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Rock type variability and impact fracture formation: working towards a more robust macrofracture method

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A B S T R A C T

Investigations into the development of weapon systems are increasingly important in archaeological debates about human evolution and behavioural variability. 'Diagnostic' impact fractures are key, but controversial, lines of evidence commonly used in such investigations. In 2009 a series of experiments was initiated to investigate the processes associated with macrofracture formation specifically focussing on the taphonomic factors affecting the formation of 'diagnostic' impact fractures (DIFs). This paper adds to that experimental data set with macrofracture results from recent knapping experiments investigating rock type variability and DIF formation. These results show that rock type variation plays less of a role in DIF formation than variables related to use and lithic taphonomy. The collective results of this experimental series show that the location, co-occurrence, type and proximity to retouch on a tool are all important means of distinguishing between weapon and non-weapon related DIFs. Collectively these macrofracture patterns are more important in diagnosing weapon components than any one 'diagnostic' impact fracture is alone. Overall, these experimental studies are showing that background 'noise' in the form of non-hunting related impact fractures, exists in many macrofracture results and that much work remains in securing the analytical robusticity of the method. The paper concludes that the macrofracture method is not a stand-alone method, but when used with caution and in conjunction with other lines of evidence it is a useful, time-efficient, tool for generating assemblage-level use-trace data.

1. Introduction

Technological complexity has become a key theme in exploring past human cognition (Wadley, 2010; Lombard and Haidle, 2012). In part this is because the conventional indicators of symbolic complexity (beads, paintings, colouring materials etc.) do not preserve as readily as stones, bones and ceramics in the archaeological record. These items are not used ubiquitously amongst human populations today, or in the recent past, and therefore cannot be used as the sole indicators of complex cognition or technology (Lombard and Parsons, 2011). The use of prehistoric hunting weapons is one element of human technological competency that has received increasing attention over the past decade (e.g. Shea, 2006; Villa and Lenoir, 2006; Pargeter, 2007; Ambrose, 2010; Schoville, 2010; Bradfield, 2012; Brown et al., 2012; Lombard and Haidle, 2012; Robbins et al., 2012; Sano, 2012; Villa et al., 2012; Wilkins et al., 2012). Weapon systems integrate the complimentary principles of multi-functionality, forethought, strategic foraging, working memory and integrated "technological symbiosis" (Lombard and Haidle, 2012: 1; also see Coolidge and Wynn, 2005; Amati and Shallice, 2007 for a discussion of these concepts). Modularized mechanically projected weapon systems, such as the bow and arrow, are amplified examples of these cognitive capabilities that may also have had significant ecological consequences for *Homo sapiens* (Sisk and Shea, 2009; Shea and Sisk, 2010; Lombard and Haidle, 2012).

Understanding when humans began to use weapons in the past, and which weapon systems were employed at specific points in time have become important research questions in archaeology (Shea, 2006; Shea and Sisk, 2010; Lombard and Haidle, 2012; Wilkins et al., 2012). Unfortunately, these are also some of the most difficult questions to answer because of the frequent lack of direct information relating to these weapon systems in the archaeological record. In the absence of direct data, a variety of strands of evidence, amongst them faunal remains, residues, micro

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and macro use-traces, ethnoarchaeological analogies and experimental data have been used to aid our current understanding of the use of various weapon systems in the past. Combining these data has allowed for the creation of multiple lines of evidence to support the hunting function of stone artefacts.

'Diagnostic' impact fractures are key, but controversial and sometimes misinterpreted, lines of evidence commonly used in these investigations (see Section 2 for background information). These fracture types alone cannot be used to determine the hunting function of stone artefacts because of the complicating processes of lithic taphonomy that affect their formation (see Sano, 2009; Pargeter, 2011a). Used in isolation, they are no more or less diagnostic of weapon-use than are residues and other edge damage traces. For this reason, the term *impact fractures* is preferred to *diagnostic impact fractures* when referring to macrofracture types associated with weaponry and will be employed in the remainder of this paper.

The experiment outlined in this paper takes a closer look at impact fracture frequencies and their relationship to rock type variability. A common approach to discussing macrofracture results involves the comparison of impact fracture frequencies between various experimental and archaeological contexts often composed of differing rock types (see Fischer et al., 1984; Lombard and Pargeter, 2008; Wilkins et al., 2012). Variations in these fracture frequencies are generally attributed to differences in site functions, activities or weapon types, but not necessarily rock types (e.g. Villa et al., 2009; Wilkins et al., 2012). Recent efforts to include archaeologically relevant rock types in macrofracture experiments suggest a growing awareness that this is a variable that may also affect impact fracture formation (Pargeter and Bradfield, 2012; Schoville and Brown, 2010; Wilkins et al., 2012). Despite this awareness, the effect(s) that varying rock types may have on the formation of impact fractures is yet to be fully explored in controlled experimental studies. This study uses an experimental framework to assess whether rock type variation and alteration (heat-treating) has any significant bearing on the formation of impact fractures, and whether the same macrofracture criteria for assessing the hunting function of stone artefacts can be applied on a variety of rock types irrespective of their structural differences. These questions were assessed through a series of direct hard hammer percussion knapping experiments on six different rock types (obsidian, heat-treated and un heat-treated silcrete, dolerite, quartzite and milky quartz) commonly found in the African archaeological record. Knapping is a controlled mechanical process through which aspects of impact fracture formation can be monitored and assessed (Cotterell and Kamminga, 1987; Sano, 2009). It is for this reason, and to explore a previously under-investigated means of impact fracture formation on African rock types, that knapping was chosen as a means of fracture formation in this experiment.

