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Stone-flaking technology at Leang Bulu Bettue, South Sulawesi, Indonesia

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ABSTRACT

Approximately 50000 stone artefacts have been recovered from the prehistoric site of Leang Bulu Bettue (LBB), on the Wallacean island of Sulawesi, in Indonesia. This large assemblage offers the opportunity to produce a large-scale, comprehensive model of the early lithic technologies of South Sulawesi. Through the analysis of half of this assemblage, this study identifies a technological shift between the artefacts produced ca.50–40 thousand years ago (ka) – the "Lower Industry" – and the "Upper Industry" artefacts produced ca.40–16 ka. The majority of the assemblage belongs to the Upper Industry, and these artefacts are associated with portable art, ornamentation, and the Homo sapiens *remains reported in previous works. These Upper Industry artefacts are largely made on chert that was brought to the site, sometimes in the form of large flake blanks, which was further reduced within the cave and used for ochre and plant processing. Artefact reduction was strategic during this period, and the bipolar method was frequently used for controlled reduction of flakes of various sizes. This represents a shift from the technology seen on the small number of Lower Industry artefacts, recovered from the deeper deposits. The oldest lithic artefacts yet reported from the site were made on immediately available limestone pieces, which were reduced through least-effort and non-intensive flake removal dictated by the available platforms. This study is compared to an analysis of Pleistocene artefacts at the nearby site of Leang Burung 2, where a similar technological shift has been observed.*

Keywords: artefacts, bipolar, Leang Bulu Bettue, lithic technology, Pleistocene archaeology, Sulawesi

RÉSUMÉ

*Environ 50.000 objets en pierre ont été récupérés sur le site préhistorique de Leang Bulu Bettue, sur l'île wallace de Sulawesi, en Indonésie. Ce grand assemblage offre la possibilité de produire un modèle complet et à grande échelle des premières technologies lithiques du sud de Sulawesi. Grâce à l'analyse de la moitié de cet assemblage, cette étude identifie un changement technologique entre les artefacts produits il y a environ 50 à 40.000 ans (ka) – la "Lower Industry" – et les artefacts de la "Upper Industry" produits environ il y a 40−16 ka. La majorité de l'assemblage appartient à la Upper Industry, et ces artefacts sont associés à l'art mobilier, à l'ornementation et aux restes d'*Homo sapiens *signalés dans des travaux antérieurs. Ces artefacts lithiques de la Upper Industry sont en grande partie fabriqués sur des nodules de chert qui ont été apportés sur le site, parfois fabriquées à partir de gros éclats, et ont ensuite été écaillage dans la grotte et utilisés pour le traitement de l'ocre et des plantes. La réduction d'artefacts était stratégique durant cette période, et la méthode bipolaire était fréquemment utilisée pour la réduction contrôlée d'éclats de différentes tailles. Cela représente un changement de technologie par rapport à la technologie du petit nombre d'artefacts observés de la Lower Industry, récupérés dans les gisements plus profonds. Les artefacts lithiques les plus anciens signalés à ce jour sur le site ont été fabriqués sur des pièces de calcaire immédiatement disponibles, qui ont été réduites grâce à un enlèvement d'éclats sans effort et non intensif écaillage des plates-formes disponibles. Cette étude est comparée à une analyse d'artefacts du Pléistocène du site voisin de Leang Burung 2, où un changement technologique similaire a été observé.*

Mots-clés archéologie Pléistocène, technologie lithique, Sulawesi, Leang Bulu Bettue, artefacts, bipolaire

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INTRODUCTION

The Indonesian island of Sulawesi is recognised as being an important region for understanding some of the earliest movements of modern humans (*Homo sapiens*) through island Southeast Asia, with implications for the peopling of Australia by at least 65 thousand years ago (ka) (Clarkson et al., 2017; but see O'Connell et al., 2018) and the dispersal of our species outside of Africa more generally. Sulawesi is the largest island in the unique biogeographical province known as "Wallacea", one of the world's major hotspots of species endemism. This network of oceanic islands is located between the continental regions of Asia ("Sunda") and Australia-New Guinea ("Sahul"). Even during Pleistocene low sea level stands the Wallacean islands were never connected to either of the adjacent mainlands, giving rise to an array of insular faunas and floras that have held the attentions of generations of biologists. It is evident that the initial peopling of Sahul required a series of maritime crossings through Wallacea (Bird et al., 2018, 2019; O'Connell et al., 2018; Samper Carro et al., 2019). For decades it has been conjectured that the large island of Sulawesi (at 174000 km^2 it is the world's 11th largest) with its extensive western coastline would have been a key "stepping stone" on the so-called northern colonisation route through the archipelago (i.e. Borneo to Sulawesi and then eastward to western Papua) (Birdsell, 1977; for modern models, see e.g. Kealy et al., 2015, 2018). As Sulawesi may have had a pivotal role in the settlement of the region by our species the nature of the technological industries and cultural lives of its Late Pleistocene inhabitants is of great interest, especially given that so little is known about either aspect. While sporadic archaeological work has been conducted in the region since the early twentieth century, investigating a large number of Mid-Holocene "Toalean" sites (e.g. Sarasin & Sarasin, 1905; see Macknight, 2018 for a summary of early work, and for a summary of recent research see Perston, Burhan, et al., 2021), it is only with recent breakthroughs in dating technologies and approaches that a picture has begun to form of Pleistocene occupation of Sulawesi. Recent work has included the identification of some of the oldest dated parietal rock art in the world, including animal figures and a possible hunting scene as well as hand stencils, which have yielded minimum Uranium-series ages ranging from between 17.4 to 45.5 ka (Aubert et al., 2014, 2018, 2019; Brumm, Oktaviana, et al., 2021; Pike et al., 2012). These rock art findings have all been made in the caves and rockshelters of the Maros and Pangkep regencies, a ~450 km area of lowland limestone tower-karst in the south-western peninsula of the island. To the northeast of Maros and Pangkep regencies stone tools excavated from the Middle Pleistocene open site of Talepu, in the Walanae River basin, indicate the presence of a pre-modern hominin species on the island (van den Bergh et al., 2016). It remains an open question whether the latter population was still established on the island at the time of the arrival of modern humans, and, if so, if there was any contact between them. Thus far, only three cave sites with deposits roughly contemporary to the Late Pleistocene rock art – and themselves containing undated rock art of Pleistocene style – have been identified: Leang Sakapao 1 (Bulbeck et al., 2004), Leang Bulu Bettue (LBB) (Brumm et al., 2017) and Leang Burung 2 (Brumm et al., 2018; Glover, 1981).

Leang Sakapao 1 is located 20 km north of LBB and LB2. The cave is located about 70 m above the base of a limestone cliff, with undated Pleistocene-style rock art (e.g. large figurative animal motifs) on the walls and roof of the cave. Excavation progressed to 80 cm deep, and 708 stone artefacts were recovered from deposits that are bracketed by four uncalibrated radiocarbon dates from 20.1 to 1.3 ka. All of the stone artefacts are chert or chalcedony, and the technology was dominated by hard-hammer reduction of chert nodules and cores made on large flakes. Retouched flakes are present, along with two flakes with silica gloss and another with ochre residues, and five bipolar artefacts (Bulbeck et al., 2004; Sumantri, 1996).

Leang Burung 2 (LB2) is a large shelter formed at the base of an overhanging limestone cliff face. In 1975 Glover (1981) identified a Pleistocene sequence at the site, and re-excavation in 2007 and 2011−2013 (Brumm et al., 2018) largely confirmed Glover's proposal that the Pleistocene deposits were disturbed and that breccias clinging to the walls of the shelter indicated significant scouring of the cave's deposits (Glover, 1981). Disturbance has inverted many of the radiocarbon dates obtained during more recent excavations, complicating chronological interpretations of the later part of the sequence (Brumm et al., 2018). Nevertheless, two distinct lithic industries were identified. The earliest is from undisturbed deposits and consists of a limestone-dominated assemblage with large cores predating 35 ka, perhaps by a significant margin (Brumm et al., 2018). Overlying this is a complex chert-based industry postdating 35 ka; the chert industry lacks the regionally-diagnostic traits of Mid-Holocene "Toalean" occupation and therefore likely predates ca.7 ka, and, although the dates are out-of-sequence, all but two of the calibrated dates associated with this industry are older than 25 ka (Brumm et al., 2018, Table 1). Both lithic industries documented at LB2 are described in detail below.

Leang Bulu Bettue (LBB), roughly meaning "cave of the mountain tunnel" in the local Bugis language, is situated at the foot of a karst cliff in the Leang-Leang ("many caves") area of the Maros regency (Brumm et al., 2017) (Figures 1a, 2a). It is a deep cavernous tunnel that opens up as a valley floor entrance on the southern end, with a modern floor level that is elevated about 5 m above the surrounding alluvial plain. The site is located ca.1.5 km northeast of LB2 and ca.300 m south of Ulu Leang 1 cave, one of the region's best-known Toalean sites (Glover, 1976; see also

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Table 1. Summary of squares sampled for this analysis of the Leang Bulu Bettue stone artefact assemblage. Dates are from (Brumm, Bulbeck, et al., 2021; Li et al., 2016; Newman et al., in pres) delete pres insert press.

Era	**Layer**	**Dates**	**Technology**	**Squares from which artefacts included in this study were recovered**	**Analysed stone artefacts (*n*)**
Phase II: Holocene	1	1.7 calBP-modern	"Neolithic"-Historic	A1, -C1, -D1, -E1, -F1, -G1/2, -H1/1, -H1/2	14
	1-4†	2.4–4.8 ka calBP	Toalean	-Z2	123
	5†	undated		-Z2	2
	2-3	flowstone	N.A.	sterile	0
Phase I: Pleistocene	4a-4e, silty clay	ca.29.5−16 ka	Upper Industry	A1, A2, -A1, -A2, B1, B2,-C1, -C2, -D1, -D2, -E1/1, -E1, -E2, -F1/2, -F1/1, -F1, -F2, -G1/2, -G1/1, -G1, -G2, -H1/2, -H1/1, -H1, -H2, -I1/1, -I1, -I2	24986
	4f, sandy clay	ca.40−30 ka	Upper Industry	A1, -A1, -A2, B1	762
	5, sandy clay	ca.50−40 ka	Lower Industry	A1, A2, -C1, -D1, -H1	13

†Note that the stratigraphic layer numbers do not correlate between -Z2 and the other excavation units.

Perston, Burhan, et al., 2021 for a summary of archaeologicals sites) (Figure 1a). The LBB assemblage consists primarily of Pleistocene artefacts, although a low-density deposit with "Neolithic" (Late Holocene) ceramics caps the Pleistocene deposits, and a small Toalean assemblage has also been recovered from deposits at the rockshelter's southern end. The excavated main deposits are deep and well-stratified, with rich Pleistocene assemblages of lithic artefacts and faunal remains (e.g. Brumm, Bulbeck, et al., 2021; Brumm et al., 2017). Two Pleistocene lithic assemblages have been identified, with an Upper Industry contemporary with anatomically modern *H. sapiens*, and a Lower Industry of presently-unknown hominin association.

Here we describe the analysis of the stone artefact assemblage recovered from LBB, and analysed by YLP, MWM, and S. We document the reduction sequence used to produce these artefacts at LBB (after Moore, 2015; Moore et al., 2009; Moore et al., 2022; Moore, Westaway, et al., 2020), combined with metrical analysis of stone-flaking by-products (Moore et al., 2009; Moore et al., 2022; Suryatman et al., 2017, 2019). We then compare aspects of the LBB reduction sequence and metrical patterning to the LB2 assemblage described in Brumm et al. (2018), and present previously-unpublished empirical data from LB2.

