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Stone tool knapping quality and raw material selection behaviour in the Inner Asian Mountain Corridor

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A R T I C L E I N F O

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A B S T R A C T

Stone tool knapping quality is an important parameter in the study of lithic technology. A number of experimental and objective studies have contributed to the discussion on how stone quality affects the knappability and the final shape of an end product. However, systematic studies on how stone mechanical properties affect knappability and raw material selection behaviour remain few. Here, we investigate geological and archaeological samples of porphyry, chert, and sandstone from the Palaeolithic sites of southern Kazakhstan to evaluate whether the acquisition of raw materials was driven by specific mechanical properties (e.g., ease of knapping). We tested their degree of knappability using the Vickers indentation method and four-point bending tests. Our results suggest high variability in the mechanical properties of the studied samples. Porphyry and chert demonstrate unexpectedly high values of force to initiate a knapping crack and low fracture predictability. Despite such knapping force requirements, these raw materials were preferred by their knappers, suggesting that raw material selection was governed by other criteria, such as resistance to abrasion and edge damage.

1. Introduction

Raw material knapping quality, a suite of physical and structural characteristics that affect a rock's suitability for controlled fracturing, is an important parameter in investigating various aspects of the technological features of lithic assemblages. A number of studies indicate that stone quality represents one of the variables responsible for the morphology of an end product (Crabtree, 1967; Andrefsky, 1994b; Eren et al., 2014). One of the central aspects of raw material quality is the force needed to detach a flake, which has been considered as one of the major variables in the discussion of raw material's knappability, or its knapping quality. Studies investigating the knapping force include real-world knapping investigations (Eren et al., 2011; Li et al., 2022; 2023; Moos et al., 2025), actualistic tests based on understanding crack formation and propagation (Nickel and Schmidt, 2022), and investigations into knapping predictability (Nonaka et al., 2010). Some researchers suggest that the predictability of flake detachment and the ease of knapping of a material were primary criteria for its procurement and choice for producing prehistoric tools (Domanski et al., 1994), while others argue that lithic raw material selection mainly relied on its abundance in the landscape (Brantingham, 2003).

Tool-stone quality has also been regarded as a major factor in the technological organization of various stone industries in the Middle and Late Pleistocene (Andrefsky, 1994b; 2012; Brantingham et al., 2000; Orton, 2008; Terradillos-Bernal and Rodríguez-Álvarez, 2014). Taking into account knapping quality and availability, earlier research has demonstrated the prevalence of expedient or curated tools (Andrefsky, 1994a). In the context of Palaeolithic archaeology, expedient stone tools are quickly made and discarded, whereas curated tools are purposefully shaped and often maintained for long-term use (Binford, 1973). However, even though quality has a direct influence on lithic technology and organization, only a handful of formal studies have attempted to explain this phenomenon by means of actual mechanical tests. Some of these studies investigated mechanical properties, such as changes in fracture toughness of heat-treated and non-heated rocks (Domanski et al., 1994; Yonekura et al., 2006; Moník and Hadraba, 2016; Schmidt et al., 2019; Moník et al., 2021b; 2021a; Namen et al., 2022a; Suga et al., 2023), the resistance to abrasion (Braun et al., 2009), or microhardness (Yonekura and Suzuki, 2009). Although such studies yield valuable data on specific mechanical properties, the relationship between the obtained values and

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tool-stone quality, as subjectively experienced by experimental knappers, remained unknown. This is problematic because the correlation of actual mechanical measurements and subjective quality is important for understanding raw material selection criteria. In this regard, the physical model proposed by Nickel and Schmidt (2022) and refined by Schmidt et al. (2024) allows for interpreting rock mechanics in terms of knapping quality. Based on this model, the authors proposed that the selection of specific rocks for the production of specific types of tools was driven by precise criteria at one Middle Stone Age site in South Africa. Additional studies applying this model to diverse raw materials from other parts of the world would shed light on our understanding of prehistoric raw material procurement patterns in general.

Central Asia, with its diverse environmental setting, ranging from ice-peaked mountains, deserts, and steppes providing an abundance of different raw materials, is an ideal laboratory to test lithic raw material mechanics (Namen et al., 2022b; 2022c). In light of the increasing body of archaeological data from the Palaeolithic of Central Asia, understanding the patterns of lithic raw material selection strategies is becoming of great interest. Archaeological data suggest that the Upper Palaeolithic tool-makers of Central Asia heavily relied on the procurement of locally occurring raw materials (Taimagambetov, 1990; 2009; Ozherelyev et al., 2019; 2023a; 2023c). In the absence of apparently good-quality raw materials, the Late Pleistocene occupants of the Central Asian foothills opted to procure volcanic rocks, such as porphyry, or sedimentary siltstones and shales. Although porphyry has large phenocrysts and experimental knappers find flake removal difficult, Palaeolithic foragers were able to manufacture laminar and Levallois technology from it. For example, the majority of all lithic assemblages from the northern Tian Shan piedmonts (Ile Alatau range) were knapped on volcanic rocks (Taimagambetov, 2009; Fitzsimmons et al., 2017; Ozherelyev et al., 2019; Namen et al., 2024). However, other than porphyry's abundance in the landscape, the reasons for its selection remain unclear. Was it 1) the mechanical properties that drove its selection, or was it 2) due to the restriction of access (i.e., territory, exchange networks, etc.) that limited the use of better-quality materials? Given the diversity of raw materials used in the Upper Palaeolithic industries of Central Asia (namely in the two regions of southern Kazakhstan), we conduct a set of quantitative mechanical analyses on chert, sandstone, and porphyry used in the Palaeolithic industries of Kazakhstan. We use Schmidt et al.'s (2024) model of knapping quality to achieve our research objectives, which are aimed at (1) understanding fracture predictability and required force for detachment to understand the knapping properties of Central Asian stones and (2) evaluating how variability in knapping force may have influenced past raw material selection and technological strategies.

2. Archaeological background

The Palaeolithic of Kazakhstan has been extensively studied since the 1950 s. Despite this relatively long history of research, most discoveries have been limited to surface scatters of lithics, with only a handful of stratified sites. The stratified sites, containing layers of human occupations, are primarily located in the foothill zones of the Inner Asian Mountain Corridor of Kazakhstan (IAMC), a chain of mountain ranges of Central Asia (Alpysbaev, 1979; Taimagambetov, 1990; Taimagambetov and Ozherelyev, 2008; Fitzsimmons et al., 2017; Ozherelyev et al., 2019; 2023b; Iovita et al., 2020; Cuthbertson et al., 2021; Varis et al., 2022; Namen et al., 2024). In this study, we collected samples of lithic raw materials from both surface and stratified sites in two regions of the IAMC: the Valikhanov and Qyzyltau sites in the Qaratau range, as well as the Maibulaq site, located in the foothills of the Ile Alatau (Fig. 1; Table 1).