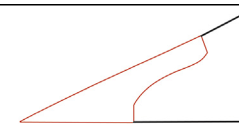
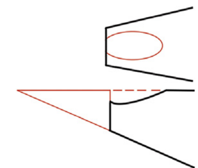
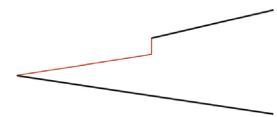
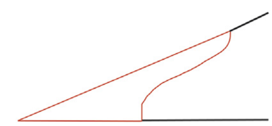
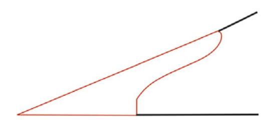
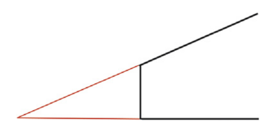
2. Background to the experimental study and the formation of impact fractures

The macrofracture method for identifying artefacts damaged through longitudinal (head-on) impact is a method that, because it operates on a macro-level, can be used to analyze large and probabilistic samples for direct evidence of weapon-related activities (Fischer et al., 1984; Lombard, 2005; Sano, 2009; Pargeter, 2011a). This method works with principles derived from studies in fracture mechanics and material sciences, which provide a means of distinguishing fractures resulting from weapon-use from fractures created by other processes (e.g. Cotterell and Kamminga, 1979, 1987; Hayden and Kamminga, 1979; Lawrence, 1979). The macrofracture method works under the assumption that a set of diagnostic macrofracture types exist that are formed through bending and cone initiating impact forces commonly, but not exclusively, associated with weapon use (Tringham et al., 1974; Fischer et al., 1984; Lombard, 2005; Sano, 2009; Yaroshevich et al., 2010; Pargeter, 2011a; Table 1).

Impact fractures, or 'diagnostic' impact fractures, are macrofractures that have been shown, through experiments and archaeological analyses, to be associated with stone artefacts used as weapon tips (e.g. Pargeter, 2007; Lombard and Pargeter, 2008). These fractures are considered to be one of the three most important lines of evidence to show that an artefact functioned as a weapon component (Villa and Lenoir, 2006). The assumption is that these fractures are caused by impact during use (e.g. hunting), and that different variations of this use will leave different breakage patterns and frequencies of impact fractures on the tools (Dockall, 1997; Lombard et al., 2004; Lombard and Pargeter, 2008; Yaroshevich et al., 2010; Wilkins et al., 2012). There are usually understood to be four main impact fracture breakage types: step terminating bending fractures; spin-off fractures >6 mm (on large points); bifacial spin-off fractures and impact burinations (for more detail on these fracture types see Fischer et al., 1984; Lombard, 2005; Table 1). However, variations in how the method is applied and what fracture types are considered diagnostic of weapon impact do exist (see Sano, 2009). Step terminating bending fractures, spin-off fractures and impact burinations are often referred to as the primary impact fracture types to identify the potential use of stone and bone-tipped weaponry (Lombard, 2005; Lombard and Pargeter, 2008; Villa et al., 2009; Bradfield, 2012; Bradfield and Brand, 2013). However, the results of recent trampling studies have shown that step terminating bending fractures do occur on replicated tools and therefore should either be used with caution, or not at all, when employing this method (Sano, 2009; Pargeter, 2011a; Iovita et al., 2013). Impact burinations are defined as intentional burins with no negative bulbs of percussion or knapping scars on their proximal ends (Lombard, 2005; Table 1). Notably absent from these definitions are descriptions of impact burination termination types. Based on their similarity to intentional burins they can presumably terminate in step, feather or hinge formations (Noone, 1934; Inizan et al., 1999; Rots et al., 2011). In this, and previous studies in this series, it has been noted that these fractures show a greater tendency towards step and feather termination types. Snap, feather and hinge terminating fractures and tip crushing are recorded during macrofracture analyses to describe the complete range of damage seen on a tool. Such damage has been recorded in relatively high frequencies from a variety of other activities (such as human and cattle trampling and knapping) and should not be used alone as potential indicators of weapon impact (Villa et al., 2009; Pargeter and Bradfield, 2012).

The macrofracture method has global applicability and has been used in investigations into the origins of bow and arrow technology (Lombard, 2011; Bradfield, 2012, 2013); Later Stone Age subsistence and risk management strategies in South Africa (Lombard and Parsons, 2008; Bradfield, 2012); and the role of hunting technologies in the evolution of the genus *Homo* (Wilkins et al., 2012). Outside of Africa the method has been tested and applied at various known archaeological bison kill and residential sites in North America (e.g. Frison, 1974) and at numerous other archaeological contexts (Barton and Bergman, 1982; Bergman and Newcomer, 1983; Odell and Cowan, 1986; Friis-Hansen, 1990; Sano et al., 2011). Macrofracture analysis has advantages over other use-trace analyses in that it is time efficient and the fractures are discrete quantifiable phenomena unlike micro-polishes, for example, that are more difficult to quantify (see Shea, 1992; Lombard, 2011). In certain micro-scale functional analyses (see Hutchings, 2011; Sahle et al., 2013), macrofractures play an important role in determining which micro-features are related to hunting and can therefore

Table 1
Summary data on the four main impact fracture (IF) types (step terminating bending fractures, unifacial spin-off fractures >6 mm, bifacial spin-off fractures and impact burinations). Summary data on three commonly recorded, non-'diagnostic', impact fractures (feather and hinge terminating bending fractures and snap fractures) are also presented. Illustrations of these fracture types are adopted from Fischer et al. (1984) and data derived from Lombard (2005) and Pargeter (2011a,b).