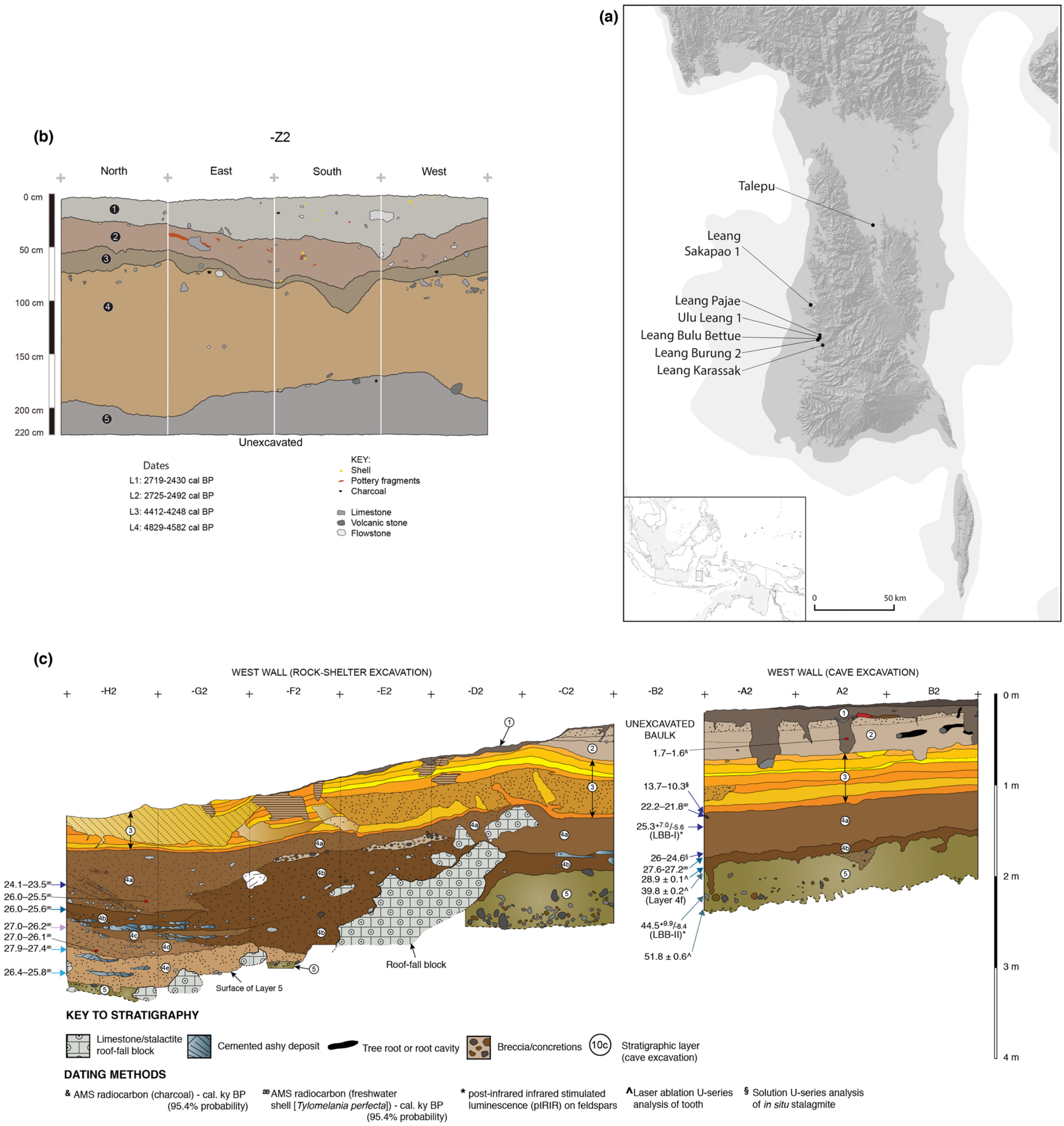
THE LBB EXCAVATIONS

Excavations at LBB are described in Brumm, Bulbeck, et al. (2021), Brumm et al. (2017, 2020) and Langley et al. (2020). The cave is 18 m above sea level (ASL) and is located around 20 km from the coast. Excavation commenced at the site in 2013 at the cave mouth, where the cave passage opens up into a well-lit rockshelter space measuring about 30 m by 4 m (Figure 2e,f). The shelter floor slopes gently downwards towards the south. Just south of the southern end of the rockshelter is the mouth of a deep and narrow valley that today intersects the underground Wae Marunge river system, to which it runs perpendicular. This valley is the product of fluvial downcutting over a long period of time, suggesting the site may always have had access to a water source, although the only evidence for prehistoric use of the valley comes from a single chert core on the banks of the exposed stretch of the Wae Marunge River (Figure 3).

In total, 36 excavation units each measuring 1 m square (labelled "squares", or *kotak* in Indonesian) have been excavated at the site (Figure 2e). Five stratigraphic layers were identified, described below, and these are unusual for the region as the stratigraphic interfaces are generally quite well defined (e.g. see Perston, Burhan, et al., 2021). The deposits were excavated in arbitrary 10 cm spits within each stratigraphic unit, with many of the finds piece-plotted using a total station, and deposits wet-sieved through 3 mm and 1 mm mesh.

At the northern end the rockshelter segues into a tunnel-like cavern consisting of linked chambers of various sizes, including several doline structures that open to the top of the karst plateau high above. The tunnel leads to Leang Samalea, a rockshelter that overlooks a neighbouring limestone valley some 300 metres to the northeast of the LBB rockshelter. Hand stencils and other rock art images are present at Leang Samalea which are consistent in style with parietal motifs dated to the Pleistocene in the surrounding karst landscape (Aubert et al., 2014). A stone arrangement of unknown age portraying Islamic writing is on the floor of Leang Samalea (Figure 2d). The tunnel complex draws a breeze from Leang Samalea and the

Figure 1. Site locations and stratigraphy. (a) Location of Leang Bulu Bettue and other sites mentioned in text within South Sulawesi, Indonesia. (b) Stratigraphic section for the -Z2 excavation square at Leang Bulu Bettue (adapted from Newman et al., in press), all baulks. The layers do not correlate to the layers of the same number in the main excavation. (c) Stratigraphic section of the West baulk of the main excavation trenches at Leang Bulu Bettue (Brumm et al., 2017, fig. 1). Note that Layer 4C is a thin lens not preserved in the West baulk.



natural vents created by large sections of collapsed doline structure into LBB, naturally cooled from passing through the deep cave system.

Damaged red ochre hand stencils adorn the walls of LBB, likely produced during the Pleistocene (Aubert et al., 2014), and Late Holocene charcoal drawings (Huntley et al., 2021). Undated child-sized hand stencils and comb-like "narrow-finger" stencils (a regionally unique style of Pleistocene antiquity; Aubert et al., 2014; Oktaviana et al., 2016) were observed in a small, difficult-to-access hollow that is suspended above the main shelter at LBB (YLP pers. obs. 2014) (Figure 2c).

Two depositional phases have been described in the main excavation (e.g. Brumm, Bulbeck, et al., 2021). Phase I, the oldest of these deposits, incorporate Layers 4a–f and 5. These have been dated to ~50–16 ka through a

Figure 2. Leang Bulu Bettue. (a) Steep karstic limestone formations dominate the otherwise flat, cultivated landscape around LBB. (b) An overview of the main excavation at LBB, 2018, facing south. (c) Hand stencils and "clawed hands" in a small recess above the main rockshelter. (d) Stone writing of unknown age in the Leang Samalea cave at the end of the LBB tunnel system that appears to spell out "Allah" in Arabic (الله). (e) Trench plan and (f) site plan of LBB (adapted from Newman et al. in press).

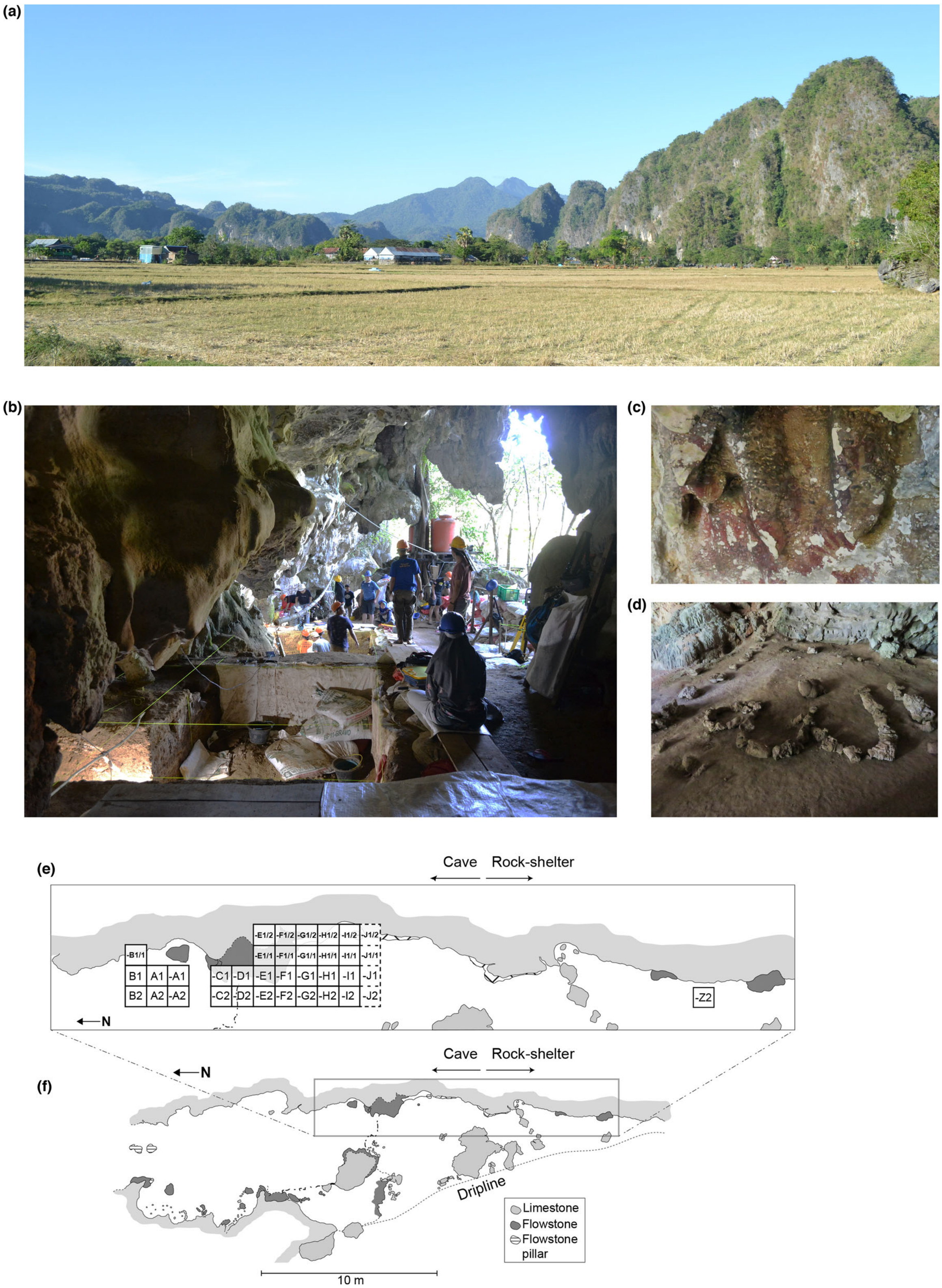


Figure 3. Chert multiplatform core approximately 7 cm across, on the banks of the Wae Marunge, where the subterranean river briefly surfaces within an intersecting narrow valley. This artefact was left *in situ*.

combination of U-series isotope analysis of stalagmites, AMS ^{14}C-dating of freshwater Mollusca, laser ablation U-series dating of Suidae teeth, and optical dating of feldspar grains (Brumm et al., 2017; Li et al., 2016). Layer 5 is a sandy clay layer that is 50 cm thick, containing sparse lithic artefacts, and is placed at ca.50−40 ka. Above this, artefact density increases in Layer 4f, a 50 cm thick lens of sandy clay deposits only found near the eastern wall of the cave at the northern extent of the current excavation in squares A1, -A1, -A2 and B1. The Layer 4f deposits have been dated to ca.40−30 ka.

Layers 4a–e, also in Phase I, have been dated to ca.29.5−16 ka. These silty clay deposits hold the densest lithic artefact and faunal assemblages. Fragments of the mandible, right and left maxilla, and three teeth from an adult *H. sapiens* individual were recovered from Layer 4a, and dated to 25−16 ka (Brumm, Bulbeck, et al., 2021). Layers 4a–e are collectively treated as "Layer 4", along with Layer 4f, throughout the rest of the text.

Phase II encompasses the uppermost deposits, Layers 1−3, dating to the Late Holocene. Within these strata are sterile sandy clays (Layer 2) and silty clays alternating with partly-cemented flowstone (Layer 3) in the north part of the excavation area. Layer 3 rests unconformably against Phase I, and erosion has stripped away the bulk of the Holocene sediments in the main rockshelter (Brumm, Bulbeck, et al., 2021; Brumm et al., 2017). Brecciated material adhering to the walls of the LBB rockshelter up to 2.45 m above the current floor dates from 20.7−10.2 ka calBP, and represents the remains of Holocene erosional events partly correlating to the disconformity between Phases I and II (Newman et al., in press). The breccia contains abundant shell, and rare stone artefacts.

Layer 1, the youngest of Phase II, was deposited in the recent past, up to ca.1.7 ka calBP, and holds Neolithic and Historic-era pottery fragments as well as some lithics. This layer includes post-hole features that intrude into the underlying deposits, and a local farmer has described burying a deceased goat and calf several years earlier which have since been revealed by the excavation.

