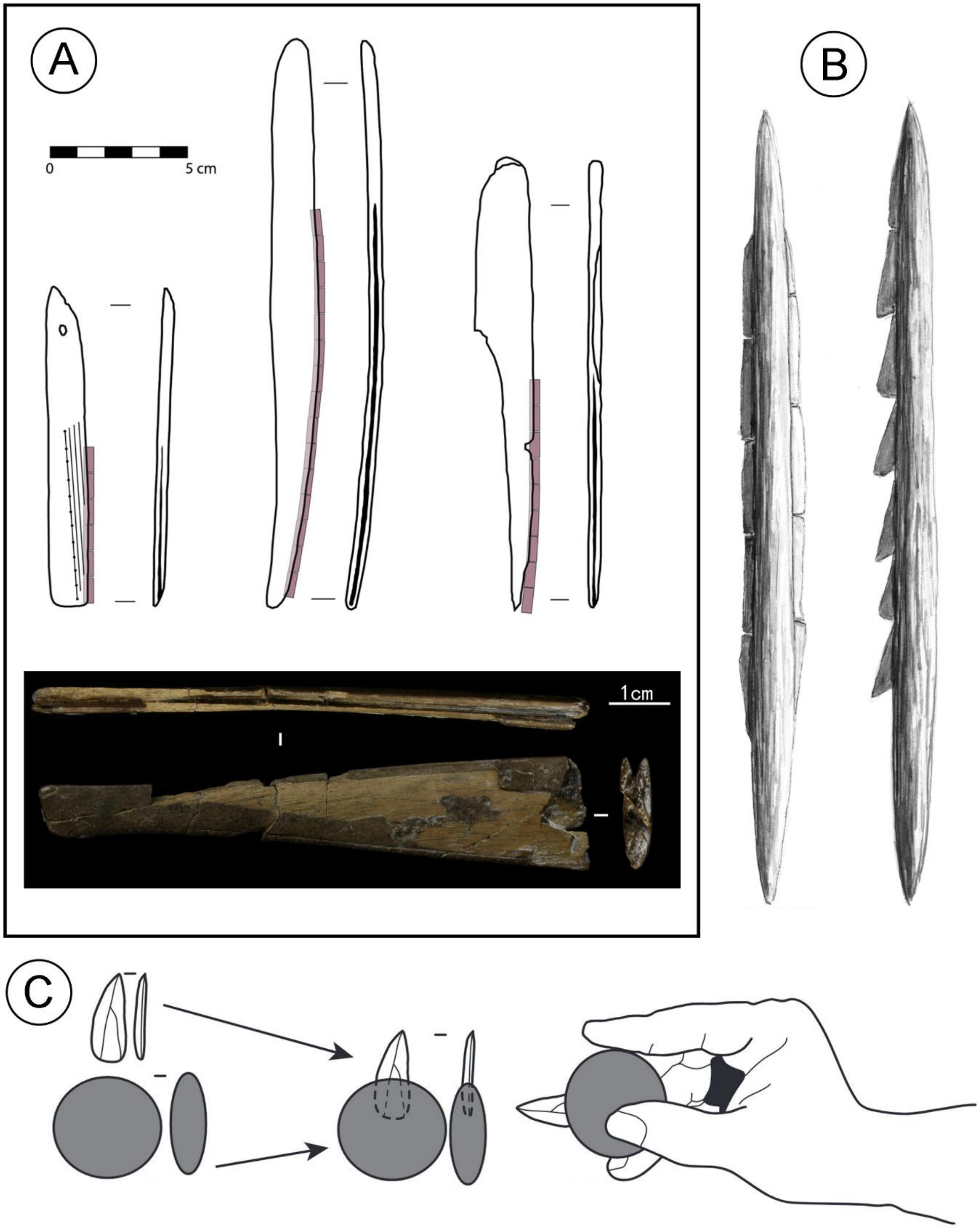

Fig 2. Archaeological composite tools, and hypothetical composite tool configurations related to the hafting and use of miniature lithic blanks. Modified after: A) Yi et al. [39]; B) Kuhn and Shimelmitz [26]; C) Pargeter and Shae [27].

Blank cutting edge efficiency is a complementary lithic parameter related to blank shape and mass, with underlying fitness implications regarding the subsistence of Paleolithic toolmakers and tool users [e.g. 22,44-52]. Essentially a measure of the amount of sharp edge per unit of mass, blank cutting edge efficiency reflects the economization of lithic raw material consumed by toolmakers to produce artifacts that could perform subsistence based cutting tasks - such as extracting edible and non-edible animal and plant tissues, or manufacturing artifacts made of bone, ivory, and wood. Blank cutting edge efficiency has been shown to have gradually increased in both measure and variation over the course of the Pleistocene in different regions [22,44-46,49,51], peaking in Europe and West Asia during the Upper Paleolithic in association with *Homo sapiens* [44,45,51]. Surprisingly [22: Fig 2], this pattern does not seem to have been driven by methods of blade production that became commonplace during the onset of the Upper Paleolithic [47,48,51], but by the subsequent surge in the production of smaller bladelet formats and the use of pressure techniques for blank production [22,40,44,45,51].

Here we test if lithic miniaturization during the Upper Paleolithic in East Asia was also paralleled by an increase in blank cutting edge efficiency at the sub-regional scale. Specifically, we apply a statistical model to a diachronic IUP, EUP, and LUP dataset excavated from a 10 km^2 locality within the Tolbor Valley [7,10,21,22]. We first make comparisons between all unretouched, complete blanks regardless of blank type, and then compare within laminar and non-laminar blank categories (Methods). Our IUP sample comes from the site of T16 (AH6, Pit 4), which dates to ca. 45 ka [7,10]. The EUP is sampled from two sites: T21 (AH4, Pit 2), and T17 (LU3) - with the T21 assemblage dating to ca. 42 ka and T17-LU3 dating to ca. 35 ka [21,22]. Finally, the LUP is also sampled from T17 (LU2) and dates to MIS 2 [22]. Each assemblage was recently excavated by collaborative field teams following modern day archaeological standards and similar field protocols (Methods).

Results

When blank cutting edge length is modeled against blank mass for all artifacts within each lithic assemblage included in our analysis, we detect a clear diachronic improvement in cutting edge efficiency between the IUP and the later phase of the EUP at Tolbor (Fig 3). The separation between the central tendencies and confidence bands for the T16 and T17-LU3 assemblages, respectively, with their lithic observations superimposed, indicates cutting edge efficiency increased from the former period to the latter [22]. However, while this increase is detectable at the assemblage level it is only illustrated by smaller sized blanks within the two assemblages (i.e., those less than 5 g based on the log10 scale). No such difference is observable between the IUP from T16 and the early EUP, represented here by T21. The central tendencies for T16 and T21 are sub-parallel, and their confidence bands overlap across the entire mass range for blanks within each assemblage. This proximity means that T17-LU3 also differs from T21 in much the same way that it differs from T16, but the separation between confidence bands for the two EUP assemblages is narrower, with a difference only illustrated for the very lightest flakes and bladelets (i.e., those less than 1 g based on the log10 scale). Finally, the central line for the LUP assemblage, T17-LU2, is slightly above and parallel with that of T17-LU3 with their confidence bands overlapping across the entire mass range for blanks. This illustrates that the smaller LUP flakes, blades, bladelets and microblades were also made more efficiently in terms of cutting edge length than their IUP and early EUP counterparts – yet they differed little from blanks of any size made during the later phase of the EUP.

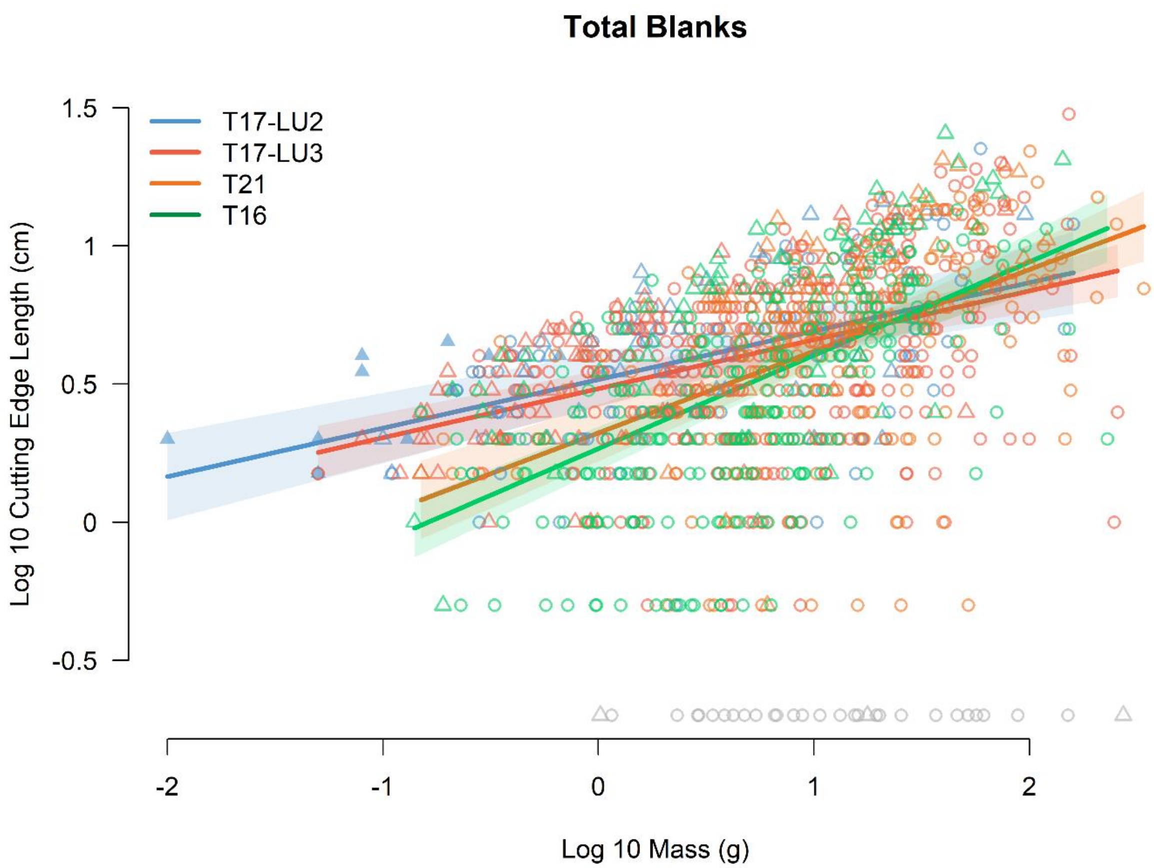

Figure 3. Fitted model comparing all complete blanks from each Tolbor assemblage. Non-laminar blanks are indicated by open circles (○), laminar blanks are indicated by open triangles (△), and microblades are indicated by solid triangles (▲). Blanks with zero-cutting edge are shown in grey. The null model assuming a common intercept and slope for all assemblages can be rejected (F=15.6 on 6 and 1146 degrees of freedom, p<2.2x10-16).

When blank cutting edge efficiency is modeled within laminar and non-laminar blank type categories (Methods) the general pattern described above is not observed (Fig 4). For the laminar blank category (which excludes microblades due to their unique scaling relationship between cutting edge length and mass [22]), the slopes and intercepts of the central lines of each assemblage differs from every other, but the confidence bands for each assemblage pair also overlap across the entire range of blank mass. This indicates little difference in cutting edge efficiency between the assemblages for laminar blanks.

We do observe a separation between the confidence bands of the T17-LU3 and T16 assemblages for medium to small sized non-laminar blanks (i.e., those less than 10 g based on the log10 scale), indicating greater cutting edge efficiency of these blanks within this size class during the later EUP compared to the IUP (Fig 4). The confidence bands for the T17-LU3 and T21 assemblages, however, substantially overlap across the range of blank mass, suggesting little difference in terms of non-laminar blank cutting edge efficiency between the early and later EUP at Tolbor. Not surprisingly, the early EUP and IUP confidence bands also overlap substantially suggesting little difference in efficiency. Finally, the confidence band for the LUP from T17-LU2 also shows separation from that of the T16 assemblage, indicating that medium to small LUP non-laminar blanks were also more efficient compared to their IUP counterparts. These LUP blanks, however, overlap with both EUP assemblages, indicating little difference between these periods.

We note that these comparisons in our model between assemblages within blank types involved fewer artifacts, and therefore have greater uncertainty as illustrated by the wider confidence bands.

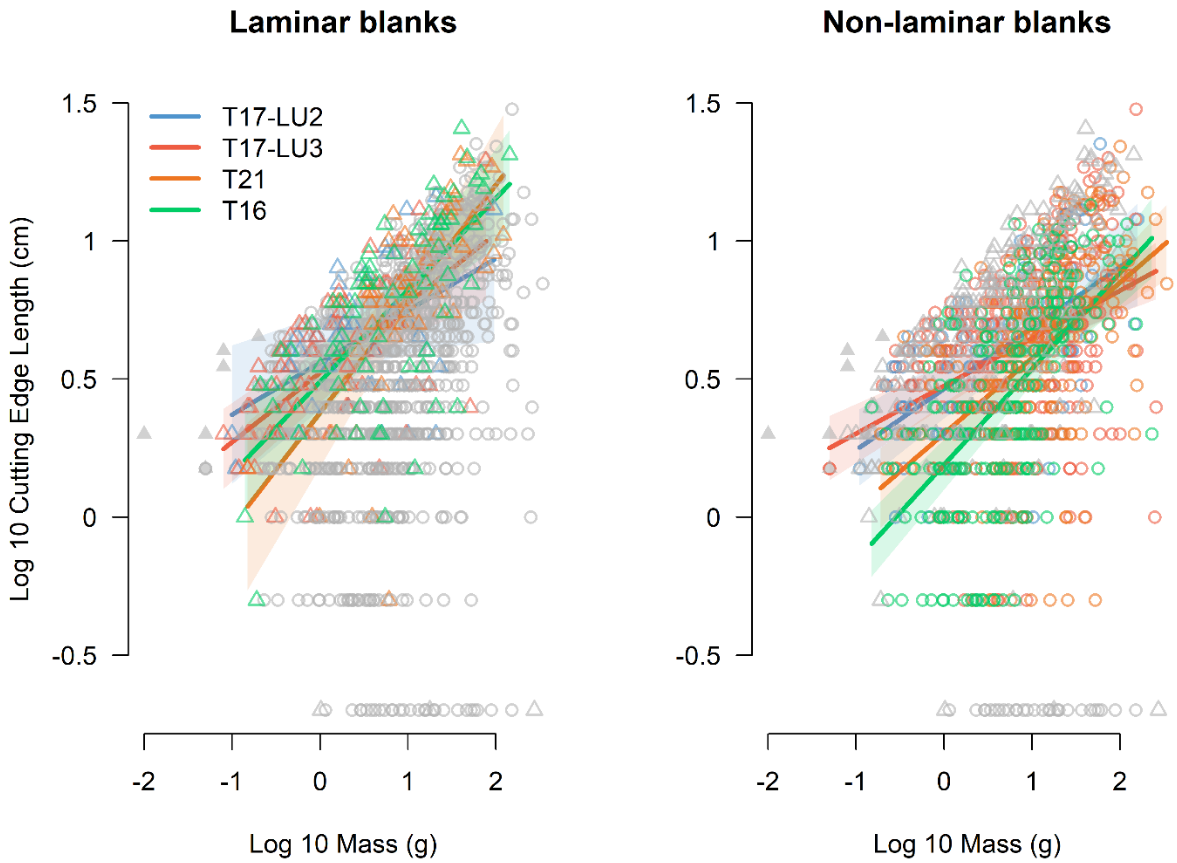

Figure 4. Fitted model comparing all complete blanks from each Tolbor assemblage separated by blank type. For each model only those blanks of the corresponding type are shown in color. Symbol conventions follow those described in Figure 3. The null model assuming a common intercept and slope for all assemblages for each given blank type can be rejected ($F=9.1$ on 12 and 1128 degrees of freedom, $p<2.2\times10^{-16}$).

Discussion

Our results indicate that blank cutting edge efficiency increased at Tolbor during the later phase of the EUP, ca. 35 ka, mostly in association with the smaller flake, blade, and bladelet component of lithic toolkits made in the valley (Figs 3 and 4). These findings provide additional archaeological support for the existence of a trend of improving blank cutting edge efficiency associated with the Upper Paleolithic in Eurasia. Previous experimental programs have suggested that while the emergence of various lithic blade technologies may not have involved a significant increase in cutting edge efficiency at the assemblage level compared to some methods of flake production [47,48,51, though see 40], the general shift from the Middle to the Upper Paleolithic did likely involve such an increase [44,45,51]. These experimental observations have been specifically validated by Režek et al's analysis of archaeological lithic assemblages from Western Eurasia spanning the Pleistocene, which suggests that blank cutting edge efficiency peaked during the last 50 ka, coinciding with the expansion and development of Upper Paleolithic technologies [44]. Even more specifically, Kadowaki et al's recent analysis of the transition from the Middle to Upper Paleolithic in the Hisma Basin of Jordan suggests that blank cutting edge efficiency did not initially improve during the shift from the Middle Paleolithic to the IUP, but instead with the increased production of bladelets and other small blanks made during the EUP and Epipaleolithic [45]. This 'delayed' increase in Upper Paleolithic blank cutting edge efficiency observed in West Asia is interpreted as stemming from the large volume and mass of individual Middle Paleolithic and IUP flakes and blades - useful for the provisioning of highly mobile persons, but relatively inefficient in terms of cutting edge utility [45]. During the EUP and beyond it is suggested that Paleolithic processes of lithic miniaturization aimed at increasing blank standardization and cutting edge efficiency [26,44,45] were also part of an economic strategy of provisioning *places* rather than individuals, as observed from the higher density of archaeological features within sites and changes in patterns of raw material procurement [45].

Our model suggests that the increase in small blank cutting edge efficiency observed from the IUP to the EUP at Tolbor was either more gradual, variable, or perhaps even further delayed than that observed in the west. The earliest stage of the EUP at Tolbor, currently represented by the AH4 assemblage from T21, shows little difference in cutting edge efficiency compared to that of the IUP from T16. Only during a later stage of the EUP, represented by the LU3 assemblage from T17, is an increase in small blank cutting edge efficiency observed in our model. Therefore, if T21 does indeed represent the earliest expression of the EUP at Tolbor then our results suggest that for some reason EUP blank cutting edge efficiency did not substantially increase until after the cold and dry period of Heinrich Event 4, which marked the disappearance of the IUP in the valley [10]. As observed by Kadowaki et al. [45], this delayed increase in EUP cutting edge efficiency at Tolbor may be explained by differences in the frequency of small blank production between assemblages. In the case of Tolbor this may also be a possibility, as there are almost five times as many blanks that weigh <1 g from the T17-LU3 sample than from the T21 sample, and almost two times as many than there are from the T16 sample - which is the range of blank mass where we observe most of the separations between confidence bands for the assemblages within our model (Figs 3). This size range also unsurprisingly contains most of the blanks technologically classified as bladelets within our dataset.

Another key similarity between the trends observed at Tolbor and Hisma is that the diachronic increase in blank cutting edge efficiency observed from the IUP to the EUP seems to have been driven by an "accumulating effect" of both small laminar and non-laminar blanks [45]. In our study, even though the null hypothesis for the "Blank Type" model (2: Methods) can be rejected (Fig 4), we do not observe a clear visual indicator regarding either blank type's individual contribution to the differences observed within the "Total Blanks" model (1: Methods), where a difference between T21 and the two T17 assemblages can be observed (Fig 3). Conversely, a unique feature of the Upper Paleolithic sequence at Tolbor not observed in the western record is the presence of LUP microblades which appear in the valley around MIS 2 [22,23]. Characterized by pressure techniques of small blank production [25,26,42], microblade technologies became widely adopted across East Asia and North-Central Asia during the glacial period of MIS 2 [25,26,28,39]. The application of pressure techniques allowed Upper Paleolithic toolmakers to produce thinner, narrower, more standardized blanks [25,26,42]. Previous analysis of the T17-LU3 and LU2 dataset also suggests that microblades had a more efficient scaling of cutting edge length to mass than their soft and hard hammer counterparts [22]. Nonetheless, within T17-LU2 both microblades and bladelets are found, suggesting that while the two classes of blank may have played unique or complimentary technological roles in the toolkits of LUP toolmakers and users at Tolbor, the presence of microblades did not preclude the production of bladelets in the valley.