At the Qaratau range, most stone tools at the Valikhanov and Qyzyltau sites were knapped on locally occurring chert, which is abundant in the landscape in the forms of rolled river pebbles and outcropping beds, providing easy access for Palaeolithic knappers (Fig. 1). However, these materials were formed under different geologic conditions, as attested by their microstructure in our earlier studies (Namen et al., 2022b). The Valikhanov site, one of the first discovered multi-layered Palaeolithic sites in Kazakhstan, has been excavated since the 1960s (Alpysbaev, 1979; Taimagambetov, 1990). It contains six cultural horizons divided by sterile loess layers. Prismatic and discoid core reduction techniques predominantly represent the lithic assemblage. The tool-kit contains chopping tools, burins, scrapers, and points. Initial studies of the lithic industry containing knapping technology characteristic to the late Middle Palaeolithic suggested the late Mousterian period of human occupation at the site. In 2017, within the framework of palaeoenvironmental studies, all six cultural horizons were OSL dated. Its chronology spans from 43.5 to 9 ka (Fitzsimmons et al., 2017). Based on both the chronology and technology of the lithic

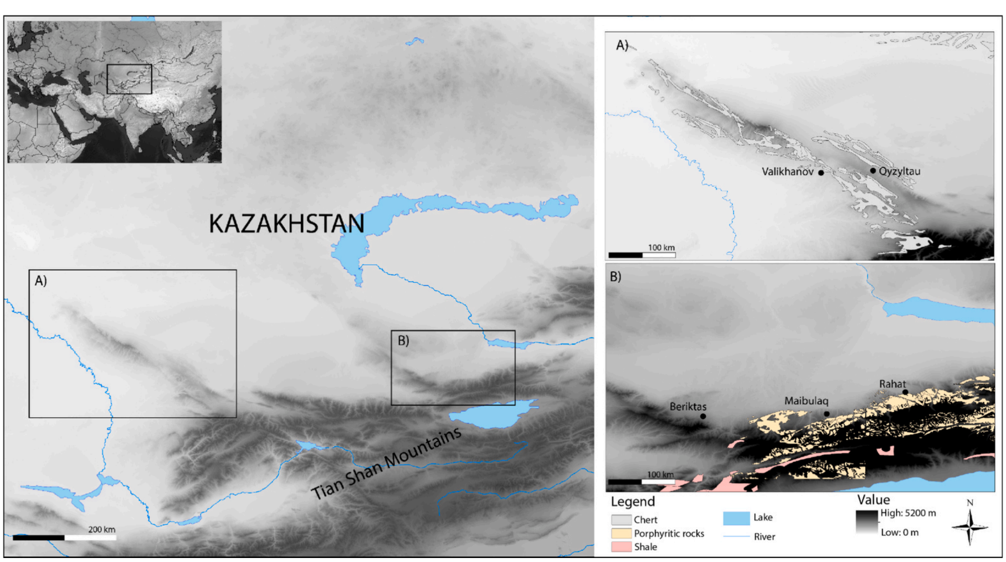

Fig. 1. Sites and study areas mentioned in the text are shown in relation to the local topography and lithic raw material sources, as extracted from the CERCAMS database (Seltmann et al., 2014). A) Qaratau range, illustrating the distribution of chert-bearing beds; and B) Ile Alatau range, demonstrating the distribution of shale formations and porphyritic rock outcrops. Data) and Shuttle Radar Topography Mission (SRTM) Version 4.
Source: Global Administrative areas (GADM); vector and raster data from Natural Earth (www.naturalearthdata.com

Table 1
Description of the samples studied.

Site ID	Sample ID	Context	Type of sample	Mountain range	Rock type	Colour	Visible inclusions	Total bars
Qyzyltau	QT-11-21	Archaeological	–	Qaratau	Chert	Dark gray	No	15
Valikhanov	VK-10-21	Geological	Bedrock	Qaratau	Chert	Light gray	Microfossils	12
Maibulaq	MB-9-21	Geological	River pebble	Ile Alatau	Porphyry	Black	Phenocrysts, quartz, feldspar	9
Beriktas	BT-6-21	Geological	River pebble	Ile Alatau	Sandstone	Green	Sand-sized grains of minerals	15

industry, the occupational history of the site has been reconsidered and attributed to the early Upper Palaeolithic. At Qyzyltau, a surface site located in the northern foothills of the Lesser Qaratau and spanning 40 km^2 of territory, systematic investigations began in the 1990s. The chronology of the site was inferred from the techno-typological attributes of the surface materials, which are associated with the Lower and Middle Palaeolithic featuring diverse knapping technology (Derevianko et al., 2002).

Our study also includes several geological reference samples of rocks collected at and around the Maibulaq site, which were used to knap stone tools there (Namen et al., 2022b). Maibulaq is a stratified open-air early Upper Palaeolithic site in the loess deposits of the Ile Alatau piedmonts (northern Tian Shan) (Fig. 1). It was first discovered in 2004 and excavated annually until 2016 (Taimagambetov and Ozherelyev, 2008; Taimagambetov, 2009; Fitzsimmons et al., 2017). The initial excavations revealed lithic materials and the stratigraphy was divided into three distinct cultural horizons separated by sterile loess. The majority of the lithic assemblage was knapped from locally available porphyry (within 20 km), with only a small portion of tools made from exogenous chert and shale. The nearest documented occurrence of it is at Beriktas, some 20 km west of the site, whereas the closest chert outcrops are located over 200 km to the northwest (Namen et al., 2022b). Due to the partial preservation of the first cultural horizon, only the two lowermost cultural horizons are of interest and provide insights into the technology of the industry. Both horizons are represented by the production of cores that are reminiscent of the Levallois technology, as well as single-surface prismatic and pyramidal cores with their flake and blade products (Fitzsimmons et al., 2017). The tool kit is predominantly represented by both end- and sidescrapers, as well as retouched flakes and blades (Taimagambetov, 2009). A chronology of the loess accumulation at the site was inferred from both radiocarbon (Feng et al., 2011) and OSL dates (Fitzsimmons et al., 2017). The absolute dates for the occupational history of the site span over 47–21 ka.

