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RESEARCH

Reconstructing Skills and Strategies of Hominins During the Early Acheulean: Behavioral Flexibility in Handaxe Production at Olduvai Gorge (Tanzania)

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Abstract

Technological strategies for biface manufacture adopted during the Acheulean represent a significant shift in the Lower Palaeolithic. The appearance of intentional bifacial shaping indicates the imposition of form on stone tools not seen previously. Despite this importance, there is considerable scope for research into hominin decision-making while factoring in the differential properties of varied raw materials. Here, we discuss the results of an experimental knapping program of Acheulean handaxes on Naibor Soit quartzites (NSQ), aiming at investigating technological strategies observed at the Lower Floor TK Site (TKLF), Olduvai Gorge, Tanzania. We examine the unique properties of the NSQ raw material and the challenges faced during knapping slabs at various stages of the handaxe reduction sequence. We explore how the selection and extraction of suitable slabs for handaxe manufacture and the impact of specific geological structures within this raw material determine the final artefact form. We note the effect this had on the need for careful choices in selecting suitable slabs at the raw material sources based on considerations of the properties of the slab, thickness, and width, amongst other factors. Functional requirements and the NSQ slabs' properties influenced strategies adopted for handaxe *façonnage* and the final tool morphology. We discuss choices made by Acheulean toolmakers when they adopted freehand and bipolar knapping techniques. These decisions can be identified through the nature of the debitage generated and the organization of flake scars on handaxes. We suggest that Acheulean hominins displayed high skill levels and evolved knapping strategies. These strategies allowed them to adapt to the complex task of implementing specific shaping techniques on NSQ slabs. This provides one of the few experimental studies that directly explore the impact of the particular requirements of flaking quartzites during the Acheulean. This study contributes to understanding the diversity of strategies and behavioral flexibility exhibited by Acheulean hominins.

Highlights
- Experimental knapping of handaxes on Naibor Soit quartzite (NSQ) slabs, Olduvai Gorge, Tanzania.
- Reproduction of the reduction sequence used for handaxe façonnage on slabs at the Acheulean level of Lower Occupation Floor in Thiongo Korongo site (TKLF).
- Investigating decision-making at various stages of the handaxe reduction sequence.
- Issues related to the NSQ, leading to breakage and steps adopted by the knapper to control for the same.
- Inferences on Acheulean technological abilities based on experimental studies and knapping decisions at stages in the reduction sequence.

Keywords Acheulean · Olduvai Gorge · Thiongo Korongo site · Experimental knapping · Handaxes · Naibor Soit Quartzite

Introduction

Research into the Palaeolithic archaeology of Olduvai Gorge has frequently incorporated different programs involving experimental knapping. These studies provide insights into specific technologies, hominin skills and cognition, functionality, aesthetics, social learning, and behavioral organization across ancient landscapes (Bryne et al., 2016; de la Torre et al., 2013; Diez-Martin & Eren, 2012; Diez-Martin et al., 2011, 2015, 2019; Eren et al., 2014; Gurtov & Eren, 2014; Jones, 1994; Leakey & Roe, 1994; Profitt & de la Torre, 2014; Sánchez-Yustos et al., 2015). Some of the earliest published experiments focused on a deeper

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understanding of the archaeological materials at Olduvai Gorge sites and were designed to investigate Beds III and IV, ‘Developed Oldowan’ and Acheulean assemblages. These studies explored questions related to technological strategies and functionality (Jones, 1979, 1994). These experiments incorporated the raw materials that Olduvai hominins used to create the large assemblages excavated from Beds III and IV. In particular, the quartzites located at the Naibor Soit and Naisiusiu Hill Precambrian outcrops were used in these experiments (Jones, 1979, 1994). The Naibor Soit quartzites (henceforth NSQ) occur as massive in situ or eroded blocks/chunks on hilltops. This rock type can also be found in the form of smaller slabs (of up to ~ 5 kg in weight) occurring along the slopes within a ~ 5 km radius of the archaeological sites at Olduvai (Jones, 1994: 256). These experiments focused on the particular flaking properties of this rock. Slabs of NSQ tend to break in characteristic ways when knapped, requiring an understanding of the raw material properties and skilled use of different strategies while flaking to achieve the desired tool. These early experiments reproduced various artefacts, including bifaces, while utilizing volcanic rocks as hammerstones and soft hammers (e.g. of bone or wood), and adopting direct percussion and ‘block-on-block’ methods. The use of alternate and unifacial flaking strategies also required careful implementation of specific knapping strategies. Jones (1994) suggested that the original shape of the slabs determined the resultant biface morphology and highlighted the need for greater flaking control along the edges of NSQ slabs.

There have been several other experimental studies of stone artefacts produced on NSQ. These studies explored bipolar knapping (BP) and freehand percussion (FHP), percussive tools, ‘battered artefacts’, stone anvils, aspects of expediency, skill, and the selection of raw material in NSQ assemblages (Byrne et al., 2016; Clark & Kleindienst, 2001; de la Torre et al., 2013; Diez-Martín et al., 2011; Eren et al., 2014; Proffitt & de la Torre, 2014; Sánchez-Yustos et al., 2015). Despite the diverse aims and methods of the various experimental studies, most highlight the distinctive properties of the NSQ material that were thought to influence the final artefact form. This rock type is susceptible to fractures, splitting of flakes along the technological axis, as well as other characteristic breakage patterns, with the debitage also comprising somewhat blocky debris and shatter.

Here, we draw on results of previous studies, and focus our experiments on the reproduction of handaxes fashioned on NSQ slabs excavated from the archaeological site known as Lower Floor TK (henceforth TKLF) (Leakey, 1971, 1975, 1976, 1978; Santonja et al., 2014, 2018). We sought to examine to what extent the unique properties of the NSQ raw material influenced decisions made during various stages of handaxe *façonnage* and their final morphology. We also sought to compare this with sites elsewhere in the world where bifaces were manufactured on slabs (Shipton et al., 2009) and to investigate decision-making at various stages of the reduction sequence (Boëda et al., 1990; Inizan et al., 1992, 1995; Isaac et al., 1981; Turq, 2000).

TKLF is located in a ravine on the north slope of the Olduvai Main Gorge, ~ 2 km east of the junction with the Side Gorge, on the top of Bed II (Fig. 1). The site was identified in 1931 by L. Leakey, based on the presence of bifaces made on quartzite slabs (Leakey, 1951: 85), but was only excavated in 1963 (Leakey, 1971: 172–197). TK presents a stratigraphic sequence of ~ 5 m thickness at the top of Bed II (Hay, 1976) and can be correlated with tuff II^{D}, dated by ^{40}Ar/^{39}Ar to 1.353 ± 0.035 Ma (Domínguez-Rodrigo et al., 2013). The sequence comprises levels of tuff, clays, and calcareous crusts, with some stone artefact-bearing levels. The two main archaeological levels are termed Lower Floor (TKLF) and Upper Floor (TKUF). Sedimentological and taphonomic analysis suggests that these levels represent paleosurfaces where large artefact assemblages were discarded on an ancient land surface in association with infrequent faunal remains (Leakey, 1971: 172–197; Santonja et al., 2014). Excavations carried out by TOPPP (The Olduvai Paleoanthroplogical and Paleoecological Project) led to the identification of a new floor termed TKSF (Rubio-Jara et al., 2017). This level is situated between TKLF and TKUF. The new level is separated from TKLF by 21 cm and 42 cm. These levels do not reflect significant temporal diachrony. However, there are substantial technological differences regarding lithic manufacturing strategies (Panera et al., 2019; Rubio-Jara et al., 2017). In the initial description of these assemblages, M. Leakey (1975: 484, 1976: 31, 1978) interpreted TKLF as an Acheulean occupation and TKUF as a Developed Oldowan. As a result of these technological differences, the TK locality played a crucial role in discussions surrounding the Oldowan-Acheulean relationship (Bower, 1977; Kimura, 2002; Ludwig & Harris, 1998; Rogers & Semaw, 2009; Sahnouni, 1991; Stiles, 1977, 1979; Willoughby, 1987). However, subsequent research led to the conclusion that lithic assemblages in both TKLF and TKUF were technologically similar and could be attributed to the Acheulean technocomplex (Santonja et al., 2014, 2018). Chronologically, the entire TK locality is temporally associated within the Early Acheulean (Bar-Yosef, 2006; Santonja et al., 2018; Schick & Toth, 2000). New excavations at TKLF (Santonja et al., 2014) led to the identification of lithic assemblages characterized by intensive use of NSQ (92.4%), with smaller proportions on volcanic rocks (6.8%), vesicular lava (0.4%), gneiss (0.1%), flint (0.01%), and other varieties of quartzites (0.29%).

Acheulean knapping strategies at TKLF focused on producing flakes (occasionally retouched) from cores as well as shaping large tools using slabs, cobbles, and large flakes. Knapping strategies included the use of both direct freehand