In conclusion, our results from Tolbor seem to externally validate those obtained from sites in Europe and the Levant which suggest that blank cutting edge efficiency significantly increased across the Upper Paleolithic *senso lato* with the development of novel small laminar blank technologies, such as bladelets and microblades [44,45]. However, we note here that methods used in most studies concerning blank cutting edge efficiency of lithic assemblages at times use proxy measurements of cutting edge length or make assumptions about the scaling relationships between blank cutting edge length and mass, which can have consequences for accurately characterizing blank cutting edge efficiency when comparing lithic assemblages that contain various blank morphologies [22,50]. Nonetheless, the similarities and differences between studies such as these encourages the investigation of changes in blank cutting edge efficiency as a means for understanding dynamic processes underlying lithic development, such as the miniaturization of lithic technology, in different regions within and outside of Eurasia - for example the Middle and Later Stone Age record of sub-Saharan Africa [27,30,33,49]. Additionally, the IUP in East Asia coexisted with, and was succeeded by, a variety of lithic technologies which show little affinity with the Upper Paleolithic [11,53,54]. Future research aimed at measuring and comparing parameters of lithic evolutionary efficiency [44], such as blank cutting edge efficiency, within these “core-and-flake” assemblages [11,53,54] may help further reveal the underlying cause of the technological variation observed during MIS 3 and MIS 2 in East Asia as members of our species began arriving on the scene.

Methods

Paleolithic assemblages in the Tolbor Valley analyzed in this study.

For this study of blank cutting edge efficiency, we sampled four Upper Paleolithic artifact assemblages from three open air sites in the Tolbor Valley of northern Mongolia. Archaeological field work in Mongolia was conducted with permission from the local authorities and in collaboration with local researchers. All artifacts studied are curated at the Institute of Archaeology branch of the Mongolian Academy of Sciences in Ulaanbaatar.

Since the 1970s, systematic surveys have led to the discovery of ca. 40 Paleolithic localities in the Tolbor valley and adjacent valleys. Most artefact concentrations at Tolbor have been identified along the Western flanks of the valley and referred to as "sites". The first full-scale excavation took place between 2004 and 2007 at the stratified site of Tolbor-4 [4]. The project was led by members of the Institute of Archaeology and Ethnography, Siberian Branch of the Russian Academy of Science, and the Mongolian Institute of Archaeology. Seasonal field work in the region has been regularly taking place ever since. The four lithic assemblages analyzed in this study are from recent and ongoing excavations at the respective sites, each of which employ modern archaeological field methods [7,10,14,21,23]. The sample studied here consists of one Initial Upper Paleolithic (IUP) assemblage from Tolbor-16 (T16), two Early Upper Paleolithic (EUP) assemblages - one from Tolbor-21 (T21) and one from lithological unit 3 (LU3) of Tolbor-17 (T17) - and one Late Upper Paleolithic (LUP) assemblage from LU2 at T17. This sample is suitable for the purposes of this study as all assemblages are found within 10 km's of one another, meaning they were situated in very similar environmental settings regarding the availability and quality of raw materials (a blackish, greenish cryptocrystalline mudstone) and other natural resources.

Tolbor 16: T16 (N49°13'62", E102 55'38") [7,10] is an open air site that sits at the mouth of a small canyon in the Tolbor Valley which facilitated sediment accumulation through a complex interplay of colluviation, eolian deposition, and solifluction. The Tolbor 16 site was discovered in 2010 by S. A. Gladyshev and A. V. Tabarev [7]. Systematic excavation first took place at T16 from 2011 to 2016 and consisted of five pits (Pits 1-5) aimed at archaeological and geoarchaeological investigation. During each stage of excavation all archaeological material >2 cm was piece plotted, and all excavated sediment was dry sieved using 4 mm and 2 mm mesh screens. Pits 1 and 4 are the largest excavated areas, whereas Pits 2, 3 and 5 are smaller trenches that provide stratigraphic and chronological control. For our study we exclusively sampled archaeological material from Pit 4. Like most sites in the valley, the deposit at T16 consists of loess, reworked loess and soliflucted laminar silt, with gravel and cobbles. Sedimentological data indicate a low-energy depositional environment. In most of the exposed sections at T16, the stratigraphy is divided into three main lithological units: the Holocene soil complex (unit 1), an underlying layer of loess and reworked loess (unit 2), and a soliflucted diamict of laminar silt with gravel and cobbles (unit 3). In Pit 4, at least five superposed solifluction lobes were identified within unit 3 (sub-units 3a, 3b, 3c, 3d, and 3e). Archaeological material is restricted to the upper 2 m of the section and is present in units 1 and 2 and in solifluction lobes 3a, b and c. Six archaeological horizons (AH1-6) were identified within the three major stratigraphic units at Pit 4. The IUP assemblage derives from AH6, which lies in subunit 3c in Pit 4, and is techno-typologically typical of the Asian variant of the IUP (Figs 5-7). Three geochronological methods (polymineral post-IR IRSL, Quartz OSL and radiocarbon) were used to determine the antiquity of the assemblages at T16. For radiocarbon, bone samples from AH2 through AH6 in Pits 1 and 4 were collected to obtain radiocarbon dates on fauna tightly associated with the archaeological deposits. The results indicate LU2 is constrained to MIS 2 and that AH3 and AH5 (subunits 3a and 3b) date between to 35.1–38.5 ka. The IUP material associated with AH6 dates to 42.5–45.6 ka (Fig 8). The high organic matter content of sediments associated with AH6 is consistent with a period of milder, relatively moist climate at the time of the occupation(s). Deterioration in climatic conditions followed the deposition of AH6; an episode of solifluction, which takes place together with a reduction in colluviation, the formation of a thick carbonate crust in Pit 1, and a possible episode of loess accumulation in Pit 4, are evidence for increased cold and aridity. Faunal analysis and use of Zooarchaeology by Mass Spectrometry (ZooMS) indicate the occurrence of *Bos* sp., Caprinae and *Equus* sp., *Felid* sp. and Elephantidea. *Bos* sp. is associated with human occupation in solifluction lobes 3a trough 3c. Most of these taxa are common in a Pleistocene open steppe or a taiga environment but they also occur northward, in sites where tundra environments predominate (e.g. Transbaikal). According to a pollen record from the region, steppe and taiga environments alternate during the cold and warm climate fluctuations in the MIS 3.

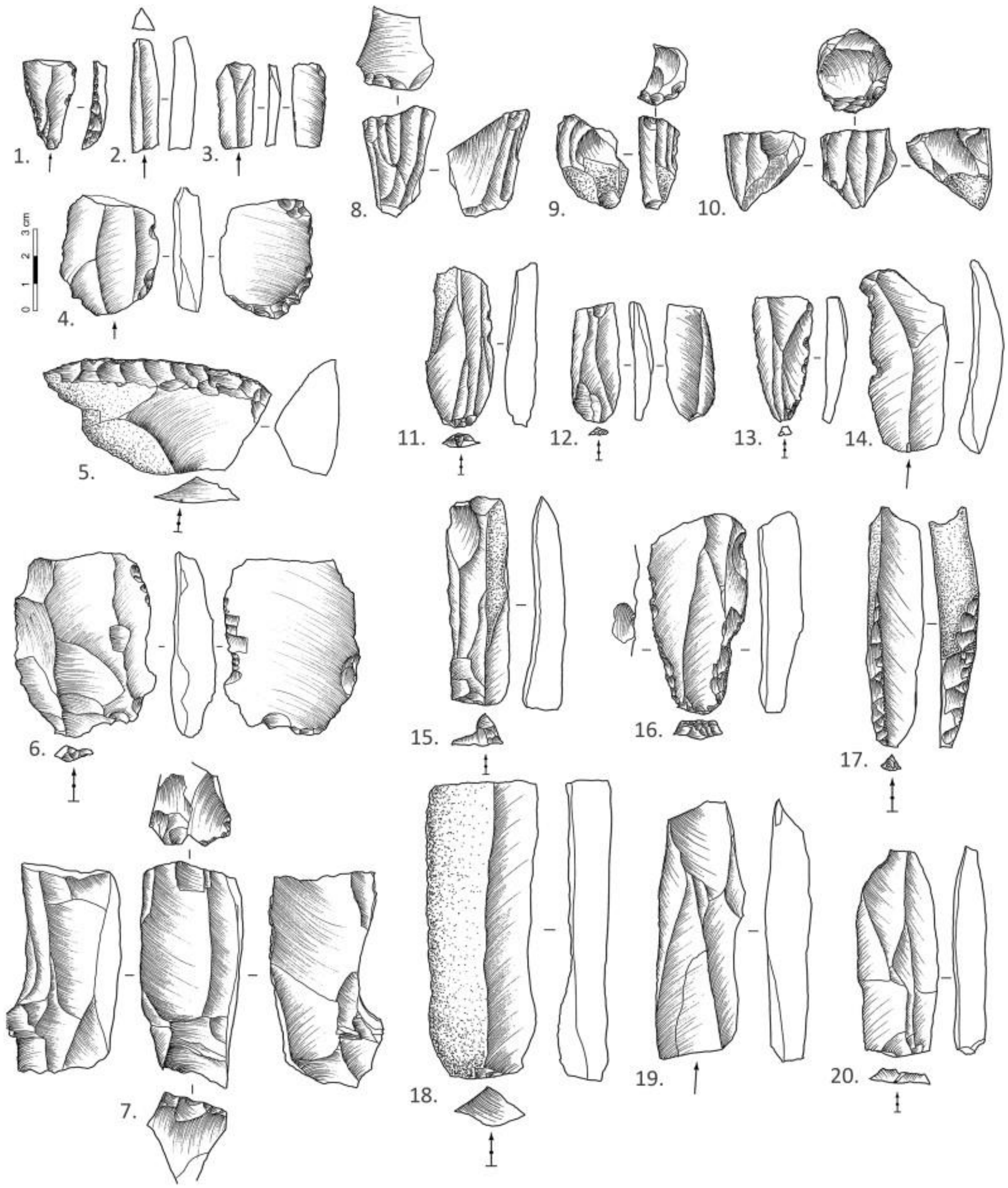

Fig 5. Example of lithics from AH 4/5 and AH 6 (drawings by Dogandžić and Zwyns). 1. Blade with proximal retouch. 2–3, Small laminar blanks, 4. Blanks with inverse proximal retouch, 5. Transversal convex scraper. 6, Flake with orthogonal dorsal pattern, 7. Blade core, 8–10. Bladelet cores. 11–13, Blades with platform bludgering and trimming. 14–16, 19–20. Blade with bidirectional dorsal pattern. 17. Neo-crested blade, 18. Large cortical blade. After Zwyns et al. [7].

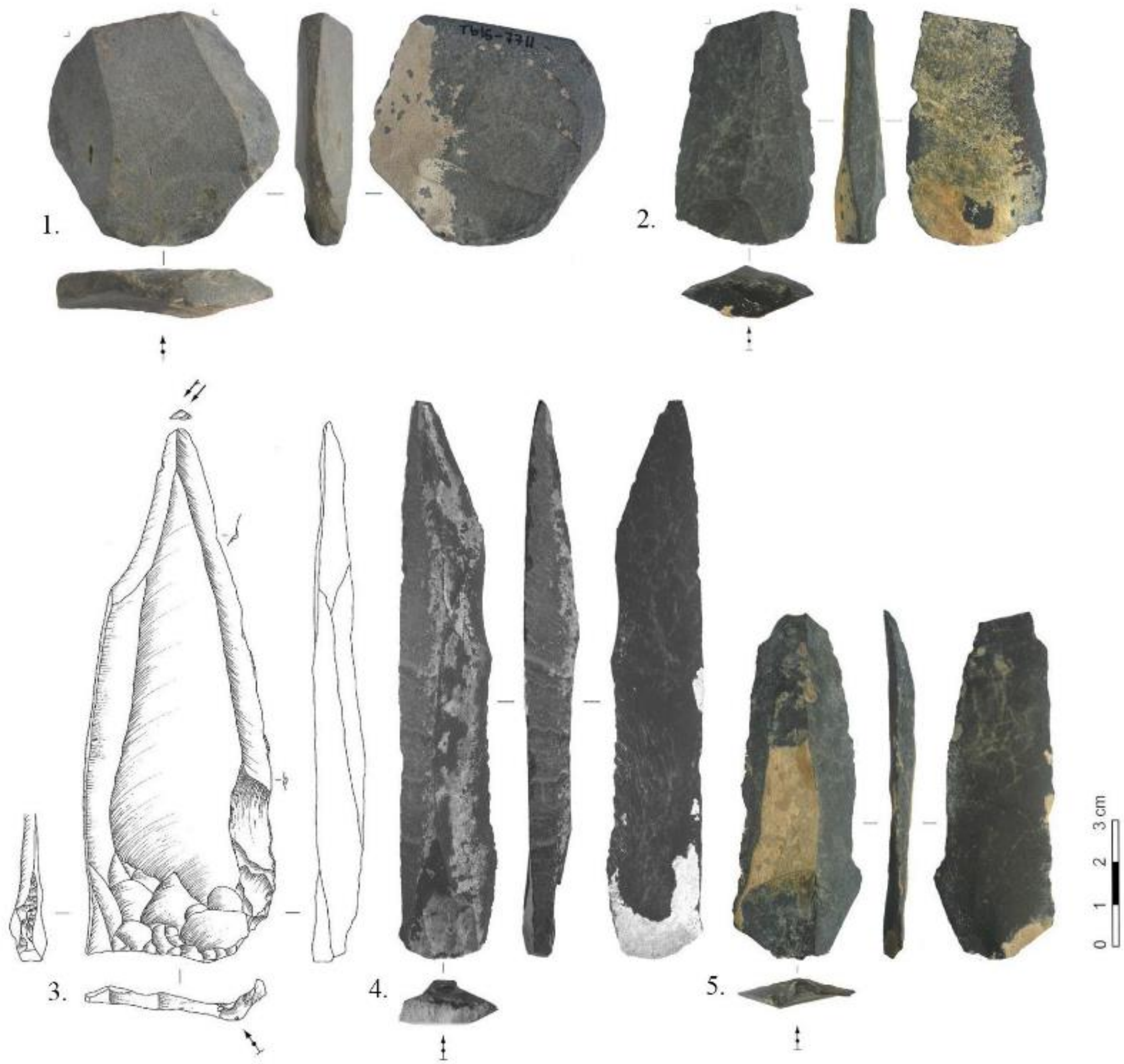

Fig 6: AH6, blade and tools. 1. Convergent laminar flake with basal thinning (inverse proximal removals **-** Kombewa). 2 and 3, convergent blades. 4 Debordant/naturally backed parallel blade. 5. Sub parallel blade with secondary cortex (rolled). After Zwyns et al. [10].

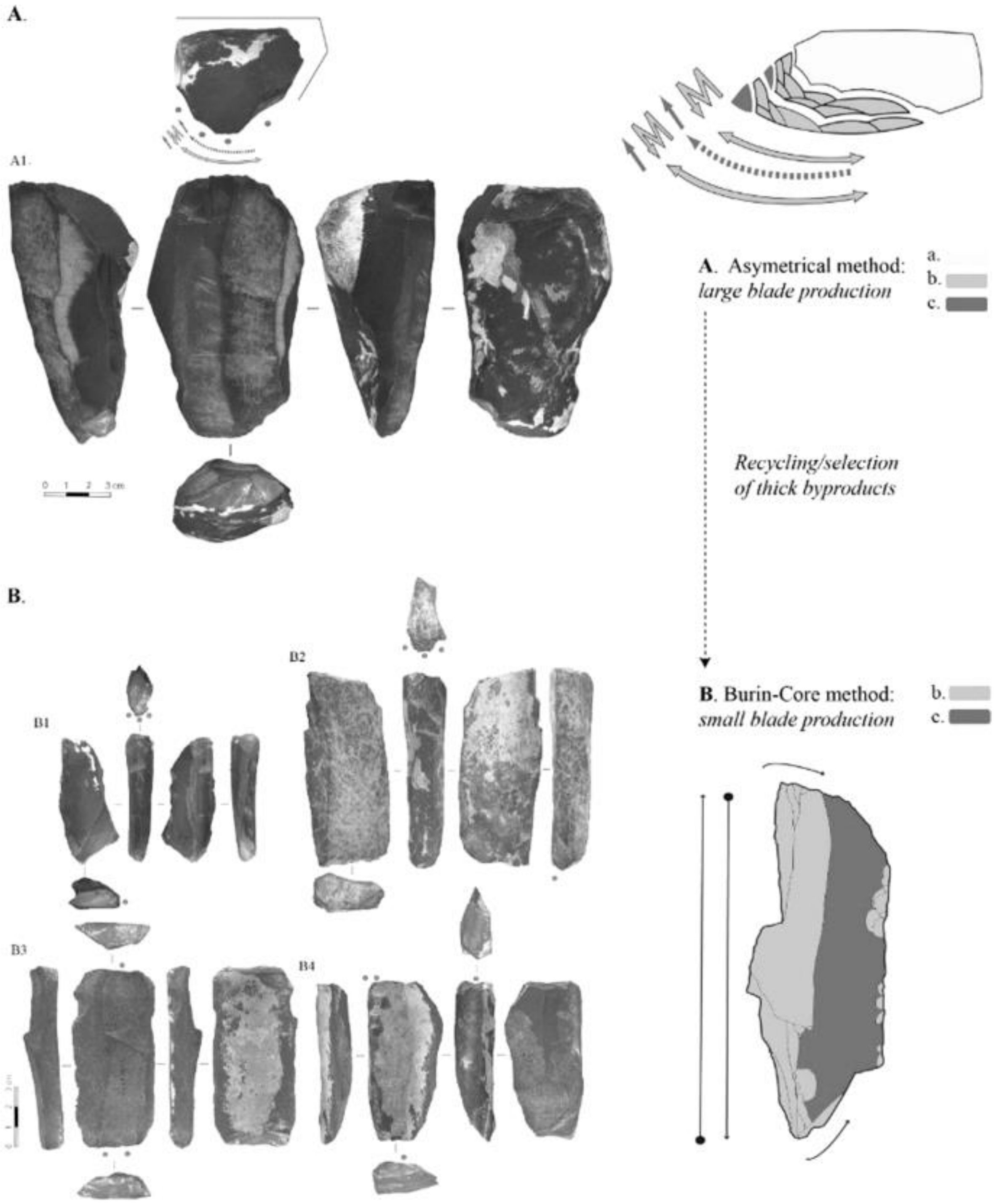

Fig 7. Reduction sequence model for the blade production in AH6. Asymmetrical reduction (**A**) produces large blades (Ab) (SI5) used as tools and thick technical blades (Ac); some of the thickest blades are turned into cores to produce small blades/bladelets using the burin-core (B1, B2; B3) or the truncated-facetted methods (B3). After Zwyns et al. [10].

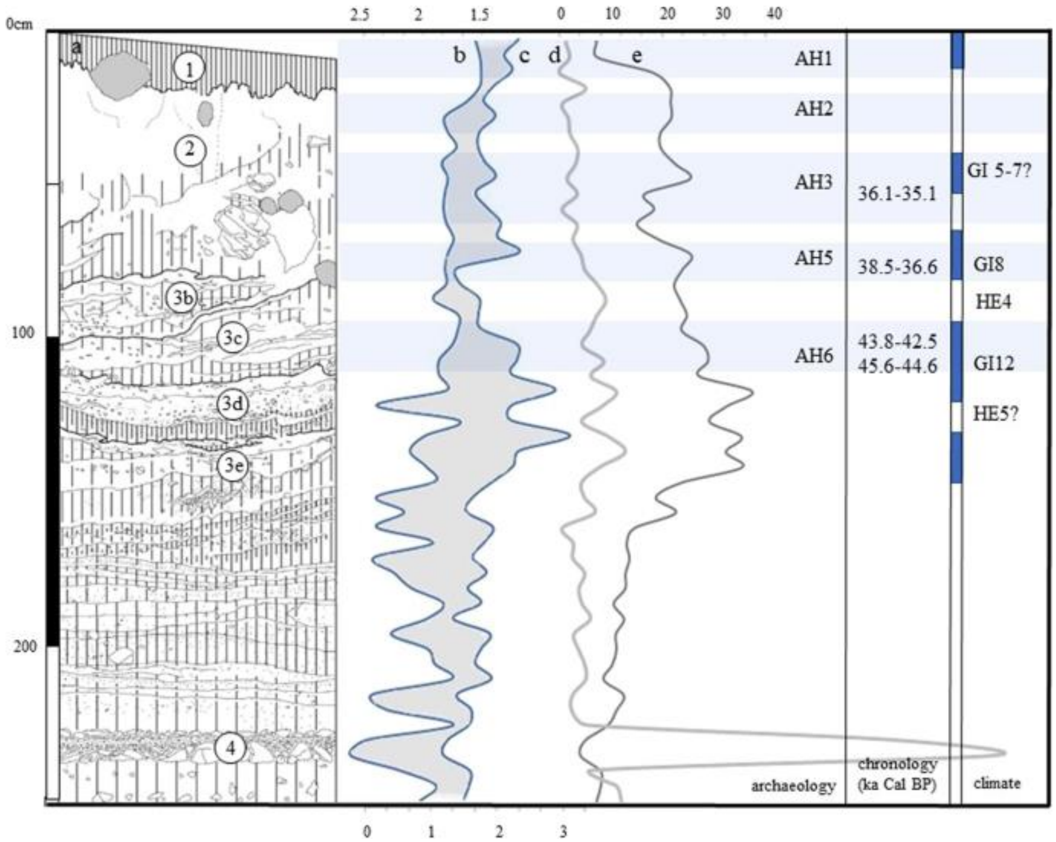

Fig 8. Modelled age of the T16 archaeological horizons (AH) and climatic interpretation using NGRIP. (**a**) North stratigraphic section at T16 Pit 4, showing the three main stratigraphic units and lobes 3b-e; (**b**) Standard deviation of the fine (<2 mm) fraction by laser particle size analysis (top axis); (**c**) Organic matter content relative to mineral matter by loss-on-ignition (%, bottom axis); (**d**) Gravel content (wt%, top axis); (**e**) Calcium carbonate content relative to mineral matter by loss-on-ignition (%, hollow dots, top axis) within the sediments at pit 4. The distance between (**b,c**) (gray area) is a rough proxy for climate, with climatic amelioration indicated where the distance is greater. The proportion of gravel from gravitation input increases during prolonged surface exposure or slow sediment accumulation. Carbonate content increases when evaporation is high relative to precipitation. After Zwyns et al. [10].

