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ORIGINAL ARTICLE

What can lithics tell us about hominin technology's 'primordial soup'? An origin of stone knapping via the emulation of Mother Nature

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Abstract
The use of stone hammers to produce sharp stone flakes—knapping—is thought to represent a significant stage in hominin technological evolution because it facilitated the exploitation of novel resources, including meat obtained from medium-to-large-sized vertebrates. The invention of knapping may have occurred via an additive (i.e., cumulative) process that combined several innovative stages. Here, we propose that one of these stages was the hominin use of 'naturaliths,' which we define as naturally produced sharp stone fragments that could be used as cutting tools. Based on a review of the literature and our own research, we first suggest that the 'typical' view, namely that sharp-edged stones are seldom produced by nonprimate processes, is likely incorrect. Instead, naturaliths can be, and are being, endlessly produced in a wide range of settings and thus may occur on the landscape in far greater numbers

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than archaeologists currently understand or acknowledge. We then explore the potential role this 'naturalith prevalence' may have played in the origin of hominin stone knapping. Our hypothesis suggests that the origin of knapping was not a 'Eureka!' moment whereby hominins first made a sharp flake by intention or by accident and then sought something to cut, but instead was an emulative process by hominins aiming to reproduce the sharp tools furnished by mother nature and already in demand. We conclude with a discussion of several corollaries our proposal prompts, and several avenues of future research that can support or question our proposal.

INTRODUCTION

The deliberate knapping of sharp stone flakes is thought to represent the first instance of 'secondary technology,' that is, the use of a tool to make another tool (Roux & Brill, 2005). Despite the impressive tool using and tool making capabilities of some nonhuman primates, including our closest living relatives within the genus *Pan*, no nonhuman animal uses tools to make other tools in the wild (Shumaker et al., 2011). Accordingly, the use of stone hammers to produce sharp stone flakes that are subsequently used as cutting tools is thought to represent a significant stage in hominin technological evolution, opening up the exploitation of novel resources, including meat obtained from medium-to-large-sized vertebrates (Ambrose, 2001; Domínguez-Rodrigo et al., 2005; Pobiner, 2020; Thompson et al., 2019). This in turn had profound consequences for hominin evolution, permitting an expansion of brain size (Aiello & Wheeler, 1995) and the eventual emergence of other technological products that required shaping through cutting actions (Gala et al., 2023; Shea, 2023).

By combining multiple cognitive abilities (i.e., insight and planning) and an understanding of causal and mechanical properties that permit the reliable release of suitable flakes via conchoidal fracture, knapping is a unique challenge in comparison with other tools made by wild nonhuman primates. Even Kanzi, a bonobo (*Pan paniscus*) chimpanzee taught to make and use stone flakes in captivity, did not accurately replicate all the features seen in early stone tool (i.e., Oldowan) assemblages (Toth et al., 2006), despite some aspects of the task, such as hammerstone and nodule selection, being made for him (Schick et al., 1999; but see Eren et al., 2020). As a technological challenge, it represents the kind of activity that is likely to have developed in stages, not as the result of a single moment of insight and innovation by a single individual (Eren et al., 2020; Gürbüz & Lycett, 2021; Marchant & McGrew, 2005). In other words, the invention of knapping may have occurred via an additive process of combining several innovative stages, subsequently socially learned and built upon by others, or what some have referred to as 'cumulative culture' or a 'ratcheting' (e.g., Boyd et al., 2011; Tomasello, 1999). Derex (2022) recently proposed that one means by which the emergence of relatively complex technological behaviors may occur is through the exploitation and improvement of natural phenomena. As Derex (2022:1) explains, '[n]atural phenomena are not created by individuals; they are simply features of our environment. Yet they generate reliable effects … that can be exploited and used for a purpose.' Ultimately, 'human cumulative culture operates by exploiting an increasing range of natural phenomena' (Derex, 2022: 2).

Archaeologists have long known that nonprimate-related processes can produce sharp stone fragments, conchoidally fractured flakes, and other products that mimic intentionally knapped artifacts (e.g., Barnes, 1939; Warren, 1905, 1914). These lithic forms are produced by natural geological, hydrological, and temperature-related processes and by nonprimate animals (Andrefsky, 2013; Domínguez-Solera et al., 2021; Eren et al., 2023). If these naturally-produced stone fragments are shown to be tools, or considered as potential tools, then we formally refer to this class of stone objects as sharp-edged 'naturaliths.' Some readers may question the need for a new term, noting that researchers have already coined 'eolith' (Brown, 1893). Setting aside the latter term's historical baggage (Ellen, 2011; Grayson, 1986; O'Connor, 2007) and that some researchers once attributed eoliths to hominin manufacture (Brown, 1893; Cotterell & Kamminga, 1990; MacCurdy, 1905), the prefix 'eo-' means 'early' or 'primeval,' but 'naturaliths' are not temporally constrained. The term 'geofact' (Gillespie et al., 2004; Haynes, 1973; Wiśniewski et al., 2023) also does not work because, as we have noted, non-geological processes can also produce such objects. The inverse argument applies to the term 'zoofact' (Lopinot & Ray, 2007). Moreover, archaeologists attempting to distinguish sharp lithic artifacts from sharp lithic geofacts or zoofacts generally assume hominins did not use the latter as tools, such that the term connotes an automatic and inherent dislocation from hominin behavior (e.g., Lopinot & Ray, 2007; although see McPherron et al., 2010). Archaeologists also attribute this dislocation to the terms 'pseudoartifact,' 'pseudomorph,' and 'naturefact' (e.g., Borrazzo, 2016, 2020; Manninen, 2007). Finally, we note that Domínguez-Rodrigo et al. (2012) use the term 'humanly unmodified rocks'; however, beyond an argument for semantic brevity, it also remains unclear whether they believe such items were, or could have been, used as tools.