One excavation unit (Square -Z2) was excavated at the southern, lower end of the LBB rockshelter, 16 m south of the main excavation block (Figure 2e,f). Since the unit is not contiguous with the main block, the stratigraphic units have not been correlated between them. The excavation in Square -Z2 reached 2.2 m deep, at which point excavation was halted by the water table. Five stratigraphic layers (Layers 1−5) were identified during excavation (Figure 1b). Layer 2 was poorly defined, however, and appeared to largely include mixed deposits with Layer 1. Three radiocarbon samples from Layers 1−3 returned in-sequence dates of ca.4.2−2.4 ka calBP, and the top of Layer 4 returned a date of 4.8−4.6 ka calBP (see Newman et al., in press for further information on the dating). The in-sequence dates suggest that these are *in situ* deposits rather than re-deposited sediments from the main rockshelter (Newman et al., in press). Based on the radiocarbon chronology, the uppermost four layers in Square -Z2 may partly correlate with the depositional disconformity noted in the LBB block excavation between Layers 1/3 and 4a, and/or with the deposition of the culturally-sterile flowstone composing Layers 2−3. These layers postdate the erosional event suggested by the earlier dates on the breccia adhering to the shelter walls (Newman et al., in press).

ARTEFACT ANALYSIS METHODS AND ANALYTICAL SAMPLING

The analytical sample from the main LBB excavations consists of a total of 25761 artefacts from the >3 mm size fraction. These represent random samples drawn from 30 of the excavation squares, as well as all artefacts from the square designated -H1. This sample represents approximately 53% of the estimated 48468 artefacts recovered from the main LBB excavation. Analysis by MWM and YLP involved classifying stone artefacts into a technological typology and measuring key metric attributes related to those types, and analysis by S focused on systematic measurement of the same suite of attributes across the assemblage. MWM and YLP analysed 6183 artefacts, including all Lower Industry artefacts included here, while 19578 Upper Industry artefacts were analysed by S. Artefacts with partially-preserved attributes that were considered discarded pieces or "debris" under S's approach were not measured by him, accounting for the large number of "unidentified" pieces. The provenance of the selected samples is presented in Table 1.

The aim of the analysis was to document the manufacturing techniques that produced the stone tools. Methods followed the "reduction sequence" approach. A reduction sequence is a reconstructed model of the steps taken to produce stone tools as inferred by the technological types present in an assemblage. Analysis involves classifying artefacts into those technological types, and assessing negative scars in order to reconstruct core orientation and patterns in approaches to flake removals to predict the flintknappers "plans of action", although no assumptions are made about whether the flintknappers conceived of those plans of action in an identical way to the reconstructed model. Although stone reduction is a continuous process, for analytical and descriptive purposes the results are abstracted as a step-based "reduction sequence" (after Moore, 2015), an approach that is similar to but distinct from the theoretical approach behind the *chaîne opératoire* (Shott, 2003). Qualitative inferences underpin the typologies used to create a reduction sequence model, but these inferences have material consequences that can be explored through metrical analysis and tested through experiments. The approach and terminology in the current analysis follows Moore (2015; Moore et al., 2009; Moore et al., in press; Moore, Weeks, et al., 2020; Perston, Moore, et al., 2021), and these methods were used to analyse both the LBB and LB2 assemblages by YLP and MWM.

Macroscopic usewear and residues, including ochre and silica gloss, were noted when observed, and supplemented by low-powered magnification (10× to 20×) with hand lenses and a *Dino-Lite* digital microscope. Comprehensive sampling and analysis for use-wear and residues using high-power techniques was not undertaken.

THE LBB STONE ARTEFACT ASSEMBLAGE

Most of the LBB stone artefacts are in good condition. The majority of artefacts in Layers 4a–f are as-struck with fresh unabraded arrises and edges. However, "white alteration" was noted on 16% ($n = 4185$) of the chert artefacts. It appears that much of the chert was originally brownish in hue but has been naturally altered to become white and friable to varying degrees, a phenomenon that has also been noted on artefacts from both Pleistocene and Toalean (Holocene) assemblages in South Sulawesi (Bulbeck et al., 2004, p. 119; Glover, 1976; Perston, Moore, et al., 2021, p. 7). "White alteration" (after Caux et al., 2018) is likely caused by silica leaching from the stone in a basic solution, as can occur in a moist limestone environment, often creating a firm outer layer of silica deposits – a "silicious film" – over a soft, porous, silica-leached "desilication layer" (e.g. Caux et al., 2018, fig. 3; Font et al., 2010), meaning that heavily affected artefacts can appear intact only to crumble if damaged. This differs from devitrification, which is the transformation of silica from an amorphous glass to a crystalline structure through heat (e.g. Marshall, 1961; Pinckney & Beall, 2008). Certain volcanic/metavolcanic materials were also prone to apparent desilification, rendering their surfaces soft and powdery.

The LBB assemblage is distributed vertically in two technologically distinct divisions, referred to here as the "Upper Industry" ($N = 25747$) with abundant chert artefacts, in Layers 4a–f; and the "Lower Industry" ($N = 13$) dominated by limestone and volcanic artefacts from Layer 5. Continued excavation of Lower Industry deposits was prevented by the global SARS-CoV-2 COVID-19 outbreak. The Upper Industry is confined to Layers 4a–e and f, deposited prior to the disconformity at the top of Layer 4a, dating to ca.40−16 ka (Table 1). The Lower Industry technological signature is expressed in Layer 5, dated from ca.50−40 ka (Brumm, Bulbeck, et al., 2021). Both Upper and Lower Industries fall within the Pleistocene depositional sequence denoted Phase I (Brumm, Bulbeck, et al., 2021).

The LBB assemblage also differentiates horizontally, with a Mid-Holocene Toalean industry (after Perston, Moore, et al., 2021) expressed in Square -Z2. The dates from Layers 1−4 in -Z2 place the assemblage in the middle of the Toalean period (after Perston, Moore, et al., 2021), ca.4.8−4.2 ka calBP (Newman et al., in press).

Stone artefacts are sparse in the Layer 1 Neolithic deposits and the sample is too small to confidently reconstruct the flaking technology. The Neolithic assemblage includes two limestone flakes – including one from posthole fill dated to 1759 ± 20 BP (WK-37740) (Brumm et al., 2017, SI table 1) – 10 chert flakes, a potlid and a chert bipolar flake. Five chert flakes were found in association with two farm animals recently buried in the rockshelter. These artefacts were reworked from the earlier deposits.

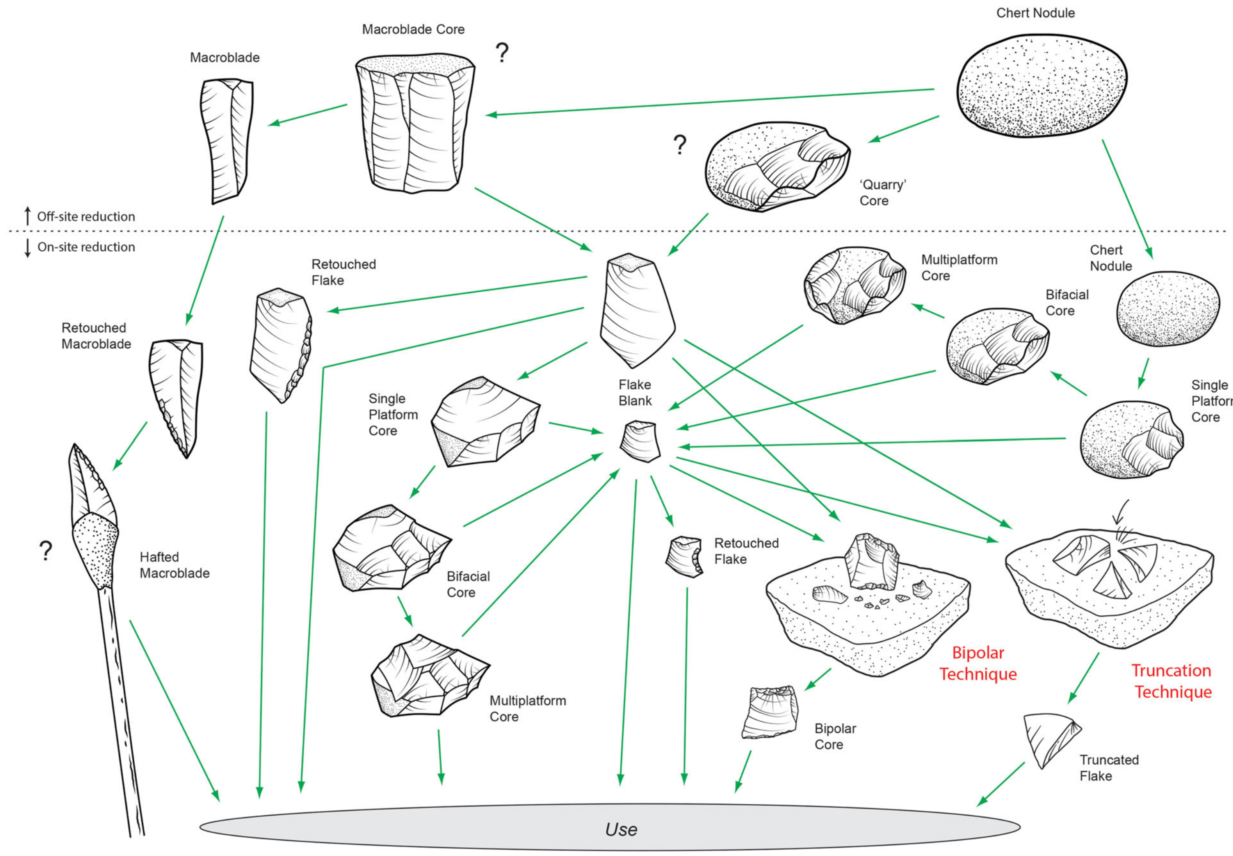
UPPER INDUSTRY AT LBB

The reduction sequence model reconstructed from the Upper Industry deposits is presented in Figure 4. The model shows the various stone-flaking techniques and trajectories that created the Upper Industry assemblage (Table 2).

All artefacts made on a flake blank are classified in Table 2 as "modified flakes". Among these are 48 "flake blank cores" and 333 "retouched early reduction flakes", and these categories could be said to represent opposite ends of a continuum. The modified flakes category also includes multiplatform cores made on flake blanks ($n = 6$), radial cores ($n = 6$); single-platform cores ($n = 6$); a retouched bipolar artefact ($n = 1$); retouched redirecting flakes ($n = 3$); truncated flakes ($n = 16$); and a quasi-"perforator" ($n = 1$). It should be noted that the "heat-fractured pieces" are stone objects that are presumed to be artefacts but are too badly damaged by heat to be placed into any defined category.

Some Upper Industry artefacts at LBB show signs of being used for more than one purpose. For example, two of the anvils had been flaked, and some of the artefacts were repurposed as hammerstones, as indicated by patches of hammerstone wear and/or percussion spall. Seven anvils – including the two flaked anvils, an assayed cobble (any core with only one or two flake scars), two multiplatform cores, and one radial core all show signs of being used as percussors (hammerstones). Further, one contact removal flake was also a redirecting flake, indicating it was not the only flake struck from the producer flake-blank. The Upper

Figure 4. Reduction sequence model for the Late Pleistocene lithic Upper Industry, based on an analysis on the lithic assemblages of Leang Burung 2 and Leang Bulu Bettue. Macroblade cores or large cobble blanks have not been recovered at either site, suggesting these reduction stages took place outside the caves, perhaps at the quarry site.



Industry assemblage is dominated by chert (91.4%), with small numbers of limestone (5.2%), quartz (1.6%) and volcanic/metavolcanic stone artefacts (1.7%, Table 3). Despite the limestone environment in the Maros-Pangkep tower-karst system, chert rarely occurs in the nearby waterways, though there has been one recorded outcrop of varying quality in a creek bed 7.5 km southeast of LBB at Pattunuang Asue, near Leang Karassak (Glover, 1978, pp. 68-69; Perston, Brumm, et al., 2021, p. 8). Creeks and drainages instead carry limestone cobbles, volcanic/metavolcanic cobbles and occasionally quartz pebbles. The cortex on stone tools suggests that two types of chert sources were exploited: soft (chalky) cortex indicates a bedrock or near-bedrock source, and hard, fluvially-rounded cortex indicates a water source, probably a creek or river. Based on the frequencies of these cortex types, the bedrock chert sources were used more often (59% of chert artefacts with cortical remnants, compared to 41% with fluvial cortex) to make the Upper Industry artefacts at LBB. Small pebbles of chert were transported in unmodified form to Leang Sakapao 1 during the Pleistocene period (Bulbeck et al., 2004) and LBB, but there is no evidence for this in the assemblages excavated at LB2.