Fracture	Description	Illustration
Step terminating bending fracture (IF)	A bending fracture terminating in a 90° step.	
Spin-off fracture (bi and unifacial) (IF's)	A secondary fracture type originating from bending fractures such as step terminating or snap fractures. Spin-off fractures tend to have a feather-like termination and are concave in profile. These can be bifacial or unifacial. Only unifacial spin-off fractures >6 mm are considered in final impact fracture counts in this analysis.	
Impact burination (IF)	A bending fracture resembling a burin spall terminating in either a 90° step, feather or hinge on the lateral side(s) of a tool. These are distinguished from intentional burination by a lack of negative bulbs of percussion and crushing near the proximal ends.	
Feather terminating bending fracture	A bending fracture terminating in an acute angle or in a curve less than 90°.	
Hinge terminating bending fracture	A bending fracture terminating in an upturned curve or lip.	
Snap fracture	A bending fracture in which the bending forces act to snap the tool in a clean break.	

affect their interpretation. In these cases, macrofracture analysis provides a useful pre-sorting tool that can increase the interpretive strength of these particular analyses. Such factors have made the macrofracture method particularly attractive for the analysis of large and probabilistically sampled assemblages and as a relatively simple addition to other more time and skill intensive use-trace analyses.

Since its inception, the macrofracture method has been continuously fine-tuned and tested in focused experiments some of which reflect a growing awareness of the role of taphonomic factors in the formation of impact fractures (Fischer et al., 1984; Sano, 2009; Yaroshevich et al., 2010). Continuing from these investigations, an experimental program was recently initiated to investigate the role of post-depositional trampling in the formation of macrofractures on stone flakes made from local southern African rock types (Pargeter, 2011a,b). Results of these experiments show that macrofractures (snap fractures, hinge and feather terminating fractures and edge crushing) occur frequently when cattle and humans trample stone tools. Impact fractures (step terminating bending fractures, spin-off fractures and impact burinations) also occur occasionally on trampled flakes, but their frequencies on the experimental tools rarely exceed 3% of an entire experimental assemblage (Pargeter and Bradfield, 2012). Lastly, when impact fractures occur as a result of trampling, they are likely the product of bending forces similar to those produced during hunting (also see Sano, 2009). These results provide evidence to suggest that it is not only a particular set of fracture types, i.e. impact fractures, which are diagnostic of hunting weaponry, but also their patterning, placement and frequencies on tools. Overall, these experimental studies are showing that background 'noise' in the form of non-hunting related impact fractures, exists in many macrofracture results and that much work remains in securing the analytical robusticity of the method. In particular, questions remain as to the range of processes associated with impact fracture formation, the role of variation in, for example, rock type in impact fracture formation and the exact ramifications of these experimental results for the interpretation of macrofracture patterns on archaeological assemblages.

3. Experimental protocols

Most stone artefacts are knapped and modified by controlled fracture propagation and the associated impact forces (Shea, 2013; Sano, 2009). It is therefore particularly important to understand the role of stone knapping in the formation of impact fractures, and how these fracture patterns might differ from those commonly associated with weapon-use (Sano, 2009). An assumption of the macrofracture method is that impact fracture formation is independent of raw material variation and that fracture frequencies across raw material types are therefore comparable (Lombard et al., 2004; Lombard and Pargeter, 2008; Wilkins et al., 2012). In order to investigate these two questions in more detail, a series of knapping

Table 2
Summary data on the six rock types examined in this experiment. Moh's hardness values for dolerite and milky quartz are from Wadley and Mohapi (2008), but were also verified in Moh's hardness tests done by the author. The author derived the Moh's values for the remaining rock types. Note that these rock types will vary in their natural states and that these Moh's values are applicable only to the varieties tested in this experiment.

Rock type	Description	Grain quality	Moh value	Reference
Obsidian	Chemically variable isotropic natural glass. Obsidian is high in silica content and is formed through intense heating during volcanic processes.	Extremely fine-grained	5–5.5	Tykot, 2002
Dolerite	A variable, isotropic, crystalline igneous rock consisting of plagioclase feldspar and a pyroxene, but deficient in silica. Occurs in the form of sheets, dykes and intrusions.	Coarse-grained	5–6.5	Kleyn and Bergh, 2008; Wadley and Kempson, 2011
Un heat-treated silcrete	Indurated silification products composed of variable quantities of quartz grains embedded in a microcrystalline silica matrix. Less workable in un heat-treated forms.	Medium to coarse-grained	5.5	Brown et al., 2009
Heat-treated silcrete	Indurated silification products composed of variable quantities of quartz grains embedded in a microcrystalline silica matrix. The fabric of silcrete is controlled by its parent geology. Heat-treatment increases rebound hardness, Young's Modulus values and the flakeability of silcrete.	Fine-grained	6	Brown et al., 2009
Quartzite	A highly variable, hard, quartz-rich rock that fractures irregularly forming both irregular and conchoidal fracture surfaces.	Coarse-grained	6.5–7	Howard, 2005
Milky quartz	A silicon dioxide (SiO_2) component of many igneous, sedimentary, and metamorphic rocks. Macrocrystalline forms include vein quartz or milky quartzes. While exhibiting micro-scale conchoidal fracture, macrocrystalline quartzes are generally anisotropic.	Medium to coarse-grained	7	Driskoll, 2010, 2011

experiments were conducted with the aim of identifying production-related impact fractures on a variety of African rock types (Table 2). In this work it was hypothesized that knapping could produce similar impact forces as trampling and that these would be lower than those associated with weapon-use (see Pargeter, 2011a). Knapping is likely to cause impact fracture formation because the bending compressive forces associated with the formation of certain impact fractures are common when stone flakes are 'peeled' away from their cores during knapping (Cotterell et al., 1985; Sollberger, 1986; Cotterell and Kamminga, 1987; see Sano, 2009).