The goals of this manuscript are twofold. The first goal is to provide a limited review of nonprimate processes that can produce sharp-edged naturaliths. Based on this review, we propose that naturaliths can be, and are being, endlessly produced in a wide range of settings and thus may occur on the landscape in far greater numbers than archaeologists currently understand or acknowledge. This proposal leads directly to the second goal, which is to explore the potential role that 'naturalith prevalence' may have played in the origin of hominin stone knapping.

NATURALITH PRODUCTION

Archaeologists and others have demonstrated via field observation, collections analysis, and controlled experiments that nature can make sharp-edged flakes, and that many natural processes can produce them. Almost universally these studies are focused on 'lithic taphonomy' (Andrefsky, 2013; Driver, 2001a, 2001b; Eren et al., 2011; Hiscock, 1985; Neubauer, 2024; Pevny, 2012; Wiśniewski et al., 2023) and thus aim to understand how nonhominin produced, and presumably unused, flakes alter stone tool assemblages.[1] However, in the context of early hominins, we suggest that this presumption of nonuse may be invalid (see McPherron et al., 2010). Thus, the plethora of natural processes that produce sharp-edged (and assertedly unused) stones in temporally later periods would be, via the principle of uniformitarianism, the same potential wellspring of naturaliths available to hominins in earlier periods.

Perhaps the most compelling field-collected evidence that nature produces naturally sharp rocks comes from Antarctica. Eren et al. (2023) presented a collection of 14 lithic specimens from Antarctica's Transantarctic Mountains (curated at Polar Rock Repository in Columbus, Ohio, U.S.A.) that, had they been found elsewhere, would likely be interpreted as hominin-produced via conchoidal fracture. But given that no primate ever colonized Antarctica during the Pliocene or Pleistocene, the most parsimonious explanation for these 14 specimens is that natural processes produced them. The specimens are comprised of various materials (chert, quartzite, hornfels, basalt, and obsidian) and mimic a variety of technological forms (flakes, cores, biface forms, choppers). More recently, we documented another collection of naturally produced lithic specimens from Western Antarctica, curated at the British Antarctic Survey in Cambridge, UK. Like the first collection, this collection comprises a variety of materials and technological forms (Figure 1; see also Supplementary Online Materials, Data S1, Images S1-S28). Both Antarctic collections are broadly consistent with the hypothesis that nature produces sharp-edged stones in different contexts. We emphasize the word 'broadly' in the previous sentence because the *specific* contexts from which those specimens were collected, and thus the potential geological process(es) by which they were produced, is unknown and not recorded.[2] Future field research in Antarctica can help to address this knowledge gap. Until then we can turn to field observations and controlled experiments in more northern environments to examine specific processes that produce naturaliths.

Trampling by large animals can produce sharp edged specimens. Lopinot and Ray (2007) demonstrated this via an experiment in which elephants walked over 4300 pebbles and cobbles. Led by handlers, two elephants in tandem trod over the gravel a total of 50 times 'with two feet of each elephant normally hitting the gravel pit per round' (Lopinot & Ray, 2007:776). The 'vast majority of the flakes were small' (<1 cm), but Lopinot and Ray (2007:776) still identified 228 'modified' pebbles and cobbles as well as 94 flakes larger than 1 cm. One might wonder whether leading two elephants over gravels 50 times is too contrived to be of any meaningful interpretive value. When considering that a herd of elephants can consist of dozens or even hundreds of individuals (Douglas-Hamilton, 1972; Global Sanctuary for Elephants, n.d.; Moss, 1988; Tsavo Trust, n.d.), however, and that gravels could potentially be trampled for hundreds or thousands of years (or more) by numerous herds, the number of sharp-edged specimens produced by Lopinot and Ray's (2007) experiment is likely conservative relative to potential elephant gravel trampling occurrences in nature.

Lopinot and Ray (2007:776–777) also attempted to conduct a bison trampling experiment, but this was 'unsuccessful' due to the 'lack of controls over the herd and the absence of continuous observation during the experimental period.' In short, the bison were 'skittish,' and Lopinot and Ray could not manipulate them to walk over the 3300 pebbles and cobbles. Yet after 5 days, a bison (or several) appeared to have 'rolled around' on the gravel pit. This action produced 34 modified pebbles and cobbles; the longest flake was 1.5 cm long.

Although cobble modification and flake production via bison rolling demonstrate yet another process whereby nonhominin processes make sharp-edged stones, the lack of bison trampling in Lopinot and Ray's (2007:776) second experiment was disappointing. They predicted that, relative to the elephant, 'large hoofed animals such as bison or elk might produce similar, or perhaps even larger, pseudoflakes and modifications to boulders, cobbles, and flakes.' This prediction originated from the observation that an elephant's weight is dispersed because its feet expand slightly in diameter upon hitting the ground; thus, the foot-pounds of a smaller hoofed animal like a bison or elk might be greater. Toward this end, Domínguez-Solera et al. (2021) recently reported an experiment that specifically examined the interaction of hoofed equids with knappable rocks. Noting that equids have a long evolutionary history and are a ubiquitous presence on landscapes occupied by hominins, Domínguez-Solera et al. (2021:1–2) assessed how quartzite and flint might be modified when three donkeys and a mare engaged in a common equid behavior: hoof trimming. After Domínguez-Solera et al. (2021:3) exposed the rock to the donkeys for 52 days and the mare for 2 days, they found that 15 complete flakes, six broken flakes, six flake fragments, five chunks, five cores, and many chips were produced. Moreover, they could refit all the trampled pieces.