We surmise that the volcanic/metavolcanic materials were collected by the Pleistocene inhabitants as river cobbles in the majority of cases (87%, $n = 47$) where source type could be identified from the cortex. Non-cultural volcanic/metavolcanic pebbles and cobbles were recovered in the cave deposits, suggesting the material is available in the local environment. Chert cobbles were also recovered in the deposits, though in much lower numbers, and it seems likely that these were deliberately brought to the site. Natural limestone cobbles are common throughout the sequence.

Twelve chert artefacts were identified in the Upper Industry assemblage with differentially weathered flake scars, suggesting that the knappers procured and reworked older flakes and tools. In one instance, a weathered flake was recycled for use as a bipolar core. The remainder of the recycled artefacts have abrasive rounding of older arisses on the dorsal face compared to fresher ventral features, or differential patination of retouching scars, indicating that these artefacts were scavenged from older deposits and reworked. Recycling is only recognisable if the scavenged blanks were significantly weathered before collection and reworking, thus the prevalence of the activity is likely to be underrepresented (e.g. Brumm et al., 2019; Moore et al., 2009).

Controlled heat-treatment can markedly reduce the tensile strength of siliceous stones, making them easier to

Table 2. Results of the analysis of a selection of Pleistocene artefacts from the Leang Bulu Bettue assemblage. Any artefact with a negative flake scar is classified as a core.

artefact type	**Upper Industry**		**Lower Industry**	
flakes	***n***	**%**	***n***	**%**
contact removal flake	14	0.05	0	0
early reduction flake	11442	44.44	6	46.15
macroblade	7	0.27	0	0
ochre flake	1	<0.01	0	0
redirecting flake	263	1.02	0	0
unidentified flake	30	0.12	0	0
uniface retouching flake	16	0.06	0	0
subtotal	11773	45.96	6	46.15
cores:				
assayed cobble	9	0.03	2	15.38
blade-like core	1	<0.01	0	0
unidentified flaked piece	61	0.24	0	0
modified flake	421	1.64	0	0
multiplatform core	132	0.51	2	15.38
radial core	24	0.09	0	0
single platform core	74	0.29	3	23.08
subtotal	722	2.80	7	50.01
other:				
anvil	13	0.05	0	0
bipolar artefact	838	3.25	0	0
eraillure	15	0.06	0	0
hammerstone or fragment	24	0.09	0	0
heat-fractured piece	247	0.96	0	0
potlid	24	0.09	0	0
unidentified piece	12091	46.96	0	0
subtotal	13254	51.46	0	0
grand total	25,747	100.00	13	100.00

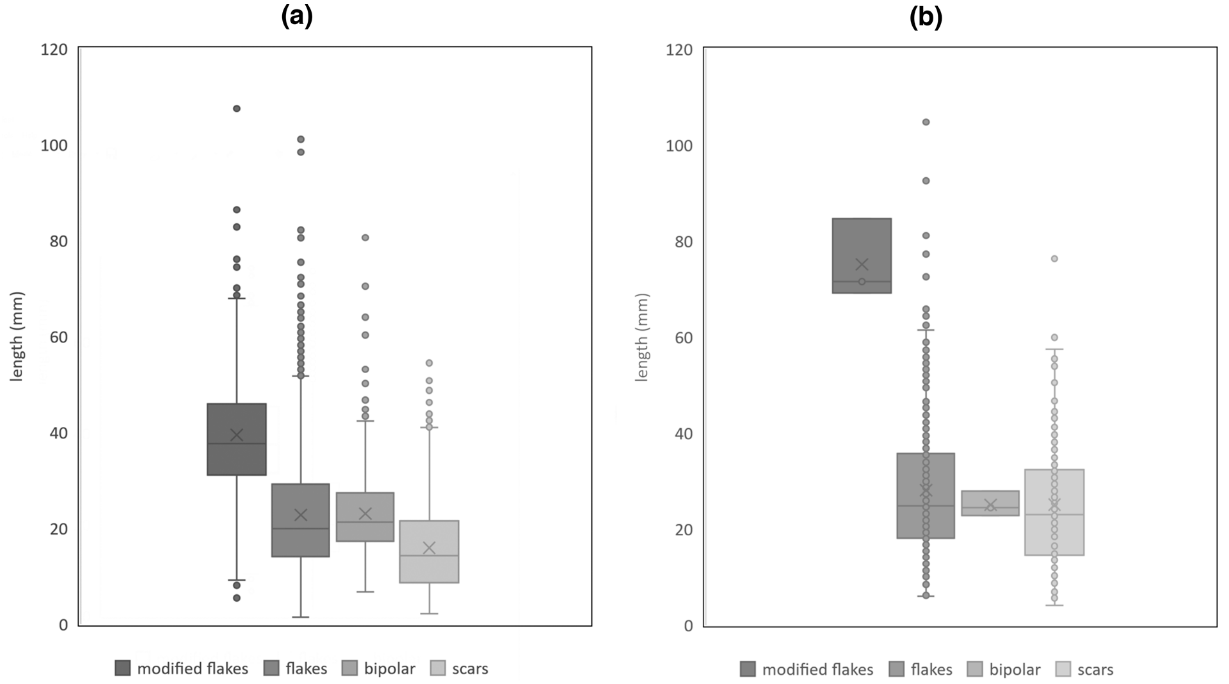
Table 3. Raw material frequency (*n*) among the Leang Bulu Bettue assemblages.

raw material	**Neolithic**	**-Z2**	**Upper Industry**	**Lower Industry**
chalcedony	0	0	1	0
chert	11	108	23,539	3
limestone	1	6	1345	9
metasedimentary	0	0	32	0
ochre	0	0	1	0
quartz	0	0	400	0
silicified wood	0	0	2	0
volcanic	1	11	427	1
total	13	125	25,747	13

flake, but the resulting tools are relatively more brittle than those made from untreated stone. Differential gloss is a signature of heat-treatment, with dull scars created prior to heating and glossier scars created after heating (Luedtke, 1992). One modified flake was recovered from the Upper Industry at LBB (Layer 4a) with dull ventral and dorsal surfaces and glossy truncation and retouching scars. The differential gloss on this LBB artefact suggests that a flake blank was heat-treated prior to further reduction. One broken flake (also Layer 4a) has a glossy ventral face and dull scars on the dorsal face, indicating that it was struck from a heat-treated core. The rarity of the practice relative to the sizes of the assemblage, and the evidence for flake scavenging, may indicate that the heat-treated stones were scavenged from incidentally-heated debris rather than subjected to deliberate heat-treatment. Some 853 Upper Industry artefacts at LBB show evidence for uncontrolled burning, in the form of potlids and crenulation damage, demonstrating that stones were exposed to fire at the site.

Flakes were frequently modified by further flaking in the Upper Industry at LBB. The average chert flake blank, represented by modified flakes, is longer than the average unmodified flake and is also longer than the average scar length on a core in the assemblage (Figure 5a). These properties suggest that many of the blanks were struck at or near the stone source and transported to LBB for further reduction. The dimensions of modified chert flakes in the assemblage (Table 4) can be seen as a proxy of the sizes of transported flakes. These are minimum dimensions, as reduction at LBB has reduced the sizes of the blanks, but this is offset by the inclusion of small modified flakes that were struck from small cores on-site. With that in mind, and judging from the larger modified flakes in the assemblage, it is noteworthy that chert flakes made at the stone sources were medium to large-sized – up to ca.105 to 108 mm in largest dimension and up to 42 mm thick. Cortex is

Figure 5. Length of modified flakes, unmodified flakes, bipolar artefacts, and flake scars of Upper Industry (Layer 4a-f), Leang Bulu Bettue. (a) Chert artefacts. (b) Limestone artefacts. Artefacts with transverse breaks are not included.



prevalent on the Upper Industry artefacts at LBB, so many of the blanks struck at the stone sources must have been partly covered in cortex. Platform attributes on modified flakes indicate that flake blanks were struck using a hammerstone from cortical (7.7%) and multi-facet platforms (5.7%) or, more often, single-facet platforms (73.1%). The prevalence of single-facet platforms on flake blanks indicates core rotation, which in turn suggests the cores abandoned at the quarry were mostly multiplatform or bifacial in morphology.

Limestone flakes, in contrast, correspond more closely to the scars seen on flaked limestone artefacts, with the exception of a small number of large modified flakes ($n = 3$) (Figure 5b). This indicates that local limestone was exploited for tool manufacture, and it is likely that natural pieces occurring within the cave were opportunistically reduced as well.

Flaking of the chert cores in the Upper Industry at LBB was done by freehand hard-hammer percussion, and the reduction process was relatively ad hoc and driven by the developing morphology of the core. Bifacial flaking was common, as was unifacial flaking by striking the blank's ventral face. Unifacial, bifacial and multiplatform cores were created by this process (Table 2). Much of the reduction may have been done to prepare an edge for use, or to resharpen or reshape the edge. Many of the flakes struck from these larger blanks were probably used as tools without modification, and some were reduced by bipolar percussion or truncating. Many of the flaked edges on retouched flakes and flake blank cores are very steep and some display considerable crushing at the platforms, suggesting that they may have sometimes been reduced using an anvil-supported freehand percussion technique (see Moore et al., 2022).

The truncation technique involved placing a flake or core on a hard anvil and striking the upper face (i.e. the dorsal or ventral face on a flake), fracturing the piece through its short axis. This often created a feature known as a "demicone" (after Knowles & Barnes, 1937) and sometimes crushing at the face in contact with the anvil. The reasons why flakes and sometimes cores were truncated are not entirely clear, but it may have been done to produce angular fragments with exceptionally stout right-angle edges. The truncation technique was a relatively rare practice compared to freehand and bipolar percussion.

The bipolar technique was commonly practiced in the Upper Industry at LBB. Bipolar reduction involved holding a flake, usually chert, edge-up on a hard surface and striking directly down on this edge with a hammer, creating small flakes (White, 1968). Since flake initiation was by wedging, platforms were often crushed, and the core sometimes split into pieces, so it is often difficult to differentiate cores from flakes; we refer to cores and flakes together as "bipolar artefacts". In most cases the blows were delivered in such a way that the stone sheared to the ventral and dorsal surfaces of the flake blank. In some cases the technique was exceptionally well-controlled, creating small, biface-like bipolar artefacts (Figure 6d–e). Flakes were initiated from both the edge struck by the hammer and the resistant support, with the platforms directly opposite each other. Often the core was then rotated cross-axis about 90° and struck again ("cross-axis rotation"), creating a second set of

Figure 6. (a–c) Toalean backed microliths from square –Z2, Leang Bulu Bettue. Dotted line indicates extent of backing. (d–l) Upper Industry artefacts from Leang Bulu Bettue. (d–g) Bipolar artefacts. (h) Blade-like core. (i) Small flake that conjoins to the dorsal face of a larger flake. Red colouration but a lack of exposed heat gloss suggests these flakes may have been exposed to heat after flaking. (j) Truncated flake. (k and l) Macroblade-like early reduction flakes. (m) Upper Industry macroblade from Leang Burung 2. Scale bar = 1 cm.