In order to investigate the effect of knapping on impact fracture formation, macrofracture analyses were conducted on knapping debris from six different rock types (heat-treated and un-heated silcrete, dolerite, quartzite, milky quartz and obsidian) (Table 2). Wadley and Kempson (2011) identify rock hardness, roughness, and impact toughness as key variables for understanding a rock's suitability for knapping. Rock hardness, as measured by the Moh's scale and roughness, as related to grain texture, were used in this study as ways of comparing the six rock types (Table 2). All of the rock types used in this experiment have received recent attention for their role in early hunting technologies in Africa (Lombard and Pargeter, 2008; Brown et al., 2009; Lombard, 2011; Sahle et al., 2013). However, very little experimental work has been done on dolerite, quartz and quartzite in a southern African context despite their prominent role in the archaeology of the region (see Wurz, 1999; Mitchell, 2000; Mackay, 2006; Soriano et al., 2007; Wadley and Mohapi, 2008; Thompson et al., 2010; Henshilwood, 2012).

Although obsidian is not a southern African rock type, it was added to this experiment for two reasons. First, obsidian was widely used elsewhere in East Africa for tool manufacture (e.g. Leakey, 1936). These results are, therefore, broadly applicable outside of the southern African region. In addition, including obsidian in the experiments enabled a comparison of the macrofracture patterns on this extremely fine-grained rock type to coarser-grained local southern African rock types, such as dolerite and quartzite, and finer-grained types, such as heat-treated silcrete. The silcrete used in the experiments was heat-treated by Kyle Brown following protocols outlined in Brown et al. (2009). Observations of both heated and un-heated silcrete, by the author, suggested a change in grain quality occurs after heat-treating, with heat-treated silcrete showing a markedly more homogenous and fine-grained matrix (Fig. 1). Heat-treated and un heat-treated rocks are therefore grouped separately with fine and medium–coarse grained rocks respectively in this experiment (Table 2). Rocks belonging to these different grain-size categories were expected to show significant differences in impact fracture frequencies, with fine-grained rocks expected to show higher impact fracture frequencies than coarse-grained rocks owing to their more homogenous matrices.

Fig. 1. Comparison of un heat-treated silcrete (left) to heat-treated silcrete (right) emphasizing the change in texture and grain quality between the two.

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The cores used in these experiments were all 2–3 kg polygonal nodules and were knapped by the author using a direct hammer percussion technique with a sandstone cobble. Only a single reduction technique was employed in this experiment and no retouch was applied to the debris prior to the analysis, as rock type was a more important variable in this test. The potential for variation in knapping strategies to affect impact formation on African rock types will be the focus of future experiments. One core was knapped per raw material type until it was no longer useable. A core was considered exhausted when multiple obstacles developed, e.g. step fractures, or when the core was too small for in-hand percussion, which was generally around 5 cm in length. Ad hoc flake production, with no platform preparation or preferred flaking orientation, was employed on all the raw materials so as to avoid the influence of particular reduction strategies on the quantity and type of debris. A random grab sample was collected from the resulting knapping debris (>1 cm) and then analysed for macrofractures (sample sizes are given in Table 3). An estimate count was made of the total debris from each nodule, which showed that the grab samples ranged between c. 20 and 30% of the total knapping debris produced (see Table 1 for estimated total sample sizes).

4. Results of the knapping experiments

Impact fractures were noted on the un-retouched knapped flakes, but these occurred in relatively low frequencies. On average between 1% and 6% of the recorded macrofractures could be considered 'diagnostic' of hunting. Step terminating bending fractures and impact burinations were the most commonly occurring impact fracture types across all the rock types (Table 3, Fig. 2A1). Unifacial and bifacial spin-off fractures were the least common impact fracture types a result that is in accordance with previous macrofracture studies in this series and those obtained by other researchers (e.g. Sano, 2009). Hinge/feather terminating bending fractures and snap fractures were the most commonly noted non-'diagnostic' macrofracture types on the knapping debris.

Very few of these fractures were noted on the ventral sides of the debris (where it was possible to determine this) and far fewer co-occurring impact fractures were noted as opposed to previous hunting experiments (Table 3 and Fig. 2B2 and D2; also see Yaroshevich et al., 2010; Bradfield and Lombard, 2011). Step terminating bending fractures were the only impact fractures noted on the ventral sides of these knapping debris, while the backed tools used the Lombard and Pargeter (2008) hunting experiments showed a much wider variety of ventrally located impact fracture and a much higher co-occurrence of impact fractures (Table 3). This result suggests that a clear distinction in the patterning and types of ventrally located and co-occurring impact fractures can be discerned for knapping in comparison with hunting. There does not, however, appear to be a clear correlation between rock type and the formation of ventral impact fractures, with only un heat-treated silcrete and quartzite not showing these fractures.

Smooth, un-retouched, semi-circular notches ranging between 1 and 5 mm were noted on 10.5% of the obsidian and 5.8% of the heated silcrete pieces. Notches have been observed on backed artefacts that were probably used as weapon inserts during the African late Pleistocene Middle Stone Age, and sometimes they are intentionally retouched in a similar fashion to the 'complex' Middle Paleolithic notches described on, for example, artefacts from the Combe Grenal Middle Paleolithic site (Singer and Wymer, 1982; Hiscock and Clarkson, 2007). Some of the archaeological notches from the Howieson's Poort levels (c. 59–64 ka) at Sibudu Cave and Umhlatuzana Middle Stone Age sites in South Africa, however, also have smooth (un-retouched), semi-circular notches similar to those documented on a transversely hafted segment used as a hunting weapon tip in previous hunting experiments (Pargeter, 2007; Lombard and Pargeter, 2008; Fig. 2C2). Associated fat, bone and collagen residues found on some of these smooth archaeological notches suggest that in certain instances they may have been associated with hunting activities (Lombard and Pargeter, 2008). However, the frequent occurrence of smooth edge notches on knapping debris suggests that un-retouched notches are not reliable indicators of hunting impacts only (see Villa et al., 2012). This conclusion is supported by the work of Hiscock and Clarkson (2007) that showed simple, un-retouched notches were more common on flakes with very little retouch that are in some ways similar to the un-retouched knapping debris in this analysis. Retouched edges are tougher than un-retouched tool edges and are therefore less likely to show these kinds of simple, smooth-edged notches. In this experiment it is not at present clear whether these notches formed during the knapping or as a result of debris hitting the floor, and therefore whether they are related to specific knapping techniques.