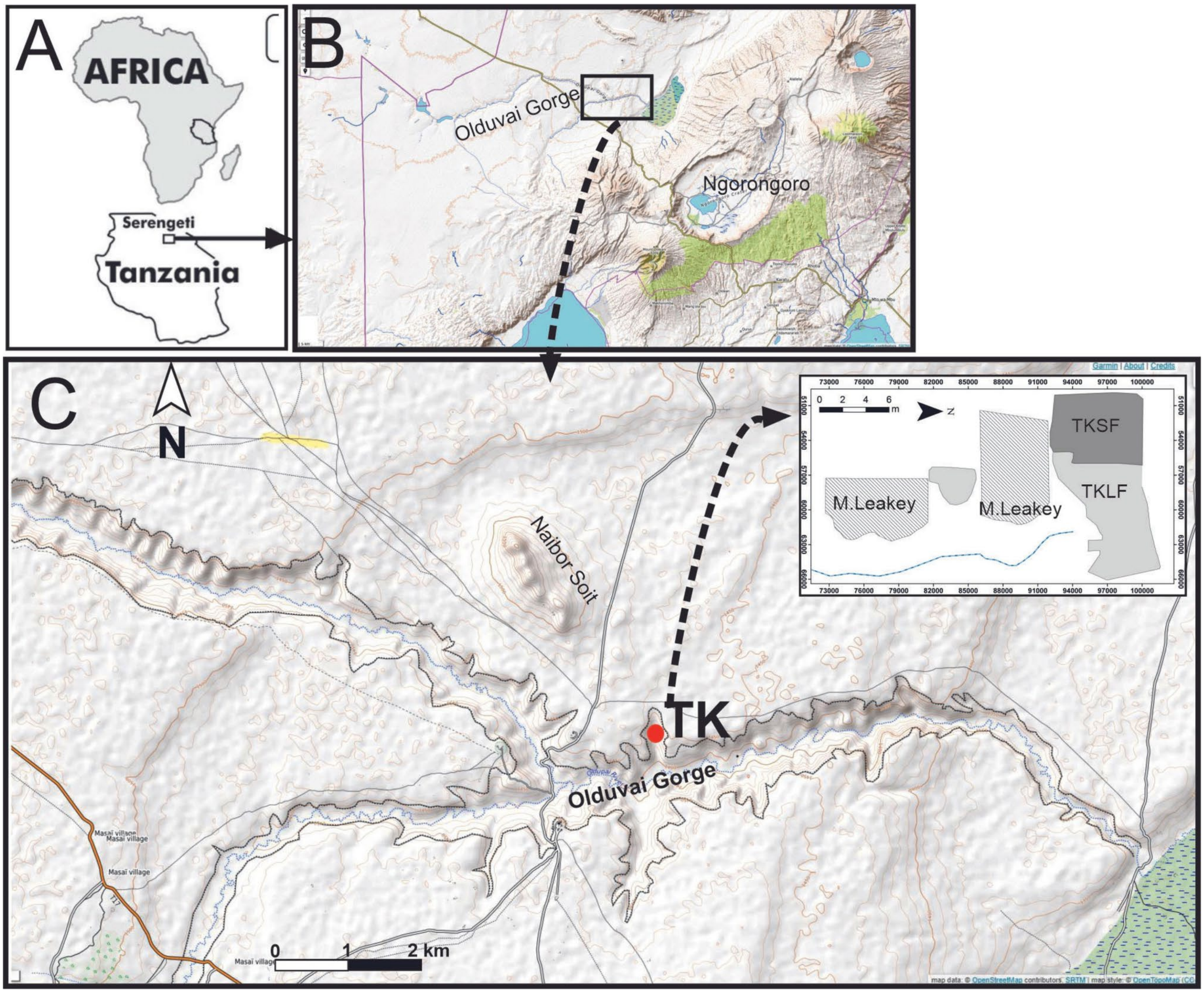

Fig. 1 The study region showing (**A**) and (**B**) the geographic location of Olduvai Gorge. (**C**) Location of Thiongo Korongo (TK) at Olduvai Gorge and Inselberg Naibor Soit, positions of the trenches excavated by M. Leakey (1971) and the sectors excavated by TOPPP

percussion (FHP) and bipolar percussion (BP). The latter, however, was only observed on NSQ. The TKLF cores were exploited opportunistically. These cores exhibit a technological strategy that has similarities with the peripheral unipolar system as described by Turq (2000) in European assemblages [sometimes referred to as the Quina concept (Turq, 2000)]. Discoidal strategies are also seen in the TKLF assemblages. The FHP cores were also reused as hammerstones and anvils. It is also important to note that NSQ reduction strategies always involve the in situ exploitation of ‘cores’. Volcanic rocks were also recovered at the TKLF locality; however, the assemblages of these rocks suggest they were flaked off-site and subsequently transported to the TKLF location.

The TKLF assemblage is characterized by a substantial amount of material that can be attributed to the *façonnage* technique (Inizan et al., 1992, 1995). This includes 85 pieces (made on NSQ and volcanic rocks) that exhibit features that we attribute to the shaping of large cutting tools. Despite the challenges of detaching large flakes from Naibor Soit quartzite, we identified 67 handaxes (65 of which were made on NSQ slabs), as well as three cleavers and a heavy-duty scraper produced on an NSQ flake (Santonja et al., 2014, 2018). In an area of 51.9 m^2 excavated at the TKLF level, the total weight of the *façonnage* on quartzite is 104.3 kg, i.e. 28% of the total NSQ used. Added to this quantity is a part of the 57.1 kg of shatter found since part of these fragments may originate from handaxe *façonnage*. This implies that hominins transported a large amount of NSQ to the site. We believe they transported these materials to exploit specific resources requiring large handaxes. In this context, the TKLF handaxes are amongst some of the longest and heaviest noted at known African sites (Méndez-Quintas, 2017).

These tools are exceptionally large with thickness values between 40 and 60 mm, and widths between 90 and 130 mm. The LCTs in this assemblage are so large that 80% of artefacts exceed 20 cm in maximum length (Santonja et al., 2014: 199, fig. 18). In some instances, the artefacts from TKLF weigh > 3 kg. Several features of this assemblage suggest that these tools were produced on the land surfaces at TKLF. This includes complete handaxes, preforms, fragments, and broken tips of handaxes likely resulting from knapping or use. In combination, this assemblage reflects patterns that would be expected if the artefacts were manufactured, used, and discarded at the site (Fig. 2).

The final morphology of handaxes reflects influences of several variables, including raw material, blank types, and the degree or extent of reduction as noted by numerous scholars (Jones, 1979; Lycett & von Cramon-Taubadel, 2014); McPherron, 2006). Our research supports the assertion that at TKLF, the choice of slabs as blanks for handaxe *façonnage* was a key factor that influenced the final morphology of the tools. Selecting slabs of appropriate thickness reduced the need for extensive flaking, which resulted in bifacial reduction limited to specific areas of the tool (Santonja et al., 2014: 197–198; Santonja et al., 2018:173–174). Knapping was primarily concentrated on the distal third of the tool to produce a functional working edge, while the remainder of the artefact was shaped to achieve bilateral symmetry through bifacial flaking. In some cases, unifacial flaking was used alone or in combination with bifacial techniques. Due to the use of slabs as blanks, nearly one-third of the tools (32.6%) have bases defined by a dihedral angle formed by two natural planes of the slab. Approximately 40% of complete handaxes feature one or two backed lateral edges. These edges are shaped either by the natural morphology of the slab or through flaking (Boëda, 2001; Santonja et al., 2014, 2018). Nearly half of the handaxes exhibit a broken tip, while the remainder show evidence of tip reshaping. We interpret the presence of vertical and lateral removals as indications of the direct shaping of these tools.

This paper discusses experimental studies aimed at reproducing reduction strategies used by TKLF hominins for handaxe *façonnage* on large NSQ slabs. These aspects encompass the entire reduction sequence from the acquisition of NSQ raw material slabs and hammerstones to the final production of handaxes. We attempt to reconstruct patterns that are reflective of breakage, as well as resharpening activities, and the associated debitage products. We discuss our tests of the efficacy and utilization of bipolar (BP) and freehand percussion (FHP) in handaxe *façonnage*. The unusually large handaxes at TKLF provide insights into how toolmakers balanced the limitations of the raw material with their goals for specific shapes and functional performance.

Naibor Soit Quartzite Slabs

Naibor Soit quartzite is one of the most preferred raw materials in the Bed I and II sites at Olduvai Gorge (Hay, 1976; Jones, 1994; Kyara, 1999; Leakey, 1971; Rubio-Jara et al., 2017; Santonja et al., 2014, 2018; Stiles, 1991, 2003). Thus, in Bed I at FLK Zinj (Leakey, 1971) of 2663 pieces, 2381 are made on quartzite (de la Torre and Mora, 2005, Table 3B), at FLK North level 6 (Leakey, 1971) 107 pieces are made on quartzite, of a total of 130 elements (de la Torre, and Mora, 2005, Table 4); in Bed II SHK (Leakey, 1971) and SHK

Fig. 2 Handaxes discovered during the excavation of TKLF level

Main Site, of 1773 elements 1180 are made on quartzite (Sánchez-Yustos et al., 2019, Table 1); FC West (Leakey, 1971) of 1162 pieces, 1000 are on quartzite (de la Torre, and Mora, 2005), and at BK (Leakey, 1971) new excavations (Diez-Martín et al., 2009: table 1) indicate that from a total of 1575 objects quartzite is represented in 1489 pieces.

This outcrop, located north of Olduvai Gorge, is a prominent Precambrian inselberg reaching a maximum elevation of 1618 m above sea level. It is part of both the Mozambique Belt and the Kissele Quartzite Formation (Pickering, 1958) and is well exposed in the Gol Mountains (Dawson, 2008). This inselberg is made up of smaller isolated outcrops that trend in an NW–SE direction. The outcrop closest to the TK site is locally known as Naibor Soit Ndogo, or Endoingyo Osokoni Hill. The quartzite derived from this outcrop is hereafter referred to as Naibor Soit Quartzite (NSQ). This promontory has a crest formed by the NSQ strata. These rocks have an inclination between 25° and 40° S. At the time when TK site was formed, the outcrop would have been about 750 m away. This estimation is based on the projection of the current slope of Naibor Soit Ndogo (cf. Santonja et al., 2014: fig. 27). However, we cannot rule out the presence of smaller outcrops that were potentially closer to TK site. These other outcrops may be buried under Pleistocene deposits at present.

Pickering (1958) and Hay (1976) described the NSQ lithologically as a pink or white metamorphic rock. The white quartzite appears foliated, in the form of slabs, produced by intense tectonic forces. These forces created a characteristic feature of this rock they termed ‘penetrative tectonic planar structures’ (henceforth, PTPS) (Davis et al., 2011). These penetrative lineations (~ 1–2 cm and 6–8 cm apart, as measured in the field) have been subvertically fractured by joints in the rocks. These joints correspond to the natural morphology of the slabs and influence the size of the resulting blocks found today on the inselberg. These blocks are found either broken along the slopes of the inselbergs or in situ on the rocky outcrops.

Table 1 Dimensions of the NSQ slabs selected for experimental knapping

	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)
N	25.00	25.00	25.00	25.00
Mean	286.72	167.32	46.32	3713.96
Median	270.00	160.00	48.00	3382.00
Minimum	230.00	65.00	28.00	1566.00
Maximum	380.00	320.00	70.00	8500.00
Std. Deviation	52.58	53.03	8.71	1853.26

The quartzite presents a high level of recrystallization (Hay, 1976), and very few of the original sandstone structures remain. The internal structure of NSQ is a coarse-grained rock with quartz grains 1–2 cm in diameter (Hay, 1976), grains of recrystallized quartz and infrequent muscovites (Bello-Alonso et al., 2019; Egeland et al., 2019; Favreau et al., 2019; Hay, 1976; McHenry & de la Torre, 2018; Soto et al., 2019, 2020). NSQ is a metamorphic rock made up almost entirely of quartz [97.97% (Santonja et al., 2014)]. The distinctive mechanical properties of this material influence the resultant breakage patterns during knapping. This is different from the other fine-grained quartzites that were used by hominins at Olduvai during the Pleistocene (Jones, 1994).