Tolbor 21: T21 (N49°15′47″, E102°57′28″) [14,21] lies in the middle of the valley on a fan-shaped slope (14°) formed by polygenetic sediments, ca. 500 m to the west of and 40 m above the current level of the Tolbor River. The site was discovered in 2011 by a joint expedition made from the Institute of Archaeology and Ethnography of the Russian Academy of Sciences, the Institute of Archaeology of the Mongolian Academy of Sciences, and the University of Arizona. An international team from the Institute of Archaeology of the Mongolian Academy of Sciences, the Institute of Archaeology and Ethnography of the Russian Academy of Sciences, and the University of California conducted excavations between 2014 and 2017 under the field direction of E. Rybin, N. Zwyns and B. Tsedendorj. The excavation consists of four Pits and two test-pits along the slope, with a goal of testing the potential of the site on the upper and lower part of the hill, and in its western and eastern flanks. The archaeological sample studied here exclusively comes from Pit 2. Pit 2 contains well-stratified Pleistocene deposits with 5 archaeological horizons (AH) attributed to the Upper Paleolithic. The lowermost layers (AH5 through AH3) modelled ages are distributed between 47,230 and 39,530 ka cal BP and based on the composition of the archaeological assemblages, they are attributed to the onset of the EUP in Central and Northeast Asia. Horizon AH4, from which the lithic assemblage studied here was recovered, is a particularly dense accumulation of lithics. It was identified in all pits with consistent modelled ages ranging between 42,410 and 41,950 ka cal BP (Fig 9). The sediments with artifacts at T21 are like that from T16, consisting of a Holocene soil complex (unit 1), aeolian silt and reworked aeolian silt with gravel (unit 2), and a long sequence of slope-wash deposits (unit 3). Like at T16, multiple episodes of solifluction affect the sediments in Pits 2, and these are likely to have influenced artifact distribution. An episode of solifluction can be seen to affect the deposits housing AH4 in both pits following their deposition (Fig 10, blue lines); following the deposition of LU3 and some of the overlying sediments, another episode of solifluction takes place (Fig 10, red lines), and the underlying deposits housing AH4 are occasionally caught up in this subsequent movement. Solifluction affects lithological units (LU) 3.1 and 3.3 as well; in fact, the entire landform on which the site sits is built up through a cycle of aeolian deposition and slope wash, interrupted by episodic solifluction, but these solifluctions show limited mixing, leaving the stratigraphic succession broadly intact. In Pit 2, AH4 has yielded 998 piece-plotted lithic artifacts, a fragmentary ostrich eggshell pendant, two ostrich eggshell-beads, three soft-stone pendants (intact and fragmented), and 115 bone fragments (MNI = 6), including *Marmota sibirica*, *Ochotona* sp., *Equus hemionus*, *Equus ferus*, *Bos baicalensis*, and *Coelodonta antiquitatis*. Overall, the lithic material includes most of the classic traits that define the EUP in Eurasia (Fig. 11-12). The technology is oriented toward the systematic production of blades (including small blades/bladelets) which represent 47.6% of the blanks. Circa 15% of the stone artifacts are retouched; and the tool types include endscrapers, sidescrapers, various retouched blades and points, along with rare bifacial tools. Pending further analysis, AH4 is described here as EUP in the broad sense.

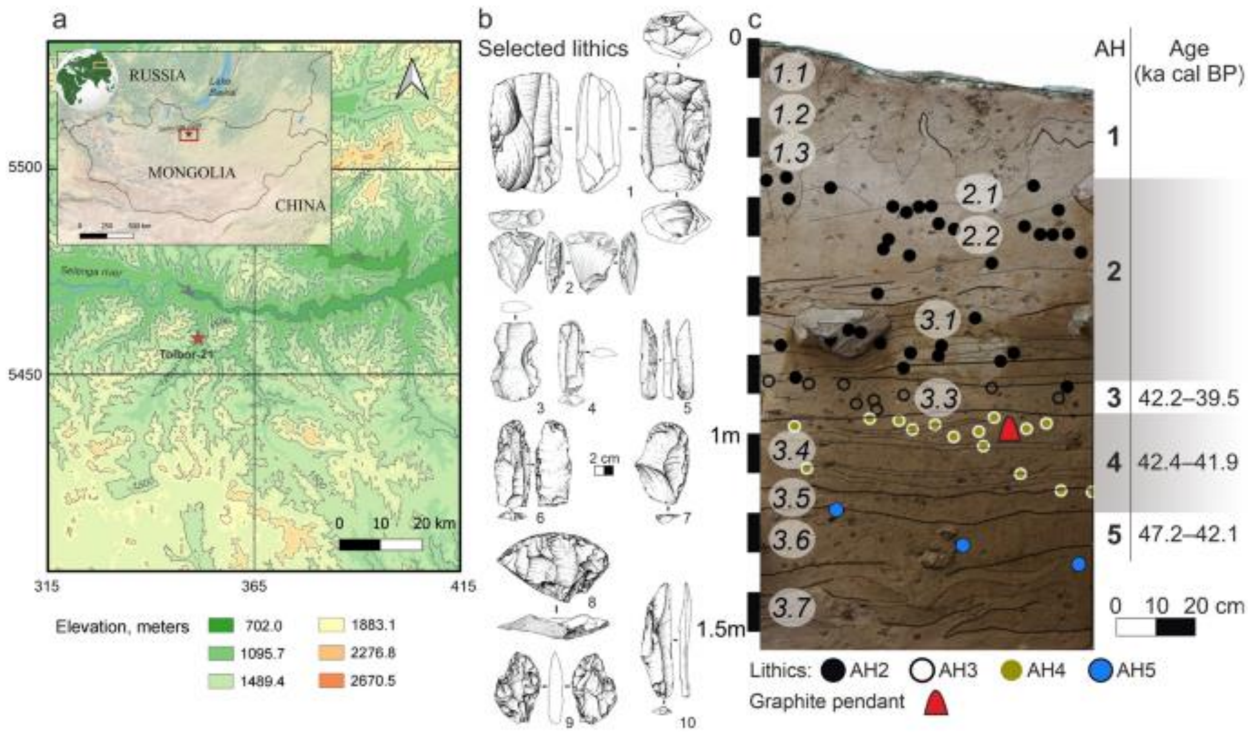

Fig 9. **Cultural and chronostratigraphic contexts of Pit 2.** (**a**) geographic location of the Tolbor-21 site, (**b**) selected artifacts from AH4. **c,** profile of eastern cross-section of Pit 2 with projected stratigraphic positions of a symbolic phallic pendant (red triangle) and lithic artifacts (circles) from archaeological horizons and calibrated radiocarbon dates. After Rigaud et al. [14].

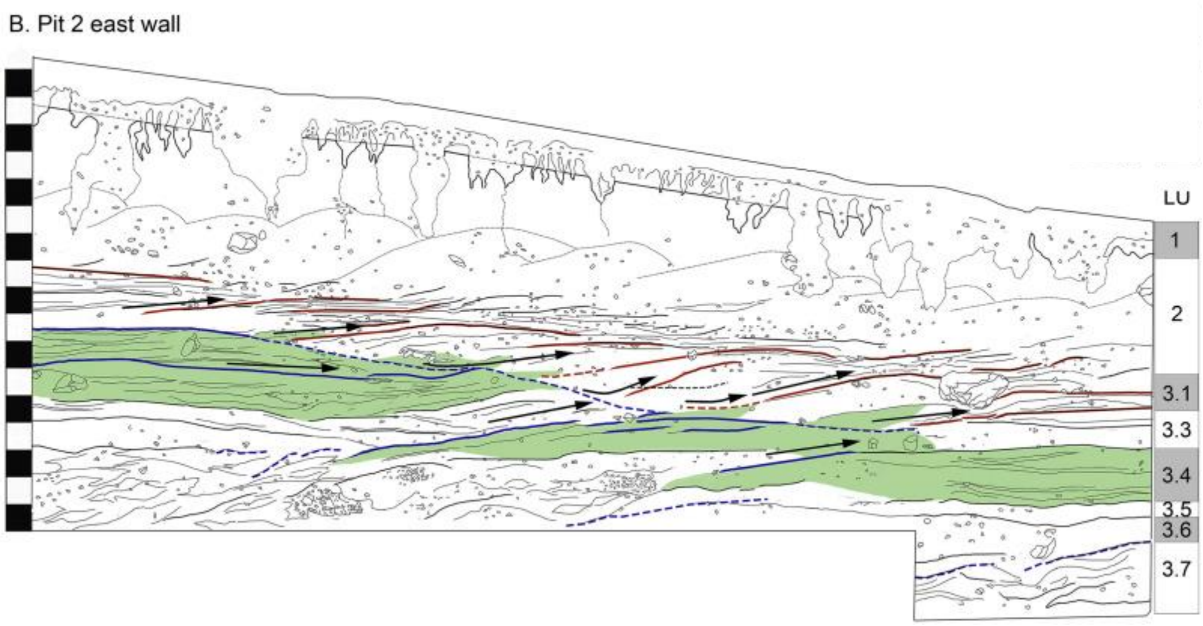

Fig 10. T21 Pit 2 stratigraphy. In places, the upper part of the sediments housing AH4 (LU 3.4; green shading) is involved in an episode of solifluction (red lines) primarily affecting the overlying sediments (LU 3.1 and 3.3); an earlier episode of solifluction (blue lines) affects LU 3.4 together with LU 3.5 and 3.6, possibly also including parts of 3.7. At least three slightly overlapping solifluction lobes from this event can be distinguished in the section. After Rybin et al. [21].

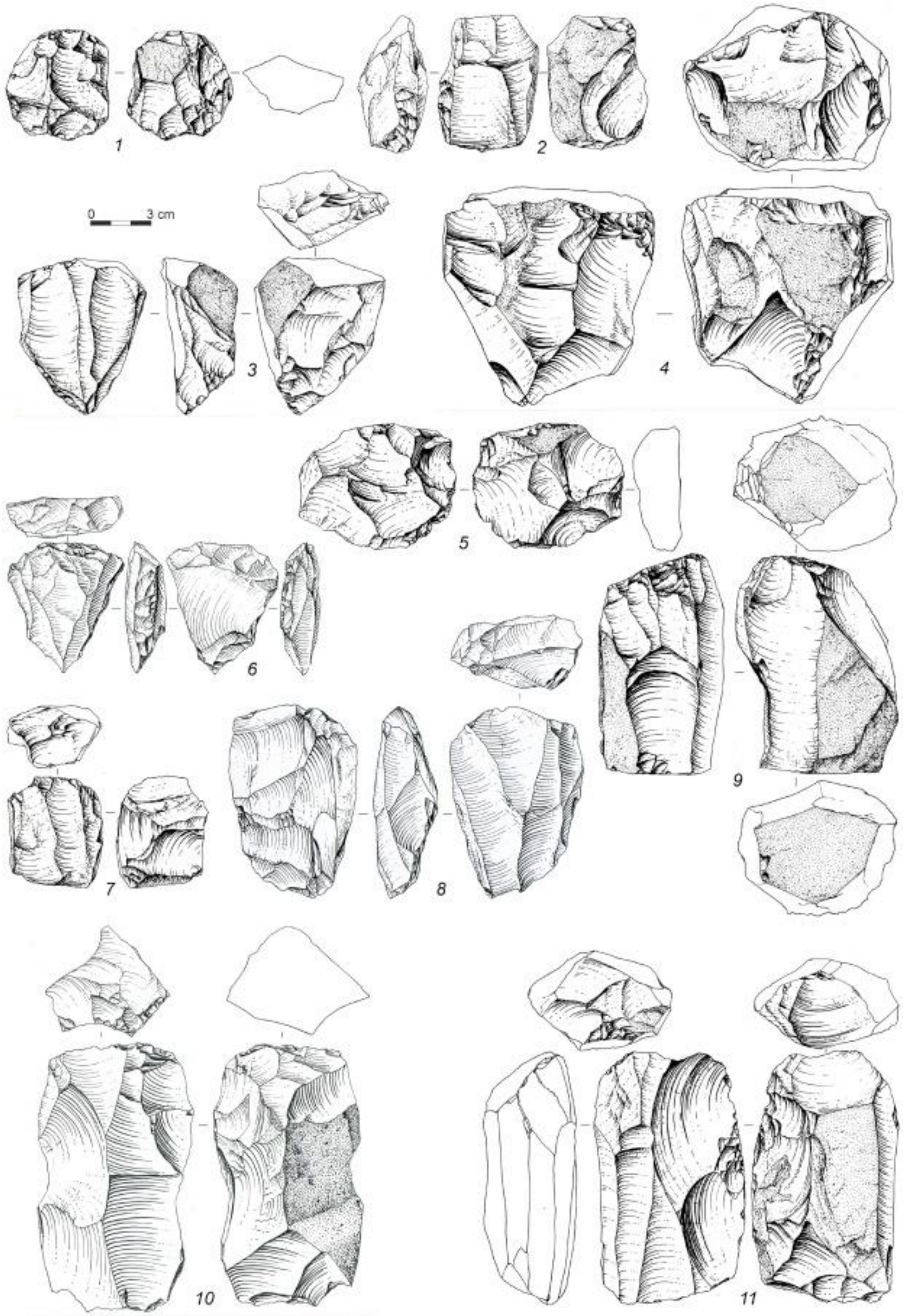

Fig 11. Cores from T21, Pit 2, AH4. 1, 5 – Flake/reduced blade cores, 2, 3 – unidirectional blade core, 4 - bidirectional core at an early stage of reduction, 6, 9 – convergent f cores , 7 - unidirectional flat-faced core, 8 -11 – bidirectional blade cores. After Rybin et al. [21].

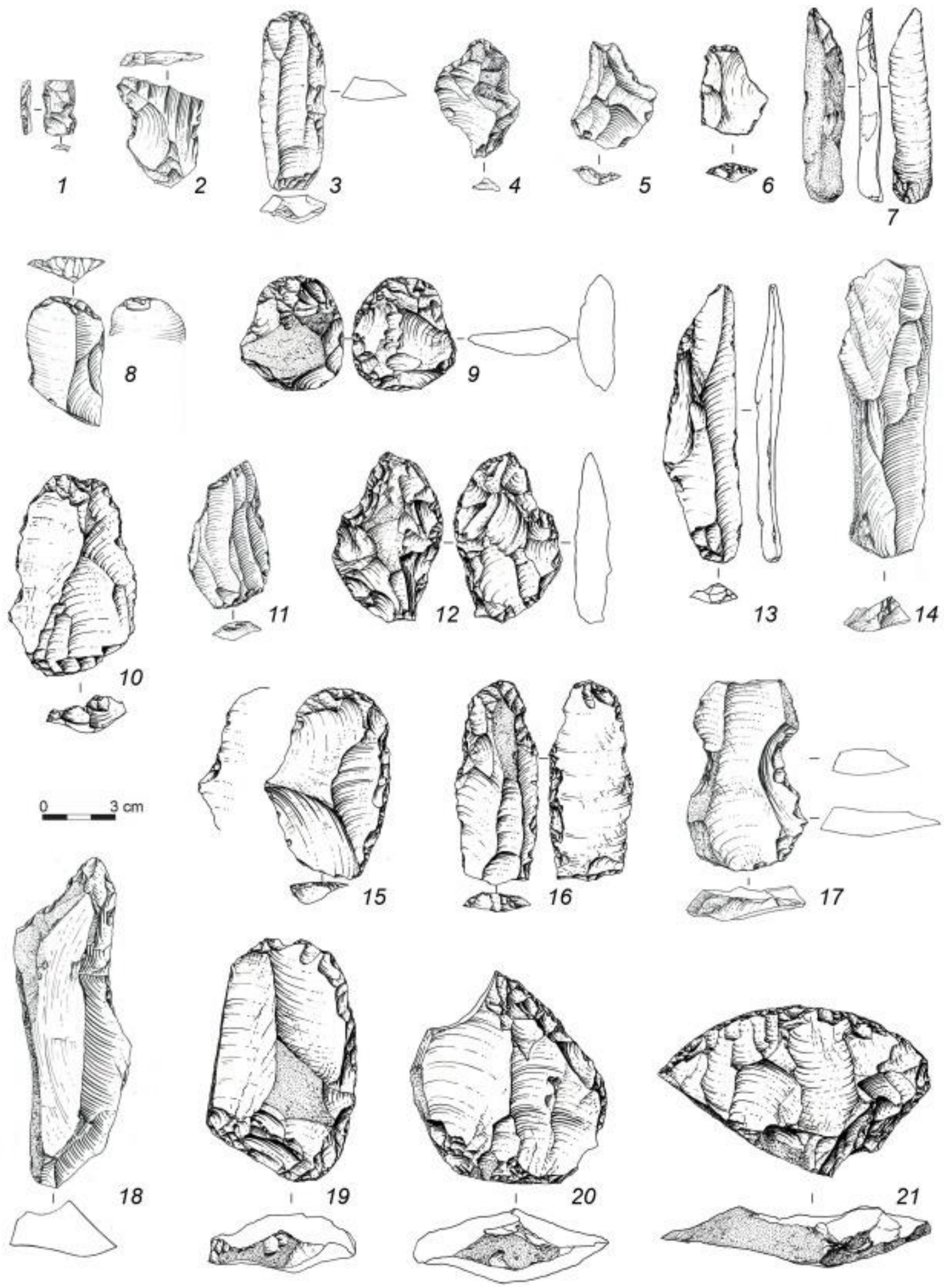

Fig 12. Tools from T21, Pit 2, AH4. 1 – backed bladelet, 2, 5, 6 – spur-like tools, 3, 4, 8, 10, 15 – endscrapers, 7 - truncated (oblique) point with inverse retouch on the proximal right edge, 9, 12 – bifaces, 11 – truncated blade, 13 – retouched bidirectional pointed blade, 14 – bidirectional blade, 16 – Blade with proximal alternate retouch and mesial retouch along the left edge, 17 – 'strangled' blade, 18 - truncated (oblique) point, 19, 20 – sidescrapers, 21 - single convex sidescraper-knife. After Rybin et al. [21].

Tolbor 17: T17 [20,22,23] was first identified by A. Tabarev and S. Gladyshev who conducted the excavation of two test pits at the site in 2010. Lithic material and a radiocarbon date obtained from that field season suggested the site was occupied during MIS 3. Full-scale excavation at T17 began in 2017 as part of a collaboration between the Mongolian Academy of Sciences Institute of Archaeology, University of California Davis, and Tokyo Metropolitan University. The new excavation initially consisted of two 2x1 m test pits, and as of 2019 the excavated surface at T17 has been expanded to ca. 18 m^2. Three main lithological units (LU1-LU3) are identified at T17, comprising the Holocene soil complex (LU1), loess and loess-like deposits (LU2), and laminar silt with gravel and cobbles (LU3). Our study samples the archaeological assemblages from LU3 and LU2. The assemblage from LU3 contains EUP lithic technology aimed at blade and bladelet production as well as diagnostic tool types such as endscrapers, and perforators presumably for working hides and making beads (Fig 13, 14). Previous test excavation at T17 dated a level that corresponds with LU3 to 33-34 ka cal. BP. Stratigraphic correlation with other Upper Paleolithic sites in the Tolbor Valley also places the material from LU3 in the latter part of MIS 3, or ca. 40–30 ka cal. BP. The LU2 sample consists of a Late Upper Paleolithic (LUP) assemblage characterized by, among other traits, microblade technology (Fig 15, 16). The equivalent unit at other Tolbor sites is always younger than ca. 29 ka cal. BP or yields an MIS 2 age. Evidence of personal ornaments have also been recovered from both LU2 and LU3 at T17 in the form of ostrich eggshell and stone beads that are small (ca. 10-15mm in diameter), circular, thin, and exhibit a perforation at their center likely for suspension. Additionally, the persistence of *H. sapiens* in the fossil record of Mongolia [55] coincides with the archaeological record preserved at T17, suggesting that the lithic assemblages preserved at the site were formed by members of our species as well.