Variations in rock and fracture types aside, the impact fractures recorded on experimental hunting weapons in the Lombard and Pargeter (2008) analysis are far higher than the knapping impact fracture frequencies in this study (Table 3; Fig. 3). When impact fractures occurring on only ventral surfaces or in clusters are considered alone, this distinction grows even further (Table 3). Odds ratio values, reflecting the comparative effect size and odds of impact fractures forming between the different rock types (see Pearson, 2011), indicate that impact fractures are between 10 and 54 times more likely to occur as a result of hunting than knapping

Table 3
Detailed macrofracture results from knapping experiments compared to Lombard and Pargeter (2008) hunting macrofracture results. Rows in bold type refer to impact fracture (IF) statistics. Note that more than one fracture can occur on a tool. Data on impact fractures occurring on the ventral sides of tools is given under the "*v*" column, columns without a "*v*" did not contain ventral impact fractures.

	Obsidian			Heated silcrete			Un-heated silcrete		Milky quartz			Dolerite			Quartzite		Knapping total		Hunting		
	$n = 267/1400$			$n = 240/1000$			$n = 50/350$		$n = 122/450$			$n = 122/400$			$n = 83/300$		$n = 844$		$n = 30$		
	n	%	*v*	*n*	%	*v*	*n*	%	*n*	%	*v*	*n*	%	*v*	*n*	%	*n*	%	*n*	%	*v*
Step terminating	12	4.5	1	6	2.5	2	1	2	1	0.8	1	1	0.8	1	0	0.0	21.0	2.5	1	3.3	6
BF spin-off	0	0.0	0	0	0.0	0	0	0	0	0.0	0	0	0.0	0	0	0.0	0.0	0.0	0	0	0
UF spin-off >6 mm	1	0.4	0	0	0.0	0	0	0	0	0.0	0	0	0.0	0	0	0.0	1.0	0.1	3	10	3
UF spin-off <6 mm	0	0.0	0	1	0.4	0	0	0	0	0.0	0	1	0.8	0	0	0.0	2.0	0.2	0	0	0
Impact burination	8	3.0	0	0	0.0	0	0	0	1	0.8	0	1	0.8	0	1	1.2	11.0	1.3	8	26.7	2
Hinge/feather term.	0	0.0	0	1	0.4	0	0	0	11	9.0	0	10	8.2	0	9	10.8	31.0	3.7	3	10	0
Notch	28	10.5	0	14	5.8	0	0	0	0	0.0	0	0	0.0	0	0	0.0	42.0	5.0	9	30	0
Snap	47	17.6	0	1	0.4	0	0	0	32	26.2	0	23	18.9	0	29	34.9	132.0	15.6	6	20	0
Tools with IFs	**16**	**6.0**	**0**	**6**	**2.5**	**0**	**1**	**2**	**2**	**1.6**	**0**	**3**	**2.5**	**0**	**1**	**1.2**	**29.0**	**3.4**	**12**	**40**	**0**
Tools with ventral IFs	**1**	**0.4**	**1**	**2**	**0.8**	**2**	**0**	**0**	**1**	**0.8**	**1**	**1**	**0.8**	**1**	**0**	**0.0**	**5.0**	**0.6**	**9**	**30**	**9**
Tools with multiple IFs	**1**	**0.4**	**0**	**4**	**1.7**	**0**	**0**	**0**	**0**	**0.0**	**0**	**0**	**0.0**	**0**	**0**	**0.0**	**5.0**	**0.6**	**9**	**30**	**0**