Methods

Knapping experiments were conducted at Aguirre-Mturi research station at Olduvai Gorge in January and February 2019. The knapper (Kumar Akhilesh, henceforth KA, an expert in lithic knapping) (Akhilesh et al., 2024; Akhilesh & Pappu, 2015, 2022) was seated on a chair placed on a tarpaulin sheet onto which a grid of 3 × 2 m (6 quadrants of a metre each) was projected to facilitate recovery of waste products and to gather data for future spatial studies (Table S1, data recording by S.Pappu). KA did not have previous experience knapping NSQ materials. There was a short period of practice needed to begin to successfully produce materials that had similar features to those found in the TKLF assemblage. The quartzites were collected from the Naibor Soit Ndogo outcrops. We recorded the shapes and lithological features of the NSQ slabs at the source. Data was also recorded on the dimensions, weight, shape, number of penetrative tectonic structures and joints, and quartzite grain sizes associated with each slab (Table S1). Hammerstones ($n = 54$) for the knapping experiments were sourced from the Olduvai river bed at Olduvai Gorge. Numerous cobbles were inspected, and 13 were selected. The sizes, shapes, and materials of these hammerstones are provided in Table 2. During the experiment, detailed records were made of the hammerstones used, flaking strategies adopted and decision-making by the knapper. The final handaxe and waste products generated were also studied (Madsen & Goren Inbar, 2004, Table S1).

Unsuccessful experiments, i.e. those where the final product could not be achieved owing to breakage, were also documented to provide data on the causes and nature of breakage during knapping of NSQ slabs. Twenty-five experiments were documented. The handaxes that were created were intended to reproduce the reduction sequences of specific large handaxes that were recovered from the TKLF locality (Roe, 1994; Santonja et al., 2014, 2018; Table S1).

Table 2 Details of the NSQ slabs selected for experimental knapping showing slab morphology

Slab morphology	Count	Table *N* %
Roughly rectangular	11	44.0%
Roughly rectangular irregular	1	4.0%
Roughly square	1	4.0%
Roughly triangular	9	36.0%
Roughly triangular asymmetric with greatest width at base	1	4.0%
Roughly triangular irregular	1	4.0%
Roughly triangular with a square base	1	4.0%

Results

Acquisition of the Naibor Soit Quartzite Slabs

The shape and size of slabs were primarily determined by the NSQ penetrative tectonic structures (PTPS) and the nature of joints in the outcrop (Fig. 3). The breakage of NSQ along the PTPS structured the thickness and width of slabs. These are critical attributes that influence the suitability of certain slabs for handaxe *façonnage*. This is evident in the slabs used for the experiments described here and potentially impacted Acheulean hominins as well. During the initial stages of the reduction sequence, the primary goal was to select a slab of suitable thickness for replicating the TK handaxe schema that has been described elsewhere (Santonja et al., 2014, fig. 20; Santonja et al., 2018 fig. 8.14). Slabs with a mean thickness of ~ 52.7 mm and a range between 40 and 60 mm were preferred. These measurements are based upon the features of the handaxes excavated from the TKLF level (Santonja et al., 2014). Most of the NSQ with appropriate PTPS (ideal slab widths) on the modern Naibor Soit outcrop are partially exposed. As a result, it was necessary to extract suitable slabs from below the surface. These sub-surface slabs acquire a patina that is not present on the archaeological specimens (Fig. 4). Acheulean hominins may thus have had access to a broader range of slabs than those which are available at Naibor Soit at present. Experimental extraction of slabs was influenced by the PTPS. These features of the outcrop facilitated the detachment of a series of parallel bedded slabs (Fig. 3B–D). In order to choose a suitable slab for shaping the handaxes, the knapper, KA, carefully inspected the natural joints in the NSQ outcrops, prior to deciding which ones to select (Fig. 5).

The experimental study demonstrated that slab thicknesses of < 30 mm or > 50 mm increased the chances of breakage. Thus, the extraction of the slab required control over slab thickness and width, although during the quarrying process it was difficult to control the latter variable. Irrespective of which technique was implemented (e.g. BP or FHP), slabs with widths that far exceeded the dimensions of the final desired handaxe were often broken during knapping. All slabs have two PTPS that intersect to constitute the two faces of the slab. We attempted to identify slabs with a minimum number of PTPS that were ideal for knapping and to avoid those with multiple PTPS (Table 3). The location of joints was challenging to control and depended on how the slab broke during extraction. Our experiments suggest that the position of joints influenced subsequent decisions on the location of the handaxe's proximal (base) end. The presence of fractures within the NSQ slabs was another important feature determining selection. Fracture lines within the NSQ slabs increased the probability of breakage during knapping. While these attributes were undesirable, both experimental and archaeological handaxes do display fracture lines, suggesting that hominins clearly were capable of overcoming these challenges during the knapping of NSQ slabs. Overall, the critical criteria for selecting NSQ slabs for handaxe *façonnage* were:

a. Slab thickness ranging from ~ 28 to 70 mm (mean = ~ 46 mm);
b. Having one or more natural joints that could be utilized for prehension;
c. A minimal number of PTPS;
d. The width of the slab should ideally be less than a few centimetres greater than the desired width of the final handaxe.

Twenty-five slabs were knapped (Tables 1, 2, 3, Fig. 5), with mean dimensions of 286.72 × 167.32 × 46.32 mm (length, width, and thickness, respectively) and a mean weight of 3713.97 g. Most slabs were roughly rectangular (around 44%) or triangular (around 36%). The number of PTPS ranged from a minimum of two to a maximum of five (Table 3). Slabs retained natural joints in 19 cases (76%). Slabs usually had two joints ($n = 10$; 40%); however, some slabs had one ($n = 6$; 24%) or three ($n = 3$; 12%). Joints occur primarily along lateral edges and, in addition, along one or both extremities (the latter representing the two edges of the slab along the longest axis and distinguished from the lateral edges).

Selection of Hammerstones

A total of 54 hammerstones, comprising a range of cobbles and pebbles of volcanic rocks, were collected. These hammerstones were tested and 13 were selected by KA based on assessments of their morphology and weight that were thought to be suitable to achieve the objectives of the experiments. Their mean dimensions were 98.77 × 78 × 58.54 mm (length, width, and thickness, respectively), and the mean

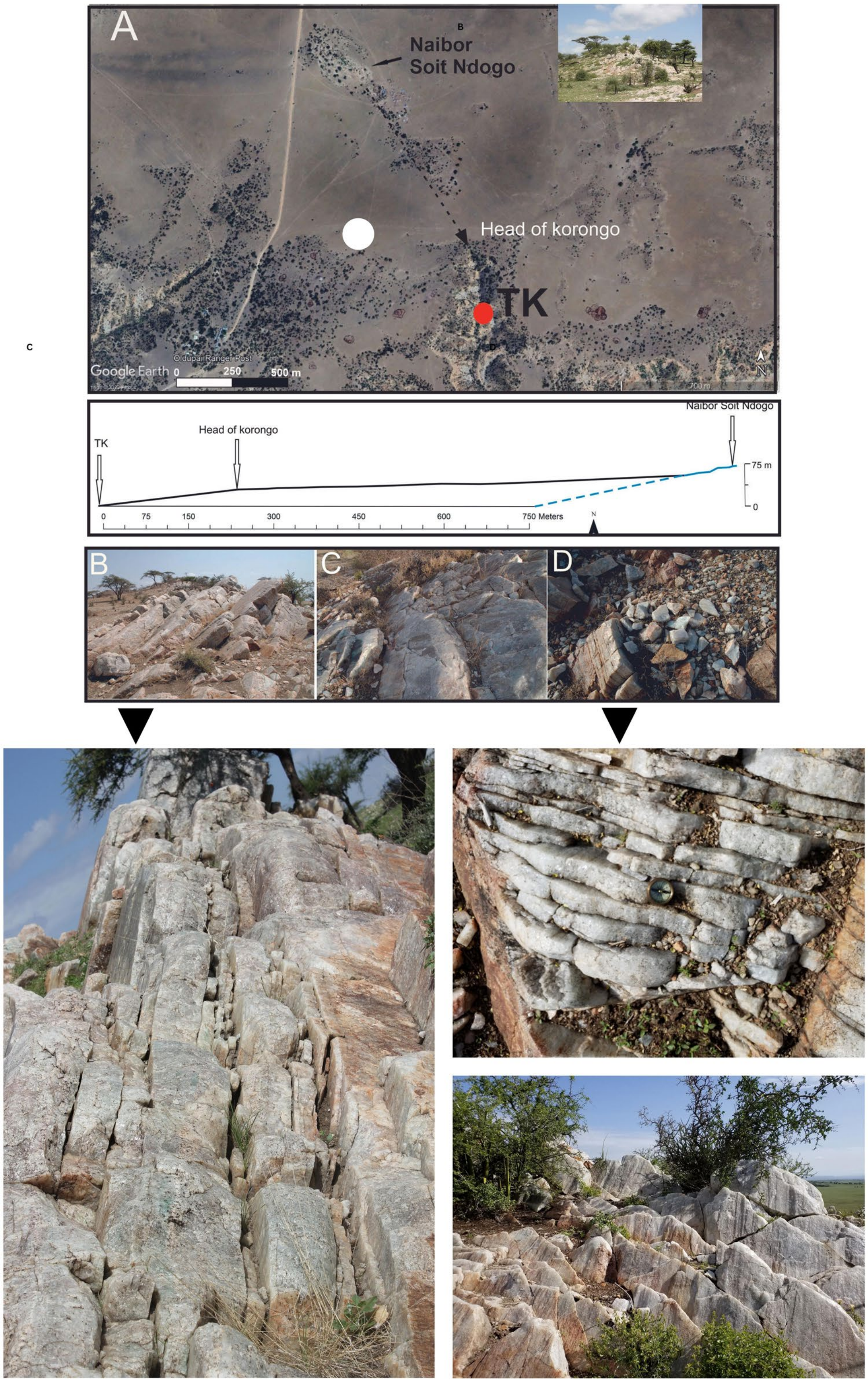

Fig. 3 The Naibor Soit quartzite sources showing: (**A**) map showing the distance of the current raw material source from TKLF; (**B**) general view of the NSQ outcrops; (**C**) closeup view of the NSQ sources; (**D**) penetrative tectonic structures and nature of joints within the NSQ raw material sources

weight was 724.31 g (Fig. 6). Some hammerstones were used more often than others (e.g. H18 for 314 blows) (Table 4). Coarse-grained volcanics (e.g. H49) were used more frequently as abraders for the preparation of the striking platforms. These volcanic rocks were often used for controlled knapping near the tip of the handaxe and for finishing the handaxe. The mechanical properties of the rock and duration of use influenced the extent of pitting and abrasion on all hammerstones (Fig. 6, Table 4). A few hammerstones broke during usage. H2 broke during BP knapping of a large slab

Fig. 4 Variability in patination of NSQ showing those currently exposed on the surface (yellow arrow) and sub-surface patinated slabs (black arrow)

S9 after only four blows. H9, a weathered hammerstone, broke during FHP (Exp_1). H42 was only slightly chipped.