Numerous geological, hydrological, and temperature-related processes can also produce sharp edged stone that could have been used by hominins. Gillespie et al. (2004:616) describe the 'power of nature' to produce naturaliths. Natural processes include:

FIGURE 1 Examples of naturally produced sharp-edged stone specimens (top row, left to right: specimens #1, #5, #4, #7), or 'cores' from which sharp edged stone specimens likely manifested (bottom row, left to right: specimens #13, #20, #15 #24), from the Antarctic peninsula. Details about these specimens are available in the supplementary online materials (Data S1). These specimens and additional specimens can also be seen in figures S1-S28. (Image by Michelle R. Bebber, Metin I. Eren, and Alastair Key).

> soil movement, glaciation, wave action, high-velocity water movement, gravity (such as alluvial fans or steep inclines), rapid temperature changes, internal pressure (such as starch fractures and pot lids), exfoliation, tectonic movements, diastrophism, [and] solifluction.

Schick and Toth (1994:95) also note natural forces that can produce sharp-edged flakes:

> Cliffs or waterfalls where rocks can drop an appreciable distance and fracture by percussion; beaches with a violent zone of crashing waves propelling rocks against each other at high velocities; and steep mountain ravines and alluvial fans spreading out from mountains where, especially during flash floods, rocks may be thrown against bedrock or each other with powerful force. Another geological force that can fracture stone conchoidally in higher latitudes is glaciation, when massive ice sheets rake over land masses and subject rock to incredibly high pressure.

Mason (1965:4) assembled South African evidence on percussion or pressure of rock due to natural processes, including:

> Glacial action of Karroo age. Fluvialglacial action of Karroo age. Alluvial action of possibly Tertiary age. Colluvial action of Quaternary age. Alluvial action of Quaternary age. Colluvial-alluvial action of Quaternary age. Lacustrine action of Quaternary age.

Many of these processes or others have been documented via field observation or demonstrated via experiment. For instance, Andrefsky (2013:419) provides an image of thousands (likely more) of sharp-edged exfoliated chert specimens from the Owyhee Uplands in Northwestern North America. Borrazzo's (2020, 2022) experiments (systematically more and less controlled) coupled with Meltzer et al.'s (1994) field observations, provide strong evidence that rockfalls make sharp-edged rocks. Accompanying his discussion of rock-fracturing properties in colder climates, Manninen (2007:79–80) shows via field observation how frost fracture or inferred glacial action can produce numerous sharp-edged specimens. Along these lines, Texier et al. (1998) conducted an experiment that monitored 400 lithic specimens in a high-altitude periglacial environment. After 5 years, 'only' a single lithic item was 'frost shattered' (Texier et al., 1998:467); however, on century or millennial scales this rate of shatter would potentially result in dozens, hundreds, or thousands of specimens. Finally, Rasic (2004) describes how natural thermal processes, such as insolation and wildfires, over time can fracture stone (see also Bar-Yosef et al., 2012:11,15).

We, too, have documented via field observation how geological, hydrological, and temperature-related processes can produce naturaliths in vastly different environments and on distinct rock types. In 2022, at Giant's Causeway in Northern Ireland, we (MIE and MRB) inferred that a combination of rockfall, rolling, and coastal wave action appeared to be flaking basalt (Figure 2). In 2024 we (MIE and MRB) documented another case of crashing waves producing sharp-edged specimens, but this time in South Africa where the rock type was quartzite (Figure 3–4). In 2023, whereas in the deserts of Oman we (MIE, MRB, RG) observed thousands of sharp-edged flakes produced from spherical flint cobbles deposited in wadi beds (Figure 5–6). In this latter case, it appeared that the flint cobbles had been fluvially transported down the channel, accumulating conchoidal and other fractures during transport. Subsequently, the fractures propagated via temperature-related processes, and, in some cases the sharp-edge specimens were removed from the 'core'. The combination of these natural processes resulted

FIGURE 2 Examples of naturally produced sharp-edged basalt specimens (bottom row) found near Giant's causeway, Northern Ireland. These specimens appear to have been produced via downward rolling processes as well as coastal action. (Image by Michelle R. Bebber and Metin I. Eren).

in thousands (likely more) of naturaliths (cf. Domínguez-Solera et al., 2021:1), most of which were 'naturally refit' together or could be refitted back together if already fallen away from the cobble. In 2022 one of us (TP) documented naturally flaked quartzite cobbles still embedded in a conglomerate cliff at Serra da Capivara National Park, Brazil (Figure 7). These cobbles all have clear flake scars caused by cobbles located above them (in some case several tens of) falling and impacting them.

On the Homa Peninsula in Kenya, carbonatite volcanism and mechanical weathering has resulted in angular clasts of various rock types, including carbonatite, altered rhyolite, phonolite, ijolite, nephelinite, limestone, and ignimbrite (Braun et al. 2008; Ditchfield et al. 1999; Kent 1942; Le Bas 1977). As one of us (EF) has observed, Homa Mountain raw materials commonly outcrop in angular blocks and further fracture, sometimes producing sharp edges (Figure 8). These naturaliths occur around the Homa Peninsula and in the vicinity of Oldowan localities, including Nyayanga (Plummer et al., 2023), Kanjera South (Plummer et al. 1999), and Sare-Abururu (Finestone et al. 2024). And with respect to the latter, at Sare-Abururu a spalled phonolite cobble was found in situ alongside the Oldowan assemblage from Excavation 1. The cobble had spalled into five sharp fragments, likely fracturing after the accumulation of the Sare-Abururu hominin-produced assemblage. Although these fragments were not used by