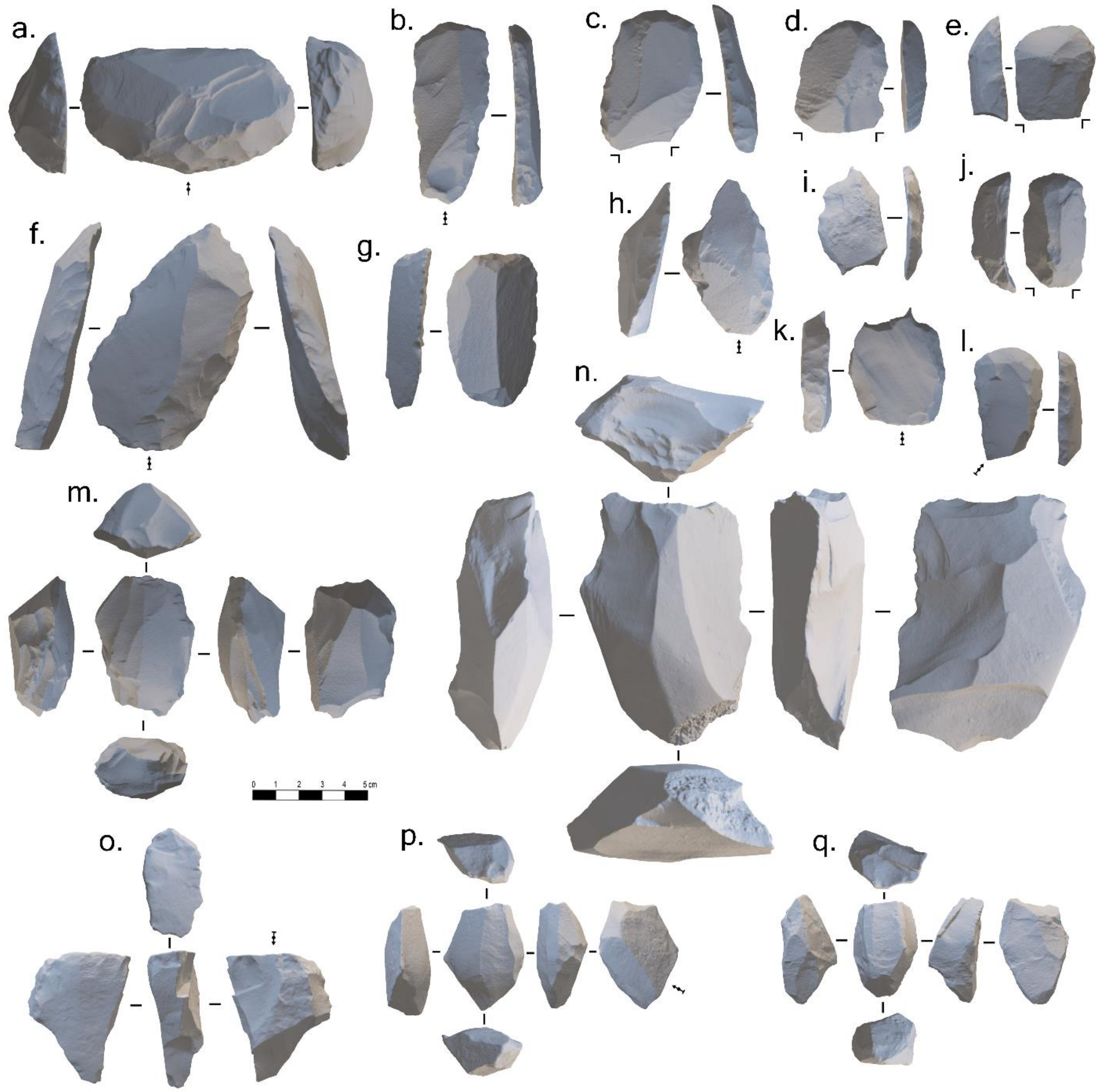

Figure 13. 3D models of cores and retouched tools from T17-LU3. a) double endscraper made on side struck blank; b-e, g, j, l) endscrapers; f) convergent scraper; h) side-scraper; i, k) perforators; m-n) blade cores; o-q) small blade, bladelet cores. Note that o) is a small burin-core made on a flake and i) is a double perforator.

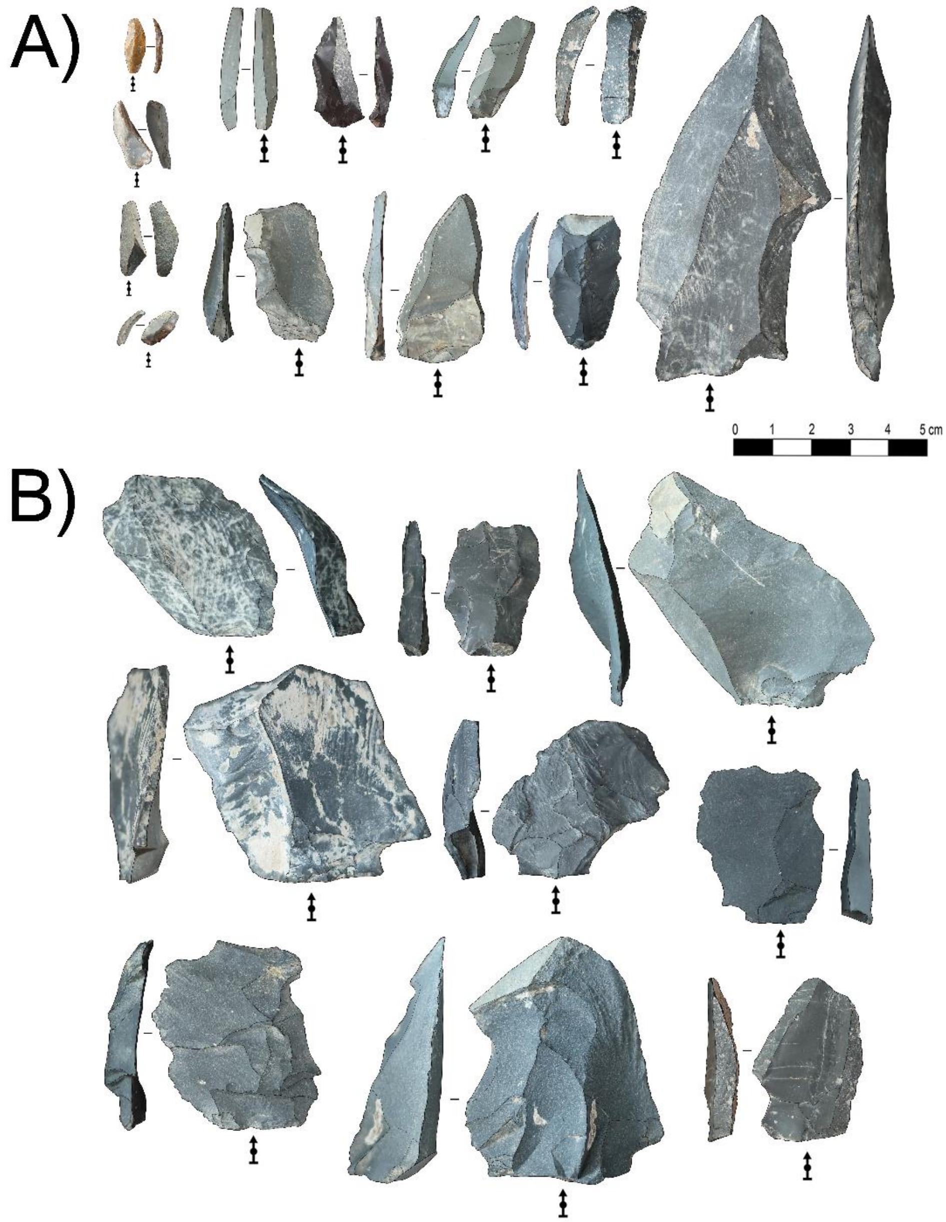

Figure 14. Laminar (A), and non-laminar (B) blanks from T17-LU3.

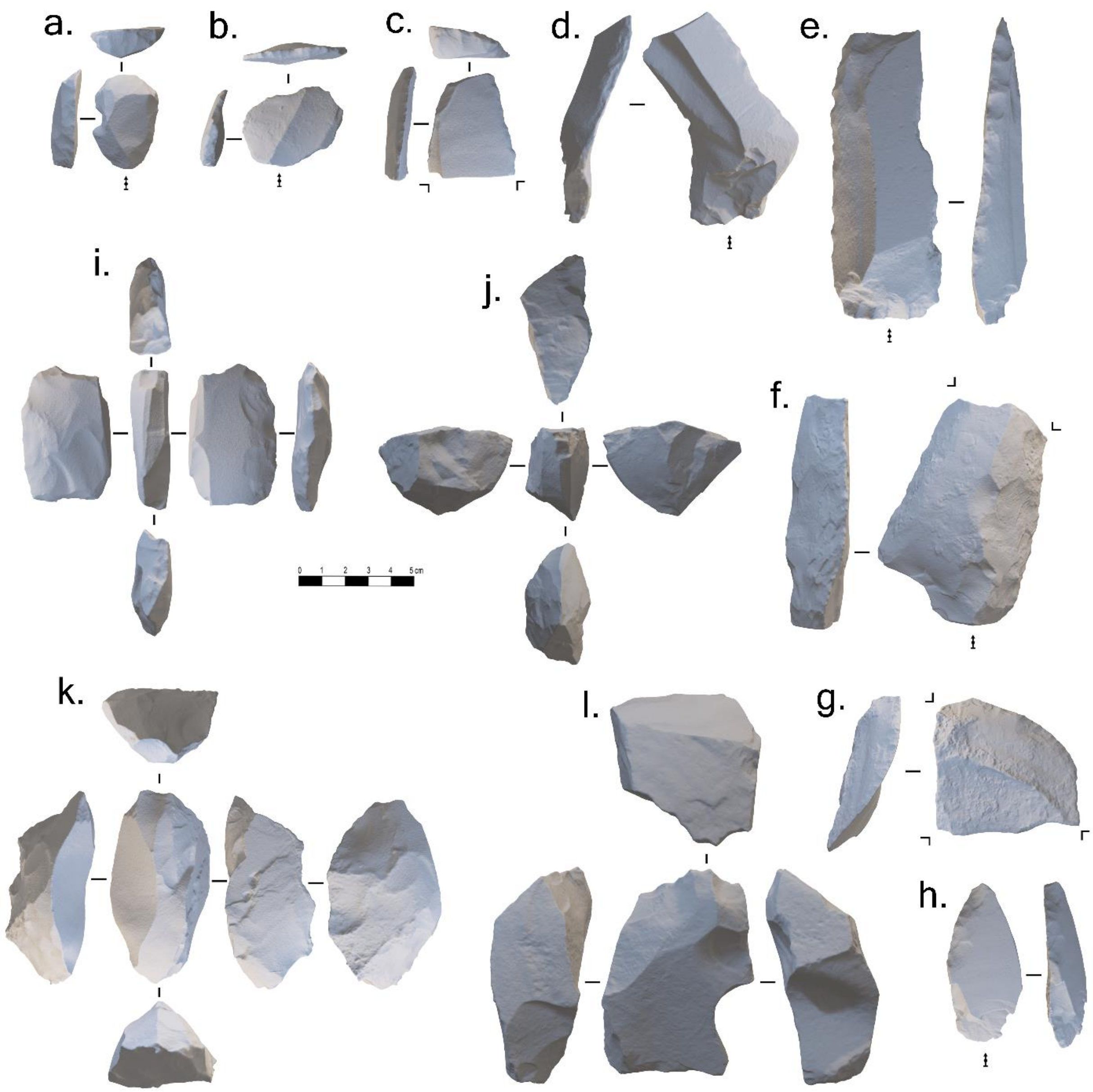

Figure 15. 3D models of cores and retouched tools from T17-LU2. a, c) endscrapers; b) transverse scraper; d-h) scrapers or knives; i, j) microblade cores; k) blade core; l) support with small bladelet removals, possibly core.

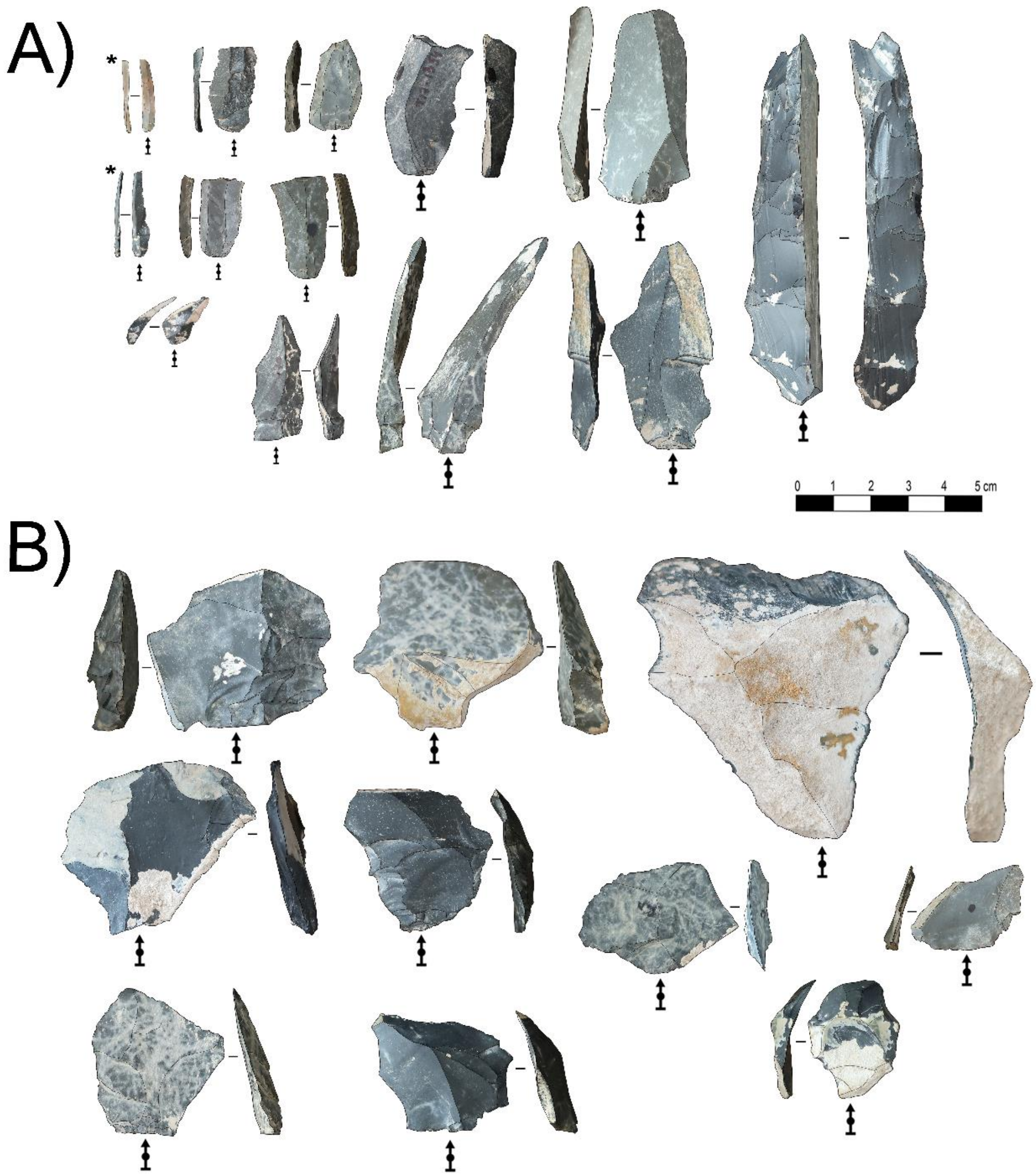

Figure 16. Laminar (A), and non-laminar (B) blanks from T17-LU2. Asterix denotes microblades.

Data collection

Data regarding blank shape, mass, production methods and techniques, and cutting edge length were collected from only complete, unretouched blanks from the four assemblages following the protocol outline by Johnson et al. [22] and references therein. Blanks were not excluded based on whether they were technologically predetermined or predetermining within a reduction system [56,57], following that any blank with a cutting edge could potentially have been used in a subsistence based cutting task [45,52,58]. Metric data for the length and width of each blank were collected using the 'box method' as described by Dogandžić et al. [50: Fig. 3b], which records the length and width dimensions of a blank relative to its axis of percussion, or technological axis. The box method also allows for a blank to be further separated into one of two technological categories, blade, or flake, as defined by the ratio between its length and width. Following Tixier et al [56] and Inizan et al. [57], a blade is a blank with parallel edges, having a length greater than or equal to twice its width. Conversely, a flake is a blank having a length less than twice its width.

Here we use two similar categories of blank shape in our analysis: laminar and non-laminar blanks. Laminar blanks are arbitrarily defined here as elongated blanks of any size with parallel edges, parallel dorsal scars, and whose dimensions satisfy the inequality Length/2xWidth ≥ 0.9, analogous to the typological and technical definitions of blades but allowing for the inclusion of other extensively elongated blanks. Our reasoning is that these other elongated blanks, which would otherwise be classified as laminar flakes and not blades or bladelets, were also likely the target or direct byproduct of blade reduction systems at Tolbor. Non-laminar blanks of any size are conversely defined here using the inequality Length/(2xWidth) <0.9. Microblades are designated to their own category because of their unique scaling relationship between cutting edge and mass as described below [22]. We only make comparisons as described below within a given blank type category based on the observation that laminar and non-laminar blanks have intrinsically different geometries [22: Fig 4].

Measurement of cutting edge length in this study only includes segments of a blank's perimeter that have an angle <50° for blanks that are <40 mm in size, and an angle <70° for blanks that are >40 mm in size. This cutoff is based on what has been experimentally observed by Key and Lycett [59,60] as a threshold for a blank to consistently perform a cutting task. All data were collected into an E4-MSAccess database (oldstoneage.com) using a standard digital caliper, digital scale, and a metric sewing tape measure following Johnson et al [22]. A summary of the number of blanks used in this study from each assemblage and within blank each type-category is provided in Table 1.

Table 1. Blank samples from Tolbor 16, 21, and 17

Site/Unit Level	Non-laminar blanks	Laminar blanks	Microblades	Total
T16	239	73	0	**312**
T21	227	56	0	**283**
T17-LU3	356	77	0	**433**
T17-LU2	108	38	10	**156**
Total	**930**	**244**	**10**	**1184**

Statistical modeling

To test for differences in cutting edge efficiency between each of the four Tolbor lithic assemblages we employed statistical models which made the following comparisons: 1) all blanks combined across assemblages ("Total Blanks"); 2) laminar blanks across assemblages; and 3) non-laminar blanks across assemblages (both latter comparisons made within a "Blank Type"). In all cases, we fit linear regression models for Log10 cutting edge length (the dependent variable), with Log10 mass and assemblage (T17-LU2, T17-LU3, T21, T16) as independent variables, like Braun and Harris [46]. For comparison of laminar (non-laminar) blanks across site-levels, blank-type was also used as an independent variable. A factorial 'Analysis of Covariance' model is used as it allows for the possibility that slopes and intercepts are unique for each group of blanks.

For blank *b*, in assemblage *a*, the "Total Blanks" model has the form:

$$\log_{10} \textit{Cutting edge Length}_{b,a} \sim \log_{10} \textit{Mass}_{b,a} * \textit{Assemblage}_{a} + \varepsilon_{b,a}. \quad (1)$$

The type of blank, *t* (laminar or non-laminar), is introduced in the "Blank Type" model, which has the form:

$$\log_{10} \textit{Cutting edge Length}_{b,t,a} \sim \log_{10} \textit{Mass}_{b,t,a} * \textit{Type}_{t} * \textit{Assemblage}_{a} + \varepsilon_{b,t,a}. \quad (2)$$

Because heavier, and therefore larger, blanks offer the potential for greater variability in cutting edge length, we apply regression weights of the form:

$$w = 1/\log_{10} \textit{Mass} \ (3)$$

to each blank in both the "Total Blanks" and "Blank Type" models, implying that the variance of ε is proportional to $\log_{10}$ *Mass* [61: Section 5.1.1].

As in Johnson et al. [22] we exclude blanks with 0mm of cutting edge from both models as defined above due to their small sample size (n=30) and unsuitability for log transformation, although they are displayed in graphs with the other blanks. Microblades, also shown in graphical displays, are included in the "Total Blanks" model but not in the laminar portion of the "Blank Type" model. This is because they are only present in LU2 and exhibit a unique scaling of cutting edge length to mass likely due to the pressure techniques used to produce them [22].