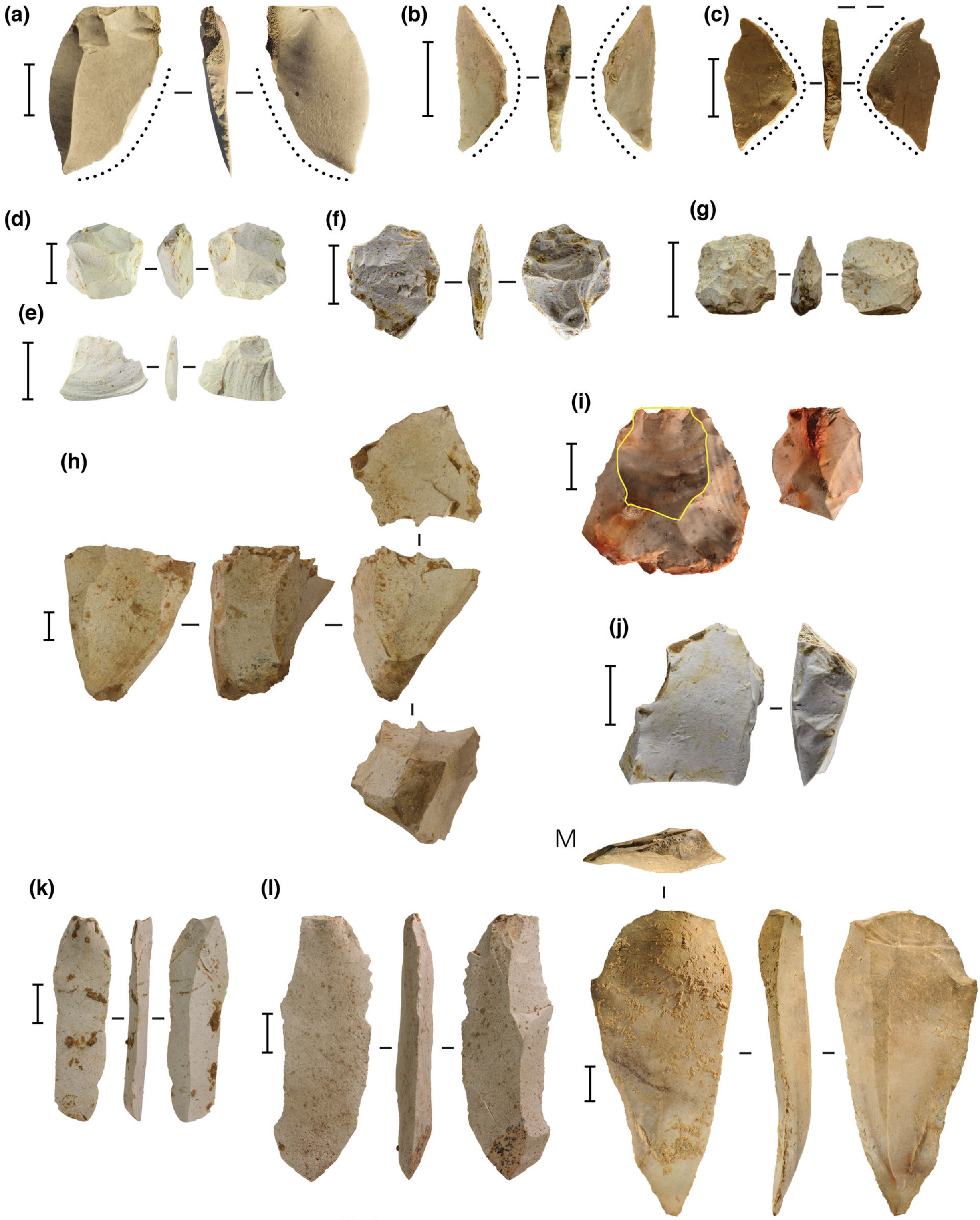


Table 4. Attributes of modified chert artefacts in the Upper Industry of Leang Bulu Bettue. Whole artefacts only, measurements given in mm.

	Modified flake			**Unmodified flake**			**Bipolar artefact**			**Other cores**		
	L	**W**	**Th**	**L**	**W**	**Th**	**L**	**W**	**Th**	**L**	**W**	**Th**
n	269	269	269	6664	6664	6664	660	660	660	202	202	202
min.	5.43	9.66	1.106	1.42	0.26	0.83	6.77	0.52	0.81	11.48	12.65	4.96
Mean	40.20	31.95	13.13	22.83	19.55	5.73	23.03	17.82	7.17	46.32	35.89	24.13
SD	14.26	11.48	6.35	11.75	9.43	3.66	8.51	6.64	4.51	13.39	11.52	8.46
Max	107.5	105.2	55.74	101.11	99.4	50.3	70.47	46.1	30.7	111.6	99.86	70.02

opposed platforms and a roughly square or rectangular bipolar core.

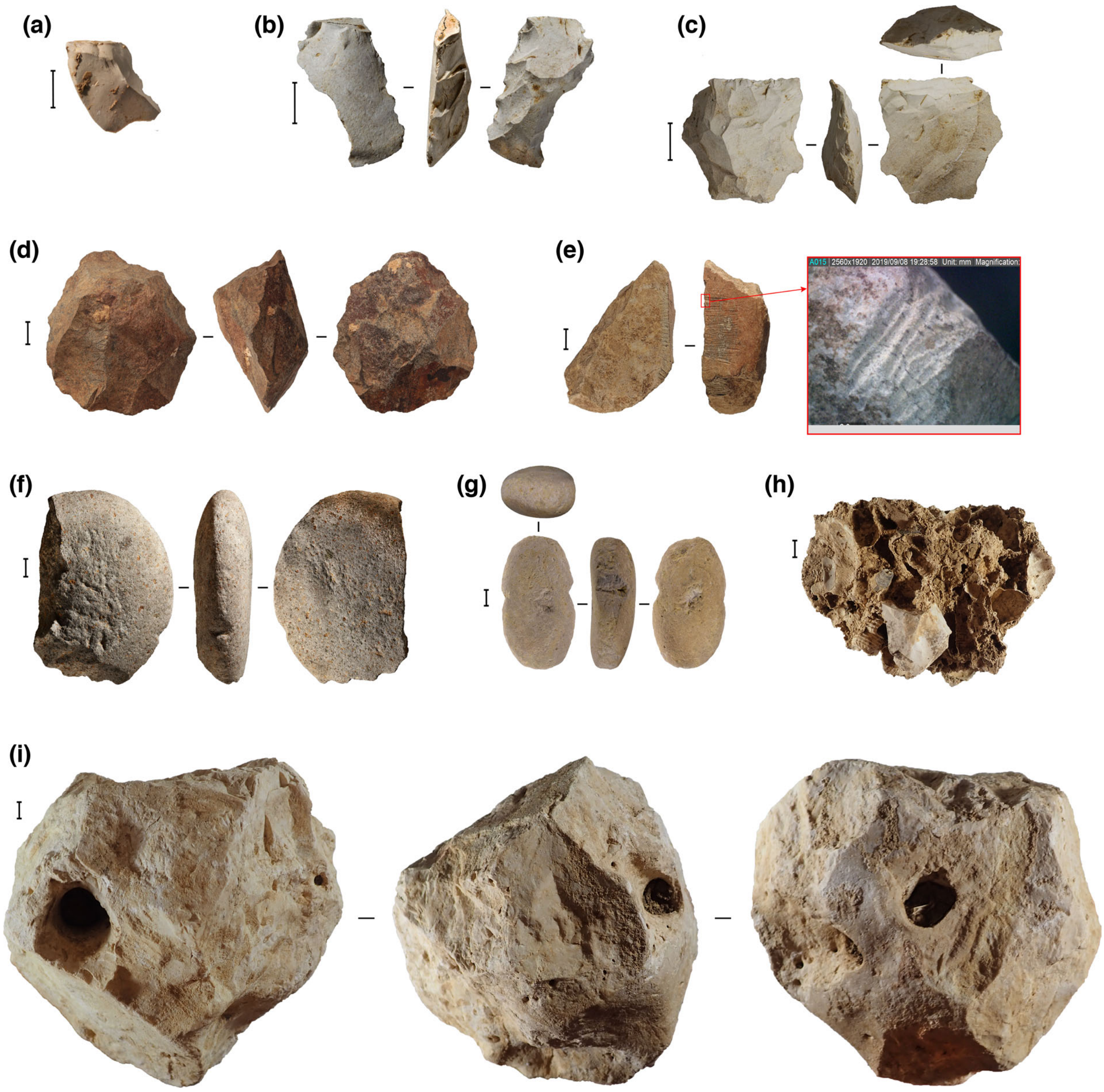
Blanks for bipolar reduction were mostly small and probably derived from the direct freehand reduction of the cores reduced in the caves. Very large examples are also present, suggesting that sometimes the bipolar technique was applied directly to the flake blanks imported from the stone sources. Bipolar cores may have been a by-product of producing small flakes for tools, or may have been a by-product of use, perhaps as wedges. Ochre residues on bipolar cores from the Upper Industry clearly show that bipolar cores were sometimes used directly as tools.

Some of the bipolar artefacts may have been produced using a stone anvil as a support. The seven Upper Industry anvils that have been identified are made on volcanic cobbles that are roughly disc-shaped, with battering in the centre of the flat faces. In most examples, the anvils have clear linear scars on the battered faces suggestive of use as anvils for the bipolar reduction of flake blanks (Figure 7f,g). Some of the anvils also have a slight notch worn into one edge, and it may be that these pieces were also used as a hammerstones for bipolar reduction. Such morphology resembles similar hammerstone/anvils recovered from the Toalean assemblage of Leang Pajae (Perston, Moore, et al., 2021, fig. 4). Subsequent to this anvil use, one LBB anvil was unifacially flaked along part of the margin, and finally broke in two (Figure 7f).

Silica gloss on stone tools has been observed at a number of Pleistocene and Holocene sites in Indonesia (e.g. Glover, 1977; Hayes et al., 2021; Marwick et al., 2016; Moore et al., 2009) and was first documented at LB2 by Glover (1981) and Sinha and Glover (1984). During our analysis 123 glossed artefacts were recorded in the Upper Industry assemblage at LBB (Figure 8h,i). Most glossed tools at LBB consist of flakes and retouched tools from the flake blank reduction trajectory ($n = 129$), but silica gloss was also identified on four bipolar artefacts. This shows that although the freehand core and bipolar core reduction trajectories involved distinctly different reduction techniques, the products of those techniques were used in a similar range of tasks. Silica gloss is interpreted to result from the use of stone tools for cutting thin stems of siliceous plants, perhaps for the manufacture of fibres and woven items (Glover, 1981; Sinha & Glover, 1984). Notably, the Late Pleistocene modern human maxilla excavated at LBB exhibits an unusual form of dental wear that may also result from the use of teeth as tools for processing plant fibres (Brumm, Bulbeck, et al., 2021).

Seven relatively large chert “macroblades”, measuring between about 80 mm and 100 mm long, were produced at the stone sources during the Upper Industry period, and exported to nearby LB2 (Brumm et al., 2018, fig. 7g; Glover, 1981). Macroblades were well-made by hard-hammer percussion and demonstrate mastery of fracture mechanics, with serial removal of blade-like flakes down a well-defined arris on the core; this arris forms a central ridge on the resulting macroblade. The manufacturing method for these blanks is presently

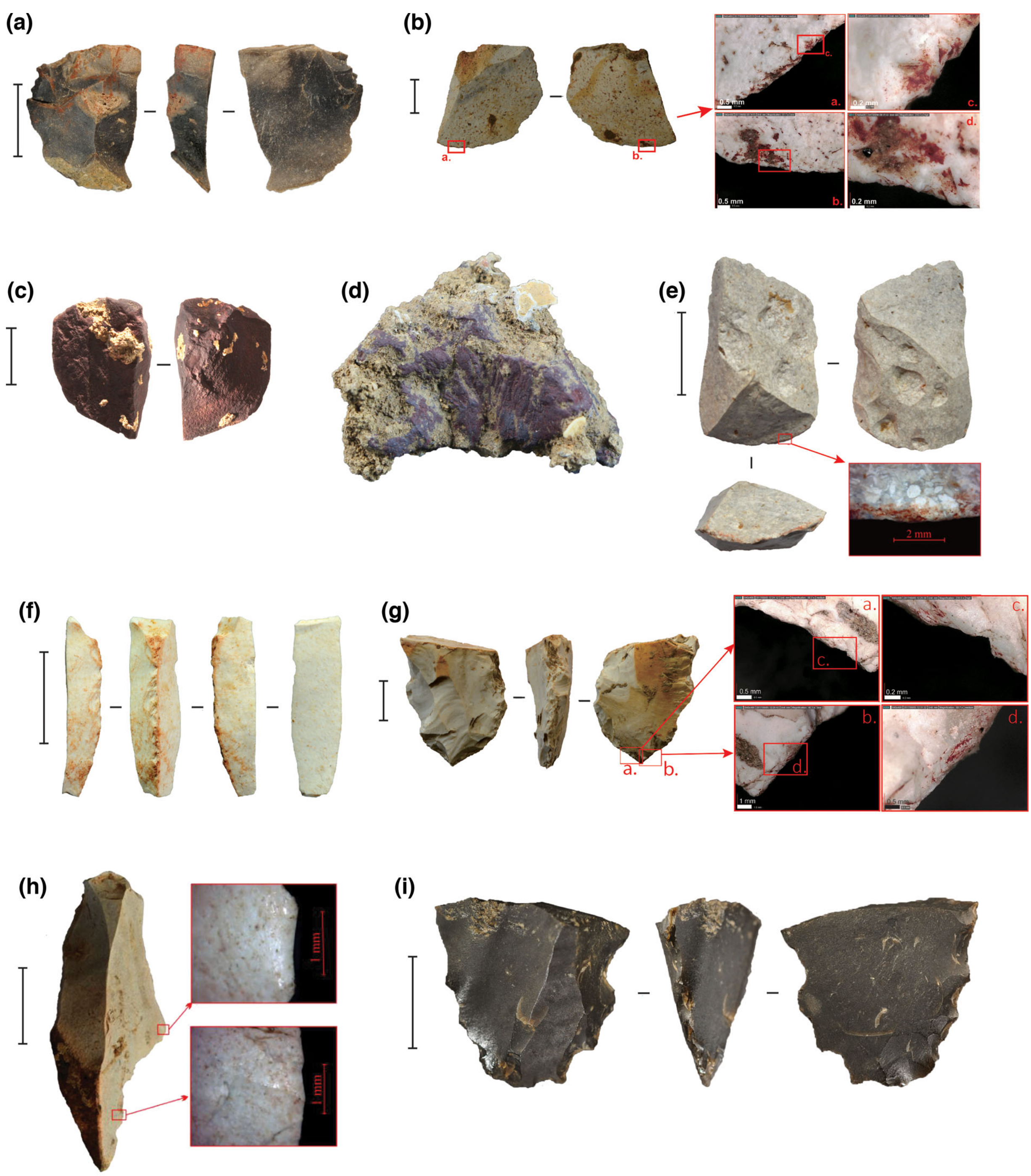
Figure 7. Upper Industry artefacts from Leang Bulu Bettue. (a–c) evidence for the use of larger flakes as blanks can be seen in (a) contact removal flakes that remove the point of force application (PFA) of the host flake, and (b) large retouched flakes which grade into (c) flake-blank cores (collectively described as “modified flakes”). (d) Radial core. (e) An unmodified stone with rodent tooth marks along the margin. (f–g) Stone anvils. (h) Brecciated deposits containing an embedded stoneartefact. (i) Unusual large limestone multiplatform core. Scale bar = 1 cm.



unknown, although it is notable that the macroblades at LB2 were often struck from multifaceted platforms, with subsequent proximal trimming and edge modification presumably to prepare them for hafting and use.