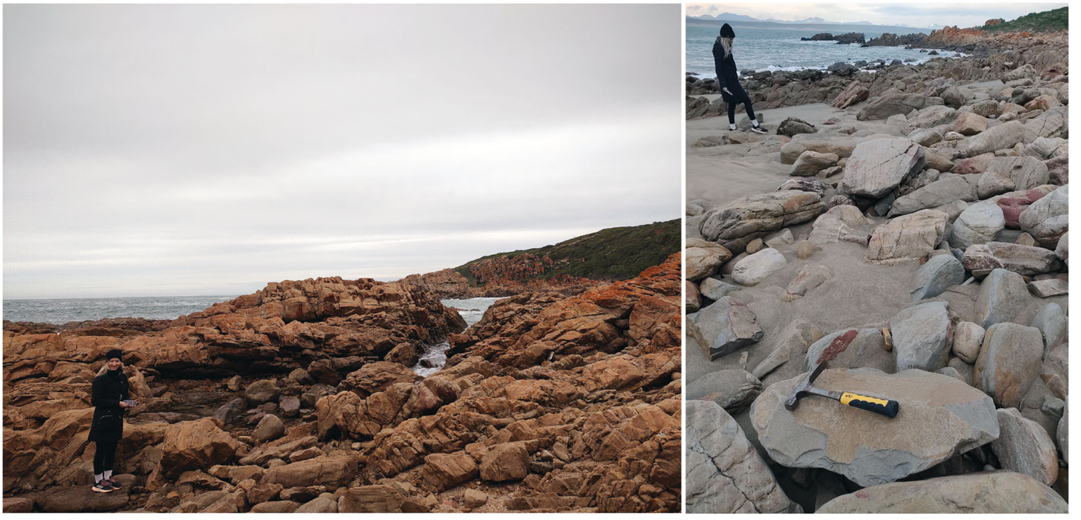

FIGURE 3 A dynamic quartzite coast near Pinnacle Point, South Africa (left) leads to the production of naturally-produced conchoidal fractures (right). See more examples in Figure 4. (Image by Michelle R. Bebber and Metin I. Eren).

FIGURE 4 Close-up examples of naturally produced, conchoidally-fractured sharp-edged quartzite specimens, or 'cores' from which sharp edged quartzite specimens likely manifested (from a dynamic quartzite coast near Pinnacle Point, South Africa, see Figure 3). The image in the bottom row, second from the left, shows a conchoidally fractured flake whose crack has not fully propagated, providing 'snap-shot' of natural flake production. (Image by Michelle R. Bebber and Metin I. Eren).

FIGURE 5 A field of conchoidal- and thermal-fractured chert ‘balls’ near Duqm, Oman. Thousands and thousands (perhaps more) of sharp flakes were produced via natural processes. See more examples in Figure 6. (Image by Michelle R. Bebber and Metin I. Eren).

hominins, they demonstrate the presence of naturaliths in close association with Early Stone Age artifacts Figure 9.

EMULATING ‘MOTHER NATURE’ MAY HAVE GENERATED EARLIEST STONE KNAPPING

Based on the above observations noted in a variety of settings around the globe, we propose that naturaliths—sharp stone fragments that could potentially be used as tools—may be far more frequent and widespread than researchers currently understand or acknowledge. To our knowledge, the notion of a potential ‘naturalith prevalence’ is a departure from the typical view of many paleoanthropologists, archaeologists, and lithic analysts. For example, Schick and Toth (1994:96) wrote that ‘misleading stones’ created by geological processes ‘are few and far between.’ Similarly, Roche (2005:35) suggested that lithics with ‘razor-sharp edges’ do not occur naturally, or only very seldom. More recently, Domínguez-Solera et al. (2021:1) suggested that the ‘friction of cobbles in conglomerates can occasionally result in accidental detachment of flakes, but these are usually isolated episodes. This commonly does not lead to multiple detachment of flakes from the same core.’ Upon reflection, these ‘typical’ views are not supported. Not only, as demonstrated in the previous section, are there a large number of natural processes that can produce naturaliths, but some of these processes produce them in very large numbers (some of which can be ‘refit’). Moreover, and as textbooks note (e.g., Fagan, 2016), stone is durable, sometimes remaining (relatively) sharp after long swaths of time. Thus, hominins in some contexts may have had access to an *accumulation* of naturaliths to exploit, produced for tens, hundreds, or thousands of years beforehand, if not more.

As recently noted by Gürbüz and Lycett (2021:1), many scholars attribute the origin of stone knapping to a transferal of percussion from chimpanzee-like nut cracking or fruit smashing to stone (de Beaune, 2004; Luncz et al., 2022; Marchant & McGrew, 2005; Mercader et al., 2007; Panger et al., 2002; Whiten et al., 2009). However, in recent years, a clearer picture of an association between the appearance of deliberately knapped assemblages (i.e., those

FIGURE 6 Close-up examples of the conchoidal- and thermal-fractured chert 'balls' near Duqm, Oman (see Figure 5). Many of the flakes are still 'refit' into their parent 'core.' Overtime, however, many flakes loosen and radiate away. (Image by Michelle R. Bebber and Metin I. Eren).

dating to around 2.3 million years and older) and faunivory is potentially beginning to emerge (Domínguez-Rodrigo et al., 2005; de Heinzelin et al., 1999; Plummer et al., 2023; Sahnouni et al., 2018; Semaw et al., 2003; Thompson et al., 2019; although see Sahle et al., 2017 for questions surrounding the evidence from Bouri, Ethiopia). Changes in behaviors relating to faunivory at this time are frequently thought essential to later events in human evolution, including the eventual emergence of larger brain sizes (Aiello & Wheeler, 1995; Key & Lycett, 2023; Shipman and Walker 1989; Thompson et al., 2019). This is not to imply that Oldowan tools were exclusively used for animal processing. Plummer et al. (2023), for example, found usewear evidence that tools at Nyayanga (Kenya) were used for processing both animals and plants. However, a more consistent association between incidences of processing animal tissue and early Oldowan assemblages may be apparent given current data from sites dating to 2.3 million years and older. The potential earlier existence of percussion behaviors directed at exploiting bone marrow and brain tissue from scavenged remains prior to, and independent from, flaked stone tool use (Thompson et al., 2019) is also an important consideration given the eventual emergence of later patterns. Moreover, substantial costs in time, energy, and injury risks (Gala et al., 2023; Pargeter et al., 2024) indicate the more substantial nutritional benefit of