3. Materials and methods

3.1. Sample description and preparation

We examined four sets of samples from archaeological and geological contexts. A more detailed macroscopic description of the samples is shown in Table 1. At Qyzyltau, we collected a large core knapped on chert, a piece that was of no archaeological value due to the problems related to its context. This is the only archaeological material studied in the current work. From Valikhanov, Maibulaq, and Beriktas, we used geological reference samples that were macroscopically similar to knapped tools. Specifically, we considered attributes such as their homogeneity, degree of translucency, presence of microfossils (e.g., Valikhanov lithics and raw materials exhibit visible microfossils), texture, and colour. No samples of lithics from stratified sites were involved so as not to disturb the integrity of the existing lithic assemblages. Therefore, we collected geological samples during a raw material survey in the vicinity of the aforementioned sites, as part of the 2021 field season (Namen et al., 2022b).

One sampling criterion was the size of the rocks. We collected relatively large blocks of raw materials, measuring approximately 10 cm by 10 cm or larger. The large size allowed us to prepare up to 15 standard bending bars to allow for a statistically relevant dataset.

Samples were prepared according to the protocol provided by Schmidt et al. (2019). Bending bars measured ~50 mm in length, ~10 mm in width, and ~10 mm in height (the precise dimensions are reported in Table 4). One side of each bending bar was diamond polished, and two edges of the tension sides were chamfered to remove any possible chips and to avoid their possible influence on the fracture behaviour of the samples. Indentation tests were performed on the polished surface after the bending tests.

3.2. Experimental protocol and data treatment

The experimental protocol followed the standards and equations proposed by Schmidt et al. (2019), Nickel and Schmidt (2022), and Schmidt et al. (2024). Different aspects of mechanical properties were measured from bending bars. These are the modulus of elasticity E (also known as Young's modulus), indentation fracture resistance K_{Ic} (a value closely related to indentation fracture toughness), fracture strength σ, fracture predictability (measured as Weibull modulus m), and necessary flaking force F_{ac}. Below, we give a brief outline of these properties and the data treatment protocols used.

3.2.1. Modulus of elasticity

The *elasticity (or Young's) modulus E* is a measure that defines a material's resistance to elastic deformation when stress is applied (expressed in GPa). Some researchers have proposed that E is an important parameter for the production of blades through "stiffness-controlled fracture propagation" (Cotterell and Kamminga, 1987). We measured E through resonance frequency & damping analysis (RFDA) from bending bars before they were broken in bending tests. These tests were conducted in flexural vibration mode at room temperature. The instrumentation of the RFDA and test measurements are described in detail by Roebben et al. (1997).

3.2.2. Indentation fracture resistance

We experimentally tested the magnitude of crack formation by indenting four bars of each rock sample using pyramid-shaped Vickers indenters. These tests result in the formation of half-penny-shaped cracks below the indentations, from which we calculated an *indentation fracture resistance* (K_{Ic}) value in MPa $m^{1/2}$, a value closely related to fracture toughness (Lawn and Wilshaw, 1975; Danzer et al., 2016). Visually, as seen from above, the cracks depart from all four corners of Vickers indentations. Samples of chert, porphyry, and sandstone were indented 40 times to obtain statistically relevant data. The load was set to 100 N. The sizes of cracks and indentations were measured using a scanning electron microscope. K_{Ic} was calculated using the formula suggested by Niihara et al. (1982). The reformulated formula used here is stated in Schmidt et al. (2019) and Namen et al. (2022a). Solving this formula requires the visible length of the cracks *(c)*, the diagonal of the indentations *(a)*, a Vickers hardness value, and E as measured from the RFDA. The Vickers hardness values were taken from our previous study (Namen et al., 2022a).

3.2.3. Fracture strength and Weibull modulus

To investigate fracture predictability and strength, we used a four-point bending test combined with Weibull statistics (Weibull, 1951). This test is commonly used to study brittle materials by exposing the material to the maximum stress until failure to calculate fracture strength (σ_f) in MPa (for details see Irwin, 1957). Therefore, σ_f is the ability of a material to resist failure. To measure σ_f, bending bars were broken using an Instron 4502 universal testing machine and a spacing of the lower bearings of 40 mm, and the upper bearings of 20 mm (Fig. 2). The polished surface with chamfered edges was placed facing downwards to form the bars' tensile side. Bars were pre-loaded with 10 N, load speed of 1 mm/min. Only the maximum load at which the bar broke was recorded. This maximum load was used to calculate σ_f, which, in turn, was used for Weibull statistics. These are double logarithmic plots of the probability of failure over the specific strength of the entire set of samples (Table 1). The method is described in detail by Weibull (1951). To calculate the Weibull modulus *m*, fracture strengths σ_f values as measured by four-point bending σ_f are ranked in ascending order and assigned failure probabilities, which are divided by the total number of bars. The natural logarithm (ln) of the strength was plotted against the double logarithmic transformation of the failure probabilities (x-axis: ln (σmax), y-axis: ln(ln(1/(1-P)))), and the slope of the resulting linear best fit gives the Weibull modulus (the best fit is generated from the plotted data using a linear regression algorithm). The intersection of the scatter with the x-axis in these plots is the value of characteristic strength σ_0, describing the entire samples and taking into account its heterogeneity in terms of fracture strength σ_f. Another value resulting from Weibull plots is the dimensionless Weibull modulus *m*. It is a measure of the homogeneity of a sample's fracture behaviour, in other words, the predictability of the force needed to induce failure. We take this measure to be a close approximation to the knapping-related concept of fracture predictability. Higher values indicate less variability and therefore greater predictability in the fracture behaviour of a material during lithic knapping. We measured *m* as the slope of the linear best fit of all data in a Weibull plot. We also calculated the force required to produce a critical crack (F_{ac}) in N, or flaking force, from these values following the relation provided by Schmidt et al. (2024). We take this measure as an approximation to the actual force necessary to make knapping flakes during real-world stone knapping. This value of F_{ac} is also relevant to understanding the formation of impact fractures in rock samples that are used as projectiles (Schmidt et al., 2024).

3.3. Petrography of the samples

Thin sections were prepared at the Institute of Geology, Satbayev University (Almaty, Kazakhstan) following the standard thin section preparation protocol. A sliced piece of the rock was glued onto a glass section and diamond polished until a thickness of 30 μm was reached. Petrographic analysis was conducted at the micromorphology laboratory of the Institute for Archaeological Sciences, University of Tübingen (Germany). Thin sections of four types of lithologies were studied using a Zeiss microscope at magnifications ranging from 100x to 500x. Photomicrographs were obtained using the Axio camera coupled to the microscope.