Handaxe *Façonnage* on Naibor Soit Quartzite Slabs

Knapping NSQ slabs was conducted to reproduce the reduction sequences noted in the TK handaxes on slabs (Santonja et al., 2014, 2018) (Tables S2-S5, Figs. S1, S2). The technological study of TKLF handaxes noted two phases of bifacial shaping (Inizan et al., 1992: 41 ff; 1995: 43 ff) (Tables S2-S5, Figs. S1, S2). The first focused on volumetric reduction, and the second on achieving bilateral symmetry. Three groups of bifaces were differentiated in TKLF based on their morphology and reduction methods. The most frequent morphologies in NSQ were pointed handaxes with amygdaloid silhouettes (68.9%), oval or elliptical forms with a peripheral edge (20%), and rectangular with a transverse cutting edge (11.1%) (Santonja et al., 2018: 159). The volumetric reduction phase was adapted to suit the NSQ slabs. This was based on bilateral shaping. This shaping was achieved through bifacial flaking in the case of pointed handaxes (Santonja et al., 2018: fig. 8.7). In some instances, one edge was flaked with bifacial reduction and the other edge was unifacial (Santonja et al., 2018:fig. 8.8, *A and F*). In some instances, two edges were flaked using unifacial flaking. The flaking sometimes extended over all or part of the contour of the handaxe. Bifacial reduction occurred primarily along the apical third. We believe this flaking was focused on shaping the point of the handaxe (Santonja et al., 2018: fig. 8.6*, C; 8.7; 8.8; 8.14. C*). The limited flaking and lack of thinning, except near the tip, resulted in the preservation of large portions of the slab's original surface (Santonja et al., 2014: 199). In some instances, the base of the handaxe was shaped. In other cases, the base represented one or two natural surfaces (the joint of a slab). In rarer cases, the base was defined by one steep edge from the original joint surfaces that intersected with a unifacially flaked surface (Santonja et al., 2014, fig. 20; 2018, fig. 8.9; *8.10*).

A total of 22 experimental handaxes were manufactured and studied ($n = 21$ on the selected slabs that could be knapped and one created during skill acquisition). The experimental handaxes followed a bilateral shaping pattern. One lateral edge was partially bifacially reduced, while the other was primarily shaped through unifacial knapping. Near the tip, bifacial flaking was used to form the point. Overall, flaking was minimal and not extensively invasive (Fig. 7). The mean dimensions of experimental complete handaxes were 241.12 × 133.11 × 44.75 mm (length, width, and thickness respectively) and 1915.67 g (weight) (Fig. 8, Tables 5, 6). The experiments also addressed the production of exceptionally large TK handaxes (over 30 cm). One of the main challenges was the selection of suitable slabs. Longer slabs had more internal fractures and a higher risk of breakage during knapping. The number of visible flake scars on experimental handaxes averaged 14.92 and 10.5, respectively, on the two faces of the slab (Faces A and B), averaging around 28 flake removals per tool. Most handaxes preserved a substantial portion of the slab's natural surface (Fig. 9).

Initial Stages of Slab Reduction

One of the critical issues in handaxe *façonnage* on NSQ slabs was to achieve an appropriate width of the handaxe through reduction. If the slab selected was approximately the desired width of the handaxe, further reduction was minimal. However, this was not always possible. Two methods were used for the reduction of the length and the width of the slab:

i. ***Bipolar reduction of slab width:*** The anvil selected for this bipolar flaking was an NSQ piece (No. A7, 310 mm

Fig. 5 A sample of the NSQ slabs selected for experimental knapping of handaxes showing differing shapes (see Table 2)

Table 3 Details of the NSQ slabs selected for experimental knapping showing features of edges, joints, and penetrative structures (PTPS)

		Count	Table *N* %
No. of slab edges	3	12	48.0%
	4	11	44.0%
	5	2	8.0%
No of penetrative structures	2	6	24.0%
	3	9	36.0%
	4	8	32.0%
	5	2	8.0%
No. of joints	0	6	24.0%
	1	6	24.0%
	2	10	40.0%
	3	3	12.0%

length × 210 mm width × 90 mm thickness) (Fig. 10). Several BP strategies were adopted as follows:

a. Placing the slab flat on the edge of an anvil with subsequent BP percussion with a large hammerstone. This was the ideal position for the knapper.
b. The slab was placed on the edge of the anvil but at a slightly tilted angle to the horizontal. The slab still rested on the anvil over most of its surface. A slight angle aided in controlling the removal accuracy. This technique was a combination of BP and FHP.
c. Placing the slab in the centre of the anvil. This was unsuitable and resulted in the fractures (Exp_20); utilization of BP reduction after the handaxe morphology was obtained to reduce the width further along the right lateral edge (Exp_19) or use of multiple methods (Exp_21).

Despite the efficacy of BP removals as a rapid manner for reducing slabs, it was not always effective. This technique often generated internal stresses that initiated or caused breakage along internal fracture lines in the slabs. Traces of initial BP reduction of slabs were often removed in subsequent flaking of the handaxe (e.g. flake scar erasure, Braun et al., 2008).

*ii. **FHP reduction of slab width***: Another way of reducing slab length and width was by FHP in order to minimize the intensity of flaking to avoid breakage. In our experiments, some degree of width reduction was unavoidable, considering the paucity of suitable slabs of an appropriate width in the modern context (Tables 1, 2, 3). This initial reduction of large slabs resulted in several by-products, including large flakes or angular/blocky pieces that, in one instance, weighed up to 1610 g (Exp_1, flake no.3). Further, the longer and wider the slab, the higher the probability of internal fracture lines that could lead to breakage

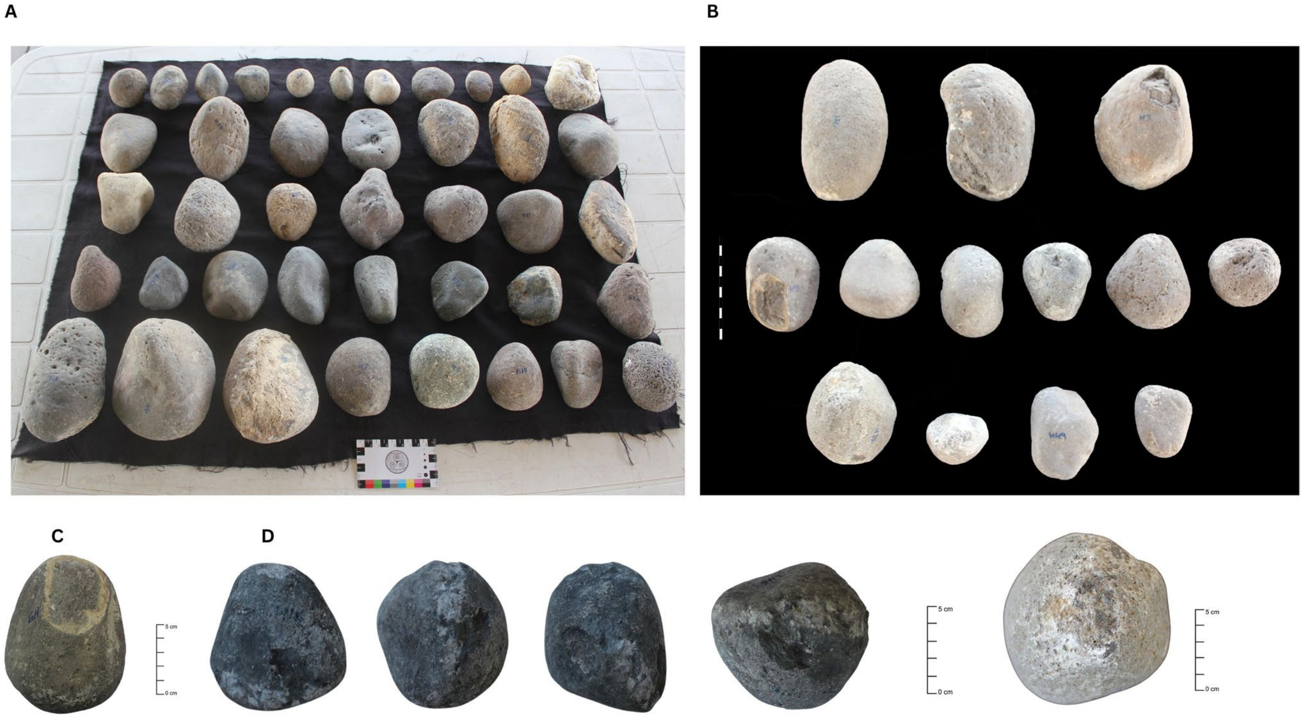

Fig. 6 Hammerstones selected for experimental knapping showing: (**A**) selected cobbles; (**B**) sample of hammerstones used during experimental knapping; (**C**) hammerstones broken during use; (**D**) views of hammerstones post-use (H16: after 2 days of use) (scale = 10 cm)

Table 4 Details of the hammerstones selected for experimental knapping (raw material: volcanics)

Hammerstone No	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)
H2	145.00	89.00	88.00	1631.00
H3	122.00	116.00	84.00	1731.00
H6	170.00	93.00	64.00	1240.00
H9	98.00	71.00	64.00	630.00
H12	86.00	80.00	49.00	476.00
H13	95.00	67.00	53.00	478.00
H16	78.00	72.00	57.00	440.00
H17	92.00	84.00	50.00	571.00
H18	74.00	73.00	66.00	456.00
H39	98.00	84.00	72.00	940.00
H42	68.00	60.00	48.00	286.00
H49	88.00	67.00	39.00	365.00
H51	70.00	58.00	27.00	172.00
Mean dimensions	*98.77*	*78.00*	*58.54*	*724.31*
Median	*92.00*	*73.00*	*57.00*	*478.00*

during knapping. Considerable effort was expended in several experiments to reduce the slab (e.g. Exp 8). The main advantage of selecting a larger slab was that, in the event of accidental breakage during knapping, enough length and width would remain to allow flaking to continue. Slabs were reduced by an average weight of 1922.47 g (ranging from 315 g to 6,301 g).

Strategies Involved in Shaping the Proximal End (Base)

The base of the handaxes often retained the initial thickness of the slab. These strategies were to a large extent influenced by the original morphology of the slab. The following are some of the forms that were present in the experimental sample:

a. A natural joint (we describe this as a ‘backed’ piece);
b. A breakage surface occurring during slab extraction;
c. Flaked unidirectionally at a 90° angle to blunt the edge (Fig. 11).

In addition, the lateral edges at the base were shaped in several ways:

a. The occurrence of two natural lateral joints;
b. Unifacial flaking on one lateral edge and partly unifacial flaking/partly natural joint surface;
c. Unifacial flaking and a natural break;
d. Unifacial flaking on both edges with evidence of BP on one lateral edge being partly retained;
e. Unifacial flaking on one edge and one natural joint;
f. A natural joint surface and partly unifacial/partly bifacial flaking;
g. Unifacial and bifacial flaking;
h. Partly natural surface/unidirectional and unidirectional flaking;
i. Partly natural joint/unidirectional and bifacial flaking. In all instances of flaking, attempts were made to create a base that was possibly suitable as a handhold. The thickness of the base retained the original thickness of the slab.