The Analyses of Covariance (1 and 2) have related statistical tests, which we use to ask whether there is evidence for differences in cutting edge efficiency across assemblages. The null hypothesis for the "Total Blanks" model is that all sites have a common intercept and slope relating log10 cutting edge to log10 mass. And the alternative hypothesis is that one or more of the sites has a unique intercept and/or slope. The null hypothesis for the "Blank Type" model is that, for a given blank type (laminar or nonlaminar), all sites have a common intercept and slope. And the alternative hypothesis is that for at least one of the blank types, one or more of the sites has a unique intercept and/or slope. We examined F-statistics, based on residual sums of squares from the null and alternative models, to decide which hypotheses are best supported. However, while the F-test uses information in the sample economically, it does not detail where differences may exist. We explore these details by displaying the samples with fitted lines and confidence bands. The confidence bands have been adjusted by the Bonferroni procedure to allow for all statistical comparisons between pairs of assemblages.

Data analysis was performed in R [62] with the addition of the libraries Epi [63] and Scales [64].

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Chapter 4: Changes in raw material selection unlikely driven by constraints on flake cutting edge efficiency at Shuidonggou Locality 2, China

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Abstract

The widespread distribution of nondescript, flake-based lithic assemblages within the Late Pleistocene archaeological record of East Asia remains one of its most defining and enigmatic characteristics. One noteworthy exception to this pattern is the site of Shuidonggou Locality 2 in northern China, where a technological turnover from an allochthonous blade technology to an unprepared flake technology ca. 35 ka is observed. Such flake technology continued to be used until ca. 28 ka, while raw material selection fluctuated at the site over this period. These techno-economic changes are thought to reflect demographic and/or ecological responses of human groups living at the interface of the Eurasian Steppe and the Summer Monsson zone. Here we diachronically model blank cutting edge efficiency from five flake-based assemblages recently excavated from Shuidonggou Locality 2. We use a Bayesian approach to test for raw material influences on blank cutting edge failure rate and efficiency. Our results indicate little difference throughout the post-blade archaeological sequence and suggest that the observed changes in raw material selection are poorly explained by selection pressures on flake cutting edge efficiency.

Introduction

Recent Paleolithic archaeological research has revealed that lithic technological behavior in East Asia during the Pleistocene was characterized by considerable diachronic and synchronic variability [1-17]. However, one of the most enduring features of the East Asian Paleolithic record are nondiagnostic, unprepared flake assemblages, visible throughout the Pleistocene record [18-24]. Traditionally known as ‘core-and-flake technology’, ‘small flake industries’, or ‘large pebble tools’, the prevalence and details of these unprepared flake assemblages and their underlying meaning for the tempo and mode of Paleolithic technological development in the region remain central topics in modern day archaeological discourse and investigation [25-30]. And while often characterized by the expedient production of generic flakes [18-24], at times casually retouched or used without further modification [31], some unprepared flake assemblages in the region present substantial, if not subtle, techno-typological variation that is only just beginning to be recognized and understood [1-3,20-24,27-30].

This feature of the East Asian Paleolithic record is arguably best illustrated when contrasting the spatial distribution of unprepared flake assemblages and Initial Upper Paleolithic (IUP) blade assemblages dating to Marine Isotopic Stage 3 (MIS 3) [17,24,30]. The appearance of the IUP in Asia is thought to have been facilitated by the expansion of *Homo sapiens* populations out of West Asia, across the Eurasian Steppe, and into northern East Asia during the first half of MIS 3, ca. 50-40 ka [13-17,32-44]. The Asian IUP is technologically distinct compared to the coeval unprepared flake assemblages, and involved the production of large blades from volumetric, asymmetrical cores which were at times retouched into Upper Paleolithic tool types or transformed into burin cores to produce smaller blades and bladelets [14-16,32-34,36,40]. During MIS 3, IUP sites in East Asia were geographically limited to the steppe region to the north, near Lake Baikal and its tributaries (Fig 1) [14,15,17,24,39,40]. South of the steppe, lithic assemblages largely consisted of unprepared flake technologies [17,24,30,39], with the key exceptions being IUP and possible IUP assemblages from Nwya Devu [13,42], located on the Tibetan Plateau, and the Shuidonggou (SDG) site complex and Shiyu site [16,17,24,37,39,43,44], respectively located within the Summer Monsoon zone in the northwestern regions of the Yellow and Hai River basins.

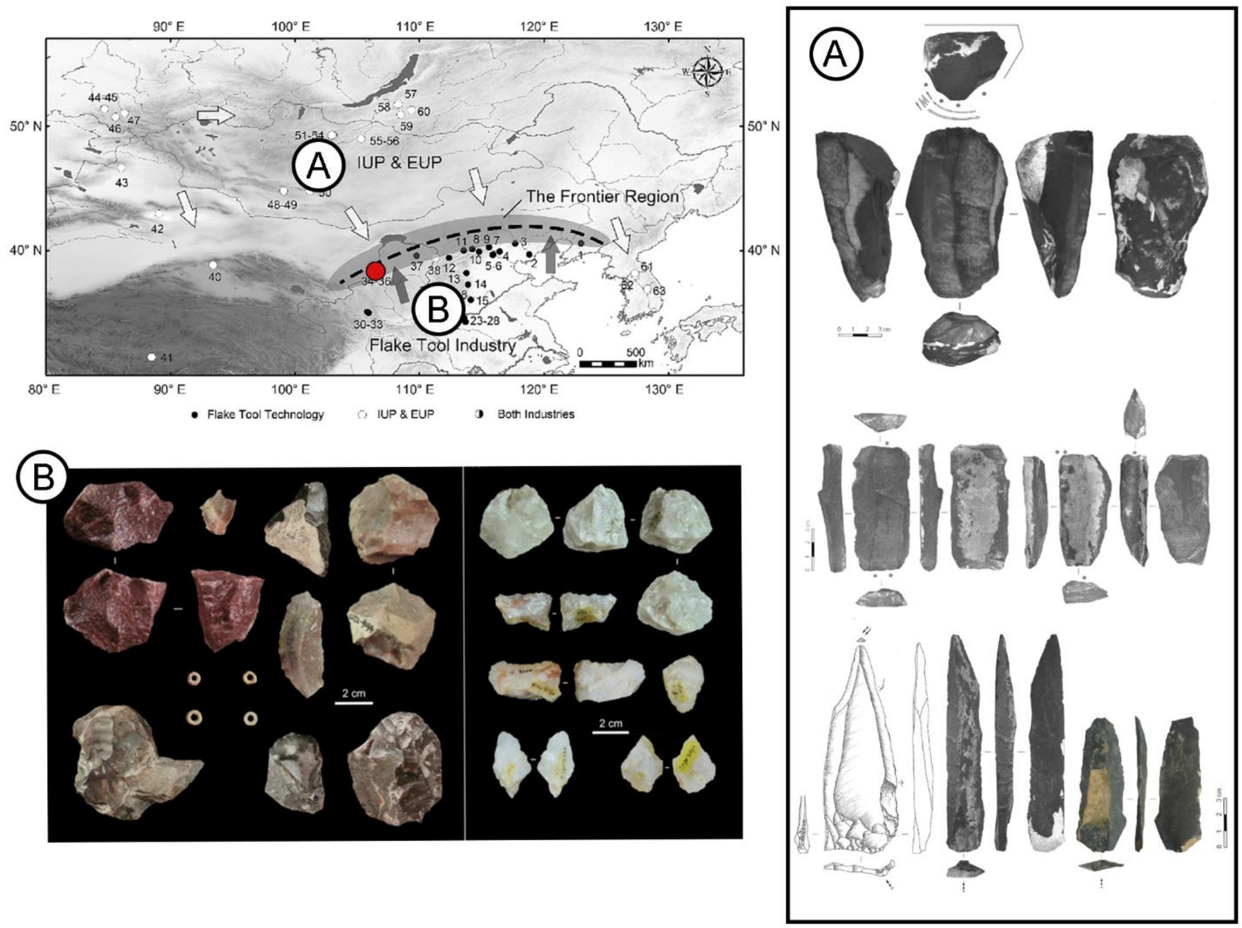

Fig 1. Distribution of IUP (A), and unprepared flake sites (B) sites in North-Central and East Asia during MIS 3. Shuidonggou indicated by red circle in the "Frontier Region". Modified after Zwyns et al. [15] and Li et al. [30].

Explanations for the continued production of unprepared flake assemblages in East Asia during MIS 3 coeval with the arrival of the IUP in the region are numerous. Some suggest that in regions where unprepared flake technologies were made, there may have been demographic issues that lead to low population densities which in turn inhibited, or even undermined, cultural innovation and transmission [45; see also 46-50]. In this scenario, IUP toolmakers in the northern steppe would have enjoyed a higher population density, or lower extinction rates, than populations in the south, which allowed them to faithfully maintain and transmit technological information underlying IUP toolkit manufacture – at least up until the disappearance of the IUP in East Asia and its replacement by equally, if not arguably more, technologically and culturally complex Early Upper Paleolithic (EUP) and Late Upper Paleolithic (LUP) toolkits [51-58]. It is unclear however, why toolmakers in the monsoon zone would be relatively more unable to maintain population sizes requisite for carrying and transmitting information for making lithic technologies more sophisticated than unprepared flake tools. Unfortunately, without more information regarding the demography in these regions during MIS 3 and its relationship to local ecological conditions at that time, this hypothesis is not readily testable.

Others have argued that the persistence of unprepared flake assemblages during MIS 3 in East Asia reflects the conservative maintenance of technological norms inherited from Early and Middle Pleistocene populations along an unbroken and autochthonous hominin lineage [27,28,59], that by some accounts culminated in the *in situ* emergence of a regional branch of *H. sapiens* [59-61]. Some versions of this scenario do not require serious evaluation, as modern genetic, fossil, and archaeological evidence all converge on a single origin for our species in Africa during the Middle Pleistocene, ca. 300 ka [62-64]. Nonetheless, if one was to consider that unprepared flake assemblages in East Asia were proprietary to one or more allochthonous *H. sapiens* populations inhabiting the monsoon zone during MIS 3 [65,66], and/or populations of other hominin species in the region such as Denisovans [67-71], several compelling scenarios begin to emerge [24], some pertinent to evidence regarding gene flow between our lineage and Denisovans [67,70,71].

The facilitating role that lithic technology played in landscape use strategies has also been emphasized regarding the widespread distribution of unprepared flake technologies in East Asia during MIS 3. For example, nondescript flake tools may have been a mediating technology for manufacturing a variety of wood and bamboo artifacts, such as spears, knives, shelters, animal traps, and fishing weirs [25,72; but see 73]. This would suggest a similar level of technological sophistication compared to the IUP, EUP and LUP to the north, with their theoretically hafted blade, bladelet, and microblade composite cutting tools and hunting weapons [14,15,34,53,58]. Relaxed selection pressure on tool assisted resource exploitation has also been offered up as an explanation, suggesting that an environmental change in the monsoon zone that increased raw material and food resource availability may have favored lithic technologies that required relatively less investment to be suitable for subsistence, with lithic toolkits not having to be heavily curated or designed for long distance transport away from raw material sources [27]. Such a scenario is somewhat contra to the population density explanation mentioned above, in that it suggests conditions in the southern monsoon zone were stable and resource dense enough to only require unprepared flake technologies for hominins to subsist in, as opposed to the more unpredictable ecological conditions of the steppe which placed strict selection pressures on lithic toolmakers to develop their toolkits to better extract resources from what would have been harsher, more barren environments.

Raw material quality and availability is another environmentally related factor that was once commonly considered to constrain hominin lithic technological behavior in East Asia [74,75]. However, this has become less persuasive of an explanation in recent times [3,76]. For example, at the SDG site complex IUP blade technologies were made using the same local raw materials that were later used to make unprepared flake assemblages after the IUP disappeared from the region [16,33,37,43,44,77-82]. This suggests that the mechanical properties of these local raw materials were not a limiting factor, at least at SDG and in the case of IUP blade production, meaning that additional explanations need to be sought to understand why toolmakers in the region switched to unprepared flake technologies.

Though there is unlikely a single explanatory factor for every instance of reliance on minimal effort lithic technological strategies in East Asia during MIS 3 [83], here we set out to investigate an underexplored parameter of lithic evolutionary efficiency [84]: the cutting edge efficiency of lithic blanks (i.e., flakes, blades, bladelets, and microblades) [57,58,84-90]. Often defined as the length of a blank's sharp edge relative to its mass [57,85,87,90], measures of cutting edge efficiency reflect the effort stone tool makers placed into economizing their consumption of lithic raw material to produce useable sharp edges.

Previous work has established that blank cutting edge efficiency, and the variation around this parameter, increased in certain regions at certain times during the Pleistocene [57,58,84,85,87,89,90]. Such increases in blank cutting edge efficiency often coincided with changes in lithic technological behavior [ibid.], as well as with changes in hominin physiology and paleoecology [84; see also 91-95], suggesting that identifying changes in blank cutting edge efficiency can help explain key issues regarding human evolutionary history. As the primary functional value of a generic flake was likely its potential to be used as a cutting tool [57,84,85,95-103], unprepared flake assemblages in East Asia dating to MIS 3, with their relatively simple reduction sequences aimed at a limited number of blank types [1-3,18-24], represent an ideal subject for cutting edge efficiency analyses. Such an approach in this case can shed light on the technological variation observed within and between unprepared flake assemblages during the Pleistocene [1-3,20-24,27,29,30] which possibly reflect major or subtle changes in hominin paleoecology that are not readily testable using traditional lithic reduction sequence reconstructions.

Here we diachronically model blank cutting edge efficiency from five flake-based lithic assemblages recently excavated from Locality 2 of the SDG site complex (SDG2), located at the boundary between the East Asian steppe and monsoon zones (Fig 1). The assemblages date to ca. 35-28 ka [24,80], post-dating the disappearance of the IUP at SDG2 [24] and are contemporaneous with the EUP to the north [57,58]. By investigating diachronic changes in flake cutting edge efficiency, our aim is to identify technological trends at the site during the latter half of MIS 3 that may have gone undetected during previous analyses of these same assemblages [24,80,81].

Shuidonggou Locality 2

The SDG site complex is located the Ningxia Hui Autonomous Region of northern China, ca. 18 km east of the Yellow River on the margins of the Ordos Desert (Fig 2). Initially discovered in 1923 by Emile Licent and Pierre Teilhard de Chardin [104,105], today SDG consists of 12 open-air localities [78,106].

Since its discovery, SDG has received considerable attention due to the identification of IUP technology from Locality 1 (SDG1) [16,33,37,43,77,78]. The SDG1 assemblage is one of the few examples of IUP blade technology in East Asia found south of the Siberian and Mongolian steppe. The presence of the IUP at SDG1 is generally interpreted as having been allochthonous, associated with populations of *H. sapiens* expanding southward from the steppe and resettling the region during MIS 3 [16,28,33,37,39,43,78, 107-109]. The IUP bearing levels at SDG1 date to ca. 43-41 ka [37,43,77-79,108], considerably younger than the appearance of this technology in the steppe ca. 45 ka, thereby supporting a sequential southward expansion into the region [14,15]. IUP technology is also reported from SDG2 and Locality 9 (SDG9), which respectively date to ca. 41-35 ka via radiocarbon and ca. 29 ka via optically stimulated luminescence (though the latter may be an underestimate due to bleaching) [24,43,44,78,79,82,110]. The archaeological sequence at SDG2 is also remarkable for preserving human occupations at the site following the disappearance of the IUP, ca. 35 ka onwards [34,110], and is the focus of this study.

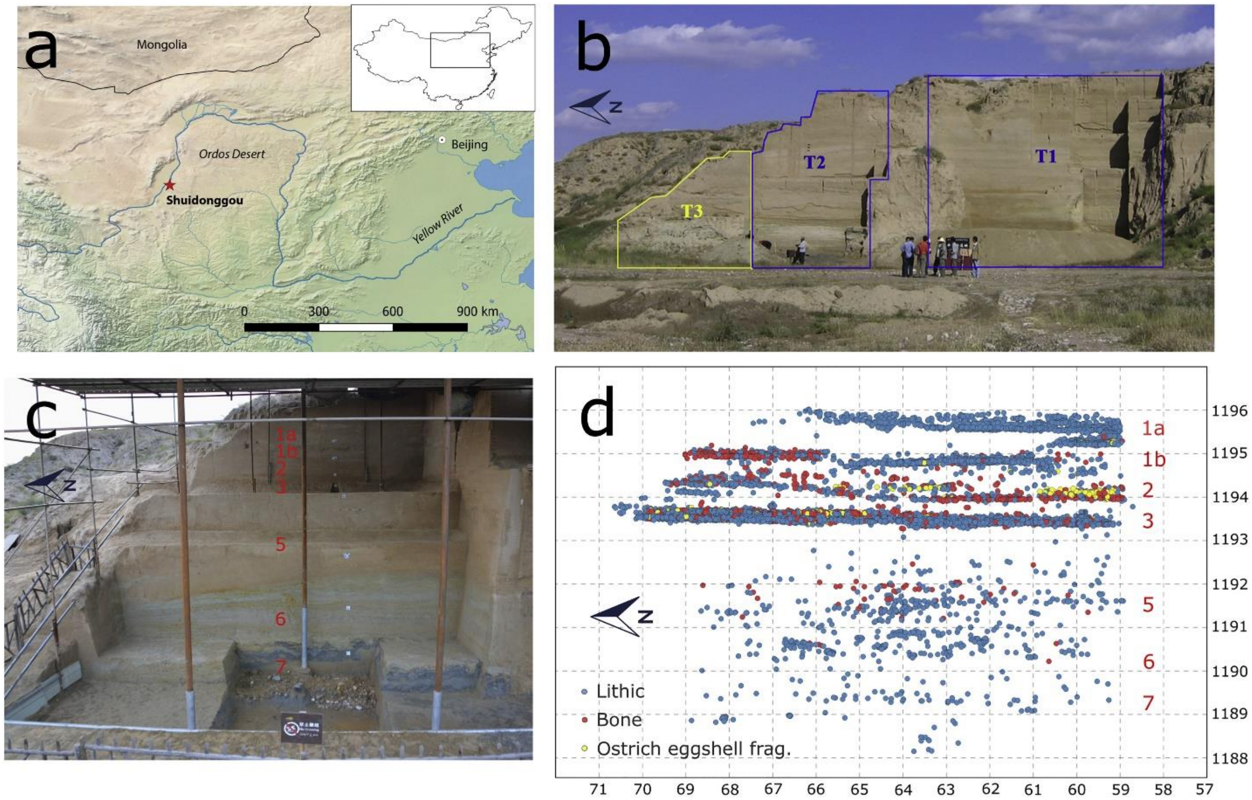

Fig 2. Geographic location of Shuidonggou Locality 2 and the stratigraphic location of the cultural layers at the site. After Lin et al. [80].

Modern archaeological field research at SDG2 was conducted in two main phases (Fig 2). The first took place between 2003 and 2007, involving the excavation of two adjoining trenches (T1 and T2), exposing a 12.5 m thick stratigraphic section [43,78,80,111]. The stratigraphic sequence at SDG2 is primarily composed of yellow silt with loess characteristics deposited under a hydrodynamically low-energy setting, likely a lake shore environment [80,111]. Laminated mire and peat deposits (greyish green/yellow in color) at the bottom of the sequence suggests that SDG2 was waterlogged within a lake or marsh setting during the earliest phases of deposition [80,111]. Pollen records indicate that the paleoenvironment associated with the formation of SDG2 was mostly semi-arid with wetland regions located nearby [73,111]. During the first phase of excavation, seven cultural layers (CL1–7) were identified from T1 and T2 based on artifact concentrations and/or sedimentary facies throughout the stratigraphic sequence

[43,78,111]. The upper four layers (CL1–4) are composed of vertically constrained concentrations of artifacts separated by sediment containing sparse to no archaeological remains; the lower layers (CL5–7) refer to artifacts distributed more loosely among the sediment body in lower quantities [82]. Lithic assemblages in CL4-1 from T1 and T2 consist mainly of unprepared flakes and casually retouched tools with some outstanding Upper Paleolithic tool types, such as endscrapers [30,59]. An IUP blade core was recovered in both CL5 and CL7 in T2, but otherwise the lithic assemblages from these levels also consist of unprepared flakes and flake tools [24,59,82,111].

In terms of chronology, Optically Stimulated Luminescence methods place CL1 at ca. 20 ka [111]. Radiocarbon analysis of samples collected from exposed hearths by Madsen et al. [112] returned ages between ca. 34 and 29 ka for CL2. Addition radiocarbon ages on samples from CL2 and CL3 yielded similar dates between ca. 35 and 30 ka [43; but see 113]. The age for CL4–6 is less certain as several dates from these layers are younger than ca. 30 ka [43,111]. Li et al. [43] estimated CL4–6 to be between ca. 34 ka and ca. 33 ka. Finally, the basal layer of CL7 is dated to ca. 41–34 ka [43,59,111,112]. In addition to the abundant lithic artifacts and faunal remains, the excavations at T1-T2 have yielded dozens of personal ornaments in the form of beads and pendants. These were made using ostrich eggshells in CL2, and freshwater mollusks in CL3, with the former also showing evidence of the application of ochre pigments [114-116].