FIGURE 7 Quartzite conglomerate cliffs in Brazil lead to natural flakes via rockfall (top). Three examples of flaked cobbles are provided with side- (upper row) and top-views (bottom row). These samples were documented in the blue highlighted band of the cliff face (top). (Image by Tomos Proffitt).

animal tissue processing would be more likely to motivate the emergence of deliberate knapping compared to the processing of vegetation. Hence, hypotheses proposing a link between chimpanzee-like percussive behaviors and the emergence of knapping, currently do not to address the potential transferal of percussive behavior from nonfaunivorous behaviors and contexts to ones directly involving the processing of animal tissue.

Accordingly, Gürbüz and Lycett (2021) recently proposed that bone flakes—created incidentally during archaeologically documented percussive bone breaking for marrow extraction[3] (Binford, 1981; Blumenschine, 1988, 1995; Brain, 1970; Capaldo, 1997; Thompson et al., 2019;

FIGURE 8 Lava outcropping around the Homa Peninsula area, western Kenya. (Image by Emma Finestone).

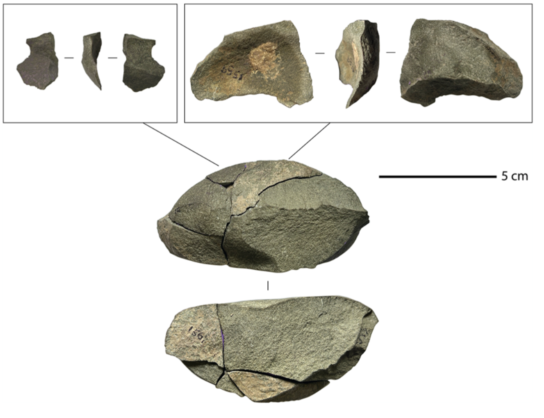

FIGURE 9 A spalled cobble recovered from Excavation 1 at the Oldowan locality Sare-Abururu, Kenya. Five fragments were recovered, two of which feature long axes with sharp edges (top). The refitted cobble is shown in two views (bottom).

Plummer et al., 2023; for a chronologically later example of possible bone tools, see Pante et al., 2020)—could have been the technological precursor to stone flakes (Figure 10). And given that there is an inevitable and immediate contextual and behavioral association between the smashing of long bones for marrow and the resultant product (i.e., bone flakes), 'this scenario is more behaviorally parsimonious than one that involves the transferal of percussive behavior from a context entirely devoid of meat processing, such as nut-cracking' (Gürbüz & Lycett, 2021:9)[4]. The appearance of bone flakes within the context of faunivory narrows the distance between a problem (a need for cutting) and its solution (sharp bone flakes) to a greater extent than any other hypothesis, both in behavioral and cognitive terms. This immediate cooccurrence of both problem and solution within the same behavioral context—especially one involving feeding behavior—effectively represents a variant of learning by stimulus/local enhancement, whereby stimulus, problem, and solution are mutually connected, which would increase the likelihood of the subsequent inception of cutting, and indeed facilitate its replication by other hominins. Yet, Gürbüz and Lycett (2021) do not address the eventual transferal of bone percussive behaviors to stone percussive behaviors. In other words, how would hominins realize that the knapping of certain stone types would result in sharp cutting edges?