Refined macroblades like the examples from LB2 are absent from the LBB assemblage, but large unmodified blade-like flakes – similar in technology to these macroblades – were recovered from LBB (Figure 6k–m). Production of the large macroblades was evidently accomplished at an undiscovered macroblade workshop site(s) outside the caves. However, the techniques and approaches to producing macroblades were sometimes used to produce small blade-like flakes inside the cave. The concept behind the macroblade manufacturing technique was to first prepare a straight ridge on the core by removing two slightly overlapping flakes, and then striking the macroblade down the ridge. The degree of elongation of the resulting flake depends on the length of the core face, and long core faces must have been maintained at the quarry sites. Inside LBB there is evidence for the same approach to reduction, although it is relatively uncommon. For instance, the single-platform core in Figure 6h was reduced by hard-hammer percussion in the manner described above, producing elongated blade-like flakes measuring about 30−50 mm in length. Since the cores reduced inside the cave were small with short core faces, the flakes are not

Figure 8. Evidence for use in Upper Industry artefacts at Leang Bulu Bettue. (a, b, e–g) Stone artefacts with ochre residue adhering to sharp margins and arises. (c) Early reduction flake made from hematite. (d) Ochre piece with engraved grooves from the production of ochre powder. (h and i) Silica edge gloss. Scale bar = 1 cm.



elongated enough to be considered "blades", and too small to be "macroblades" (i.e. true macroblades are generally over ca.80 mm long), but the stoneworkers in the cave were demonstrating a similar technical knowledge. Maintaining the correct platform angle on the core is also an essential element of macroblade production, and manipulation of this angle is what created the multifaceted platform on the macroblades recovered from LB2. Furthermore, like the core face maintenance techniques, stoneworkers at LBB sometimes practiced this on the smaller cores, creating flakes with multifaceted platforms.

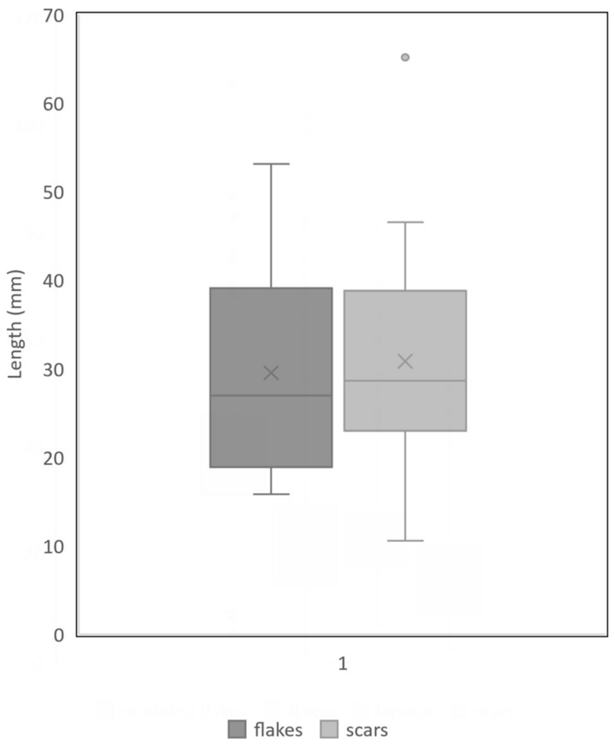
The technically-sophisticated Upper Industry macroblades – in combination with evidence for parietal art (Huntley et al., 2021, p. 7), portable art (Brumm et al., 2020; Langley et al., 2020), beads, and bone tool technology (Brumm et al., 2017) – highlight the complex technological and social relations between groups at this early period. Symbolism specifically related to stone flaking or tool use during the Upper Industry is suggested by five stone artefacts with geometric engravings on the cortex from the Upper Industry at LBB (Brumm et al., 2017, 2020). Further, red ochre residues were found on both bipolar artefacts ($n = 6$) and freehand-struck flakes ($n = 50$) at the site (Figure 8a,b,e–g); while these ochre residues have yet to be conclusively linked to parietal art in the cave, it is clear that red pigments carried symbolic value during this period. The stone tools with ochre residues were likely part of the pigment-producing behaviours, specifically to scrape powder from ochre lumps (Figure 8d) (Brumm et al., 2018, fig. 7h), and were likely used in processing pigmented items. One of the flakes with engraved cortex was also used to process ochre (Brumm et al., 2020). A single haematite flake was also recovered, in Layer 4b (Figure 8c).

Finally, some artefacts among the Upper Industry were unusual and unique, but worth recording for posterity. These include a large, heavy limestone cobble from Layer 4c with a natural hole through it and flake scars initiating from multiple platforms creating a rounded core (Figure 7i). The purpose of this artefact is unknown; the flaking appears to be opportunistic, targeting every available potential platform, suggesting the unusual form might simply be a by-product of flake production. One un-flaked stone is covered in heavy, paired grooves that appear to be rodent incisor marks (Figure 7e) (Gobetz & Hattin, 2002). Another artefact shows clear evidence for the utilisation of unmodified scar ridges, as this small, elongated flake was struck down a heavily stained ridge that had previously been used to scrape ochre (Figure 8f). Among the LBB assemblage 10 conjoin sets (Figure 6i) were recovered, all chert, though these were identified incidentally during analysis and the true number is likely far higher. This indicates some flaking occurred on-site, and further supports the stratigraphic integrity of the deposits. Among these conjoins are eight flakes with an average length of 22.40 mm, as well as three conjoin-pairs of bipolar artefacts.

LOWER INDUSTRY AT LBB

The distinctive characteristic of the Lower Industry at LBB is the relatively high instance of cores made on limestone and water-rolled volcanic/metavolcanic cobbles, and a preference for limestone for toolmaking (Table 3). Both of these stone types are available in local streams and within the cave itself. Chert artefacts are also present, but in smaller proportions to the Upper Industry – no evidence for chert seams within the limestone bedrock of the cave has been observed thus far. Core reduction was accomplished by freehand hard-hammer percussion, creating single-platform and multiplatform cores (Table 2). Relatively few flakes were struck from the cores prior to discard (Mean ± SD: 2.7 ± 1.4 scars). Flakes were slightly larger than the average Upper Industry flake, and the size

Figure 9. Length of flakes (modified flakes and unmodified flakes), and flake scars of Lower Industry (Layer 5) artefacts, Leang Bulu Bettue. All artefacts, including broken artefacts are included.

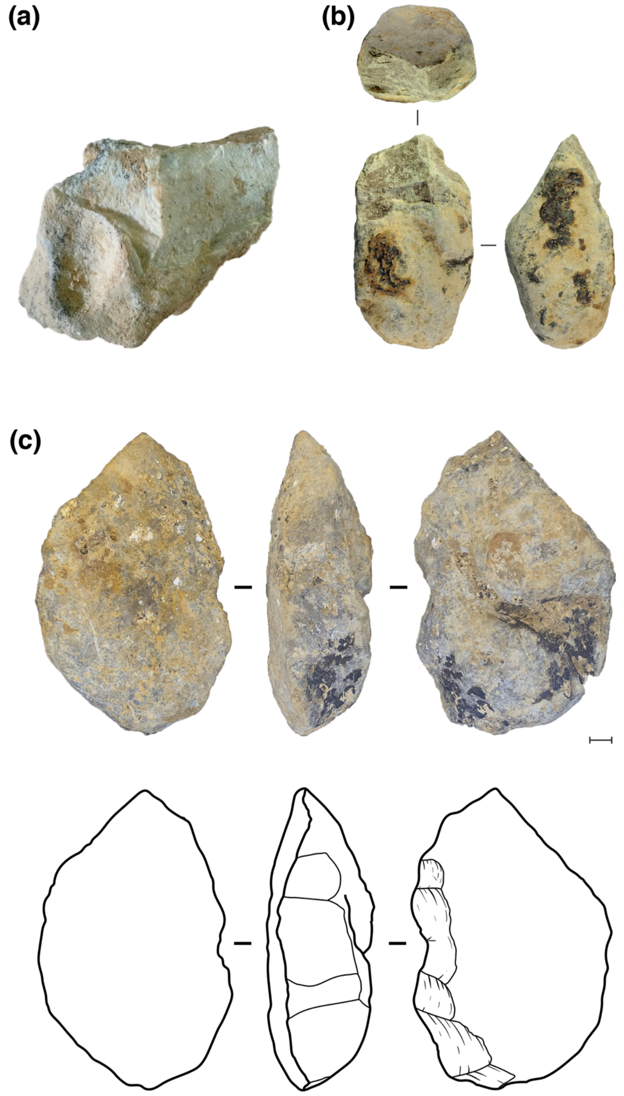


distribution of core scars and flakes suggests that most flakes were struck on-site (Figure 9).

The Layer 5 assemblage includes a limestone cobble with a possible assay scar – resulting in a star-fracture – at one end; a minimally-reduced limestone multiplatform core with four scars removed from two separate platforms; a limestone core with two side-by-side flakes struck down a long axis of the cobble, one flake struck from a flat face with low dorsal mass, and a fourth scar across the end; an elongated volcanic cobble with one end modified by three unifacial removals (Figure 10b); and three minimally modified limestone cores with unifacial flaking and a maximum of five scars on one core (Figure 10a,c). In addition to these modified pieces, six flakes were recovered (Table 2) – three chert and three of limestone.

A pronounced shift in lithic technology occurred between the Upper and Lower industries by about 50 ka at LBB, at least in as much as can be identified from a small sample size. The key changes included 1) a switch to chert as the preferred raw material in the Upper Industry, with far less reliance on locally-available limestone and volcanic cobbles from the local creek (Table 3); 2) a focus in the Upper Industry on the use of chert flake blanks struck at the as-yet unidentified stone sources and carried to the caves; 3) the introduction of novel flaking techniques and reduction trajectories in the Upper Industry; and 4) the use of stone tools in new ways in the Upper Industry, including in plant and ochre processing. Combined with evidence of other

Figure 10. "Lower Industry" artefacts recovered from Layer 5 of Leang Bulu Bettue. (a) A minimally modified limestone core with two large flake scars visible. (b) An elongated volcanic cobble with one end modified by three unifacial removals. (c) Photo and sketch of a minimally modified limestone core with five large flake scars visible. Photo **C** courtesy of Anton Ferdianto. Scale bar = 1 cm.



symbolic behaviours (Aubert et al., 2014; Brumm et al., 2017, 2020; Brumm, Oktaviana, et al., 2021; Langley et al., 2020), the Upper Industry displays the hallmarks of behaviourally modern humans in the Maros and Pangkep karsts landscape. In contrast to the Upper Industry, the Lower Industry at LBB reflects reliance on stone local to the cave for tool manufacture; a technological structure with fewer reduction trajectories and more restricted reduction techniques; and an absence of silica residues and ochre traces on the stone tools.

The hominin association of the Lower Industry is unknown at present; Layer 5 occurs in depositional early Phase I at the site, with an upper date of 50 ka, postdating the early *H. sapiens* occupation of Sumatra (Westaway et al., 2017), and contemporary with (O'Connell et al., 2018) or postdating the modern human colonisation of Australia (Clarkson et al., 2017). The Lower Industry extends into much deeper deposits at LB2, however, potentially pre-dating the regional incursion by *H. sapiens* (Layers A and B, see Brumm et al., 2018, pp. 20-24), although dating these deposits has proved difficult. A non-modern hominin presence on Sulawesi is indicated by the >118000 ka tools recovered from Talepu, but the species that made the Talepu tools is unknown (van den Bergh et al. (2016) and Brumm et al. (2018), p. 33) raise the possibility that the equivalent Lower Industry at LB2 was made by non-modern hominins. Whichever hominin species was responsible for making the Lower Industry at LBB, it may have been produced at the same time hominins (almost certainly *H. sapiens*) were creating sophisticated rock art (including narrative compositions – "scenes") in the surrounding Maros and Pangkep karsts (Aubert et al., 2019; Brumm, Oktaviana, et al., 2021).