Between 2014–2016, a second excavation project was carried out at the site in the newly designated T3, found adjacent to the previously exposed T2 (Fig 2) [80,117]. Apart from CL4, which is absent, all cultural layers described by the previous excavation were identified as exhibiting similar sedimentary and archaeological characteristics - though there remain some disagreement concerning the antiquity of the upper layers [30,79,110]. Regardless, the upper three layers in T3 (CL1–3, with CL1 further subdivided in CL1a and CL1b), are also vertically constrained concentrations of artifacts, as opposed to the lower layers (CL5–7) which exhibit lower quantities of artifacts loosely distributed within the sequence [80,82].

During the excavation artifacts with a maximum dimension ≥2 cm was piece-plotted by total station, while objects smaller than 2 cm were collected via screening of 5 cm spits within one square meter excavation units [24]. Over 5000 lithic artifacts with maximum dimension ≥2 cm were recovered from T3 during this second phase of excavation [80]. Computer simulation of artifact accumulation in CL3-CL1a shows deposition on a slightly variable substrate with signs of very low-energy water movement that only slightly changed artifact orientations [118].

The T3 lithic assemblages are technologically analogous to those recovered from T1 and T2, in that they are composed predominantly of unprepared flakes, some more or less informally retouched tools showing no clear patterning of standardized production - though also showing some considerable technological and typological variability (Figs 3-5) [24,43,82]. No additional IUP cores were recovered from any of the cultural layers in T3 at SDG2. Examples of symbolic ornaments, such as ostrich eggshell beads and a bone pendant, have also been recovered from the upper layers of T3 [24].

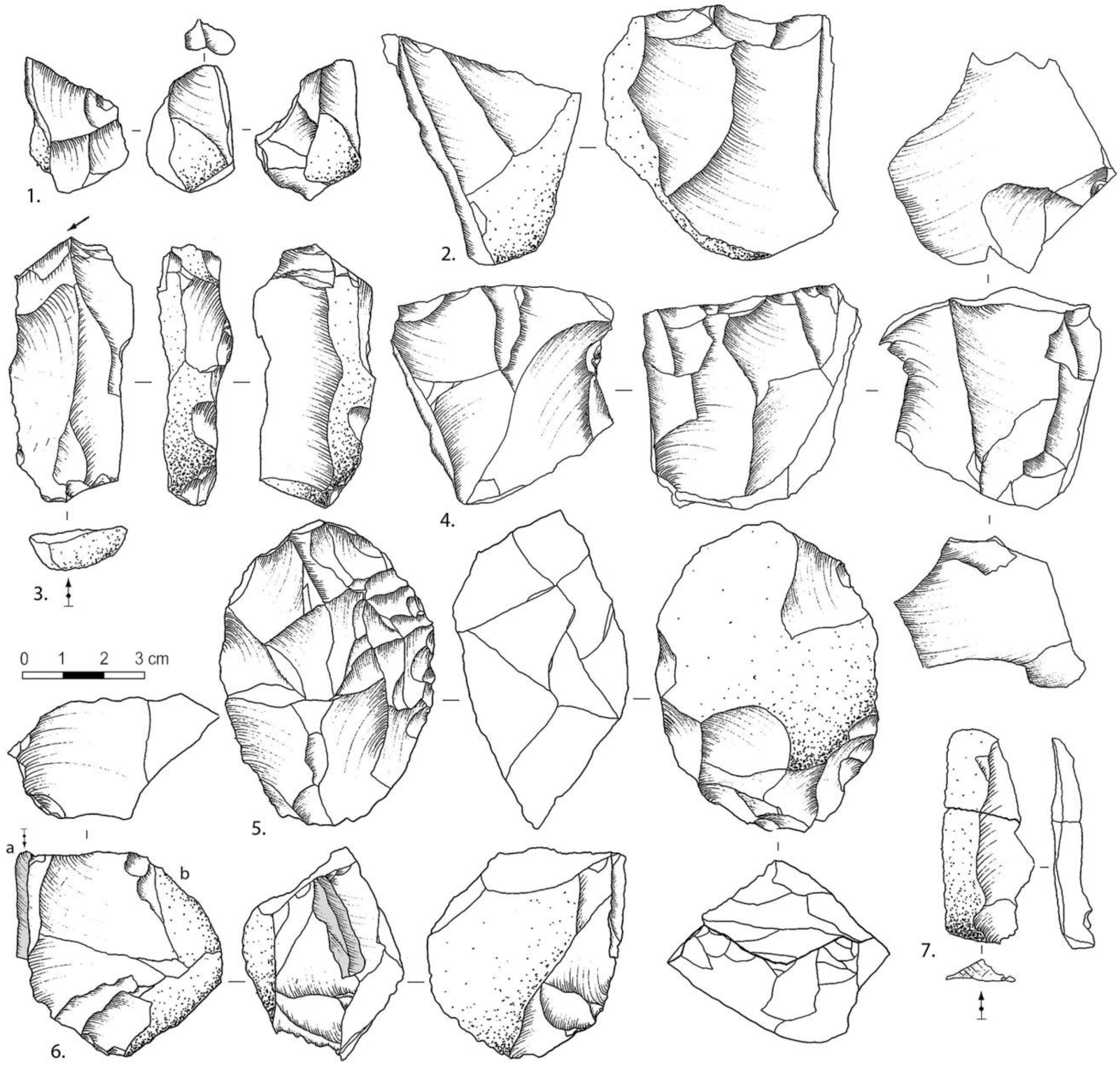

Fig 3. Variations in core shape and reduction method at CL3. A few known examples of atypical blank forms and core types in low frequency. 1, 2; 4–6, cores; 3, 7, flakes. Small flake core (1); Unidirectional asymmetrical core (2); Pseudo-burin on core-edge transverse flake (3); Bidirectional core (4); Discoid-like core (5); Discoid-like core (b) with a refitted accidental bladelet removal (a) (6); Elongated flake (7) (drawings by N. Zwyns). After Zhang et al. [24].

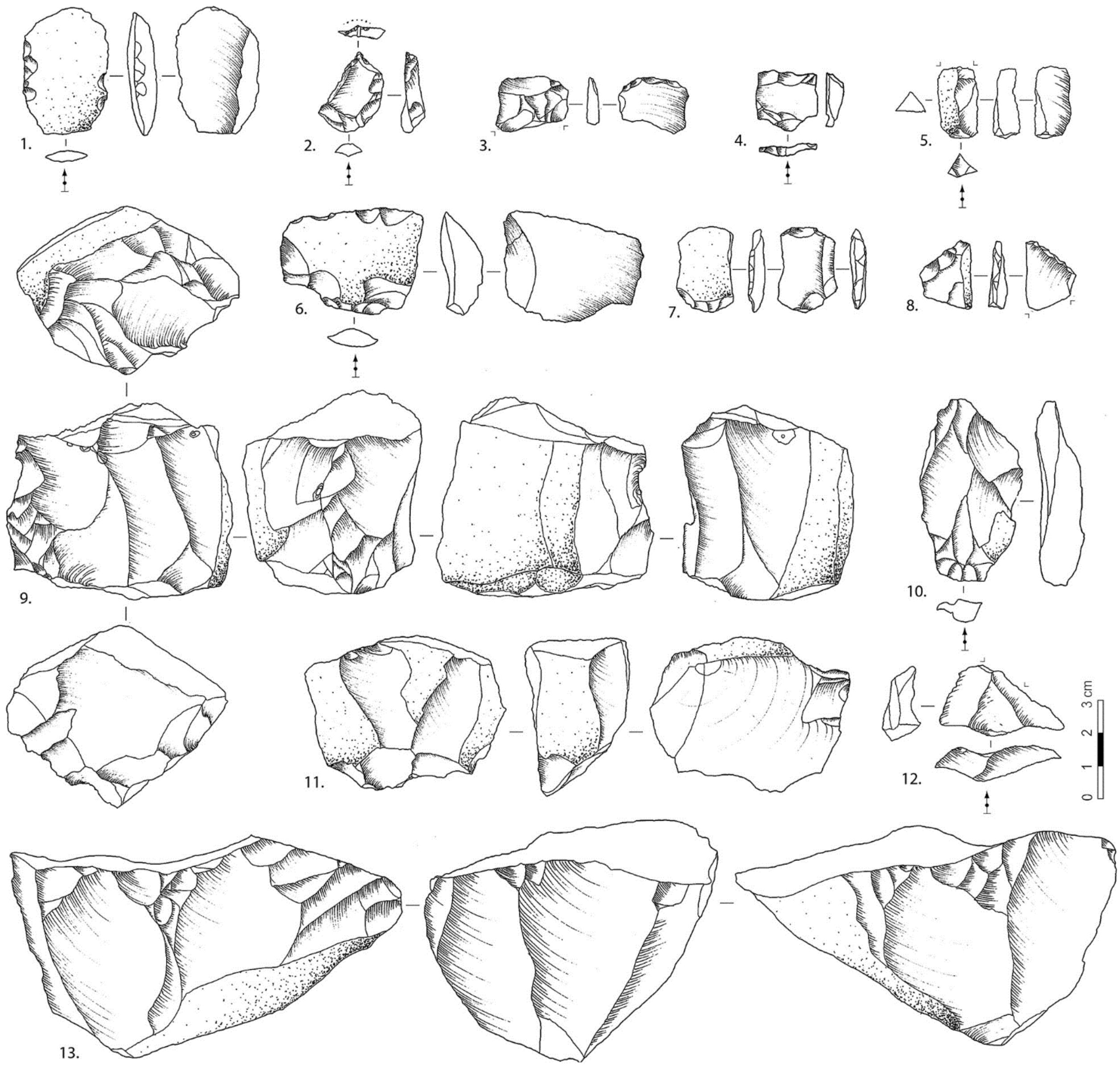

Fig 4. The illustration of variability in technological markers at CL1b. A few technological variations accrued low frequency at site. 1–4, 6–8: retouched/used flakes; 5, 10, 12: flakes; 9, 11, 13: cores. Retouched cortical flake (1); Perforator (2); Flakes with used edge (?) (3, 4, 8, 7); Multiple platform core (9); Levallois Flake (10); Type 1—Core on flake (11); Pseudo-Levallois point (12); Anvil-assisted core (?) (13) (drawings by N. Zwyns). After Zhang et al. [24].

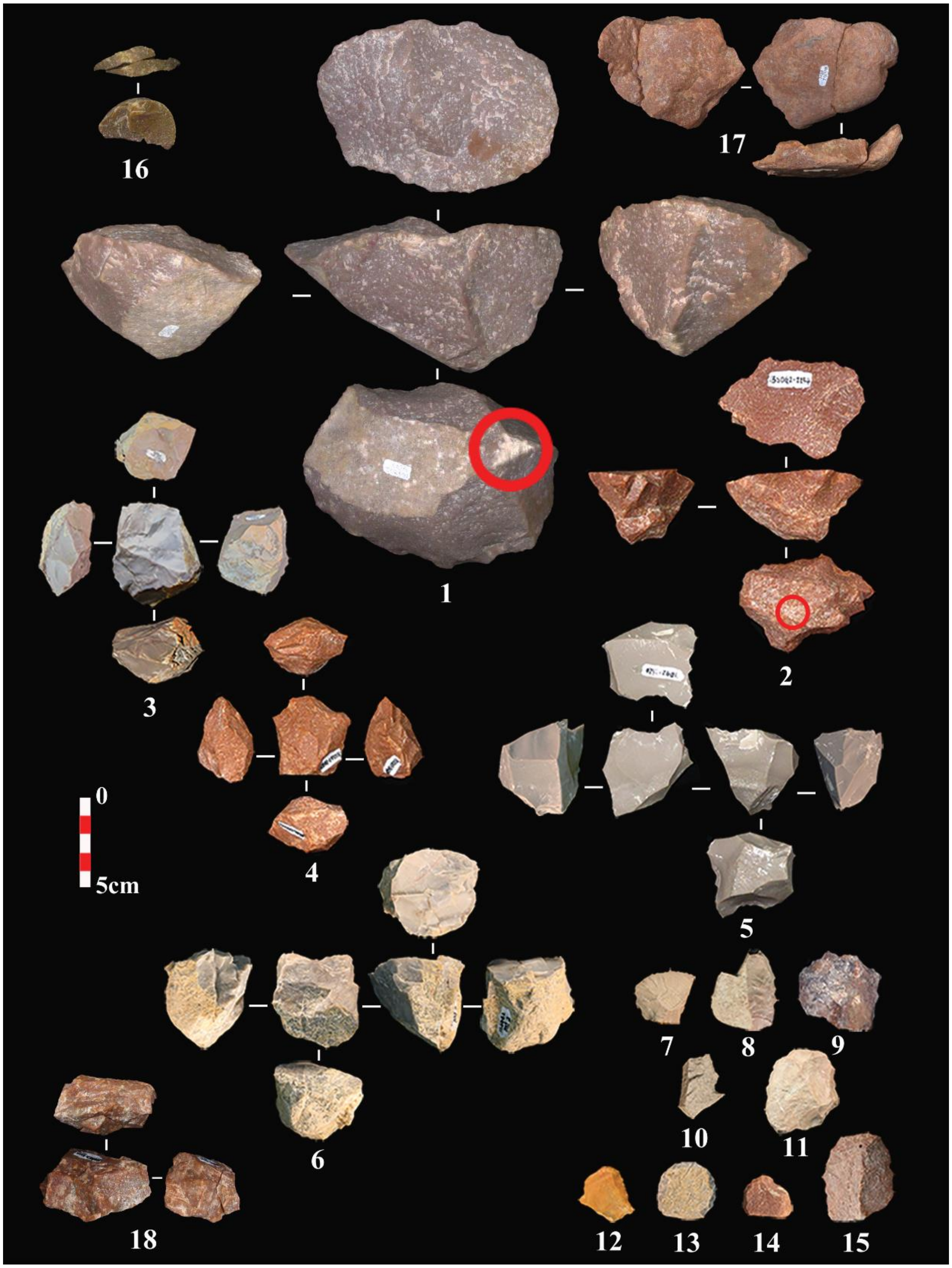

Fig 5. A few examples of cores and tools at SDG2. Single-platform cores (anvil-assisted cores?) (1–2); Discoid-like/alternating flaking cores (3–4); Multi-platform cores (?) (5–6); Side scrapers (7–8); Denticulate (9); Notch (10); Splintered piece (11); End scrapers (12–15); Refits (16–18). After Zhang et al. [24].

The lithics throughout the SDG2 sequence are mostly made from locally available raw materials, namely chert, siliceous limestone, quartzite, sandstone, and quartz [24,80,82]. Variation in raw material selection between the layers at SDG2 has been reported from studies on material from all three trenches [24,80-82]. The assemblages from CL5-1a were made exclusively on local raw materials collected as pebbles from nearby cobble fields and exposed cobble layers [24,80,82]. Low overall patterns of reduction intensity and retouch frequency among the unprepared flake assemblages SDG2 indicate limited artifact curation and/or transport at the site [82]. Such a situation is interpreted as indicative of a residential mobility pattern of landscape use, with a foraging radius centered on the local river valley at SDG [80,82]. In contrast, the presence of curated artifacts made on non-local chert in the CL2 assemblage has been interpreted as representing an increase in the frequency of long distance foraging trips [24,80,82]. Alternatively, it may illustrate an expansion of social networks involving groups outside of the SDG region which facilitated the transport of non-local raw material and artifacts made on such material to toolmakers at SDG2. Such a changes in residential mobility and/or regional social networks observed within CL2 have been suggested as possibly reflecting the colder and dryer climatic conditions at this time, which would have impacted the distribution of food resources in the local environment [80,82]. Such an interpretation might also be supported by the appearance of ostrich eggshell beads in these levels which can serve a social signaling function for individuals and groups [114,115].

Comparison of the archaeological pattern of raw material selection at the site with the baseline of raw material availability in the local environment, estimated from systematic surveys, suggests that raw material preferences at the site at times positively and negatively deviated from baseline raw material availability [24,80]. Though chert was not considered in the survey, archaeological patterns for the selection of silicious limestone, sandstone, and quartzite did not match baseline frequencies across CL5-1a [24,80,81]. Additionally, cortex percentages of these raw materials indicate that all the assemblages from SDG2 have about half or less the amount of cortex expected for their given volume, suggesting that between ca.35-28 ka lithic artifacts were regularly being transported away as groups subsisted around the Yellow River basin [80,81].

In terms of blank selection for retouch, larger formats were preferred when using silicious limestone, but no trend was observed for chert or quartzite [24]. Usewear studies of the unretouched and retouched flakes from CL3 and CL2 excavated from T3 also indicate that both artifact types exhibit microscopic evidence of having been used in similar frequencies, suggesting that use of unretouched flakes for cutting tasks regularly took place at the site in these levels [31]. This final point is critical, as the analysis of blank cutting edge efficiency focuses exclusively on unretouched blanks [57]. The situation at SDG2 therefore suggests that the unprepared flakes within the archaeological assemblages post-dating the disappearance of the IUP were intentionally made to be used in cutting tasks without further modification. Therefore, differences in cutting edge efficiency between cultural levels at SDG2 may reflect ecological changes in tool making behavior that might not be observable using traditional techno-typological analyses [e.g. 2,3,12,19-24].

Material and Methods

The SDG2 lithic assemblages sampled here were excavated from T3 during the 2014–2016 filed seasons [24,80,81,110,117]. The studied material is curated at the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences in Beijing, China. Data was collected from the CL5-1a artifact assemblages and included: 1) flake completeness; 2) flake length, width, thickness, and mass; 3) flake production method(s) and technique(s); 4) the presence or absence of retouch; and 5) cutting edge length following previous studies [57,58]. All complete, unretouched flakes are included in this study given that incomplete or retouched flakes are missing part of their initial mass and cutting edge length [57,58,84,85,87,90]. Flakes were not disqualified from our analysis due to their role within a reduction sequence, whether predetermined or predetermining [57,58,87,90], as any flake with a cutting edge could potentially have been used in a subsistence based task [31,88,90]. The total artifact sample included in this study consists of 1189 flakes from CL5-CL1a and chronologically spans the latter half of MIS 3, between ca. 35-28 ka [110] (Table 1). In terms of raw material, the largest number of flakes within the study sample are made from locally available quartzite, followed by silicious limestone, chert, sandstone, and quartz, respectively. Due to sample size limitations quartz flakes (n=30) are included within the sandstone (n=114) category for modeling purposes (N=144). Cherts were not differentiated between local and non-local, as identification of chert provenience is still an open issue at SDG [80]

Table 1. The total frequency of flake raw material types sampled within each cultural layer.

	Raw material				
Cultural Layer	**Quartzite**	**Limestone**	**Chert**	**Sandstone**	**Total**
CL1a	26	9	31	5	**71**
CL1b	163	19	46	81	**309**
CL2	54	52	31	16	**153**
CL3	141	264	171	34	**610**
CL5	18	15	5	8	**46**
Total	**402**	**359**	**284**	**144**	**1189**

As in previous studies [57,58], we only measure segments of cutting edge length from a flakes perimeter that exhibits a sharp edge between its dorsal and ventral surface - defined here as <50° for flakes that are <40 mm in size, and <70° for flakes that are >40 mm in size. All relevant data were collected into an E4-MSAccess database (oldstoneage.com). For metric data, a standard digital caliper, digital scale, and a metric sewing tape measure were used following Johnson et al. [57,58]. The sewing tape measure was used to record the length of a flake's cutting edge to the nearest 5 mm to minimize precision error [57].

Statistical modeling

A notable percentage of flakes in our sample have no measurable cutting edge, here termed 'failed blanks' (Table 2). In past work we have reported the existence of failed blanks [57,58], but their numbers were low enough that there was no practical analytic approach for incorporating them. In the present sample the number of failed blanks is large enough that they cannot be ignored. For this reason, we turn to a two-part model [119] having both outcomes: 1) blank failure; and 2) cutting edge length, given that the blank did not fail.

Table 2. The number of failed blanks per cultural layer and raw material type

	Raw material				
Cultural Layer	**Quartzite**	**Limestone**	**Chert**	**Sandstone**	**Total**
CL1a	5	3	5	3	**16**
CL1b	15	3	1	22	**41**
CL2	3	5	2	0	**10**
CL3	5	17	19	4	**45**
CL5	2	2	0	0	**4**
Total	**30**	**30**	**27**	**29**	**116**

The two part model, often call a Hurdle Model, has the following form for cutting edge length, *l*:

$$h(l;\pi,\boldsymbol{\gamma}) = \begin{cases} 1-\ \pi; l = 0 \\ \pi g(l;\boldsymbol{\gamma})\ ; l > 0 \end{cases}$$

where π is the probability of blank success and *g* is a probability density for a cutting edge length that is greater than zero with parameter $\boldsymbol{\gamma}$. Models of this form have diverse applications, including Paleolithic archaeology and human behavioral ecology [120-122].