Shaping of the Apex

This was achieved by bifacial flaking to thin the apical end in a roughly symmetrical manner (Fig. 12). In one tool, the morphology of the apex was convex (Exp_17), resulting from resharpening after the tip broke. The knapper sought to retain the length of the tool and thus modified the apex. One response to the breakage of the tip along the fracture line (Exp_18) was a rotation of the tool to reverse the location of the apex. In Exp_13, the presence of a visible fracture in the slab, forced the knapper to stop flaking. This resulted in a thick apical end. When the slab has sufficient length, the breakage of the apex could easily be overcome by subsequent flaking. Despite the frequent shifts in the flaking strategy during the experiment, there are only rare traces of this resharpening on the final form of the handaxe.

Shaping of the Lateral Edges

The thick slab edges occurring at 90° angles to either face and the number and nature of PTPS influenced whether unidirectional or bifacial knapping was to be adopted to shape the tool. In experiments, percussion angles of around 90°

Fig. 7 Archaeological and experimental handaxes showing: (**A**) examples of the TKLF and experimentally reproduced handaxes and (**B**) methods of knapping showing location of knapper on a tarpaulin to map spatial distribution of waste products, free hand and bipolar percussion and final handaxes knapped

were adopted using both FHP as well as BP as discussed above.

Influence of PTPS

PTPS influenced the decisions made about the direction of force when knappers detached flakes. In some instances, the PTPS obstructed flake detachment. Flakes often terminated with step fractures along a PTPS, thereby obstructing further flaking. Thin PTPS near the apical end (e.g. as in Exp_8) prevented further thinning. This results in slightly thicker apical ends. These pieces may reflect decisions to stop flaking rather than risk breakage. Thicker PTPS along the lateral edges of the tool could be utilized as suitable striking platforms to flake the edges. In one instance (Exp_13, flake no. 15), a flake was detached along a penetrative structure, resulting in a deep invasive scar and destroying the symmetry of the tool.

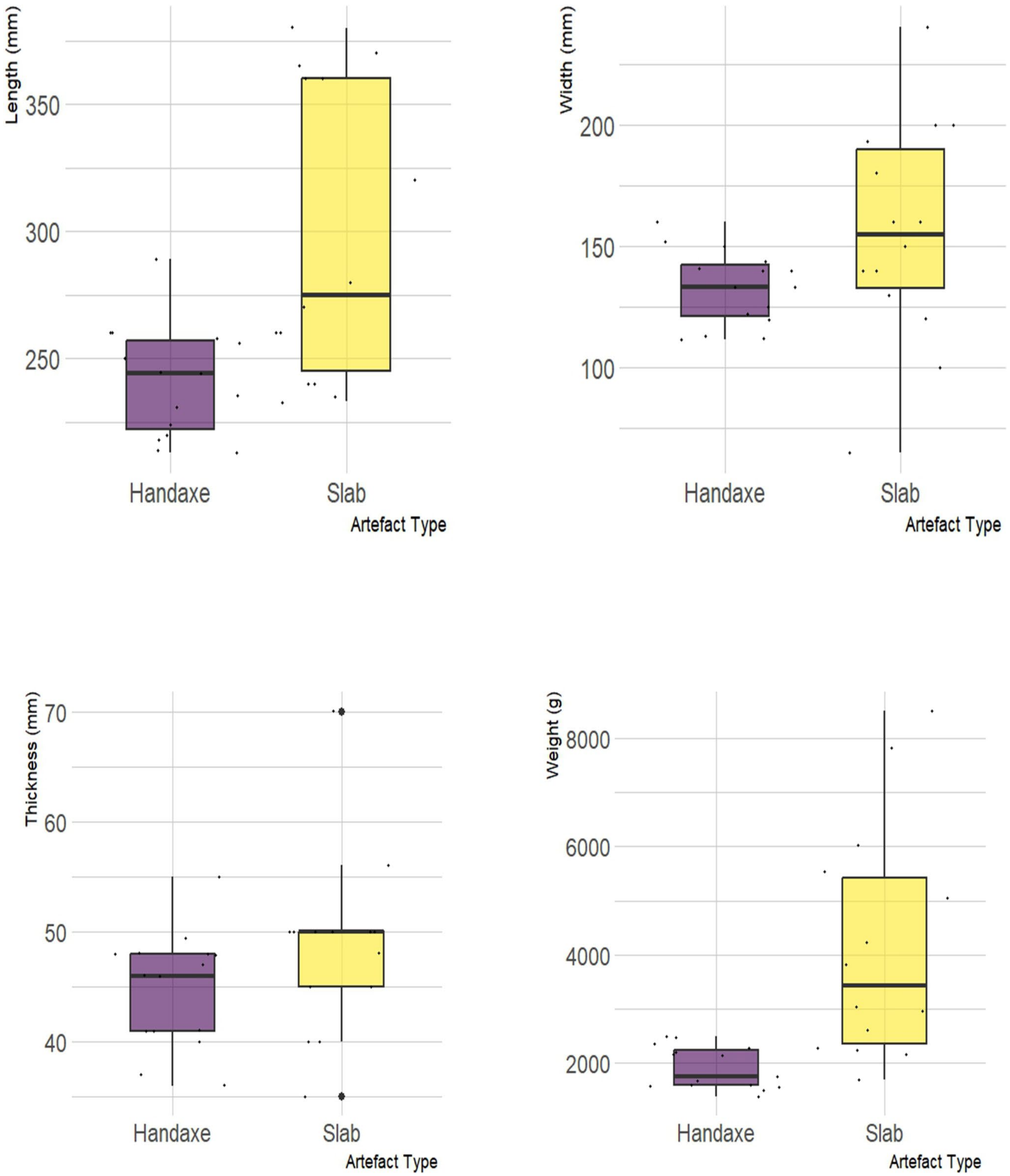

Fig. 8 Dimensions of experimentally knapped handaxes (complete) and slabs selected for the same

Influence of Fracture Lines

Internal fracture lines on the slabs were challenging to avoid. In several instances, this resulted in breakage of the tool. However, conscious decisions were made to factor these into knapping strategies to prevent breakage. For example, in Exp_26, further flaking of the lateral edges to reduce the width was avoided as a fracture line cut through the mesial part of the tool (Fig. 13).

Table 5 Metrical dimensions of all complete experimentally knapped handaxes ($n = 15$)

		Length (mm)	Width (mm)	Thickness (mm)	Weight (g)
Complete handaxes	***N***	15	15	15	15
	Mean	241.12	133.11	44.75	1915.67
	Median	244.00	133.10	46.00	1748.00
	Minimum	213	112	36	1380
	Maximum	289	160	55	2488
	Std. Deviation	21.624	15.397	5.195	389.281

Table 6 Metrical dimensions of all experimentally knapped handaxes (broken and complete) ($n = 22$)

		Length (mm)	Width (mm)	Thickness (mm)	Weight (g)
All handaxes	**N**	22	22	22	22
	Mean	239.67	136.48	43.42	1905.50
	Median	239.50	140.50	45.50	1764.00
	Minimum	210	96	28	1380
	Maximum	289	170	55	2837
	Std. Deviation	22.040	18.228	6.283	394.729

Breakage of Handaxes During Knapping

One of the principal causes of breakage was the presence of fracture lines in the NSQ slabs (Fig. 14). These enhance breakage along the apical end, mesial part, and base [apex ($n = 4$), mesial ($n = 1$), base ($n = 1$), tip ($n = 1$)]. Breaks were horizontal and transverse with occasional vertical breakages along the length of the handaxe (Fig. 14). In one instance (Exp_25), the tool broke along a fracture line during an attempt to flake the base. In this case, the slab selected was too thin (28 mm). Breakage along the apical third in another handaxe (Exp_24) was possibly due to building up stress along the junction of the base and the apical end, along an internal fracture line. In another instance (Exp_23), breakage was along the proximal end whilst attempting to remove a PTPS that obstructed knapping. This broke after 24 flake removals and was a knapping error combined with the effect of internal fracture planes. In Exp_6, the handaxe broke along a fracture line near the

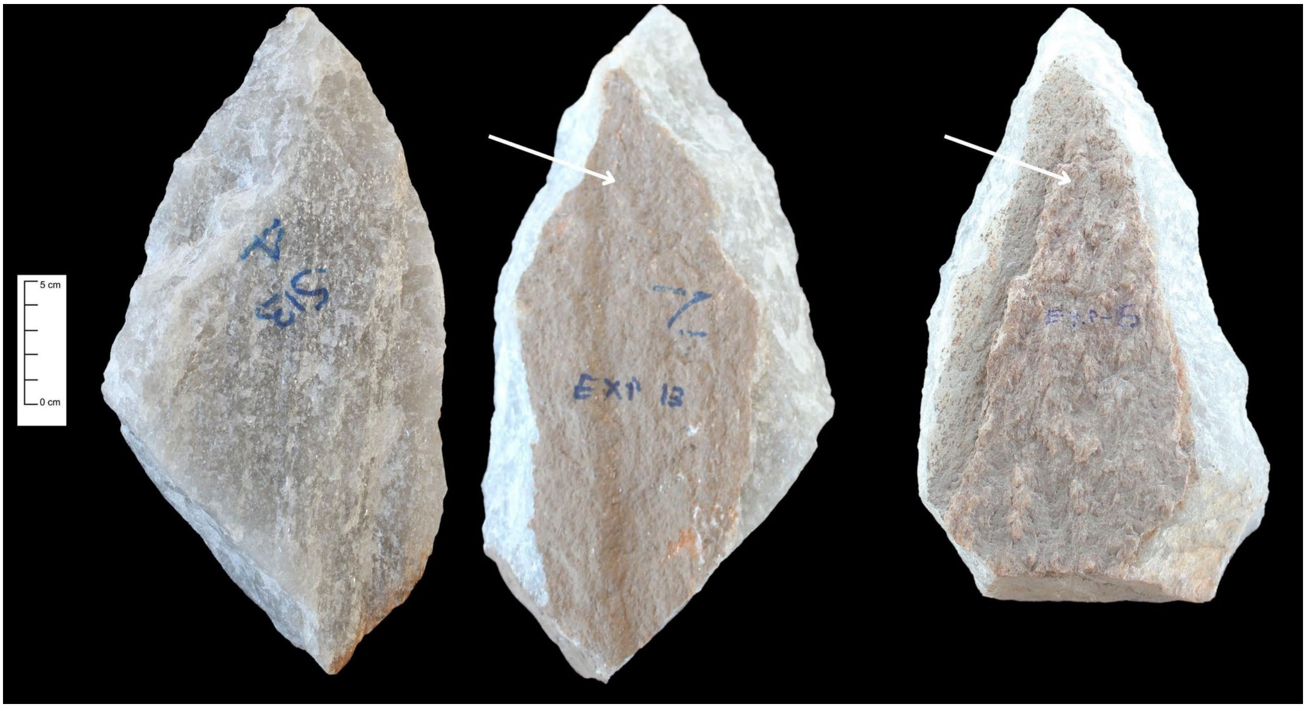

Fig. 9 Retention of natural surfaces on experimental handaxes

Fig.10 Bipolar reduction of slabs showing (**A**) Anvil (A7) and hammerstones used for BP knapping; (**B**) placing the slab flat on the edge of anvil; (**C**) placing the handaxe preform at a slightly tilted angle to the horizontal; (**D**) placing the slab in the centre of the anvil at a slight angle; (**E**) shaping the blank

apex. This is a typical transverse break (broken apex dimensions = 100 × 110 × 40 mm). Breakage of another handaxe (Exp_7) was transverse arising after 17 blows, the last of which was to shape the apex. In another instance (Exp_14), the tool broke into two halves along a fracture plane while shaping the apical end owing to a hard blow seeking to remove two major PTPS near the tip. Knapping errors resulted in the breakage of the tip in Exp_16. Thus, we note breakage along the apical third, along the mesial part, the base, and vertically across the length of the tool.