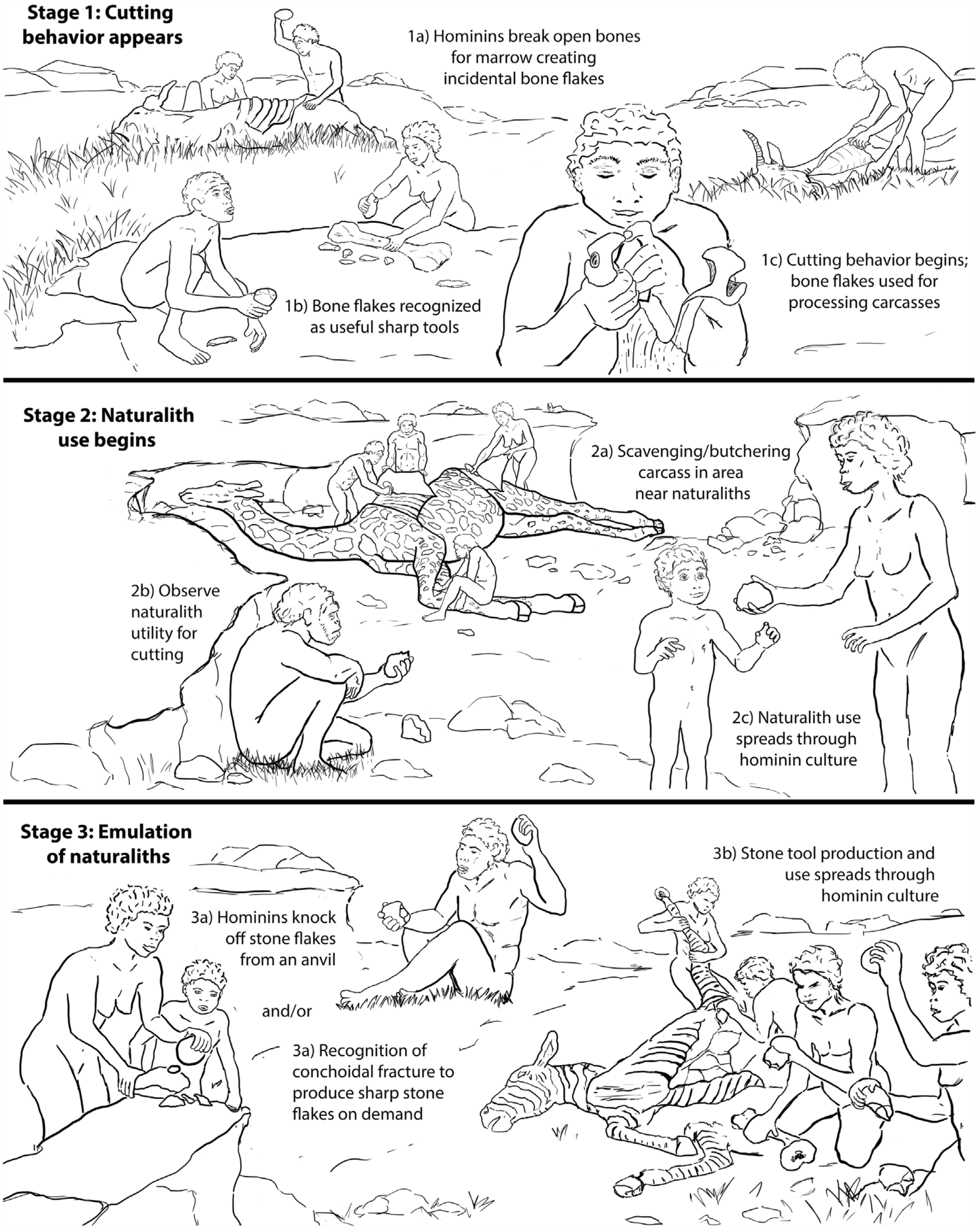

FIGURE 10 A schematic of the origin of knapping. We note that this figure is not meant to imply by what means (e.g., hunting or scavenging), or when (primary or secondary access), hominins processed carcasses. The animals are drawn here for clarity; in reality, exploited carcasses would have been likely been disarticulated and bones scattered. However, on occasion, it is entirely possible that hominins may have had primary access to carcasses. (Illustration by Michelle R. Bebber).

What could potentially further close the inferential or associative gap between using sharp-edged stones to cut and applying percussive behaviors to produce those sharp-edged stones?

We propose that naturaliths could have acted as a crucial link between the use of bone flakes for meat cutting and the eventual emergence of the deliberate production of stone flakes via percussion. Hominins, guided by maximizing efficiency, could initially have been motivated to use incidentally produced bone flakes to complete cutting tasks during animal butchery, especially because, as we have noted, this scenario would be less cognitively demanding in terms of the characteristics involved in deliberate tool making, such as insight, planning, and foresight (Gürbüz & Lycett, 2021:9). During one or more of these animal processing events, a carcass may have been present in the vicinity of naturaliths (Figure 10). The likelihood of this is reinforced by the observation that early hominin food processing sites often occur near naturally occurring sources of stone, particularly in the early archaeological record (reviewed in Plummer & Finestone, 2018). Either intentionally or by accident, a hominin could have picked up and used one of these naturaliths (i.e., a behavioral 'mutation' occurs). It has been noted via butchery experiments that bone flakes potentially produce fewer cutmarks on bones (Gürbüz & Lycett, 2021) and produce shallower cutmarks compared to those made when using stone flakes (Gürbüz & Lycett, 2021; Shipman & Rose, 1988). This suggests stone flakes are sharper than bones flakes, and ultimately more efficient.[5] Naturalith sharpness may have, and likely did, exceed that of bone, which would have provided impetus not only for the initial utilization of naturaliths, but for hominins to seek them out, carry them across the landscape, and socially transmit their use to other hominins. Thus, bone percussive behaviors + naturalith use would have provided two of the necessary ingredients for the conceptual origin of stone knapping.

This is not to say that chimpanzee-like percussive behaviors played no role at all, far from it (Figure 10). After all, the smashing of bones by Oldowan hominins to extract calorific marrow, is likely a direct extension of similar extractive foraging behaviors seen in a range of nonhuman primates, including chimpanzees, macaques, and capuchins (Carvalho et al., 2013; Carvalho & McGrew, 2012; Luncz et al., 2022; Malaivijitnond et al., 2007; Marchant & McGrew, 2005; Wynn & McGrew, 1989). The controlled use of hard, durable materials to transmit kinetic energy to a focused point fulfills a requirement of controlled knapping. Moreover, the existence of a repertoire of percussive behaviors would have provided the final link in the chain for the emergence of stone knapping, with the full sequential steps being: apply percussion to bone + use bone flakes to cut meat + use naturaliths to cut meat and vegetation + apply percussive behaviors to extract sharp stone flakes. This final step could certainly have been aided by the accidental production of stone fragments during stone hammer and anvil use in other contexts of percussion, such as nutcracking (Luncz et al., 2022; Mercader et al., 2007; Proffitt et al., 2016). These sequential steps narrow the 'problem–solution distance' (Haidle, 2010) to the eventual emergence of knapping, but moreover, they also clarify that the initial problem to be solved was cutting, not knapping. Only after the emergence and persistence of cutting behaviors within hominin populations, and then only after the use of naturaliths for those cutting behaviors, would the problem of how to obtain sharp flakes 'on demand' (i.e., the motivation for knapping) emerge.