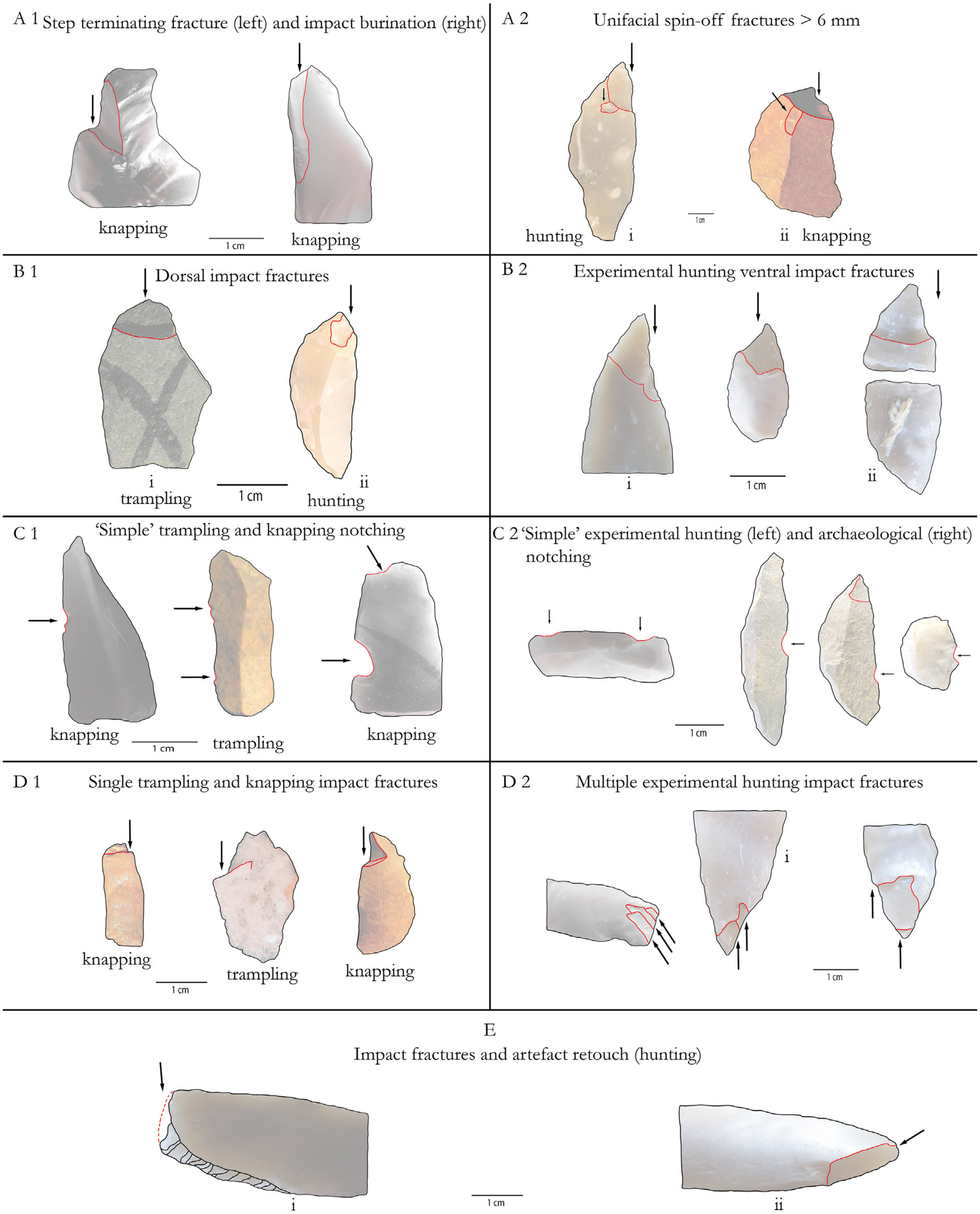

Fig. 2. Impact fractures (marked by red outlines) from trampling, knapping and experimental hunting (right hand column and B1ii). A2i: Spin-off fracture >6 mm, A2ii: Unifacial spin-off fracture >6 mm B1i: Step terminating bending fracture, B1ii: Step terminating bending fracture. B2: All are step terminating bending fractures. C1: Trampling and knapping notches. C2: Archaeological notches are from Sibudu Cave and Umhlatuzana Cave Howieson's Poort assemblages and are courtesy of Marlize Lombard. D1: All impact fractures are step terminating fractures; D2: All are step terminating fractures except for i) which are unifacial spin-off fractures. E: Impact fractures having removed part of a retouched edge, Ei: Transverse bending fracture, Eii: Step terminating fractures. Trampling impact fracture figures are from Pargeter (2011a,b); experimental hunting figures are from Pargeter (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Table 4). This is to be expected and is in agreement with the results of previous trampling macrofracture studies, which showed a significantly lower impact fracture rate resulting from experimental trampling than hunting (Sano, 2009; Pargeter, 2011a). Not all the knapping debris would have come into direct contact with the impact forces of a hammer stone and this fracturing is also the product of various other subsidiary forces experienced during the conchoidal fracturing of stone. These subsidiary forces are also

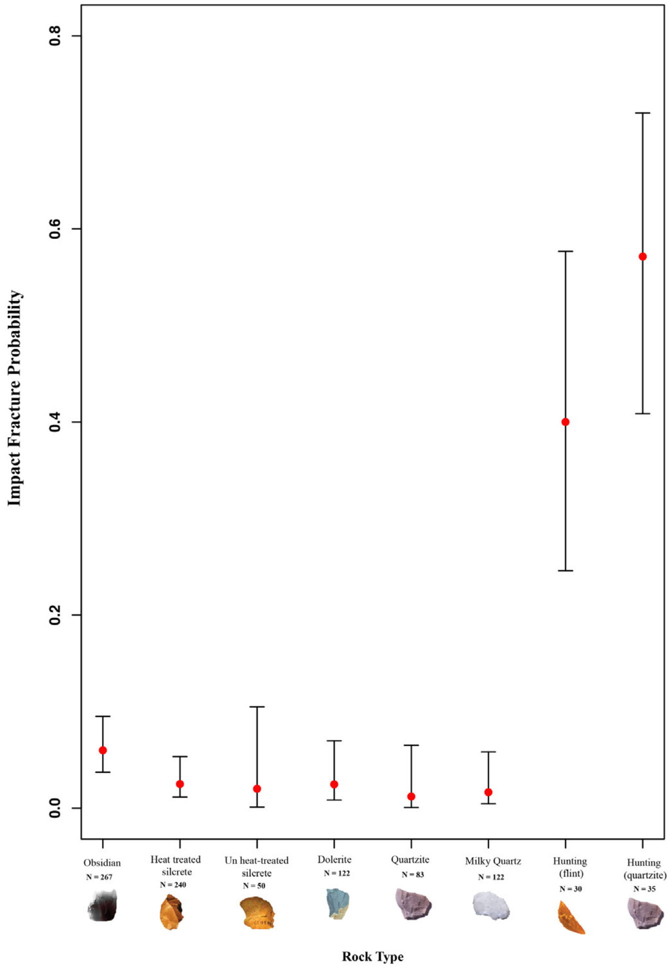

Fig. 3. Visual representations of the impact fracture results (knapping and hunting) with mean probability values indicated by red dots and 95% confidence intervals indicated by black bars. Data for the flint hunting sample is from Lombard and Pargeter (2008) and for the quartzite hunting sample from Lombard, et al. (2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

likely to be responsible for some of the numerous snap fractures and edge crushing seen on the knapping debris.