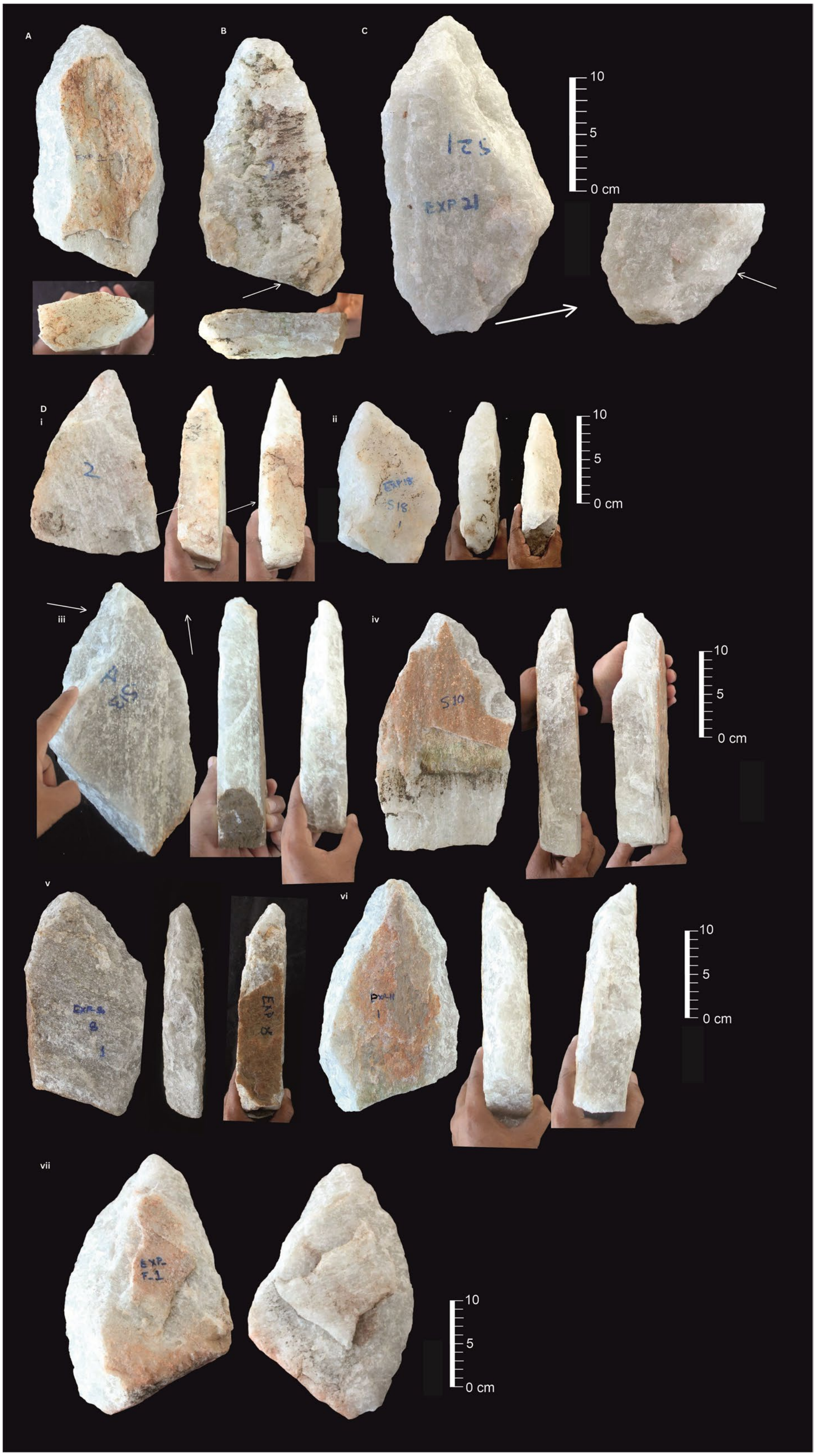

Fig. 11 Experimental replication of strategies to shape the handaxe base (proximal end) showing: (**A**) base comprises a natural joint (technologically called a back); (**B**) base comprises a breakage during extraction; (**C**) base is flaked unidirectionally at a 90° angle to blunt it; unifacial flaking of one edge and one natural joint; (**D**) shaping of the handaxe lateral edges at the base showing (i) two natural lateral joints; (ii) unifacial on one lateral edge and partly unifacial/partly natural joint on the other lateral edge; (iii) unifacial and natural break; (iv) unifacial on both edges with BP on one lateral edge partly retained; (v) natural joint and partly unifacial/partly bifacial; (vi) unifacial and bifacial; (vii) partly natural/unidirectional and bifacial

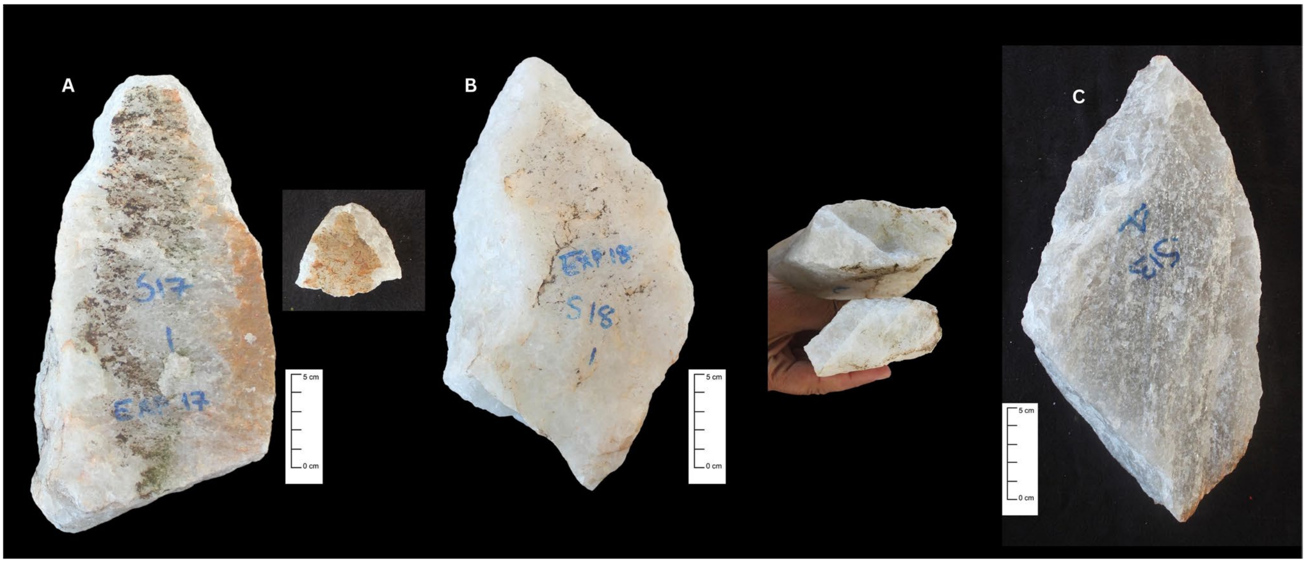

Fig. 12 Experimental examples of shaping of the apical third showing: (**A**) convex apical end following rejuvenation after initial breakage of the tip; (**B**) rotation of the tool to reverse the location of the apex, after breakage along a fracture line; (**C**) thick apex caused by presence of a fault leading to a decision to stop knapping along the apical region

Fig. 13 The influence of PTPS in constraining the morphology of the handaxe is shown with arrows marking its position on the slab and on the artefact

Waste Resulting from Handaxe *façonnage*

A sample of 3322 waste products (6 handaxes) was studied in detail (Susana Rubio-Jara and Joaquín Panera). Here, we distinguish intentional flakes that arose as per the knapper's intention and shatter that arose either as a byproduct of the intentional flake or as an unintentional consequence of percussion (total weight of 16,641 g; Tables 7, 8; Fig. 15). The more extensive use of FHP and special characteristics of the NSQ produced a considerable amount of waste (Li et al., 2017). Shatter gradually reduced across the duration of the experimental program from 739 to 232 pieces (Exp_1 to Exp_27) (Table 7), as the knapper gained experience.

Fig. 14 Breakage of handaxes during knapping showing: (**A**) handaxes that broke during *façonnage*; (**B**) following breakage, a part of the broken slab was then shaped into a handaxe

The weight of shatter including complete and fragment flakes, fragment of slabs, and debris is similar between the different experiments, and ranges between 171 and 311 g (Table 7). In all experiments, the number of complete flakes was higher than flake fragments (Table 8), there being more in the first experiments as compared to the later ones (1.7:1 complete flakes: flake fragments in Exp_1 and 4.2:1 in Exp_27). In all experiments, the statistical tests and graphical analyses provide robust evidence of a morphological tendency toward broad flakes (Figs S4a, S4b). Intense percussion led to fractures; 36.9% of flakes (23 pieces) are broad, with siret fractures. The initial reduction phase consisted of reducing the slab's volume, removing the corners or irregularities of the slab's edges, and achieving an appropriate angle for subsequent knapping. Therefore, between 17.5% (Exp_1) and 53.2% (Exp_27) of flakes have more than half of the dorsal area reflecting a natural surface (Table 8). With one exception (Exp_27), flakes with no natural areas or with cortex coverage being < 1/3 of the dorsal surface dominate in 5 experiments with percentages between 60.9% (Exp. 10) and 82.5% (Exp_ 1). These flakes were usually aimed at creating the point or configuring the edges of handaxes. Thus, more than half of the assemblage (61.4%, 108 complete flakes) had plain striking platforms. Cortical or natural butts were substantial in a quarter of flakes (24.5%, 43 items), the majority coming from the removal of the joint or the PTPS of the slab. While flakes with facetted or dihedral striking platforms were infrequent (7.4% and 4.5%, respectively), it was noted that these 'facetted' butts derive from abrading the slab to create a surface suitable for the knapping; this action could generate concave butts also (2.3%). The use of slabs generally produced flakes with triangular and rectangular silhouettes (50.6% and 33.1%, respectively), regardless of whether they were aimed at bifacial flaking along the lateral edges or the tip of the handaxe.