When framed in this way, the origin of knapping was not a 'Eureka!' moment whereby hominins first made a sharp flake by intention or by accident and then sought something to cut, but instead was an emulative process by hominins aiming to reproduce the sharp tools furnished by mother nature and already in demand (Figure 10). Indeed, the stage-step sequence we are proposing for the evolution of knapping aligns well with Derex's (2022) ideas about cumulative culture exploiting an increased range of natural phenomena, with repeated bouts of inspiration and embellishment. At Step 1, hammer mass (whether of wood or stone) and the tendency of long bones to break in ways that create sharp edges (alongside their immediate contextual association with animal tissue) is being exploited. This inspires the exploitation of naturally occurring sharper and more durable stone flakes. And finally, there is the combination of increased hammerstone mass (and durability) for a given size of hammer over wood, with percussion of rocks that have the natural property of conchoidal fracture, in order to produce flakes with similar sharp edges on demand. The creation of sharp-edged flakes sets the stage for the eventual emergence of tertiary tool use: the use of a tool, to make a tool, that is used to make another tool in order to complete a given task. From a technological perspective, this emphasizes the importance of knapping in the eventual emergence of the potential for 'the open-ended dynamic that characterizes human cumulative culture' (Derex, 2022).

If naturaliths are prevalent on the landscape, what motivations could there be for hominins to produce them via knapping? Although we propose here that naturaliths may be far more frequent and widespread than archaeologists currently understand or acknowledge, we are not suggesting that they are *ubiquitous*. Thus, one potential motivation for knapping would be to readily solve the problem of limited supply and how to acquire sharp stone flakes in contexts where naturaliths were not present. In this case, knapping helped hominins unrestrict their movements from natural sources of flakes to a new broader resource distribution of natural sources of raw material appropriate for knapping. Another motivation for knapping may have to do with the number of hominins engaging with naturaliths and cutting behaviors. If, for example, some naturalith sources only provided a small number of tools relative to the number of hominins who wished to use them, then knapping may have been a solution to provide sharp cutting edges to a greater number of individuals. A third motivation for knapping may be to combat edge degradation. Key et al. (2018) demonstrated that blunting causes rapid reductions in stone tool edge performance. Hominins may have been motivated to solve this problem via the production of freshly knapped edges on demand. Finally, hominins could feasibly have learned over time to recognize that certain naturalith traits—size, mass, edge angle, or raw materials—increased their efficiency during cutting tasks (Jobson, 1986; Key, 2016; Kuhn 2021). As reviewed by Key and Lycett (2017:84–86), nonhuman primates in a range of wild and captive environments have been observed to pay attention to specific tool properties that have functional impacts, including in the case of knapping experiments with Kanzi (*P. paniscus*), where he favored the use of larger stone flakes and tested their sharpness with his tongue (see Schick et al., 1999). Thus, an additional motivation for emulating naturaliths via knapping may have been to improve upon mother nature's invention by producing stone flakes with desired characteristics, rather than spend time and energy searching for naturaliths that possessed them (cf. Derex, 2022). We note that these motivations are not mutually exclusive and could have acted in concert.

CONCLUSIONS AND FUTURE DIRECTIONS

The capacity to generate socially learned, cultural patterns is deeply rooted within our great ape heritage, especially in terms of tool-related behaviors such as knapping (Lycett, 2019; Whiten et al., 2009). The eventual inception of knapping behaviors around 3.3–2.6 million years ago appears to have initiated a biocultural feedback loop between socially learned behaviors, increased faunivory, and the subsequent course of human evolution, including increases in brain size (Gala et al., 2023; Key & Lycett, 2023; Pargeter et al., 2024). When there is no selective pressure to cut, there is no reason to knap flakes, especially given the associated costs of time, learning, energy, and injury risks involved (Gala et al., 2023; Lycett et al., 2015; Lycett & Eren, 2019; Pargeter et al., 2024). We propose that naturaliths—sharp-edged stones shown to be, or considered as potential, tools—may be far more prevalent than paleoanthropologists, archaeologists, and lithic analysts currently understand or acknowledge. Assuming this hypothesis to be true, we propose that the use of naturaliths served as a 'missing link' between already established cutting behaviors with bone flakes and the subsequent origin of stone knapping. Importantly, this takes the bigger problem of knapping invention and turns it into a series of smaller, cumulative steps, none of which by themselves appear to be beyond the capabilities of living chimpanzees. Knapping was not a solution looking for a problem: It was a solution to problems established through the prior existence of cutting behaviors.

Several corollaries extend from these proposals. First, if naturaliths were indeed prevalent, then assertions of their use by hominins (e.g., McPherron et al., 2010) become far more plausible. Second, our hypothesis emphasizes that stone knapping was not a behavior that invented sharp-edged stone tools but instead was a behavior that merely emulated a naturally occurring product already appropriated for cutting tasks. Third, our hypothesis emphasizes that use of sharp stone tools preceded stone knapping, possibly by a substantial amount of time (e.g., hundreds of thousands or even millions of years). Naturaliths could have served as a 'natural laboratory' for figuring out desirable features, which were later deliberately targeted through knapping. Thus, perhaps the reason some early instances of early stone tool knapping at sites like Gona (Ethiopia) appear relatively advanced (Braun et al., 2019; Semaw et al., 1997, 2003; Stout et al., 2005, 2019; Toth et al., 2006) is because hominins, after millennia or more of naturalith use, collectively possessed and socially transmitted information regarding which naturalith morphologies or raw materials optimized cutting tasks. When knapping commenced, hominins targeted these optimal naturalith forms in their knapped flakes. Fourth, Lomekwi 3 (Harmand et al., 2015) may represent an early instance of this emulative process as it gradates into the Oldowan, which means archaeologists should search for naturalith use before 3.3 million years ago. Finally, the use of naturaliths may extend into the Oldowan, and perhaps later; employment of knapping does not necessarily result in a total and immediate abandonment of naturaliths.