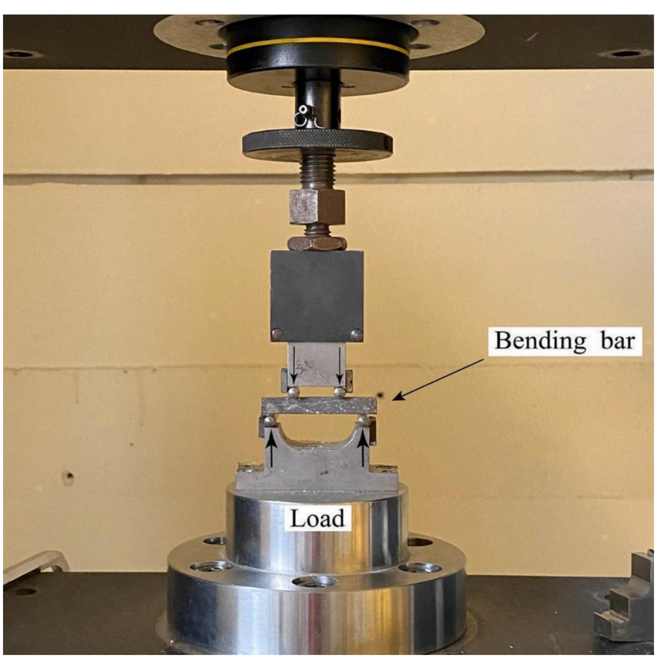

Fig. 2. Instrumentation and set up of the four-point bending tests.

4. Results

The values obtained for indentation fracture resistance K_{Ic}, elastic modulus *E*, fracture strength σ_f, and Weibull modulus *m* are summarised in Table 2, along with the force required to obtain a critical crack F_{ac}. K_{Ic} and *E* are graphically represented in Fig. 3 and σ_0 is represented in Fig. 4.

4.1. Indentation and four-point bending experiments

Scanning electron microscope images of the indentations allowed us to assess the crack length as half that of the half penny-shaped indentation cracks. The half diagonal of the indentation itself, which is part of Niihara et al's (1982) relation for finding K_{Ic}, could not be measured in all cases due to frequent flaking off of the edges of the indentations. This phenomenon is related to the chisel edge structure of the Vickers indenter tip and heterogeneous composition (Han et al., 2020) or microstructural flaws within the samples. Instead, we calculated this value from the standard hardness values of our samples, which were known from previous works on these rocks (Namen et al., 2022a).

Overall, K_{Ic} of chert samples from Valikhanov and Qyzyltau demonstrate significant variation with mean values equal to 2.77 MPa m$^{1/2}$ and 3.58 MPa m$^{1/2}$, respectively. Our porphyry and sandstone K_{Ic} values are more similar to the Valikhanov chert. The mean value of porphyry is 2.86 MPa m$^{1/2}$, and that of sandstone is 2.41 MPa m$^{1/2}$. Our values of *E* show porphyry and Valikhanov chert to be the least stiff materials with mean values of 69.22 GPa and 69.81 GPa, respectively. Qyzyltau chert and sandstone yielded higher values, of 88.58 GPa and 75.79 GPa, respectively.

Results of the four-point bending tests are summarised in Tables 2-4, and graphically shown in Fig. 4. Comparing F_{ac} of the four samples from the IAMC provides an understanding of the ease of knapping them. All four samples demonstrate significant differences in the force required for knapping (Table 3). In an effective volume V_0 of 30 mm^3 (for a justification of the choice of this volume, see: Nickel and Schmidt, 2022), Valikhanov chert (VK-21) fractures at forces approximately 100 times lower than those needed to flake porphyry (MB-21), around 170 times lower than Qyzyltau chert, and 5 times lower than Beriktas sandstone (BT-21), making Valikhanov chert the easiest material to knap (Fig. 5). However, F_{ac} is volume dependent. This volume dependence is graphically shown for volumes between 0 and 100 mm^3 in Fig. 5. For some samples (e.g., BT-6–21 sandstone), the amount of force needed to obtain a critical crack is two times lower than for Valikhanov chert (VK-10-21) in larger volumes. This volume dependence is not linear, so that samples with Weibull moduli $\gtrsim 3$ yield a steep increase of F_{ac} in greater volume but the F_{ac} of samples with $m \lesssim 3$ plateaus out in larger volumes. Such trends were observed for heat-treated samples but also for different quartzites (Schmidt et al., 2024). The steepest increase in force to cause critical crack is observed in porphyry (MB-9-21), whose Weibull modulus *m* equals 3.8. The progression of F_{ac} as a function of volume is different in different samples. This leads to the fact that some of the samples (for example, porphyry and Qyzyltau chert) allow easy flake detachment in lower volumes, while they do not break easily in larger volumes. This has important consequences for their quality in terms of near edge flaking, because there are only small volumes in which flakes develop, as compared to cases where larger volumes play a role (e.g., impact fracture formation, but also the detachment of large

Table 2
Mechanical properties of the four rock types from the IAMC. V_0 is the specific volume for which σ_0 was calculated (for the calculation, see Schmidt et al., 2024, supplement).

Sample ID	E [GPa]	Mean c [μm]	K_{Ic} [MPa m$^{1/2}$]	σ_f [MPa]	m	V_0 [mm^3]	σ_0 [MPa]
MB-9-21 (porphyry)	69.2	139	2.86	21.80	3.8	130	24.12
VK-10-21 (chert)	69.8	173	2.77	56.46	1.9	221	66.96
QT-11-21 (chert)	88.6	160	3.58	37.51	6.4	73	40.37
BT-6-21 (sandstone)	75.8	134	2.41	51.37	4.2	114	56.82

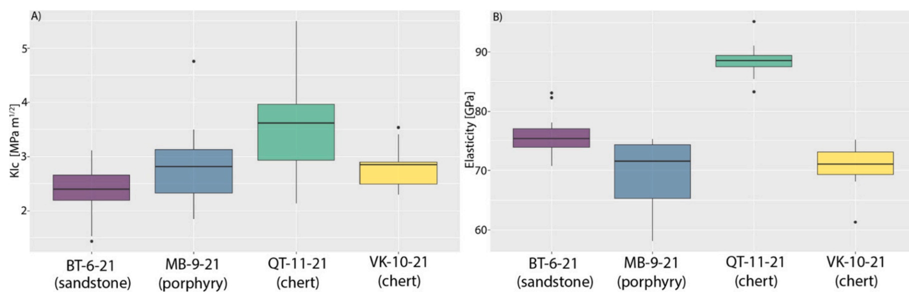

Fig. 3. Boxplots showing indentation fracture resistance K_{Ic} (A) and modulus of elasticity E (B) values.