The organization of the dorsal surfaces of the flakes facilitates an understanding of the production sequences to shape the handaxe. There were 161 complete flakes (from six experiments) that bore scars, with predominantly one, two, or three scars on the dorsal face (51, 31.7%; 57, 35.4%, and 36, 22.4% respectively). Analysis of the scar polarity in the 133 flakes where it was possible to discern (following Santonja et al., 2014), we found that most flakes displayed unipolarity (31.6%, $n = 42$) or bipolarity (44.4%, $n = 59$). This suggested a relatively short reduction sequence of the slab, where the blank was rotated relatively infrequently during knapping. Most of these flakes were the product of shaping near the apex of the handaxe. It was thus possible to observe scars detached to adapt to the problems created by the penetrative structures of the slab. Flakes with three scars with at least two polarities ($n = 17$, 12.8%) and more than three polarities ($n = 15$, with 3–6 scars) were also observed. We interpret these flakes as reflective of longer reduction sequences arising from the last phases of shaping bifacial edges.

Table 7 Waste: size (mm) and weight (g) of complete 'cognitive'/intended flakes arising from a study of the materials arising from handaxe *façonnage*

Waste								
	First phase (debitage arising from handaxe manufacture)			**Second phase (incidental shatter)**				
	Complete flakes	**Fragment flakes**	**Slabs**	**Complete and fragment flakes**	**Fragment of slabs**	**Debris**		
	n	**n**	**n**	**n**	**n**	**n**	**n**	Total pieces and weight
Exp. 1	36	21	4	10	33	(intervals: 25x13x5 mm and 16x9x5 mm) n=74	(intervals: 10x7x2 mm and 8x3x2 mm) n=665	**843**
	4093 g			157 g		156 g		**4406 g**
Exp. 5	37	14	3	12	30	(intervals: 27x12x5 mm and 16x13x12 mm) n= 84	(intervals: 13x10x3 mm and 8x7x3 mm) n=443	**623**
	4947 g			151 g		160 g		**5258 g**
Exp. 10	18	5	2	14	12	(intervals: 20x16x4 mm and 10x8x3 mm) n= 100	(mean: 8x5x2mm) n=194	**345**
	979 g		135 g			101 g		**1215 g**
Exp. 11	36	6	1	9	30	(intervals: 28x10x3 mm and 10x8x4 mm) n= 101	(intervals: 8x7x3 mm and 6x4x1 mm) n=255	**438**
	2044 g			152 g		184 g		**2380 g**
Exp. 21	19	5	1	11	12	(intervals: 26x9x5 mm and 12x5x3 mm) n= 44	(intervals: 10x9x2mm and 8x3x2mm) n=188	**280**
	1168 g			87 g		84 g		**1339 g**
Exp. 27	38	9	5	32	30	(intervals: 24x4x6 mm and 16x11x3 mm) n= 86	(intervals: 15x12x4mm and 6x4x2mm) n=592	**793**
	1646 g			153g		244 g		**2043 g**

Table 8 Cortex on flakes and flakes fragments by experiment (percentage between brackets)

	Cortex > 2/3	Cortex 1/3–2/3	Cortex < 1/3	Decortical	Total
Experiment 1	2 (3.5)	8 (14)	16 (28.1)	31 (54.4)	57
Experiment 5	5 (9.8)	5 (9.8)	23 (45.1)	18 (35.3)	51
Experiment 10	7 (30.4)	2 (8.7)	11 (47.8)	3 (13.1)	23
Experiment 11	4 (9.5)	10 (23.8)	18 (42.9)	10 (23.8)	42
Experiment 21	4 (16.7)	2 (8.3)	9 (37.5)	9 (37.5)	24
Experiment 27	8 (17)	17 (36.2)	15 (31.9)	7 (14.9)	47

During experiments, occasional use of BP was adopted in the first phase of shaping to reduce slab widths. This decision by the knapper, KA, was thought to achieve greater control of percussive force during knapping and to lower the risks of breakage along penetrative planar structures. This was conducted along with FHP to achieve the final handaxe morphology. Flakes created by BP percussion are often difficult to identify, owing to frequent proximal and distal fractures that eliminate butts and bulbs, significant attributes for determination of this method. When applying criteria established in experimental studies (Diez-Martín et al., 2011; Sánchez-Yustos et al., 2012), we obtained only preliminary results that cannot be generalized. Both BP and unidirectional FHP struck at 90° angles resulted in experimental flakes with similar morphologies (divergent in shape, with cortical/natural striking platforms and terminations; the angle between the striking platform and bulb being around 90°). The sole difference was the retention of the point of percussion along both the striking platform and the distal end. Owing to this, we treat variation in flakes as a group, without distinguishing between those arising from bipolar (BP) or freehand (FHP) knapping techniques.

Discussion

In this paper, we examined the *chaîne opératoire* related to handaxe *façonnage* on slabs of Naibor Soit quartzite from Olduvai Gorge, Tanzania. The experiments focused on

Fig. 15 Waste products from handaxe *façonnnage* (Exp_21)

reproducing some of the strategies for handaxe manufacture identified at the Thiongo Korongo site, Bed II (1.35 Ma). The NSQ is ubiquitous at archaeological sites found in the Pleistocene sediments within Olduvai Gorge (Darmark, 2010; Herzlinger et al., 2017a, 2017b; Lycett et al., 2016; Shelley, 1990; Winton, 2005), and our research provides additional information on ways in which knappers resolved issues arising from its unique properties. For successful flaking, Acheulean hominins required a clear comprehension of the NSQ's internal fractures, penetrative tectonic structures, and joints that influenced slab availability. These properties involve structured decision-making in the careful selection and extraction of a series of parallel bedded slabs.

Our knapping experiments demonstrated that slab thicknesses of < 30 mm or > 50 mm increased the chances of breakage of the slab. The presence of fractures within the NSQ slabs could accelerate breakage along the point and mesial part of the handaxe (horizontally or transversely) and vertically across the length of the tool. These are similar to the breakage patterns previously identified in the technological analyses of NSQ artefacts from TKLF (Santonja et al., 2014). We selected slabs with a minimum number of PTPS to reduce the possibility of fracture while knapping. A selection of slabs with relatively few PTPS is noted in the assemblages from TKLF. This suggests that hominins may have also selected specific slabs to minimize similar breakage problems. The knapping process may have involved conceptualizing the handaxe morphology, followed by transforming the raw material volume to create a pointed tool with components that may have been shaped specifically for prehensile purposes.

The slabs we selected for the experiments were a few centimetres wider than the TKLF handaxes. Slab widths were reduced using BP and, to a lesser extent, FHP strategies. Rectangular or square slabs were preferred (mean dimensions of 287 × 167 × 46 mm and mean weight of 3,714 g) with around 2–5 PTPS and with joints along the lateral edges. The 13 preferred hammerstones (Table 4) fell broadly within the range of the TKLF percussors (Table S5) (Santonja et al., 2014: 188, Table 4). At the TKLF locality, volcanic rock hammerstones show a continuous size distribution, with frequency peaks in the 200–300 g and 400–500 g weight ranges. The lengths and weights of these hammerstones range from 132 mm/52 g to 90 mm/1786 g, with an average weight of 568.98 g.

The experimental handaxes exhibited bilateral shaping, with bifacial reduction applied along both edges or part of one lateral edge. The remaining edges were shaped using unifacial flaking. Bifacial flaking was also present at the apex to form the point of the handaxe. Overall, flaking was minimal, averaging around 15 flake scars per handaxe, with much of the original slab surface left intact. At TKLF, the average number of flake scars was 21.18, with a range of 9 to 37. Multiple strategies were employed to shape the base of the handaxes, aiming to improve grip and handling. The thickness of the base often reflected the original thickness of the slab. The shaping of the point was complex. Many of the experimentally produced handaxe tips were thick. The very pointed ones frequently broke. Overall, most experimental handaxes preserved a substantial portion of the slab's natural surface, similar to that noted at TKLF (Fig. 9; Figs. S1, S2; Tables S2-S5). The shaping of the lateral edges, following the TKLF tools, was primarily unifacial at angles of almost 90° to one lateral edge, with bifacial flaking occurring along the other lateral edge. FHP achieved the 90° angle. Traces of BP on archaeological artefacts are often unclear owing to weathering or subsequent flaking.

The lithic waste products from experimental handaxe *façonnage* show a variety of distinctive attributes, including the organization of dorsal flake scars, size ranges, and cortex proportions. These features reflect both short, simple knapping sequences and more complex, extended reduction strategies. They also indicate deliberate rotation of the handaxe during shaping, as well as patterned flaking used to create the edges of handaxes. Striking platforms, as in the TKLF assemblage, are not truly facetted but have 'pseudo-facets' that result from flaking along the lateral edges (Akhilesh & Pappu, 2015; Presnyakova et al., 2018). It is often difficult to distinguish between BP and FHP flakes in both the archaeological and experimental assemblages. In the former contexts, owing to the weathering of the quartzite, traces of percussion marks along the distal end of flakes in the case of BP may not be preserved.

Handaxes at TKLF tend to have bilateral symmetry. Some have suggested that the imposition of forms, such as the technological decisions we infer from the assemblages at TKLF, are reflective of cognitive developments such as spatial cognition and possibly aesthetic cognition (Diez-Martín et al., 2019: Fig. 18; Wynn & Coolidge, 2016). In the TKLF assemblage, we observe a potential appreciation of the mechanical properties of NSQ materials. The selection of slabs as well as the flaking patterns appears to factor in the unusual properties of this raw material (Santonja et al., 2014, 2018). The handaxes are within specific size ranges; two-thirds of all handaxes have lengths from 177 to 278 mm, widths from 90 to 132 mm, thickness from 40 to 63 mm, and weights from 985 to 2251 g. The two dimensional planform of these tools are pointed, oval, or rectangular. A characteristic technical feature of TKLF handaxes are the intense reduction of the distal third focused on shaping of these tools (Santonja et al., 2018:171,173). In the TKLF assemblage, broken handaxe apexes and handaxes with fractured pointed tips suggest knapping errors and/or heavy-duty use. Previously, some researchers have suggested that the handaxes at TKLF reflect a different kind of technology compared to classic Acheulean tools. The TKLF tools strategy has been termed the rhomboidal reduction method (Boëda, 2001; de la Torre & Mora, 2005a, 2005b; de la Torre et al., 2013). However, this specific type of technology is not abundant in the TKLF assemblage. Only seven tools conform to these patterns (Santonja et al., 2018: 177). Backing (shaped or not) predominates in the basal areas of handaxes in almost 40% of cases (19 of 48 complete handaxes of NSQ). This may be the result of a need for prehension, although we cannot prove this requirement. In 21% of handaxes, backing occurs along two sides, suggesting an intentionality for this design that was aimed at creating a pointed apex. The cutting edges were shaped by unifacial or bifacial knapping or a combination of both. The apex was sometimes resharpened through a tranchet blow (a large transverse blow across the edge of a tool that is considered an attempt to resharpen an edge). This suggests a repetitive and prolonged use of the tool. This is somewhat unexpected given the proximity of the Naibor Soit outcrops. As regards shaping of the lateral edges, in the TKLF level, the unifacial flaking on one lateral edge and unifacial with bifacial flaking on the other lateral edge were the preferred strategies. Percussion angles of around 90° were also observed (Santonja et al., 2018: 172, fig. 8.14). While BP could have been used (see Santonja et al., 2018), this would be undetectable in the absence of characteristic points of percussion. We identified bipolar percussion in a significant percentage (16.98%) of cores in TKLF (Santonja et al., 2014). Identification is not very easy in the case of flakes, in which the frequent proximal and distal fractures have eliminated the butts and bulbs that could have provided significant criteria for identification. (Diez-Martín et al., 2011; Santonja et al., 2014: 189; Sánchez-Yustos et al., 2012, de la Peña, 2015). It is likely that both BP and FHP were implemented during the manufacture of the handaxes at TKLF. However, in the archaeological record, owing to the weathering of the quartzite, traces of percussion marks along the distal end of flakes in the case of BP may not be preserved.