Our proposal has several testable implications, exploratory research avenues, and questions that can, and should be, pursued in both the field and the laboratory. First and foremost, naturaliths must be identified via microwear, edge damage, transport, or other means. Additionally, we suggest that paleoanthropologists, archaeologists, and lithic analysts must address the following questions:

- How frequent are naturaliths in different nonhominin and hominin contexts?
- Can conchoidally fractured naturaliths be distinguished from hominin conchoidally fractured rocks? How much morphological and technological overlap exists between these two datasets (Eren et al., 2023)?
- How common are the processes that produce naturaliths?
- How many more natural processes can produce naturaliths beyond those currently identified?
- Were there environmental changes that occurred between six and three million years ago that increased the frequency or occurrence of naturaliths on hominin landscapes?
- How long can naturally sharp flakes keep their edge in given contexts?
- What are the morphologies and relative functional capabilities of bone flakes, naturaliths, and sharp stone flakes in cutting tasks?
- What is the morphological tendency and variability of cut marks produced by bone flakes, naturaliths, and knapped flakes?
- How much cutting edge can be produced via natural processes versus hominin knapping?
- Do captive nonhuman primates (particularly great apes) trained in the use of bone flakes to obtain food rewards readily switch to using naturaliths when these are provided as the only solution?

Addressing such questions can help improve the logical consistency of our argument. However, we feel it important to emphasize that these questions help delineate obtainable answers that merely strengthen informed, parsimonious, but ultimately inferential conjecture. The frequency and functional performance of naturaliths can be examined via modern field observations and controlled experiments; the use of naturaliths by hominins can potentially be tested via assessments of the archaeological record. But naturalith frequency, functionality, and so forth do not prove our proposed scenario is correct, or that our proposal is the only pathway to knapping (e.g., the 'by-product hypothesis,'[6] Luncz et al., 2022, Proffitt et al., 2025; hence our use of the word 'an' in the title of this manuscript). Assessments of naturalith frequency, functionality, and use by hominins can, however, support the inference that naturaliths served as a vital step toward stone tool knapping.

As recently noted by Gala et al. (2023:296–297):

> [a]lthough the inception of knapping itself may not necessarily have required cognitive or behavioral capabilities beyond those possessed by the last common ancestor that humans share with the genus *Pan* (Schick et al., 1999; Wynn & McGrew, 1989), the longer-term biological implications of this behavioral shift in strategies (Aiello & Wheeler, 1995; Key & Lycett, 2023), as well of the technological beginnings of a more 'plastic' world in which virtually all human artifacts are 'cut,' cannot be overstated.

Accordingly, answers to these questions can shed light on the inception of behaviors that ultimately changed the course of human biological, cognitive, technological, and cultural evolution.

AUTHOR CONTRIBUTIONS

Metin I. Eren, Stephen J. Lycett, Michelle R. Bebber, Alastair Key, and Briggs Buchanan conceived the study. Michelle R. Bebber, Briggs Buchanan, Metin I. Eren, Roman Garba, Joe Ortiz, Jeffrey Rose, and David Singer acquired funding that led to this study. Metin I. Eren and Stephen J. Lycett wrote the initial manuscript draft. Metin I. Eren, Michelle R. Bebber, Emma Finestone, Alastair Key, Stephen J. Lycett, and Tomos Proffitt created the figures. All authors read, commented on, and/or provided text and/or edits to the manuscript. All authors approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data available within the article or its supplementary materials.

DECLARATIONS

The authors have no relevant financial or nonfinancial interests to disclose.

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ENDNOTES

[1] We acknowledge that another major goal of 'lithic taphonomy' is to understand how stone flakes, stone tools, or stone edges are altered or broken by postdepositional processes. Given that our interest here involves the natural production of sharp-edged stones that could potentially have been used by hominins, this aspect of lithic taphonomy falls outside the scope of our discussion.

[2] Following Eren et al. (2023), we limited our presentation to these 28 specimens out of an abundance of caution because, unlike some other specimens we observed in the collections, they did not possess recent marks, such as those that could be produced from modern geological hammers.

[3] It is entirely possible that bone flakes may have also been created naturally in some contexts on occasion, for example, if hyenas cracked them with their jaws or if elephants trampled them. Along these lines, the cutting potential of other 'naturally' available items, like wood or teeth, might be considered and experimental tests of these items' sharpness would be informative.

[4] Gürbüz and Lycett (2021) also note that, unlike suggestions regarding the accidental damage of stone anvils used for nutcracking as the inspiration for knapping, the bone flake hypothesis requires no assumptions regarding the material used either for an anvil or hammer (e.g., wooden anvils, or even the ground, alongside wooden hammers/billets would suffice). Moreover, a direct routeway to knapping via stone anvil damage also assumes that the anvils were of a material suitable for conchoidal fracture. The bone flake hypothesis requires no such assumptions.

[5] Notably Kanzi, a bonobo (*P. paniscus*) chimpanzee raised in captivity and the subject of an experiment into the origins of knapping and stone tool use, sought out sharp flakes, testing their sharpness by pressing the edges of flakes against his tongue (Schick et al., 1999). This suggests an ability to recognize relative sharpness and its consequences would likely also have been present in Oldowan hominins.

[6] However, it is worth reiterating that bone flakes would have occurred in the direct context of the carcasses in need of cutting; stone flakes produced incidentally via accidental fracture of hammers and anvils during nut/fruit processing likely would not have (also see endnote #4). And as Gürbüz and Lycett (2021) demonstrated, the transferal of accidentally produced stone flakes to a butchery context would take at least six behavioral steps, whereas the use of bone

flakes in a butchery context requires only three steps. However, we emphasize that 'parsimony' is not necessarily 'correct,' and that the ideas proposed in this paper require testing and evidence.

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