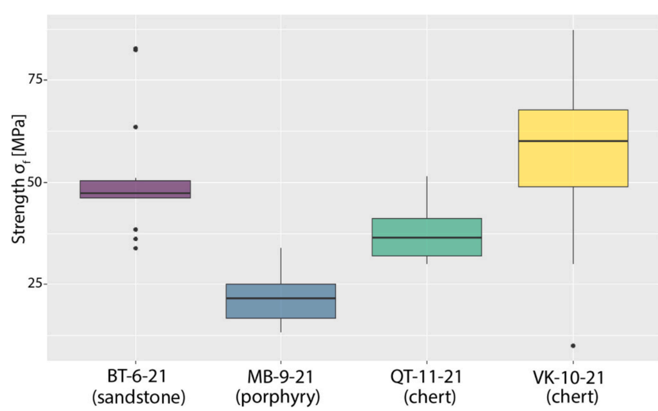

Fig. 4. Boxplots of fracture strength σ_1 of the studied samples. Note the higher fracture strength σ_1 values for the Valikhanov chert (VK-10-21) and Beriktas (BT-6-21).

Table 3
List of samples studied, their descriptions, and predicted knapping force for an effective volume of 30 mm^3.

Sample ID	Rock type	Description	F_{ac} in 30 mm^3 [N]
MB-9-21	Porphyry	Rolled river pebble. Sampled directly at the Maibulaq river bed adjacent to the Maibulaq site	3447
VK-10-21	Chert	A fragment collected from the chert bed adjacent to the Valikhanov site. The microstructure of the sample contains radiolaria fossils	24
QT-11-21	Chert	Surface lithic. Sampled directly at the surface site of Qyzyltau	4256
BT-6-21	Sandstone	Rolled river pebble. Sampled from the dried river bed of Beriktas, located approx. 20 km west of the Maibulaq site	132

flakes) (Fig. 5).

Fracture predictability, or the samples' Weibull moduli m, are graphically shown in Fig. 6. Qyzyltau chert has the highest m value of 6.4 indicating that it has the best fracture predictability. The rest of the samples have lower m values ranging from ~ 2 to ~ 4.

4.2. Petrography

Petrographic analysis was conducted to enable a microscopic comparison between geological reference samples and the previously analyzed archaeological assemblage described by Namen et al. (2022b). However, we recognize the inherent limitations of this approach, including the potential for circular reasoning. To address this, only in-depth provenance analysis would be able to confirm the exact match. As it stands, the rocks we selected are those that most closely resemble those made into tools at the site. We also made sure that their texture is sufficiently similar so that the statements we make about the rocks appear to be relevant to the raw materials used for making stone tools. Photomicrographs of the four samples are shown in Fig. 7. Under polarized light, porphyry exhibits a porphyritic texture with large phenocrysts (Fig. 7A). They are surrounded by smaller sized inclusions of felsic minerals such as feldspar and quartz grains, embedded in a fine-grained silica-rich aphanitic matrix. The feldspar inclusions display characteristic Carlsbad twinning, suggesting they are alkali feldspar. Based on the petrographic description, this rock is consistent with porphyritic rhyolite (henceforth, referred to as porphyry in the text). The groundmass of the porphyry supports conchoidal fracture patterns, however the phenocrysts may deflect force upon knapping. The Beriktas sample displays fine-grained, sub-angular to angular shaped crystals of K-feldspar, plagioclase, quartz, and chlorite with minor inclusions of white mica (Fig. 7B). The sample also contains clasts of sedimentary and volcanic origins. Due to the high amount of feldspar minerals, the Beriktas sample can be classified as feldspathic sandstone. Under the microscope, both chert samples reveal considerable microstructural variation. We previously reported that cherts found in the Qaratau range differ structurally (Namen et al., 2022b). Valikhanov chert is dominated by microcrystalline quartz with a uniform, cryptocrystalline matrix. It also exhibits fossil remains of radiolaria and cavities occupied by megaquartz (Fig. 7C). In contrast, the Qyzyltau chert is largely formed by length-fast chalcedony and minor inclusions of quartz. Its texture can be characterized as slightly heterogeneous due to the nonuniform distribution of quartz inclusions and length-fast chalcedony (Fig. 7D).

5. Discussion

The mechanical tests conducted during this study allow us to draw conclusions about the knappability of the raw materials in two distinct sub-regions of the IAMC (the Qaratau and Ile Alatau ranges) and their

Table 4
Bending bar dimensions, modulus of elasticity E, and fracture strength σ_f of all samples. Each set of bending bar samples is ordered as a function of increasing σ_f.

Sample ID	length [mm]	width b [mm]	height d [mm]	mass [g]	E [Gpa]	load F [N]	σ_f [MPa]
MB-9-21	50	7.08	7.37	6.63	65.29	170	13.23
MB-9-21	50	7.36	7.30	5.98	58.09	186	14.20
MB-9-21	50	7.04	7.41	6.32	61.74	216	16.79
MB-9-21	50	7.21	7.13	6.73	74.74	260	21.27
MB-9-21	50	7.24	7.34	6.68	69.03	280	21.55
MB-9-21	51	7.42	7.22	6.74	73.03	290	22.53
MB-9-21	50	7.06	7.12	6.46	74.33	298	25.00
MB-9-21	50	7.31	7.08	6.69	75.2	339	27.73
MB-9-21	50	7.26	7.07	6.47	71.54	410	33.86
VK-10-21	50	6.86	6.89	6.03	61.29	110	10.14
VK-10-21	50	6.98	6.72	5.47	62.76	314	29.85
VK-10-21	50	7.11	7.24	6.41	72.95	407	32.77
VK-10-21	50	6.97	6.89	6.09	75.18	598	54.26
VK-10-21	51	7.05	7.03	6.29	73.60	672	57.86
VK-10-21	50	6.56	6.79	5.60	68.07	597	59.17
VK-10-21	50	6.64	6.55	5.45	69.49	577	60.79
VK-10-21	50	7.19	7.06	6.38	71.69	767	64.19
VK-10-21	49	6.87	7.12	6.06	68.69	760	65.49
VK-10-21	50	6.84	6.94	6.07	73.55	816	74.31
VK-10-21	50	7.24	6.97	7.45	70.35	956	81.52
VK-10-21	50	6.71	6.92	5.82	70.11	933	87.14
QT-11-21	51	6.97	6.76	6.09	90.77	317	29.89
QT-11-21	51	6.91	6.77	6.08	89.84	322	30.51
QT-11-21	50	7.08	6.77	6.21	87.55	340	31.46
QT-11-21	50	6.90	6.57	5.86	83.30	315	31.72
QT-11-21	50	6.56	6.85	5.84	85.42	332	32.37
QT-11-21	50	7.18	6.77	6.31	87.48	359	32.72
QT-11-21	50	6.77	6.95	6.02	88.55	397	36.43
QT-11-21	50	7.01	7.06	6.36	88.87	424	36.44
QT-11-21	50	7.11	6.90	6.34	87.62	412	36.49
QT-11-21	51	6.79	6.91	6.05	88.55	425	39.31
QT-11-21	50	7.12	7.01	6.40	88.61	474	40.62
QT-11-21	51	6.86	6.81	6.08	88.98	442	41.69
QT-11-21	51	6.83	6.81	6.05	95.15	455	43.13
QT-11-21	50	6.93	6.59	5.93	87.03	485	48.30
QT-11-21	51	7.12	7.25	6.72	91.04	643	51.54
BT-6-21	51	6.79	6.89	6.26	74.15	365	33.93
BT-6-21	51	7.28	7.02	6.74	82.30	433	36.25
BT-6-21	51	6.95	7.29	6.75	78.04	474	38.51
BT-6-21	51	6.83	7.08	6.41	77.40	524	45.96
BT-6-21	51	7.13	7.24	6.80	74.72	579	46.44
BT-6-21	50	6.94	7.12	6.55	73.73	553	47.16
BT-6-21	51	6.71	6.85	6.07	75.71	495	47.17
BT-6-21	50	6.94	6.84	6.23	71.10	511	47.25
BT-6-21	50	6.86	6.99	6.28	70.75	543	48.58
BT-6-21	50	7.14	6.90	6.46	75.37	564	49.77
BT-6-21	51	6.77	6.81	6.08	74.38	521	49.78
BT-6-21	51	6.91	7.06	6.44	76.80	585	50.97
BT-6-21	50	6.94	7.44	7.32	83.11	815	63.63
BT-6-21	49	7.17	7.11	6.67	76.61	995	82.34
BT-6-21	50	7.72	7.74	7.71	72.61	1276	82.79