TOALEAN (MID-HOLOCENE) EVIDENCE AT LBB

Despite the close proximity of Ulu Leang 1, one of the key sites for defining the Toalean Industry (Chapman, 1986; Glover, 1976; cf. Perston, Moore, et al., 2021), no evidence has been recovered for the Toalean in the main excavation at LBB. Toalean assemblages are characterised by the presence of artefacts such as backed artefacts, Maros points, backed "sawlettes", or other typologically distinctive implements (Perston, Moore, et al., 2021). The timing of the Toalean at Ulu Leang 1 appears to correlate at LBB with the depositional disconformity between Layer 3 and 4. Based on dating evidence, Newman et al. (in press) propose that the lack of Toalean material was due to the removal of those deposits by erosion.

Evidence for Toalean occupation was recovered from Square -Z2 at the southern end of the LBB rockshelter (Figure 2e). Five layers were identified during excavation and labelled numerically; however, these labels bear no connection to the layers of the same number in the main excavation. In total, 121 lithic artefacts were recovered from the upper 1.1 m, within Layers 1–3 and the upper extent of Layer 4 and associated with the dated samples. A single volcanic flake was recovered 1.7 m deep, near the bottom of Layer 4, and one chert flake and one assayed volcanic cobble were recovered in the undated Layer 5, at 1.7 m and 2 m depth. The 86 artefacts within Layers 3–4 include 10 Toalean backed microliths (Figure 6, Table 5). Artefacts found in -Z2 were made on chert, with small amounts of limestone and volcanics (Table 3). The core reduction technology is dominated by freehand hard-hammer percussion, but four bipolar artefacts were also recovered.

The artefacts from the Toalean deposits in -Z2 are unweathered and none show white alteration. The only

Table 5. Summary of excavation layers and artefacts from the -Z2 trench at the lower end of the Leang Bulu Bettue rockshelter.

Layer	Dates†	Artefacts	Heat damage
1	2719–2430 calBP	14 early reduction flakes 1 hammerstone 1 assayed limestone cobble 1 flake-blank cores	
2	2725–2492 calBP	13 early reduction flakes 1 single platform core 1 redirecting flake 1 retouched flake	
3	4412–4248 calBP	8 backed microliths 2 bipolar artefacts 1 backed bipolar artefact 45 early reduction flakes 1 macroblade 1 retouched flake 1 single-platform core 1 truncated flake 4 heat-fractured pieces 1 unidentified flaked piece 3 unidentified	some
4	4829–4582 calBP	1 backed microlith 1 bipolar artefact 15 early reduction flakes 2 hammerstones 1 redirecting flake 1 retouched flake 1 single-platform core	some
5	undated	1 early reduction flake 1 assayed volcanic cobble	

†Dates from Newman et al. (in press).

exception is one heavily weathered volcanic macroblade-like flake – in that it is 66 mm long by 33 mm wide and struck down a dorsal arris, but with no platform treatment – and this artefact may be reworked from Pleistocene deposits. In contrast, the majority of the Toalean assemblage are rather small, thin flakes. Thirteen chert flakes have overhang removal, and 13 flakes are blade-like in that they are twice as long they are wide; however, the latter do not appear to represent systematic blade production technology as they fall within a continuum of forms and no blade-core technology has been identified (Perston, Moore, et al., 2021; Suryatman et al., 2019). Of the 38 chert artefacts with preserved cortical surfaces, half of these were procured from river cobbles (50%), with the balance procured from bedrock sources. Of the seven volcanic pieces with cortex, six were from fluvial sources. The artefacts recovered from the deposit in -Z2 are quite small, with unbroken and unmodified flakes having a mean weight of 2.5 ± 2.6 g (grams) for flakes and 7.8 ± 6.4 g for the cores.

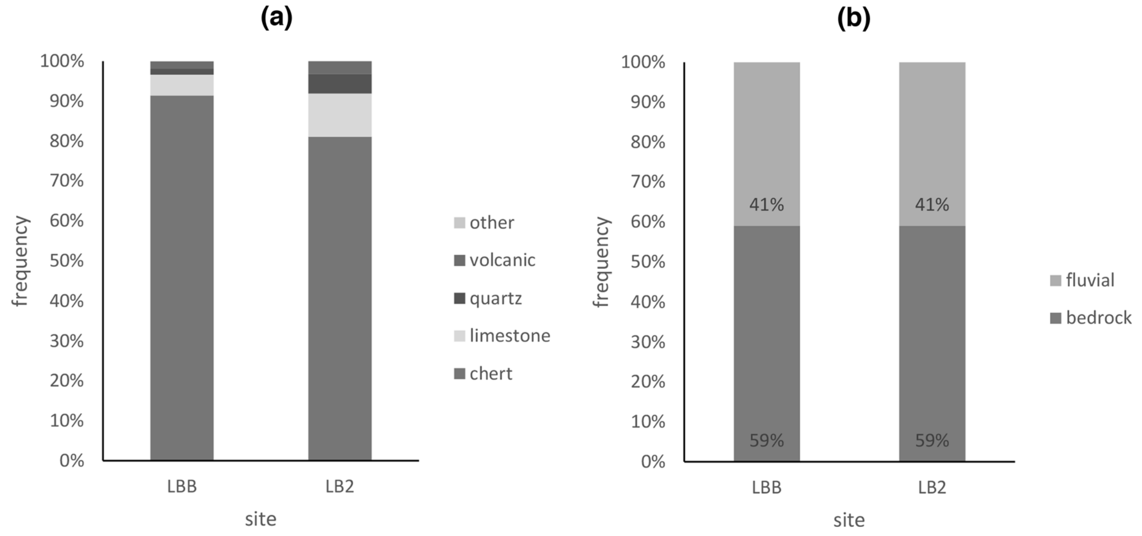
A small number ($n = 13$) of lithic artefact from –Z2 showed damage from uncontrolled burning, including four heat-shattered fragments. No evidence for deliberate heat treatment was identified, however, and this burning occurred after the artefacts were manufactured. Silica gloss was present on six artefacts (Di Lello, 2002; Sinha & Glover, 1984).

TECHNOLOGICAL COMPARISON BETWEEN LBB AND LB2

LBB and LB2 are broadly contemporaneous and located about 1.5 km apart. Both sequences were analysed by MWM and YLP using similar analytical techniques, and the LB2 technology is described in Brumm et al. (2018). Here we compare the two technological sequences, using data from artefacts recovered from the excavation squares of D10 and D11 of LB2 during the excavation by Brumm et al. (2018). The assemblages at both sites are characterised by an Upper Industry ($N = 2672$, Layer II, spits 13−46) and a Lower Industry ($N = 489$, Layers I and A, spits 47–59), and the similarities in reduction sequences indicate that they derive from the same technocomplexes, although with variations in expression between the two sites.

The Upper Industry at LBB is dominated by chert, a trait shared with the LB2 assemblage (Figure 11a). The chert artefacts at LB2 do not show the "white alteration" (after Caux et al., 2018) seen at LBB. Like at LBB, the Upper Industry at LB2 has small amounts of limestone, quartz and

Figure 11. Comparison of the Upper Industry assemblages at Leang Bulu Bettue and Leang Burung 2. (a) raw material frequencies. (b) Cortex type on chert artefacts.



volcanic stone artefacts. The proportion of chert relative to these minor materials was higher at LBB. Cortex is more prevalent on Upper Industry chert artefacts at LBB (12.8%) than LB2 (6.2%). Given the proximity of the two sites and the similarity in flaking technology, this likely has more to do with idiosyncrasies of human land-use and chert procurement strategies than access to stone sources. The cortex type – indicating the nature of the stone sources – shows that bedrock cherts were favoured over river cobbles equally at both sites (Figure 11b). A total of 15 scavenged and reworked chert artefacts were recovered from the Upper Industry at LBB, and three reworked chert artefacts were noted in the Upper Industry at LB2, suggesting that this method of procuring tool blanks was widespread during this period. As has been previously indicated, the prevalence of recycling activity of this kind is likely to be underrepresented. Two artefacts were noted in the Upper Industry at LB2 with glossy ventral surfaces and dull dorsal attributes, indicating that the flakes were struck from heat-treated cores. As with LBB, the practice was uncommon relative to the amount of stoneworking, and the cores may have been incidentally burned or heated rather than deliberately heat-treated.

The key artefact types documenting a reduction sequence model are referred to as “technological proxies”. Table 6 lists the Upper and Lower Industry proxies for the LB2 reduction sequence, which can be compared to the frequency of those types in the LBB Industries in Table 2. Most of the key proxies are present in both assemblages, indicating that they derive from a similar technological approach to stone reduction. Flake blanks at both sites were reduced by freehand percussion and truncating. Bipolar flaking was particularly common at both sites. Clear evidence for the burination technique – documented at LB2 – are not present on LBB cores, although redirecting flakes – created in targeting core edges as zones of high mass – indicate a similar conceptual approach to striking burin flakes, and redirecting flakes were identified at both sites (Tables 2, 6). Core rotation like this sometimes produces multiplatform cores (Moore et al., 2009), 138 of which were recovered at LBB. Evidence for macroblade production is arguably present in the Upper Industry at both LBB and LB2 (cf. Glover 1981) (Figure 6k–m).

The frequency of bipolar flaking in the Upper Industry at LB2 relative to other techniques, gauged by the proportion of bipolar artefacts, was nearly three times as common as the frequency of bipolar flaking at LBB. This different expression of the one technique may be related to a more limited range of activities occurring at LB2. Bipolar artefacts at LB2 were made on a wide range of flake sizes and include biface-like specimens similar to those at LBB. As with the LBB bipolar artefacts, the LB2 artefacts were made on flake blanks and were often rotated 90° during reduction. Bipolar artefact sizes are similar at the two sites, with most under 30 mm in maximum dimension but with outliers that are larger than this (Figure 12a).

Flakes modified by freehand percussion are proportionately less common at LBB than at LB2, and this is also reflected in by-products of flake modification such as uniface retouching flakes. The linear dimensions of the modified chert flakes in the Upper Industry at LBB are on average 15 mm longer than those recovered from LB2 (Figure 12b) and weigh, on average, about 4.4 grams more (Figure 12c).

The incidence of burning at LBB, Upper Industry, is much lower than at LB2. Evidence for artefact burning includes two by-products – heat-fracture fragments and potlid flakes – and attributes of burning (potlid scars and crenulation damage) on classifiable artefacts. Some 3.3% of the LBB assemblage ($n = 853$) was damaged by heat or was

Table 6. Results of the analysis of the Pleistocene artefacts from the Leang Burung 2 assemblage, squares D10 and D11.

Artefact type	**Upper Industry**		**Lower Industry**	
flakes	***n***	**%**	***n***	**%**
contact removal flake	6	0.22	0	0
early reduction flake	952	35.70	263	65.10
macroblade	2	0.07	0	0
redirecting flake	37	1.39	1	0.25
uniface retouching flake	36	1.35	10	2.48
subtotal	*1033*	*38.73*	*274*	*67.83*
cores:				
assayed cobble	2	0.07	13	0
unidentified flaked piece	13	0.49	5	1.24
modified flake	90	3.7	7	1.73
multiplatform core	3	0.11	7	1.73
radial core	4	0.15	9	2.23
single platform core	5	0.19	5	1.24
subtotal	*117*	*4.71*	*46*	*8.17*
other:				
bipolar artefact	245	9.1	1	0.25
eraillure	6	0.22	0	0
hammerstone or fragment	2	0.07	0	0
heat-fractured piece	151	5.66	1	0.25
potlid	125	4.69	2	0.50
utilised cobble	0	0	1	0.25
unidentified piece	988	37.05	79	19.55
subtotal	*1517*	*56.79*	*84*	*20.80*
Grand total	2667	100.00	404	100.00

a by-product of incidental burning, compared to 32.5% at LB2 ($n = 868$). This suggests a more extensive use of fire inside LB2 than LBB, or perhaps activities more likely to expose stone artefacts to excessive heat.

Edge-glossed artefacts are more common in the LB2 assemblage than in the LBB assemblage. The LB2 assemblage includes 23 edge-glossed tools and nine flakes struck to resharpen glossed edges, preserving the gloss as an attribute on the dorsal surface of the flake.

Stone tools were used to process ochre in the Upper Industries at both sites. This evidence includes stone-tool scraped ochre "crayons", tools with ochre traces on them, and, at LB2, flakes struck to resharpen tools used to scrape ochre or to process ochre-coated materials. Some 15 artefacts with ochre residues were recorded at LB2, as well as two small haematite flakes that were likely struck in processing hard lumps of ochre.