When the macrofracture results are analysed according to rock type we see that 5 of the 6 rock types showed impact fracture frequencies below the 3% experimental trampling impact fracture mean derived from the Pargeter (2011a,b) and Pargeter and Bradfield (2012) tramping experiments. Flakes used in these experiments were made from all the rock types used in these trampling experiments, except obsidian, and were selected for trampling after knapping macrofracture analysis was conducted on them. These results are therefore broadly applicable to one another.

Significance tests on these fracture data were calculated using standard contingency tables and the Fisher's Exact Test to compare impact fracture frequency distributions for the different rock types ($p[F]$ values). These results are compared with an adjusted alpha level of 0.001 corrected using the Dunn–Sidak method to account for Type I errors that occur in null hypothesis significance testing through multiple comparisons (Quinn and Keough, 2002: 50; Table 5). None of the rock types sampled showed a statistically significant difference in mean impact fracture frequencies. However, the range of impact fracture probabilities at the 95% confidence interval is more consistent for milky quartz, quartzite, dolerite and heat-treated silcrete than for un heat-treated silcrete or obsidian (Fig. 3). In comparison to un heat-treated silcrete, obsidian has a higher mean impact fracture frequency and unique structural qualities making it an outlier in relation to the other rock types (also see Brown et al., 2012). This difference in means is, however, not statistically significant even though impact fractures are between 2.49 and 5.23 times more likely to form on obsidian than any other rock type in this experiment (Tables 4 and 5). The discrepancy between these two observations concerning obsidian is likely to stem from the fact that we are comparing the frequencies of similarly extreme and unlikely events that can be affected by differences in sample sizes (Table 5). In such cases odds ratios provide a more accurate means of comparing these samples (Sánchez-Meca et al., 2003). Flint backed tools used for hunting are at least two times as likely to incur impact fractures similar to obsidian (odds ratio = 10.46) than any of the other rock types (odds ratios = 26–56.47) (Table 4). In general, these results suggest that how a tool was used or altered through taphonomic processes has a greater impact on impact fracture frequencies than does rock type variability. This point is illustrated in Fig. 3 where impact fracture means with 95% confidence intervals from two previous hunting experiments using flint and quartzite are plotted against these knapping experiments. Data for the quartzite hunting sample used here derives from the Lombard et al. (2004: Table 4) spear experiments. The two hunting sets are more alike and are significantly different from the knapping samples ($p < 0.001$), which themselves form a collective population. In spite of this clear distinction, it must be kept in mind that the grain size and texture of a rock can effect the detection of impact fractures making impact fractures on, for example, obsidian easier to diagnose and therefore also potentially less ambiguous.

At the outset of these experiments, it was expected that the strongest association in impact fracture patterning would occur between the finest-grained rock types in the experiment, obsidian and heat-treated silcrete. This expectation was not clearly seen in the overall sample statistics for these two rock types, with both

Table 4
Odds values, reflecting the comparative odds of impact fractures forming between the different rock types (see Pearson, 2011), calculated to show the odds of impact fractures forming across the different rock types and an experimental hunting sample. Hunting values are from the Lombard and Pargeter (2008) analysis. Obs: Obsidian; Hts: Heat-treated silcrete; Uhts: Un heat-treated silcrete; Dol: Dolerite; Qtz: Quartzite; Mq: Milky quartz.

	Obs	Hts	Uhts	Dol	Qtz	Mq	Hunt
Obs		0.40	0.32	0.40	0.19	0.26	10.46
Hts	2.49		0.80	0.98	0.48	0.65	26.00
Uhts	3.12	1.26		1.24	0.60	0.82	32.67
Dol	2.53	1.02	0.81		0.48	0.66	26.44
Qtz	5.23	2.10	1.67	2.07		1.37	54.67
Mq	3.82	1.54	1.22	1.51	0.73		40.00
Hunt	0.10	0.04	0.03	0.04	0.02	0.03	

Table 5
Probability values from significance tests on the impact fracture results outlined in Table 3. These are calculated using the Fisher's Exact Test to compare impact fracture frequency distributions ($p[F]$ values). The results are compared using an alpha level of 0.001 adjusted using the Dunn–Sidak method to account for increased Type I errors that occur in null hypothesis significance testing through multiple comparisons (Quinn and Keough, 2002: 50).

	Obs	Hts	Uhts	Dol	Qtz	Mq
Obs						
Hts	0.08					
Uhts	0.49	1.00				
Dol	0.20	1.00	1.00			
Qtz	0.09	0.68	1.00	0.65		
Mq	0.07	0.72	1.00	1.00	1.00	

samples showing mean fracture probabilities not statistically different to the coarser grained rock types Fig. 3. This result suggests that the grain of a rock type (coarse vs. fine) cannot be used to predict its impact fracture frequencies. A further expectation at the outset of these experiments was that heat-treating silcrete would significantly enhance its fracturability and therefore increase its impact fracture frequencies. In light of the tests for statistical significance in Table 5 the hypothesis of heat-treated and un heat-treated silcrete having equal impact fracture frequencies cannot be rejected. In addition, impact fractures are only 1.26 times more likely to form on heat-treated as opposed to un heat-treated silcrete, showing that the overall odds of an impact fracture forming on either of these rock types is relatively similar (Table 4). The data in Fig. 3 do, however, indicate that heat-treating silcrete reduces the amount of variability in the distribution of impact fractures. These differences may be a product of the relatively small sample size for un heat-treated silcrete in this experiment and will need to be verified with larger sample sizes in future experiments. Based on this limited data, thermally altering silcrete appears to create not only a more knappable rock, but also one that accrues impact fractures more predictably.