implications for prehistoric stone tool selection strategies. The variations in mechanical properties of the studied samples highlight the importance of investigating lithic raw material procurement strategies, contributing to broader discussions of how hominins balanced raw material accessibility and knappability when selecting lithic resources – a pattern observable across Palaeolithic contexts globally.

5.1. Quality of our data, comparability, and limitations

Only a small number of studies using indentation and four-point bending tests to determine the mechanical properties of lithic raw materials have been published (e.g. Schmidt et al., 2019; Moník et al., 2021a; Namen et al., 2022a; Schmidt et al., 2024). This is the first time that this methodology for quantifying tool-stone knapping force, and its implications for raw material selection behaviour, has been applied to the Central Asian Palaeolithic. We verified our data with the data published by Schmidt et al. (2024) as well as comparing the indentation fracture resistance values with a previously published dataset from a European context (Moník et al., 2021a). For instance, both Valikhanov and Qyzyltau chert K_{Ic} values are significantly higher than other silica rocks published by Schmidt et al. (2019), where the chert samples yielded values varying from 1.3 to 1.9 MPa m$^{1/2}$. Moník et al. (2021a) also report a value close to 1 MPa m$^{1/2}$ for chert samples from Moravia, Czech Republic. It is difficult to determine the factors that cause these differences in the values, but we presume that such differences between silica rocks could be due to microscopic impurities present within the samples or other microstructural effects acting as toughening mechanisms. Alternatively, this could be linked to the microstructural heterogeneity represented by length-fast chalcedony and quartz grains present in our samples (Fig. 7), where fracture propagates either transgranular or around the edges of the grains possibly resulting in higher indentation fracture resistance values (Mardon et al., 1990; Namen et al., 2022b). However, our conclusions on this matter should be regarded with some caution, as more studies specifically targeted to investigate this phenomenon are necessary to confirm these assumptions.

Additionally, we acknowledge that the present dataset may not fully capture the full range of inter- and intra-source variability as demonstrated by the variation observed in the two chert samples (see section 5.2). Considering that we generated a set of bending bars from one type of raw material, broader generalizations should be made with some caution. Future work should prioritize expanding the sample size, by generating several sets of bending bars from one type of raw material to produce a robust statistical dataset. This approach would allow for a more comprehensive evaluation of knappability and improve the reliability of comparisons with archaeological assemblages.