The similarities between the pointed handaxes at TKLF, constituting 70% of the TKLF tools, could be interpreted as implementation of a preconceived scheme or 'mental templates' (García-Medrano et al., 2019; Gowlett, 1984; Toth & Schick, 2009). They may have been designed for a specific function which may be related to the functions that were required at the TKLF locality (see Leakey, 1971: 177, Fig. 80, and Santonja et al., 2018: fig. 8.15). We believe that the morphology of these artefacts at this specific place supports the hypothesis that these handaxes were manufactured within a complex web of different functional contexts (Diez-Martín & Eren, 2012) and that handaxes played an important role in the functional requirements of stone tools in the Pleistocene (Tables S2-S5; Figs S1, S2).

The wide range of handaxe shapes in the Olduvai assemblages is likely the result of several factors, including the type of raw material used, the intended function of the tools, and possibly aesthetic preferences (de la Torre, 2004; Isaac, 1977; Roe, 1994; Rubio-Jara et al., 2017; Santonja et al., 2014, 2018; Shipton, 2018). Here, we do not explore the detailed morphometric variation of handaxes at TKLF; however, we highlight how the reduction sequence, as well as raw material type and morphology, influences the discarded handaxe form. Our experimental manufacture can provide insights into constraints on the manufacture process. The detachment of large and thick slabs at the NSQ source was time-consuming and an unlikely solution to raw material procurement. Thus, as noted in the TKLF assemblage, the unmodified NSQ slabs, despite their challenges, were preferred for handaxe *façonnage* (in the TKLF assemblage, only 2.6% of handaxes are produced on large flakes).

We hypothesize a potential scenario of raw material procurement at TKLF during the time when hominins occupied this area. We believe that the slabs available for artefact manufacture had greater exposure (Santonja et al., 2014, 2018). Our experiments highlight the fact that slab morphology played an important role in shaping the overall morphology of some of the handaxes. It is possible that Acheulean knappers could implement certain flaking strategies regardless of the original form of the raw material (Gurtov & Eren, 2014; Hovers and Braun, 2009). However, there is clearly some influence of raw material on the ability to execute certain shaping strategies. Our experiments suggest that TKLF hominins selected blanks that had two symmetrical surfaces, which made bifacial reduction easier (Gallotti et al., 2014). Hominins that created the TKLF assemblage reduced both sides of these slabs in a way that resulted in a characteristic shape that was reflective of the original morphology of the slab. The nature of these NSQs resulted in limitations in knapping, constraining the location and intensity of flaking. Toolmakers also had to account for the material's high tendency to break, which required careful control during knapping. Despite the challenges posed by this raw material, the presence of exceptionally large handaxes at the TKLF—80% of which are over 20 cm long—suggests that Acheulean hominins found ways to overcome these difficulties. The ability to perform specific knapping strategies on this intractable raw material may be a reflection of knapper skill, which was evident in our experiments as well. The selection of the original slab appears to be the basis for the ability to implement these knapping strategies (Akhilesh & Pappu, 2015). The knapper alternated between using FHP and, occasionally, bipolar percussion (BP). The latter was mainly used to reduce the width of the tool. Instead of investing energy in reducing slab widths, the Acheulean hominins at TK appear to have selected slabs that were already well-suited for toolmaking and required minimal modification. This strategic selection is also evident in how they oriented the slabs for flaking the base. In many cases, the bases retained one or more natural joints or a cortical back (Santonja et al., 2014: 199 and fig. 20; 2018: 173).

The thickness of the slab selected for shaping can be inferred from the preserved thickness of the handaxe base because the NSQ blanks correspond to stratiform slabs. Therefore, if they have not been subjected to invasive knapping that affects the entirety of at least one face, which is not the case at the base of the handaxes, the thickness of these handaxes reflects that of the original slab.

The shaping of the proximal third of the handaxes was more complex. This portion of the handaxes was generally relatively thick, possibly based on the functional requirements of the final handaxe. If the tip of the handaxe was excessively pointed, it may have been prone to breakage during use. Alternatively, it is possible that limitations in thinning this part of the tool were due to the material properties of the NSQ.

The impact of raw material properties is easily identified in the TKLF assemblage. In particular, 5 specific artefacts highlight this raw material constraint. Two handaxe tips in the TKLF assemblage (length ranges between 106 and 146 mm) as well as three fragments of handaxes broken into two (fractures occurring in the centre and proximal ends along fracture lines) emphasize the difficulties of the NSQ material (Santonja et al., 2014: 200; 2018: 168). Similar fractures occurred during our experiments.

Our analysis of the TKLF assemblage highlights the ability of hominins to incorporate aspects of raw material form and mechanical properties in the manufacture of handaxes. TKLF hominins used the natural joints and cracks to form the backs of handaxes [(op. cit. figure 8.9) (Santonja et al., 2018)]. Hominins used both unipolar and bipolar flaking strategies to shape tools around the constraints that are inherent in flaking the NSQ raw material (op. cit. Figure 8.7). These material properties usually resulted in breaks that occur in the centre of the tool (Santonja et al., 2014: Fig. 22). The presence of numerous handaxes at the TKLF locality suggests that hominins had developed strategies for selecting appropriate blanks and following protocols that prevented extensive tool breakage. These knapping strategies may have been executed closer to the source of the raw material. In our experiments, the shaping process created large amounts of shatter. This volume of shatter was not observed at the TKLF excavation. One possible explanation for this is that the shaping of these tools occurred elsewhere on the Olduvai landscape. This hypothesis would need to be supported by more extensive taphonomic analyses of the TKLF site.

The production of handaxes on slabs of material is relatively rare in the study of the Acheulean technology. In particular, the study of *façonnage* on handaxes made on slabs is relatively understudied. A notable exception being that at the Acheulean site of Isampur, India (Shipton et al., 2009). At both the Isampur and TKLF locality Acheulean knappers had to overcome specific difficulties when knapping raw material in the form of slabs. At the site of Isampur, breakage patterns were largely perpendicular to the limestone bedding planes. This bedding plane was a natural feature of the limestone rocks that was used for artefact manufacture. Flaws that ran parallel to the bedding planes resulted in splitting and shatter when creating handaxes from these blank types (Shipton et al., 2009). At Isampur hominins identified particularly suitable slabs with a specific thickness of around 50 mm. These parallel patterns seen at TKLF where most handaxes have a thickness range between 40 and 60 mm, with a mean of 52.7 mm. At Isampur, large slabs were first split into two or more pieces, with the resultant blocks being flat with steep surfaces on many edges. It was suggested that these blocks were used because the higher frequency of angles were conducive for flaking. It was suggested that hominins at Isampur broke these slabs by placing them on an anvil and hitting them with a hammer; this strategy may have controlled the location of breakage (Shipton et al., 2009). The studies from Isampur, along with our experiments and the TKLF assemblage, indicate flexible behavioral strategies. Acheulean hominins from both sites demonstrated a strong geographic and spatial understanding of the landscape and locations of raw material sources. At both localities they adapted their techniques to achieve specific technological goals despite the challenges associated with raw material properties.

Conclusion

Our experimental study of handaxe production on Naibor Soit quartzite slabs and the archaeological research of the TKLF assemblage offer insights into early hominin technical proficiencies, problem-solving approaches related to their nuanced knowledge of raw material properties, and execution of specific knapping strategies. This study underscores the important role of raw material properties in influencing technological strategies used for handaxe manufacture and their final morphology at the TKLF site. As observed in our experiments, the inherent characteristics of NSQ, such as its thickness, internal fractures, and penetrative tectonic structures, were important factors influencing slab selection and choice of knapping strategies. The hominins at TKLF most likely understood these variables choosing appropriate strategies to tackle issues during knapping. The technical characteristics of the handaxes produced in our experiments closely align with those found in the TKLF assemblage. Experimental knapping indicated a range of factors that influenced artefact breakage; fracture lines in the NSQ slabs and slab thickness being key variables (Fig. 14; Table 3). Thus, for example, TK hominins may have intentionally selected relatively thick slabs, thereby avoiding breakage noted in experiments with excessively thin slabs (Panera et al., 2019; Rubio-Jara et al., 2017; Santonja et al., 2014, 2018).

The experimental knapping also revealed the efficiency of bipolar percussion as a technique for reducing slabs. Internal joints or areas of mechanical weakness in the slabs sometimes led to breakage. The TKLF knappers must have adapted their strategies to mitigate the risk of breakage on these tools. While we assume that each handaxe was made by a single individual, we recognize that other scenarios are possible. Different individuals may have contributed at various stages of production—from quarrying the raw material to the shaping of the tool. Our observations of the ability of hominins to integrate mechanical properties into the flaking strategy is in line with previous observations of Acheulean tool production (Herzlinger et al., 2017a, 2017b; Shipton, 2018). We hypothesize that the handaxes conform to previously proposed notions of Acheulean technological capacity such as the handaxe as an end goal (Herzlinger et al., 2017a, 2017b) as well as active monitoring and flexibility to adapt to unexpected outcomes in the knapping process. In addition, we believe the knapping strategies at TKLF exhibit a hierarchical organization of technical components and sequential procedures. As described in other Acheulean assemblages, we believe the TKLF hominins may have had the ability to modify the shapes of handaxe forms in ways that adapt to raw material constraints and conform to functional needs. In summary, our study offers an experimental perspective on handaxe production. It adds to the growing body of information on early human cognition, technological adaptability, and the relevant role raw materials play in shaping Acheulean technology (Bruner, 2010; Hecht et al., 2015; Hezlinger et al., 2017a; Madsen and Goren-Inbar, 2004; Stout et al., 2011).

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Declarations

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