The two parts of the Hurdle model are further specified by their dependence on blank mass as well as other factors of potential interest such as cultural layer. For blank *b* in cultural layer *c* the log-odds of blank success are:

$$\log\left(\frac{\pi_{b,c}}{1-\pi_{b,c}}\right) = \beta_0 + \beta_m \log Mass + \beta_c + \beta_{m*c} \log Mass, \qquad (1)$$

where β_0 is the intercept, β_m is the coefficient of log Mass, β_c is the additive effect of cultural layer c, and β_{m*c} is the interaction effect of log Mass and cultural layer c. Similarly, the cutting edge length l, given that the blank did not fail, is:

$$l_{b,c} = \gamma_0 + \gamma_m \log Mass + \gamma_c + \gamma_{m*c} \log Mass + \varepsilon_{b,c}, \qquad (2)$$

where the roles of γ_0, γ_m, γ_c, and γ_{m*c} are as above. As in past work [57,58], we assume that the variance of the error term, ε, increases with blank mass and therefor apply regression weights of the form:

$$w = 1/\log Mass.$$

Previous work has identified changes in raw material economy across the cultural layers at SDG2 based on formal and informal comparisons of raw material frequencies across assemblages [24,80]. Here we make a formal statistical comparison of our flake sample by analyzing a contingency table of raw material type by cultural layer. Based on our findings described below, we proceeded to incorporate raw material type as a factorial covariate in an extended version of the hurdle model described above. For blank b, of raw material type t, in cultural layer c the log-odds of blank success are:

$$\log\left(\frac{\pi_{b,t,c}}{1-\pi_{b,t,c}}\right) = \beta_0 + \beta_m \log Mass + \beta_t + \beta_c + \beta_{m*t} \log Mass + \beta_{m*c} \log Mass + \beta_{t*c} + \beta_{m*t*c} \log Mass.$$

Analogously, the cutting edge length, given that the blank did not fail, is:

$$l_{b,c} = \gamma_0 + \gamma_m \log Mass + \gamma_t + \gamma_c + \gamma_{m*t} \log Mass + \gamma_{m*c} \log Mass + \gamma_{t*c} + \gamma_{m*t*c} \log Mass + \varepsilon_{b,t,c}.$$

Practically, these models containing three-way interactions allow for unique differences in the two outcomes, blank failure and cutting edge length, between layers for each raw material type.

Although the total sample from SDG2 is relatively large, the number of artifacts per layer is not balanced; furthermore, the cross tabulation of layer and raw material type at times results in small sample sizes (Table 1). Failed blanks were common enough in these assemblages to require a Hurdle Model, but when cross tabulated the number of failed blanks at times is also very few (Table 2). We undertake Bayesian modeling to investigate questions regarding temporal trends in cutting edge efficiency at SDG2 despite these small sample sizes. Bayesian approaches can prevent numerical problems often encountered when using more conventional methods on small samples [123,124]. A Bayesian approach furthermore allows us to use informative prior distributions for model parameters, derived from subjective expert reasoning.

The intercept of the Hurdle Model, β_0 in equation 1, captures the log odds of blank failure for a hypothetical blank having log mass in mgs equal to zero, in other words a blank of mass 1mg. Although such a blank is imaginary in this case, as no blanks of such small size exist in the study sample, the Bayesian approach encourages us to carry out the thought experiment of imagining the failure rate of such blanks, as part of specifying prior distributions. Reasoning that a 1 mg flake would have a failure probability of 0.9, therefore a log odds of failure log(0.9/0.1) = 2.2, we specified a Gaussian prior with mean 2.2 and standard deviation 1 for β_0. We had no prior beliefs about the relationships of blank failure to blank mass, cultural layer, or their interaction, and so specified Gaussian priors with mean 0 and standard deviation 1 for β_m, β_c, and β_{m*c}.

Reasoning that a 1 mg flake would have the smallest measurable cutting edge length, 5 mm, following our method of measurement, we set a Gaussian prior with mean log(5) = 1.6 and standard deviation 1 for

γ_0 in equation 2. Considering the slope of log Mass, γ_m in equation 2, which describes the relationship between the volumetric mass of a blank and its linear cutting edge length, we invoke geometric considerations to set a Gaussian prior with mean 1/3 and standard deviation of 1. We had no prior beliefs about the relationships of cutting edge length to cultural layer, or their interaction of blank mass and cultural layer, and so specified Gaussian priors with mean 0 and standard deviation 1 for γ_c, and γ_{m*c}.

Data analysis was performed in R [125] with the addition of the libraries Epi [126] Scales [127], Brms [128], and Dplyr [129].

Results

A Chi square test of independence with a simulated p-value (based on 999 replicates) shows a significant difference between cultural layers in terms of raw material type (X-squared = 262, p-value = 0.001). When the Pearson residuals are displayed, we can see which raw materials in which levels have highly deviant frequencies (Table 3). We observe that for CL1a chert is slightly overrepresented from what would be expected based on the study sample. Quartzite and sandstone are overrepresented in CL1b, limestone is underrepresented, and chert is slightly underrepresented. An even distribution of raw material types is observed in CL2, while CL3 shows the opposite pattern observed from CL1b. Finally, CL5 also shows an even distribution of raw material types.

Table 3. Pearson residuals of Chi square test of raw material type per cultural layer.

Over (+) and underrepresented (-) raw material frequencies are shown in bold.

	Raw material			
Cultural Layer	**Quartzite**	**Limestone**	**Chert**	**Sandstone**
CL1a	0.4	-2.7	**3.4**	-1.2
CL1b	**5.7**	**-7.7**	**-3.2**	**7.1**
CL2	0.3	0.9	-0.9	-0.6
CL3	**-4.5**	**5.9**	2.1	**-4.6**
CL5	0.6	0.3	-1.8	1

Our model regarding the odds of a flake being produced without a viable cutting edge (1) shows little difference between levels (Fig 6). Though the fitted lines of central tendency show some diachronic stratification in terms of their intercepts, notably CL1a, confidence bands show high levels of uncertainty around the central tendency for each cultural layer. A positive relationship between probability of blank failure and flake mass can be observed for each cultural layer as well. When the model is elaborated to include raw material type as a parameter, we see some reorganization of the lines of central tendency and an increase in uncertainty, but in general the previous pattern observed in Fig 6 holds (Fig 7).

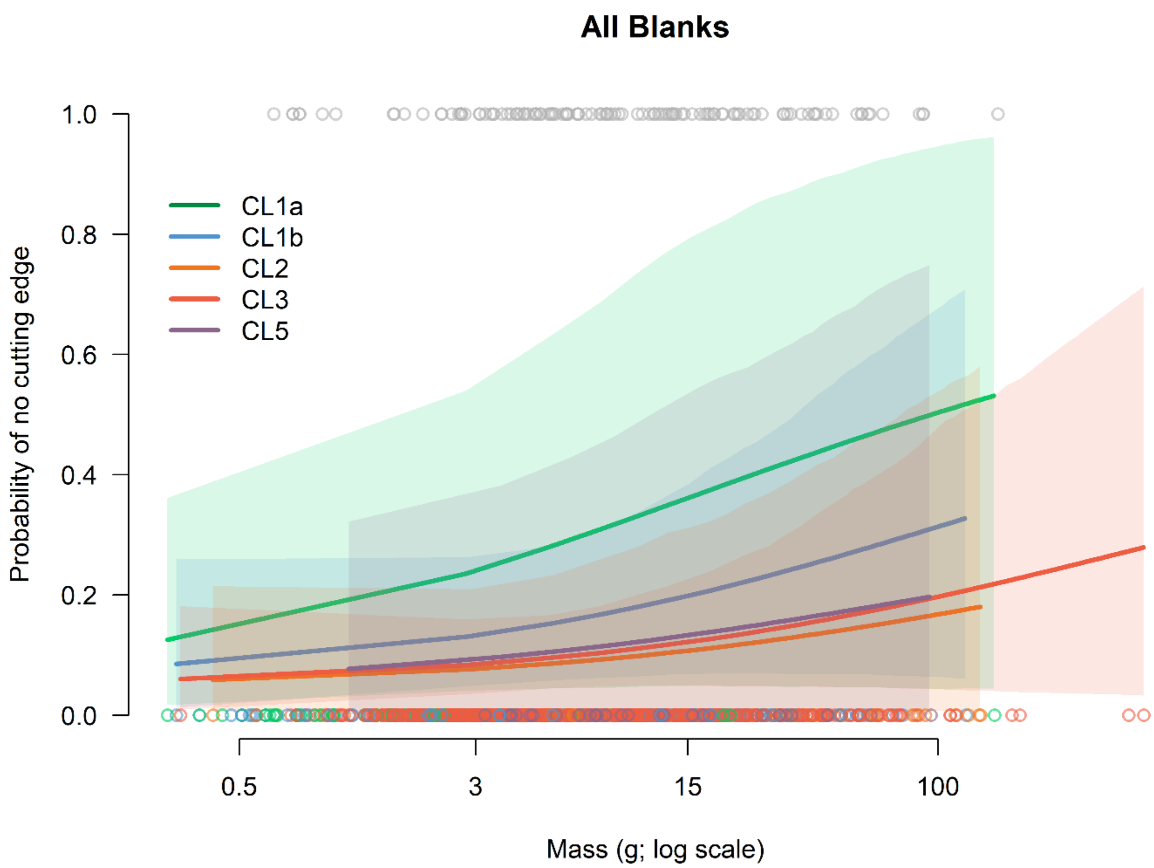

Fig 6. Fitted model illustrating log odds of blank failure within each cultural layer.

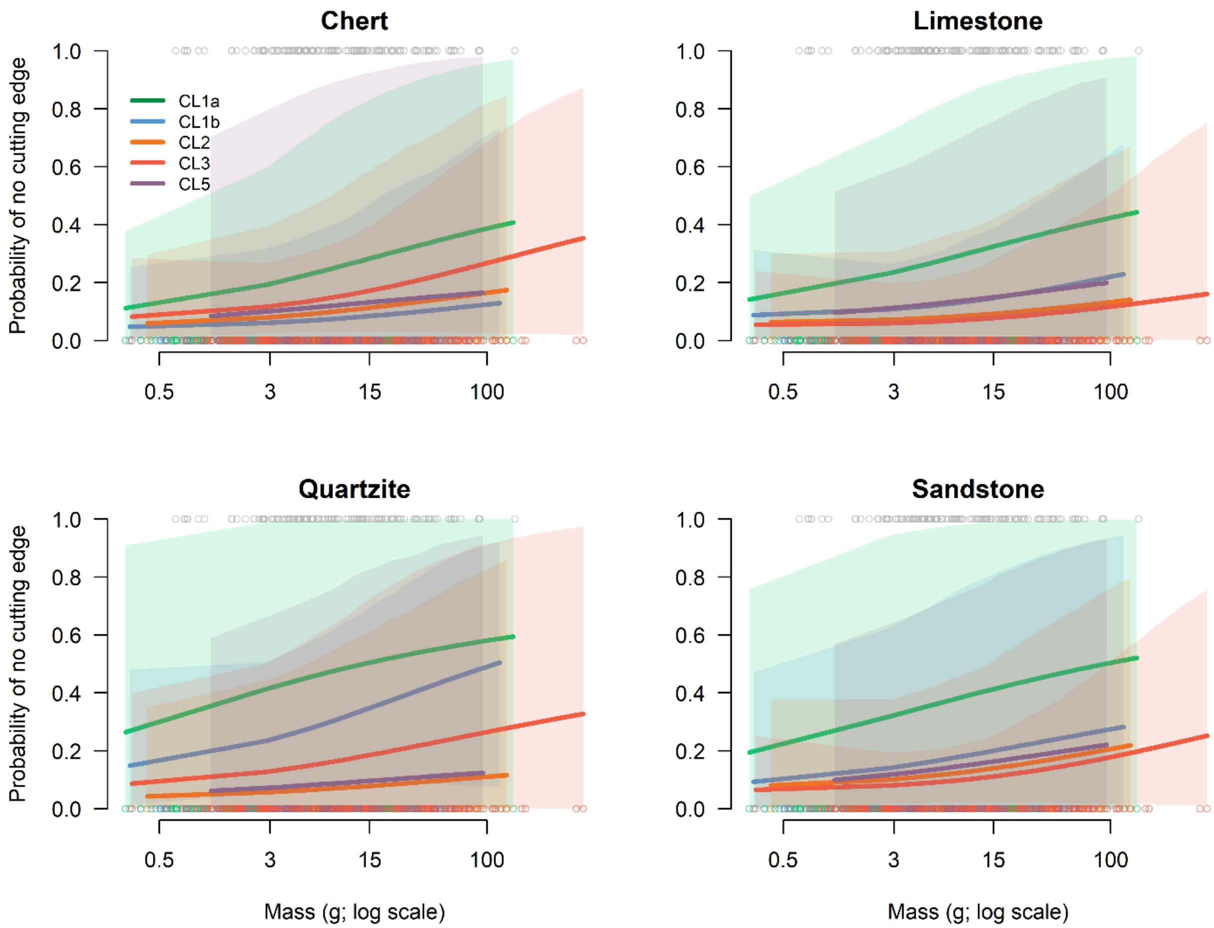

Fig 7. Fitted model illustrating log odds of blank failure within each cultural layer by raw material type.

Similarly, our model regarding blank cutting edge length (2) found little difference in cutting edge efficiency between the cultural layers (Fig 8). Cutting edge length increases with blank mass in a predictable way in all samples, however a difference in cutting edge efficiency between the five layers, which would be indicated by a vertical separation of the central lines [57], is not observed. Though the intercepts of the central lines are in some cases quite separated, for example CL1a, suggesting differences in efficiency, their confidence bands substantially overlap across all levels. Interestingly, the amorphous shape of the scatter suggests that variance in cutting edge length only slightly increases with blank mass, a different pattern than what was observed for lithic assemblages in the steppe region to the north [57,58]. When this model is elaborated to include raw material as a parameter the above pattern holds (Fig 9).

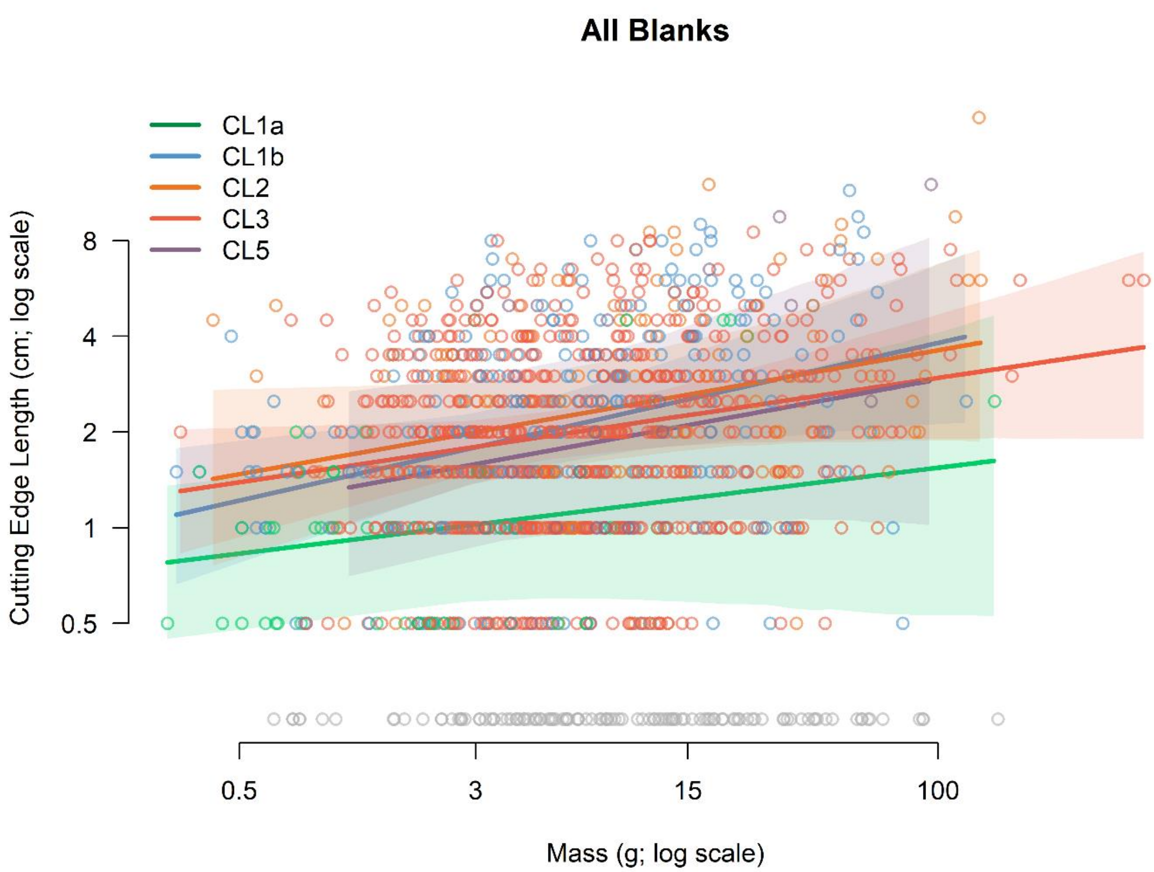

Fig 8. Fitted model illustrating cutting edge efficiency for all flakes within each cultural layer.

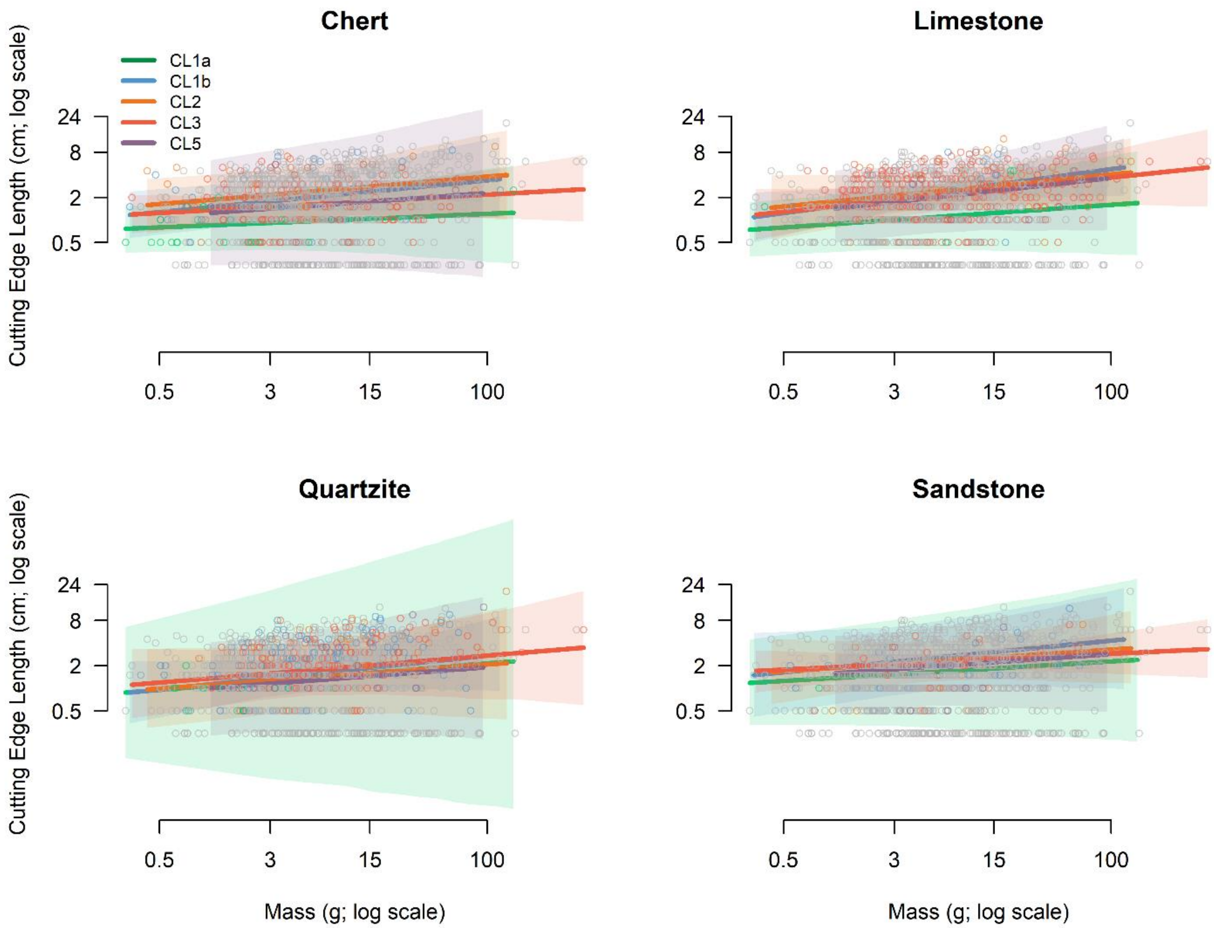

Fig 9. Fitted model illustrating cutting edge efficiency for all flakes within each cultural layer by raw material type.