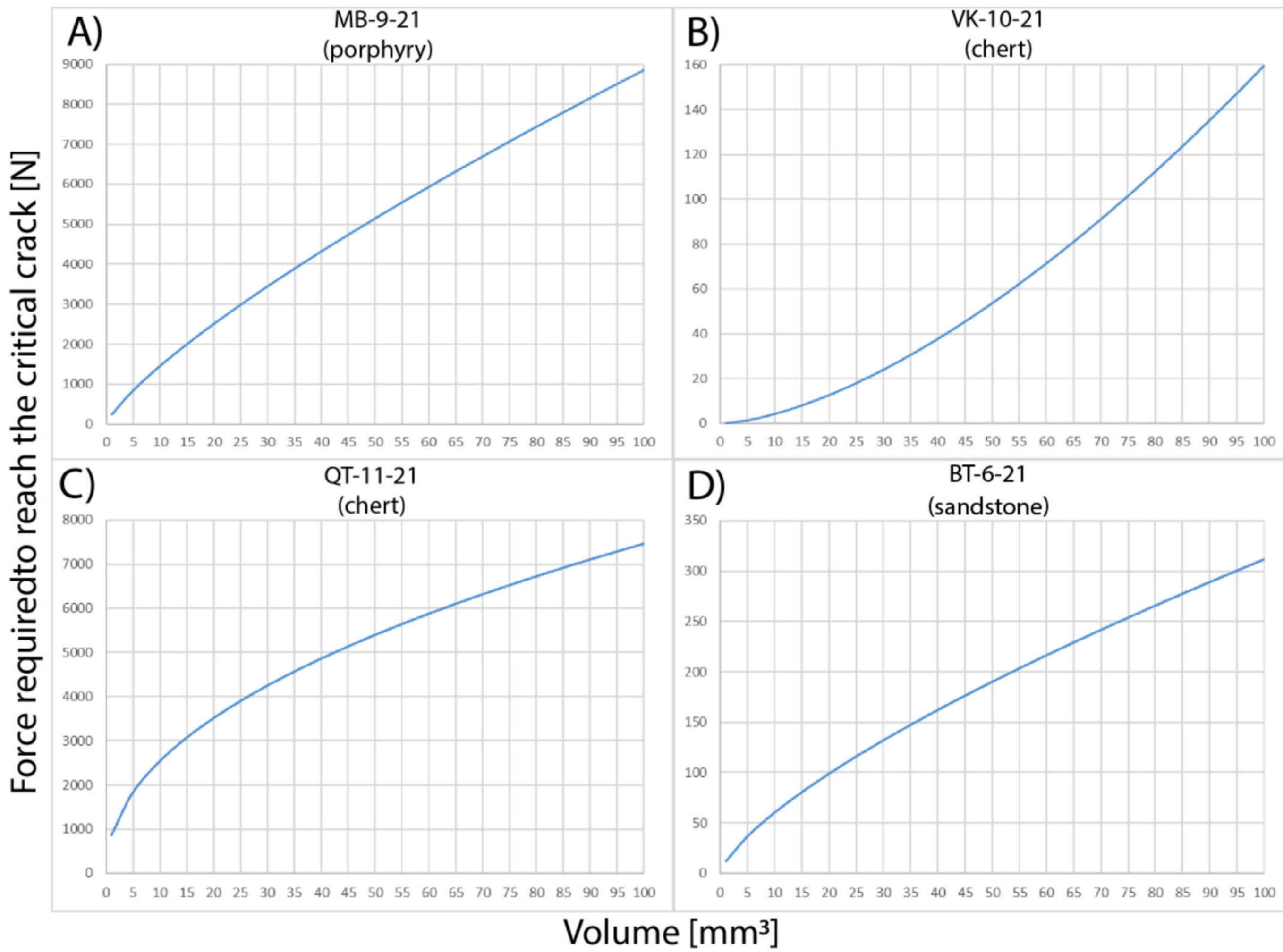

Fig. 5. Illustration of volume dependence of the force F to reach critical crack length a_c in four different rocks: A) Maibulaq porphyry, B) Valikhanov chert, C) Qyzyltau chert, and D) Beriktas sandstone. Note the different scales on the y-axis.

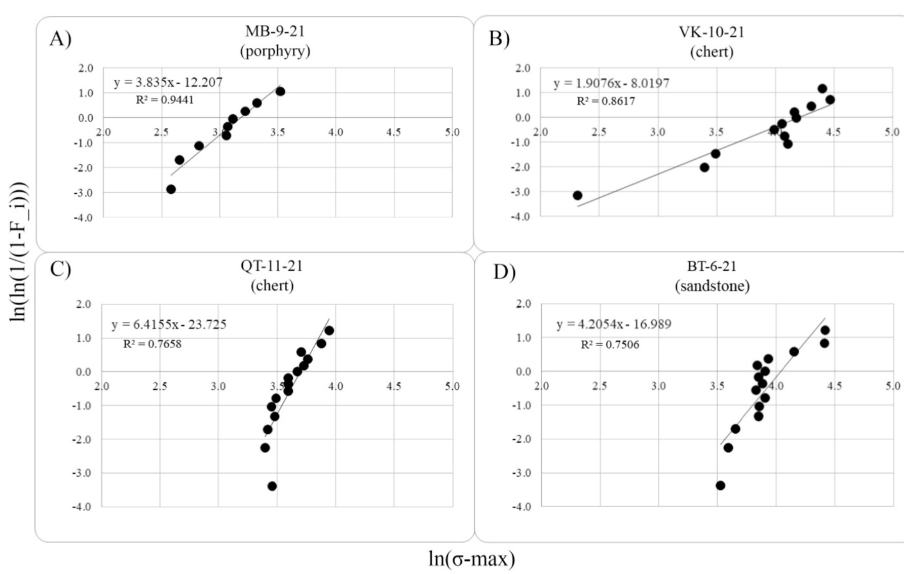

Fig. 6. Weibull plots of the four analysed samples. Note that these plots result in a characteristic strength value, the intersection of the best fit with the abscissa, and a Weibull modulus, the slope of the best fit, being indicative of fracture predictability.

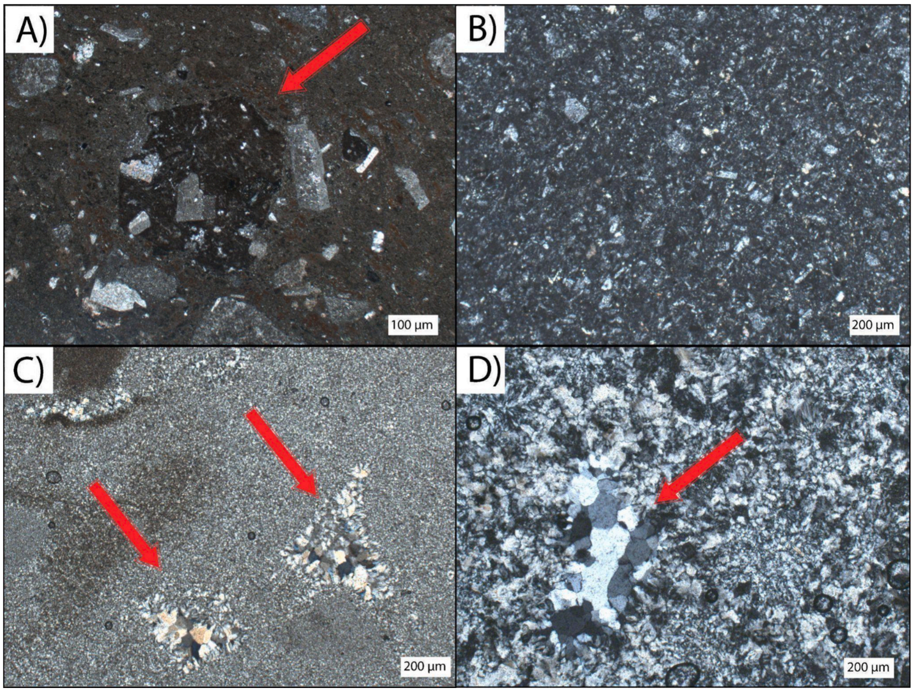

Fig. 7. Photomicrographs of the samples studied: A) Maibulaq porphyry with large phenocrysts of feldspar and quartz grains (red arrow) in a silica-rich matrix. B) Beriktas sandstone with angular inclusions of feldspar and quartz. C) and D) Valikhanov and Qyzyltau chert exhibiting considerable microstructural variation, arrows indicate cavities infilled by mega-quartz.

5.2. Lithic raw material quality

Our experimental tests reveal that two types of cherts that are visually similar exhibit substantial variability in their mechanical properties (Domanski et al., 1994; Schmidt et al., 2019; Moník et al., 2021a; Namen et al., 2022a). For example, among all our samples, the Qyzyltau chert demonstrates unexpectedly higher indentation fracture resistance K_{Ic} and elastic modulus E compared to other previously tested silica-rich raw materials. It is also significantly different from the Valikhanov chert tested in this study. Both chert samples also differ in fracture predictability: Qyzyltau chert demonstrates higher fracture predictability, making it possible to better predict the outcome in a knapping situation, compared to other samples (see section 4.1 and Table 2). These differences suggest that Qyzyltau chert is a raw material that, while requiring higher force to flake due to greater resistance, exhibits more homogeneous and predictable fracture behaviour than Valikhanov chert. Our results also imply that different types of cherts, that are visually similar to one another, are not necessarily similarly good upon knapping. They might require significantly different knapping forces.