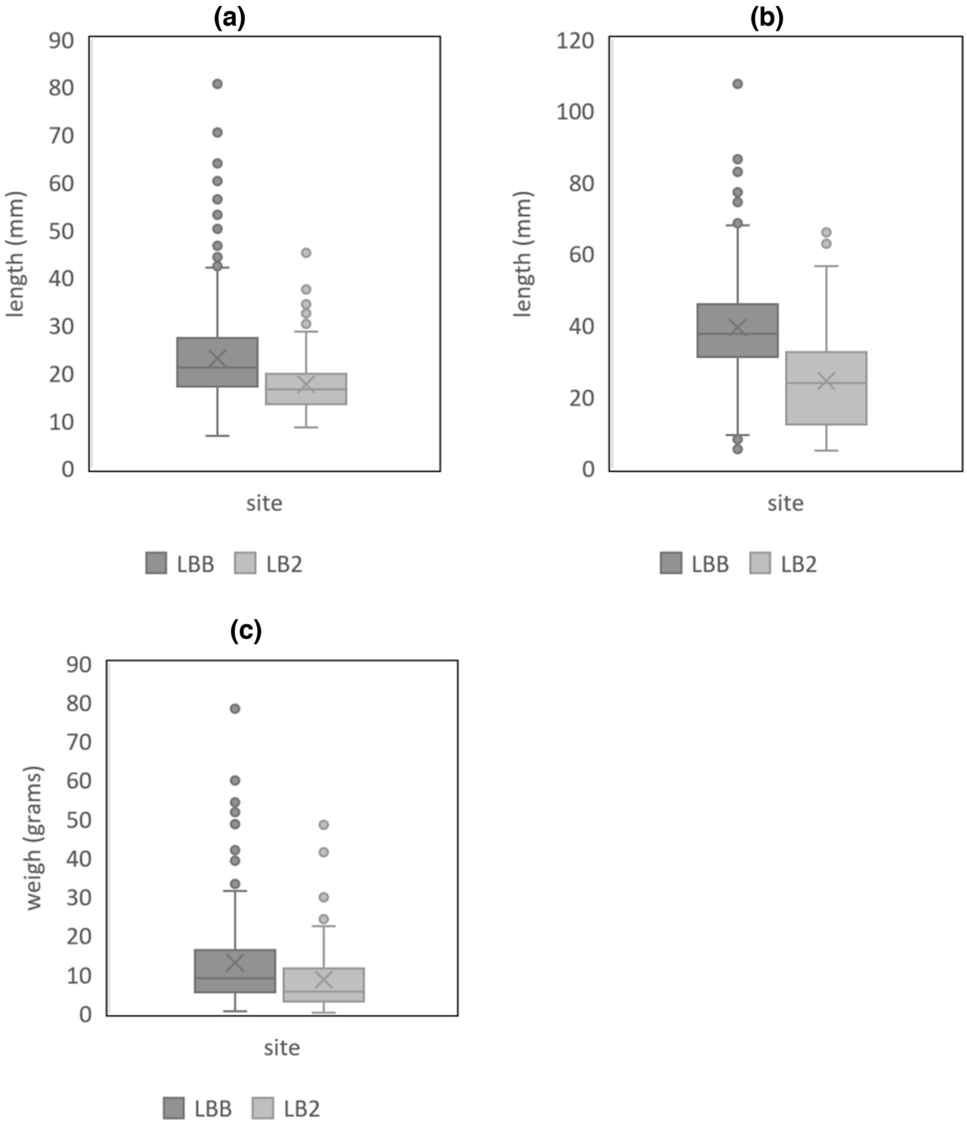
The artefact types in the Lower Industry at LBB (Table 2) reflect a similar emphasis on cobble reduction to that seen in the Lower Industry at LB2. The Lower Industry at both LBB and LB2 is characterized by a greater emphasis on on-site cobble reduction than the Upper Industry, particularly of locally-available limestone and volcanic/metavolcanic stones. The Lower Industry at both sites is dominated by the use of limestone as a raw material, although the LBB assemblage shows a slightly higher variation on this (Figure 13). One possible bipolar artefact was recorded in the Lower Industry assemblages at LB2, raising the possibility that this piece was a contaminant from younger deposits.

DISCUSSION AND CONCLUSION

Sulawesi is emerging as a crucially important region for addressing key questions in human evolution, including the colonisation and occupation of Sunda by archaic hominins (van den Bergh et al., 2016), the timing and nature of movements of early *H. sapiens* populations through the region (Westaway et al., 2017), and the ways that these earliest modern human colonisers adapted to these landscapes through symbolically-mediated behaviour (Aubert et al., 2017, 2019; Brumm et al., 2017). Further, understanding adaptations of *H. sapiens* to post-LGM (Last Glacial Maximum) conditions – and the morphological and genetic affiliations of these early people (Brumm, Bulbeck, et al., 2021; Carlhoff et al., 2021) – are crucial for understanding the origins and nature of the Toalean culture (Perston, Burhan, et al., 2021), and the impacts of the subsequent Austronesian expansion (associated with the first agriculture and domesticated fauna and the earliest so-called "Neolithic" technologies, including ceramics and ground stone axes), within the context of the Late Pleistocene and Holocene prehistory of Indonesia. Answering these questions turns in large part on developing a more complete understanding of the technological changes that occurred across these events, particularly using the period's most enduring and abundant evidence – the stone tool technology.

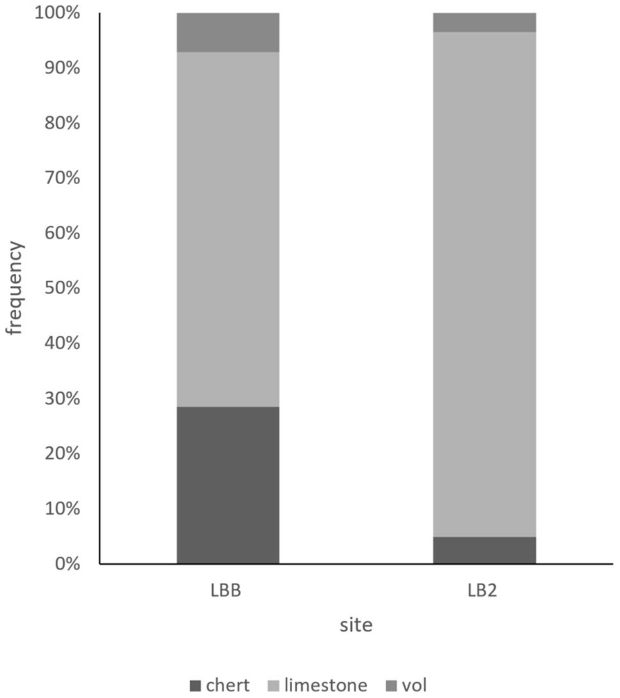
An emerging picture for the early occupation of Sulawesi – as documented in part by the LBB and LB2 assemblages described in this paper – is that an abrupt technological

Figure 12. Comparison of modified artefacts from the Upper Industry assemblages of Leang Bulu Bettue and Leang Burung 2. (a) Average length of bipolar artefacts. (b) Average length of modified flakes (excluding bipolar artefacts). (c) Average weight of modified flakes, with three large outliers removed from the LBB sample.



change occurred at ca.40−50 ka. Prior to this period, the stone technology of what we are calling the Lower Industry involved least-effort and non-intensive reduction of stone cobbles procured in the area local to the site, such as riverbeds and possibly within the cave-sites themselves. Core reduction was by hard-hammer percussion, with choices of platforms and resulting core forms driven by the morphology of the original stone, and, in the more-reduced cores, by the constraints of stone-flaking design space (see Moore & Perston, 2016). The technology is similar to that documented in the So'a Basin on Flores, dating between approximately 1.0−0.5 million years ago (Brumm et al., 2016), and presumably made by the ancestors of *Homo floresiensis*, and the size and nature of the cores is similar to the technology documented on Sulawesi at Talepu dating to 194–118 ka (van den Bergh et al., 2016). Complicating the picture is the stone technology dating to 130 ka at Sembungan on Java (Rizal et al., 2020, p. 384), and likely made by *Homo erectus*: the cores there are small, reflecting the size of the raw materials available (cf. Moore & Brumm, 2007), although the core reduction at Sembungan is also driven by the shapes of the stones chosen for reduction. Although dating later, ca.190−50 ka (Sutikna et al., 2016), and further complicating the picture, the stone technology practiced by *H. floresiensis* at Liang Bua cave on Flores is technically similar to the pre-Neolithic technology later practiced by *H. sapiens* at the same site, differing mostly in the preferred raw material and the degree of damage to the artefacts by burning (Moore et al., 2009). Indeed, the stone-flaking technology of *H. floresiensis* involved making large flakes at the stone source and modifying them inside Liang Bua cave in a broadly similar fashion to the Upper Industry stoneworker (modern *H. sapiens*) on Sulawesi.

Figure 13. Comparison of raw materials (chert, limestone, volcanics) represented by the Lower Industry assemblages of Leang Bulu Bettue and Leang Burung 2, shown as a percentage of the total artefact count.



The technological shift to the Upper Industry on Sulawesi, after 50–40 ka, involved a dramatic shift in preference to non-local chert for toolmaking. Rather than carrying chert cobbles to the cave, the stones were reduced into medium- to large-sized stone flakes, and it was often these stone flakes that were carried to LBB and LB2. Macroblades – elongated blade-like flakes – were also made at the stone sources, indicating the development of a specialised stone reduction trajectory more complex than simply responding to the natural morphology of the stone as flaking proceeds. Once at the cave, the flake blanks were used as tools, and were themselves reduced into flakes for tools, before being discarded as depleted objects. A technique rarely, if ever, applied by Lower Industry stoneworkers on Sulawesi – bipolar flaking – was frequently applied to flake blanks of all sizes, but mostly to the flakes struck from the flake blanks. Further, flakes found on archaeological sites on the landscape were scavenged, transported, and further reduced. New tool uses led to archaeologically-visible residues, such as ochre from pigment processing, and silica gloss from processing phytolith-rich plants. The spatial differentiation of stone tool manufacture implies that aspects of the technology were socially mediated (Tostevin, 2012), and the practice of engraving cortex prior to reduction (Brumm et al., 2017, 2020) hints at symbolic practices related to stone flaking at LBB. These changes may have occurred contemporaneously to the creation of the world's earliest figurative parietal art, although the oldest minimum ages for local cave paintings pre-date the minimum ages for the Lower Industry (Layer 5) at LBB (Aubert et al., 2014, 2019; Brumm, Oktaviana, et al., 2021).

A technological shift to the Toalean occurred after the Upper Industry on Sulawesi. This involved the addition of multiple stone-flaking trajectories onto the core-and-flake technology inherited from the Upper Industry, and the shift in core reduction gestures to create different types of tool blanks. New techniques were also innovated to transform those blanks into multiple tool forms, including anvil-backed microliths and pressure-flaked points. Although we have a good morphological understanding of Toalean tool forms from decades of research in South Sulawesi, our knowledge of the details of Toalean reduction trajectories, and therefore the precise nature of the shift from Upper Industry toolmaking, is poorly understood (Perston, Moore, et al., 2021). This is partly because of the poor preservation of archaeological deposits from the crucial period (Newman et al., in press), from ca.15 ka – the *terminus ante quem* for the Upper Industry at LBB – to ca.8–6 ka, the first appearance of the Toalean industry at various sites across South Sulawesi (see Perston, Burhan, et al., 2021). Even less well understood are the changes to stone technology that may have occurred with the movements of Austronesian-speaking societies in late prehistory. Significant changes are suggested by the appearance of edge-ground adzes during this shift from hunting-and-gathering to agriculture. It is possible that the Austronesians and earlier peoples may have coexisted for generations (Bulbeck, 2004; Hasanuddin et al., 2020; Suryatman et al., 2017, but see Perston, Burhan, et al., 2021), with presently-unknown effects on stone tool technology and its role in the social lives of these peoples. A further shift in stone technology likely occurred with the advent of metallurgy; stone and metal tools were made contemporaneously in parts of South Sulawesi (Suryatman et al., 2021).

Although an efflorescence of research in South Sulawesi from the 2000s has greatly expanded and improved our understanding of the key developments of the island's prehistory (Perston, Burhan, et al., 2021), concerted research is necessary to identify and analyse key sites that can address gaps in our understanding, thereby capitalising on this research momentum. Of particular interest for stone technology studies is 1) identifying the hominin toolmakers of the Lower Industry and early Upper Industry, and 2) analysing technological transition points between these industries, the Toalean, and later turning points in the archaeological record. The results of these efforts will complement the recent internationally-relevant discoveries of archaic hominin sites on the island (van den Bergh et al., 2016) and exceptionally early parietal art (Aubert et al., 2014, 2019), and, by doing so, contribute important new information to our global understanding of the human story.

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