Discussion

Our results indicate that neither the odds of blank failure nor blank cutting edge efficiency differed between CL5-1a, both in general and within the four main raw material types used by toolmakers at SDG2. This indicates that despite having different strategies of raw material selection over time [Table 3; see also 24,80,82], the groups which produced the CL5-1a archaeological assemblages were consistent in how efficiently they produced useable flakes from the raw materials they collected. Our results parallel

Zhang et al.'s [24] technological study of the T3 flake assemblages from CL5-1a, which suggests that after the disappearance of the IUP at SDG2 [43,78,110] little to no additional substantial technological changes took place regarding methods and techniques of core reduction and artifact manufacture at the site. Additionally, our results parallel analyses of cortex frequency within the flake assemblages recovered from CL5-1a at T3, which indicate no significant differences in how lithic artifacts were transported away from the site between ca.35-28 ka for use in and around the region [80,81].

The diachronic trend in local blank cutting edge efficiency at SDG2 is distinct from that observed in the Tolbor Valley of northern Mongolia, where the IUP was followed by a technological shift to the EUP [53-58]. As also observed from some sites in Western Eurasia [84,90], the technological shift to the EUP at Tolbor ca. 42-35 ka involved the miniaturization of lithic toolkits and coincided with an increase in the cutting edge efficiency of small flakes, blades, and bladelets [57,58]. The production of these small EUP blanks is generally thought to have been part of a technological strategy involving the production of highly standardized, interchangeable lithic inserts that could be hafted into the mortises of composite cutting tools and hunting weapons [58]. The shift from the IUP to the EUP in some contexts is also interpreted as involving a shift from a pattern of residential mobility to a more logistical strategy [90] - as toolmakers went from organizing their technological behavior around provisioning highly mobile individuals that planned their landscape use around resource availability within a daily foraging range, to provisioning fixed places in one or more locations on the landscape from which some group members would periodically operate over long distances and extended periods of time before returning.

The SDG2 unprepared flake assemblages from CL5-1a are interpreted as being part of a residential mobility strategy as well [82], with artifact accumulation representing a palimpsest of activities common to a base camp setting, such as making lithic artifacts, personal ornaments, and cooking food stuffs [130]. Though there is little inference regarding the mobility strategies underlying the prior IUP toolmaking groups at SDG between ca. 43-35 ka., it might also be assumed that theirs involved residential patterns of mobility and landscape use as well. Mobility patterns are thought to have changed at SDG2 during the period in which CL2 formed, as indicated by the increase in 'non-local' chert use [24,82], which is taken as being a proxy for an increased, possibly logistical, mobility strategy and/or the novel participation in social trade networks by residents at SDG2 - the latter also possibly indicated by the coeval appearance of ostrich eggshell beads and use of ochre at the site in [115,116]. These changes are framed as an adaptive response to the colder and dryer climatic conditions in East Asia ca. 30 ka, triggered by the onset of MIS 2 [82]. However, more recent dates from T3 places the age of CL2 closer to ca. 33 ka [110]. Nevertheless, if such a change in mobility or social organization took place at SDG2 during the formation of CL2, and if there was an ecological change in the region prompted by the onset of MIS 2, our results indicate that neither factor involved nor triggered an increase in blank cutting edge efficiency. This is notable, as increasing cutting edge efficiency would have hypothetically been adaptive in the context of a heightened mobility strategy requiring longer forays away from raw material resources, possibly related to maintaining social networks or subsisting in a landscape characterized by a low carrying capacity due to an overall colder and dryer climatic regime.

Instead, our results suggest that toolmaking behavior related to flake cutting edge efficiency at SDG2 between ca. 35-28 ka was more likely under a kind of stabilizing selection, wherein those behaviors which significantly increased or decreased the cutting edge efficiency of flakes away from a certain baseline of efficiency would have been selected against. A recent usewear study suggests that some of the unprepared flakes made at SDG2 were used in cutting and scraping tasks involving medium to soft organic materials, but also harder materials such as wood [31]. This preliminary evidence for woodworking taking place at SDG2 is noteworthy, considering that some explanations for the use of unprepared flake technologies during MIS 3 in East Asia suggest that flake dominated toolkits from this period may have been largely geared toward curating wooden artifacts, such as thrusting or throwing spears, or structural poles for shelters [25]. The paleoenvironment at SDG2 is interpreted as a wooded savannah within a lacustrine dominated ecosystem [24], theoretically meaning wood as a raw material would have been readily available for toolmakers and tool users in the region. This is supported by substantial evidence for hearth features as well [130], which could suggest that MIS 3 groups at SDG2 may not have had to regularly rely on alternative sources of fuel for cooking and heating [54].

Currently, our results do not provide any additional insights into the cause of the observed changes in lithic raw material selection at SDG2 after the disappearance of the IUP in the region. The fluctuations in raw material frequency observed in CL5-1a so far do not seem to be based on technological decisions related to mobility or flake cutting edge efficiency. In some cases, the largest produced flakes of silicious limestone were selected for retouch at the site, which could be explained by toolmakers preferring this material for its more easily controllable fracture mechanics when producing large flakes [24]. However, if this were the case the relative absence of silicious limestone in CL1b-1a remains to be explained (Table 3) [24,80]. Additionally, while cutting edge efficiency may not have changed at SDG2 between 35-28 ka, future research aimed at determining whether there was a change in cutting edge efficiency during the shift from the IUP to unprepared flake production at SDG ca. 35 ka would be helpful for understanding whether this major technological turnover was at all related to changes in ecological factors which inform lithic toolkit evolutionary efficiency in the region [84].

Without knowing the taxonomic identity (identities) of the tool makers at SDG2, interpreting our results is additionally difficult. Evidence for *H. sapiens* in East Asia coinciding with the formation of the CL5-1a assemblages suggests that unprepared flake technologies may be proprietary to our species at SDG2 [131-133]. Supporting this are the symbolic ornaments from CL3-2 [24,114-116] and other coeval sites in the monsoon zone [134] suggest a “modern” cultural capacity of human groups living in the region during MIS 3. However, *H. sapiens* in East Asia during the latter half of MIS 3 had already met and hybridized with Denisovans [67,70,71,135], and the Denisovan last appearance datum in mainland East Asia is not until ca. 30 ka based on sediment aDNA from the Tibetan Plateau [69]. This suggests that while the presence of symbolic behaviors in CL3-2 at SDG2 post-dating the disappearance of the IUP may indicate the persistence of one or more allochthonous populations of *H. sapiens* in the region, the switch to a technological strategy emphasizing unprepared flake production in CL5-1a may have instead been the result of Denisovan, or *H. sapiens* and Denisovan joint occupation of SDG. Knowing more about the general and specific technological behaviors of Denisovans in East Asia and the kind(s) of energy budget(s) toolmakers at SDG2 needed to maintain will help our understanding of changes in the cutting edge efficiency of lithic tool kits in the region during MIS 3. Interestingly, the genetic signatures of *H. sapiens* individuals living in both the steppe and monsoon zones of East Asia also suggest that human groups in the two regions were in contact with one another along the boundary, or "frontier region" [30], between the two areas [66]. The interplay of population dynamics and its past influence on the formation of archaeological record in East Asia, and economic details regarding the degree to which technological turnovers reflect adaptive responses to changing ecological conditions during MIS3, are both topics that cutting edge efficiency analyses, such as that described here and elsewhere [57,58], can contribute to meaningfully.

Conclusions

We employed a Bayesian approach to model raw material influences on cutting edge efficiency and failure rate of unprepared flakes within five lithic assemblages (CL5-1a) from SDG2, dating between ca. 35-28 ka. Our results indicate little difference throughout the archaeological sequence, and that observed changes in raw material selection are poorly explained by selective pressures related to cutting edge efficiency. These results parallel observations of little to no change in core reduction methods and artifact transport at the site. Together, the picture from SDG2 seems to be one of a major technological turnover from the allochthonous IUP to a relatively stable techno-economic strategy emphasizing unprepared flake production. Why an unprepared flake technological strategy was adopted by populations living at the site after the disappearance of the IUP, and why raw material selection for lithic toolkit production fluctuated so extensively between ca. 35-28 ka has yet to be satisfactorily explained.

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Chapter 5: Conclusion

Statistically modeling changes in blank cutting edge efficiency in the Tolbor Valley, and at Shuidonggou Locality 2 (SDG2), has provided useful insights into the pattern of lithic technological variation observed in each region during Marine Isotope Stage 3 (MIS 3) and MIS 2.

In the northern steppe, the Initial Upper Paleolithic (IUP) arrives at Tolbor ca. 45 ka and is then followed by the appearance of the Early Upper Paleolithic (EUP) between ca. 42-35 ka, and finally the Late Upper Paleolithic (LUP) after ca. 28 ka [1-5]. Our model suggests that the shift from large IUP blade production to bladelet and later microblade production at Tolbor, characteristic of a technological process known as lithic miniaturization [6-8], coincided with increases in the cutting edge efficiency of small blanks within lithic assemblages formed in the region. The increase from the IUP to the EUP at Tolbor was gradual, in that the earliest instance of the EUP ca. 42 ka shows no detectable difference in cutting edge efficiency within our model compared to the IUP ca. 45 ka, but the later stage of the EUP ca. 35 ka does [5]. The increase in cutting edge efficiency from the EUP to the LUP in the valley is subsequently inferred by the improved scaling that microblades exhibit compared to their bladelet, blade, and flake counterparts [4].

In the summer monsoon zone to the south, the IUP is documented at SDG2 between ca. 43-35 ka [9-10], before its replacement by a series of non-descript, unprepared flake assemblages dating between ca. 35-28 ka [10-13]. These unprepared flake assemblages from SDG2, like many other MIS 3 sites in the monsoon zone, do not exhibit specific production tendencies beyond subtle technical and typological variations - though they do document shifts in strategies of lithic raw material selection and use [11,12]. Furthermore, the cutting edge efficiency of the SDG2 flake assemblages show no detectable difference from one another within our model, despite the observed shifts in raw material selection over time [13].

Thus, the trends in blank cutting edge efficiency at Tolbor and SDG2 can be said to mirror their respective regional patterns of lithic technological development.

At Tolbor, increases in small blank cutting edge efficiency coincided with the resettlement of the East Asian steppe by *Homo sapiens* expanding into the region from the west along a 'northern route' [2,4,14-16], suggesting that ecological pressures on our species in this area may have favored technological behaviors that economized the production of lithic cutting edges. These increases in cutting edge efficiency within the model from Tolbor are specifically associated with the small fraction of the lithic assemblages - i.e. small flakes, blades, bladelets, and microblades - thought to have been used as inserts in composite cutting tools and hunting weapons [4,5]. Such tools would have been advantageous in landscapes with low carrying capacities that required more complex and long ranging extractive foraging strategies - where retooling damaged hunting gear, while far afield, could be easily accomplished by producing small, standardized blanks from easily transportable cores [17-21].

The first increase in small blank production at Tolbor, observed during the later stage of the EUP ca. 35 ka, took place after Heinrich Event 4 (H4), a cold period that occurred ca. 38 ka. With the passing of H4 the IUP seems to have disappeared in the valley, and much throughout the steppe [2], leaving EUP strategies with their associated methods of bladelet production to monopolize the region. The increase in efficiency associated with the later stage of the EUP may therefore have been an adaptive response of human groups living in the region to the ecological effects caused by H4, which may have necessitated a considerable shift in subsistence strategies that informed lithic technological behavior. The second increase in cutting edge efficiency, indicated by the unique scaling relationship of LUP microblades, corresponds to the climatic period of MIS 2, which was even colder and dryer than the preceding MIS 3 phase [4]. This suggests that LUP microblade production behavior, and its ability to improved cutting edge efficiency, may have also been an adaptive response to yet another severe climatic downturn in the steppe region.

In the Hisma Basin of Jordan, a similar increase in cutting edge efficiency from the IUP to the EUP, also associated with small blank production, is interpreted as being part of a shift from a residential foraging strategy to a logistical one [22]. Future research should be aimed at determining whether the shift from the IUP to the EUP at Tolbor also coincided with a shift from a strategy of provisioning individuals with lithic resources, to one of logistically provisioning places. Doing so would help determine whether the increase in cutting edge efficiency observed between the IUP and EUP at Tolbor can be partly explained by a shift in the mobility related subsistence strategies adopted within the changing MIS 3 landscape.

In West Asia the transition from the IUP to the EUP is also thought to have been the result of *in situ* innovations by *H. sapiens* groups living in the region [23-25]. Whether the transition from the IUP to the EUP at Tolbor was similarly the result of *in situ* innovations by the direct descendants of allochthonous IUP groups, or alternatively was the result of subsequent eastward extensions of EUP groups into the region, or the transmission of their technology and culture into the region, or some combination of all these scenarios, is unclear at this time [26]. This same uncertainty somewhat surrounds the appearance of LUP microblade technology in the Tolbor Valley as well [27]. Nonetheless, what is evident is that some groups of *H. sapiens* living in the steppe and coeval with the EUP in the region carried alleles inherited from Denisovans, as well as from *H. sapiens* populations inhabiting the monsoon zone to the south [28-29]. However, the relevance of these population dynamics on the emergence and development of the EUP and LUP in East Asia also remains unclear.

Regarding the more southern region of the Yellow River basin, our model does not detect a difference in cutting edge efficiency between the five unprepared flake assemblages at SDG2 dating between ca. 35-28 ka [11]. These flake assemblages are interpreted as being part of a residential subsistence strategy until ca. 33 ka, when a longer-distance mobility strategy is inferred from an archaeological signal of increased non-local raw material use during the formation of CL2 [12,13]. However, if such a brief change in mobility took place at SDG2 at that time, it is not reflected in our model as would be expected if mobility were related to blank cutting edge efficiency, considering that increasing landscape mobility decreases raw material availability and places pressure on increasing efficiency of sharp edge production [30-31].

The flake assemblages from SDG2 also post-date the disappearance of the IUP in the region ca 35 ka, leaving open the question as to whether the shift from IUP blade production to unprepared flake technology at SDG coincided with a corresponding change in blank cutting edge efficiency. One expectation would be that, because blades intrinsically have more cutting edge per unit of mass than flakes [4,32], there would have been a decrease in cutting edge efficiency associated with this technological turnover. However, recent studies suggest that IUP technology, and blade production in general, may not have been more efficient at creating usable sharp edges than some generic and prepared flake production strategies [32,33]. With the data from SDG2 already modeled here [13], the inclusion of data from SDG1 for comparison would be a relatively straight forward effort.

Whether or not the shift from the IUP to flake production at SDG2 involved a change in cutting edge efficiency, the stability around this parameter at the site between ca. 35-28 ka suggests stabilizing selection on sharp edge production in the region during this period. Notably, the environment at SDG shifted ca. 35 ka from a lake marsh to a terrestrial lake shore setting [10], corresponding with the appearance of unprepared flake production [12]. Flake technologies may therefore have been better adapted to this new environment, resulting in their succession within the record. For example, it is possible that resources in the region became sufficiently available to be optimally exploited by lower effort lithic technological strategies (i.e. unprepared flakes) while practicing residential patterns of landscape use, and that IUP blade production became too costly or too poorly suited to the new paleoenvironment in some way.

The findings from investigating flake usewear at SDG2 can also be reevaluated considering the results from our cutting edge efficiency model [34]. The results of a recent usewear study of the post-IUP flakes from SDG2 suggests that unretouched and retouched flakes exhibit usewear traces at similar frequencies, indicating that unretouched blanks were regularly used at the site without further modification [34]. The range of activities reflected in the usewear study identified the use of archaeological lithic edges against both soft and hard materials, including wood. The use of flake edges to modify wooden objects at SDG2 is noteworthy as some explanations for the widespread production of unprepared flakes during MIS 3 in the monsoon zone of East Asia propose the use of flakes as an intermediary technology for producing artifacts made of wood [35] – such as thrusting or throwing spears for hunting large to medium game, and poles for constructing transportable, collapsible shelters.

And while classic Upper Paleolithic tool types from SDG2 such as endscrapers may have also been involved in woodworking and other activities at the site, we must consider the possibility that they may have also been made for small flake and bladelet production [36]. As the screened material from SDG2 have not been studied yet, future work will have to target this component of the lithic assemblages from the site to confirm that bladelet production strategies were indeed not taking place at SDG2 between ca. 35-28 ka [12,13]. An alternative hypothesis is that toolmakers at SDG2 were technologically unable to develop a formal bladelet or microblade production strategy from an unprepared flake technological background because the prerequisite information and skills for laminar blank production were not part of the knowledge-pool of groups in the region after the disappearance of IUP blade technologies.

The taxonomic identity of the toolmakers at SDG2 also has some bearing on the results of our cutting edge efficiency model, as knowing their general physiology provides important context regarding the energy budget that their technology was geared toward maintaining. It can be safely assumed at this time that *H. sapiens* were the makers of the IUP at SDG [14-16], but what about the makers of the unprepared flake assemblages? Of the known MIS 3 hominin species in East Asia only two currently seem plausible: *H. sapiens* and Denisovans. The case for Denisovans is admittedly the weakest considering there is currently no direct evidence for Denisovans dating to MIS 3 outside of the Tibetan Plateau, where only aDNA from archaeological sediment dating to ca. 30 ka has been recovered [37]. Aside from this, the only other potential signature for Denisovans in the area during MIS 3 comes from evidence of Denisovan introgression into the antecedents of the Tianyuan and Salkhit individuals [28,29,38,39].

The producers of the flake assemblages at SDG2 being *H. sapiens* seems more parsimonious based on fossil evidence for their presence in East Asia during the latter part of MIS 3, as mentioned above [28,29]. Evidence for the interaction of two genetically distinct human groups, one located in the southern monsoon zone and the other in the northern steppe, identified from the Salkhit fossil crania also better supports this scenario [28]. The Salkhit individual inherited genes from both these groups and was discovered in the steppe of northeastern Mongolia. This suggests that the technological turnover identified at SDG may have been due to the expansion of the more southern group, probably after H4, which were responsible for producing the flake assemblages. Whether this southern group of *H. sapiens* coeval with the unprepared flake assemblages in the monsoon zone originated from populations expanding along the southern or northern route is unclear at this time [29].

The SDG2 flake assemblages also contain evidence of symbolic ornaments [12,13,40], an artifact type which has also been recovered from MIS 3 contexts in the steppe associated with Upper Paleolithic technologies [26,41], and from elsewhere in the monsoon zone associated with *H. sapiens* fossils [42], further supporting the hypothesis that our species continued to occupy SDG after the disappearance of the IUP. However, it is noted here that there is no evidence currently suggesting that Denisovans were incapable of creating symbolic artifacts. In fact, the evidence for introgression between our two species during MIS 3 suggests that human groups living in East Asia at this time may have also exchanged technological and cultural information with Denisovan groups, or members of both species may have cohabited sites as members of the same social group. Why there is not more early evidence of Denisovan introgression along the southern route of *H. sapiens* expansion is curious, as one would expect such a pattern given the presence of Denisovans in East Asia during MIS 5 [37,43] and the supposed earlier timing of our species traversing the southern route during MIS 5 to MIS 4 [44-50].

All this brings us to the question: can we compare the cutting edge efficiency of Tolbor and SDG2 directly with one another? The answer is yes, just not yet. Doing so would require a much more sophisticated model that considers parameters such as raw material differences between regions, and any other technological and ecological factors which might affect cutting edge efficiency between regions. Identifying what these parameters are and their effects on blank cutting edge production in the archaeological record is another important avenue for future research regarding this topic. In time such a model can be built, one which will become more and more necessary as continued research into changes in blank cutting edge efficiency generates comparable results from different regions.

A critical part of making such comparisons will involve standardizing the measurement and analysis of cutting edge efficiency. One of the most important insights from this project is that methods which assume the scaling relationship between cutting edge length and mass, and which use proxies of edge length, are less sound than methods which infer these scaling relationships and use direct measures of cutting edge length [4]. Additionally, comparisons of blank cutting edge efficiency within and between assemblages can be greatly improved by traditional technological studies that reconstruct which blanks were made and subsequently selected for use and which were just byproducts of artifact manufacture. Complementary research approaches such as lithic usewear studies are also particularly equipped for this task. Understanding which blanks were used can tell us more about intentionality and agency underlying changes in blank cutting edge efficiency. Additionally, understanding how other materials besides lithics were used in cutting tasks, such as bone [51] or bamboo [35], will be important for a more complete picture of this fundamental evolutionary parameter of Pleistocene toolkits.

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