Elasticity and indentation fracture resistance of Maibulaq porphyry and Beriktas sandstone show values similar to the Valikhanov chert (Table 2). Porphyry requires higher force for knapping, as compared to other samples (see discussion below). This corroborates previous opportunistic knapping experiments of porphyry pebbles, where knappers regularly reported that they had the feeling of applying higher forces to detach flakes from porphyry, or that they had to use larger hammerstones. Our data confirm that all analysed samples break at different forces during knapping. Valikhanov chert and sandstone are among the raw materials that require less force for knapping, as compared to the Qyzyltau chert and porphyry, although both demonstrate relatively lower fracture predictability.

5.3. Implications of mechanical properties for stone tool selection in the IAMC

Archaeological data suggest that lithic raw material procurement predominantly aimed at utilizing locally occurring raw materials (Taimagambetov and Ozherelyev, 2008; Taimagambetov, 2009; Derevianko, 2017; Fitzsimmons et al., 2017; Iovita et al., 2020). While there is evidence of exogenous raw material use, the number of tools knapped on them is small (2004–2005 excavations at Maibulaq, n = 48) (Taimagambetov and Ozherelyev, 2008; Namen et al., 2022b). Chert was extensively knapped throughout the Palaeolithic of southern Kazakhstan (Qaratau range), as attested by several stratified and surface sites (Derevianko, 2006; Taimagambetov, 2009). Fine-grained shale, volcanic porphyry, and sandstone were also readily used by the Palaeolithic occupants of the Ile Alatau foothills (Fitzsimmons et al., 2017; Ozherelyev et al., 2019; 2021; Namen et al., 2024; Ozherelyev, 2024; Ozherelyev and Mamirov, 2025). Below, we discuss raw material selection criteria possibly driven by the rocks' mechanical properties.

At Valikhanov, the production of scraping tools (i.e., end- and side-scrapers) on local chert dominates all cultural horizons with a small fraction of chopping tools and burins (Taimagambetov, 1990; Fitzsimmons et al., 2017). Occupants of the Valikhanov site had access to raw materials that are easy to knap. The Valikhanov chert yielded a relatively low knapping force in volumes < 100 mm^3 but demonstrates low fracture predictability ($m = 1.9$) (Table 2). The availability of this raw material, directly at the site, must have been part of the reason for its selection. The abundance of primary, unretouched, reduction products (i.e., chunks, flakes, etc.) reflects the expedient knapping strategy, most likely aimed at easy-to-produce expendable knapping products. Another consequence of this chert's properties is that it would be a comparatively bad material for projectile making. Impact fractures are expected to occur frequently in this chert. And indeed, there are only a few artifacts found at Valikhanov that can be interpreted as projectiles. In contrast, chert from Qyzyltau, where a large number of surface lithics typologically are Lower and Middle Palaeolithic tools, requires higher knapping force but allows relatively good fracture predictability (m = 6.4).

Normally, the higher force needed for knapping is known from coarse-grained rocks (i.e., porphyry, etc.) (Schmidt et al., 2024). High force requirements make the knapping process harder to control, effectively requiring higher investment and precise workmanship. At Qyzyltau, the typology of the scatters of surface lithics ranges from Levallois technology to the production of blades (Derevianko et al., 2002). The presence of Levallois technology suggests that the knappers were highly skilled in prepared core technology and had an understanding of the fracture mechanics of the rock, allowing them to efficiently exploit it despite its hardness for knapping. Besides its availability in the landscape, preference for this chert might have been driven by its resistance to impact fracturing or edge damage during activities such as hacking or wood working. Generally, raw materials that require high flaking forces in large volumes are considered good for projectiles because they are resistant to impact fracture formation (Schmidt et al., 2024).

At the Upper Palaeolithic sites of the Ile Alatau range (southeastern Kazakhstan), the production of blades, scrapers, points, and Levallois cores knapped on porphyry dominates the lithic assemblages (Fitzsimmons et al., 2017; Ozherelyev et al., 2021; 2023b; Namen et al., 2024; Ozherelyev and Mamirov, 2025). The high knapping force and low fracture predictability of porphyry (Tables 2 and 3) make this raw material one of the most difficult types of rocks for the production of stone tools. Even in smaller volumes, porphyry requires high force to initiate a critical crack. As we previously reported on the presence of felsite at Maibulaq, a raw material that is comparatively easier to knap, an apparent preference for porphyry may be explained by the need to produce tools that are resistant to edge damage and impact fracture formation (Namen et al., 2022b). Considering the composition of the Maibulaq tool-kit, where scraping tools dominate, the major criterion might be that raw materials resist edge dulling due to micro chipping during repeated use. In this case, the raw material selection strategy in the Ile Alatau foothills would be driven by functional needs. Future tests on the abrasion resistance of this porphyry will shed further light on this question.

In addition, the reliance on locally occurring raw materials and an objective assessment of their quality demonstrate that local knappers were highly skilled in working with various types of stones. Despite the difficulty of knapping, illustrated by the force values required to detach a flake, Palaeolithic craftsmen managed to produce stone tools required for their subsistence activities. It is also important to note the strong preference for porphyry at the sites in the Ile Alatau piedmonts, which may have been driven by the demand for tools that are resistant to abrasion, edge damage and/or impact fracturing.

6. Conclusion

This study provides one of the first insights into the lithic raw material quality and knappability of rocks from the piedmonts of the Inner Asian Mountain Corridor of Central Asia. Our results suggest that porphyry, sandstone, and chert, commonly used raw materials in various Late Pleistocene archaeological sites of Kazakhstan, have different qualities for knapping. Our mechanical tests demonstrate that some of the studied stones are better suited for knapping (e.g., ease of detaching a flake), whereas others are tougher, although they were still preferred as primary raw material for the production of tools. These findings contribute to our understanding of the lithic raw material selection behaviour, suggesting that procurement of stones was driven, not only by their ease of knapping, but perhaps also by their robustness to withstand specific use types during the subsistence activities of Palaeolithic groups. The Palaeolithic knappers readily used the available raw materials and adapted their lithic reduction schemes to their knapping quality. The ability to reproduce sophisticated knapping technologies, such as the Levallois technique, on raw materials that require greater force, demonstrates the high investment and craftsmanship of prehistoric knappers. While our study provides valuable insights, the lack of experimental functional studies hinders the discussion of the use and edge damage rate of the studied samples. This study advances our understanding of lithic raw material procurement strategies in the Central Asian piedmonts, and it also opens new avenues for more targeted approaches to investigate the effects of quality on lithic technology.

CRediT authorship contribution statement

Abay Namen: Writing – original draft, Visualization, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Patrick Schmidt:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All relevant data are included in the article.

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