The Mohs values for these 6 rock types (Table 2) compared to the impact fracture probabilities in Fig. 3 indicate, as expected, that there is some correlation between the hardness of a rock and its mean impact fracture probability under knapping conditions. However, when the sample variances are taken into account we can see that this difference is not statistically significant (Fig. 3). Nor does this association hold when we compare the quartzite used in this experiment to that used in the Lombard et al. (2004) spear experiments (Fig. 3). Mohs hardness values can vary within a single rock sample depending on where the test is performed. When considered together with the significance test results for the various rock types in Table 5 it is clear that Mohs values alone are also, therefore, not reliable indicators of the uniform hardness of a rock type (see Lerner et al., 2007). From these results it appears that the brittleness of a rock edge (obsidian and heat-treated silcrete having more brittle edges than either dolerite or quartzite) might be a useful indicator of potential fracture rates in addition to rock hardness values, but that again these are less important variables than the context of use or alteration.

5. Discussion

The experimental results outlined above have noteworthy methodological implications for the role of the macrofracture analysis and how and why we employ this method. It has been suggested that analysts cannot reliably determine whether individual fracture scars were created through use or taphonomic processes (see Bird et al., 2007). However, the results of this work suggest that ambiguous impact fractures can be eliminated from analyses by recording not only impact fracture types, but also their patterns, locations on the tool and relationship to artefact retouch (as is discussed below). The key concern here is to establish criteria for when one can confidently speak of tools as weapon components, while taking into account the various aspects of lithic taphonomy.

Based on these and previous hunting and non-hunting macrofracture experiments it appears as if certain impact fracture types are more likely to occur as a result of taphonomic and tool manufacturing processes. The trampling and knapping studies have shown consistently higher frequencies of step terminating (2.49% of knapping impact fractures) and impact burination bending fractures (1.25% of knapping impact fractures) than bifacial and unifacial spin-off fractures (0.11% of knapping impact fractures and 0% of trampled pieces). In contrast, spin-off fractures >6 mm were noted on 3 (10%) of the backed artefacts from the Pargeter (2007) hunting experiments (Lombard and Pargeter, 2008; also see Bradfield, 2012; Yaroshevich et al., 2010, for recent hunting examples). These fracture types have also been recorded in relatively high frequencies in other hunting experiments (e.g. Fischer et al., 1984; e.g. Odell and Cowan, 1986; Lombard et al., 2004), suggesting they are more reliable indicators of tools being used as weapon components than step terminating bending fractures and impact burinations. Recently Iovita et al., 2013 called for step terminating bending fractures to be discarded as a diagnostic fracture type. While this call makes sense in light of their experiments and the results presented here, we need to recall that in many of the hunting experiments conduced thus far, step terminating bending fractures have been some of the most commonly occurring fracture types (Fischer et al., 1984; Lombard et al., 2004; Lombard and Pargeter, 2008; Bradfield, 2012). Using the step terminating bending fracture frequencies outlined in this series of experiments it may be possible to distinguish taphonomic from weapon-related step fracturing. From this perspective, assemblages characterized by very high frequencies of this fracture type (significantly above 3%) are unlikely to represent only trampling and knapping activities. The place of step terminating bending fractures in the category of 'impact fractures', while ambiguous, is therefore far from being clear enough to call for their retirement.

The results also necessitate a brief comment about the distinction between unifacial spin-off fractures less or greater than 6 mm. A metric marker of 6 mm was originally designated to distinguish between spin-off fractures resulting from trampling (<6 mm) and hunting (>6 mm) (see Lombard, 2005; cf. Fischer et al., 1984). The results presented here show that large spin-off fractures (>6 mm) do form, albeit infrequently, as a result of knapping, but not trampling, and are not solely associated with hunting impacts (also see Sano, 2009). The frequency of this particular fracture type, however, is very low in comparison with all of the other impact fracture types in these experiments. Therefore, in order to continue to tighten the application of the macrofracture method, the distinction should still be retained because it does at least separate trampling (post-depositional) from knapping and hunting (pre-depositional) spin-off fractures.

The location of impact fractures on tools is a possible distinguishing factor between taphonomic and weapon-related impact fractures (see Sano, 2009; Villa et al., 2010; Pargeter and Bradfield, 2012). Non-hunting impact fractures are more likely to be associated with proximal ends and dorsal surfaces of tools as opposed to the ventral and distal portions of tools used as weapon inserts. Ventrally located impact fractures were noted on only 5 pieces (0.6%) of knapping debris (Table 3; Fig. 2B2), suggesting that fracture location can be used to reduce the margin of error in macrofracture results. Using just this criterion alone to distinguish hunting from taphonomic related impact fracturing could have resulted in an 82% reduction of production-related impact fractures. Another aspect of fracture location is determining whether an impact fracture occurred before or after the retouching of a tool. This is a useful means of eliminating knapping as an agent of impact fracture formation. Theoretically, secondary tool retouch would occur before impact fracturing as a result of weapon-use and can therefore be used as a chronological marker of impact fracture formation (Fig. 2E). However, not all artefacts are retouched and many have complicated taphonomic and life histories. Because of this we are still left with the possibility that ambiguous impact fractures may form on trampled, un-retouched, tools or of impact fractures being removed by the repairing and maintenance of tools. These latter removals could be distinguished by the absence of knapping scars, for example negative bulbs of percussion, eraillure scars, striking platforms and ripple marks in association with impact fractures (also see Lombard and Pargeter, 2008). Future experiments will be designed to address this question.

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Recent hunting and non-hunting macrofracture studies have shown that tools with more than one impact fracture are more likely to occur in hunting scenarios than in non-hunting situations, where they tend to occur as isolated occurrences (Table 3; Fig. 2D2). Various configurations of impact fracture types were noted on 9 (30%) of the backed tools from the Pargeter (2007) hunting experiments, but on only 5 pieces (0.6%) of knapping debris. This is likely a result of the combination of bending and cone initiating forces experienced more often during weapon impacts and because of the repeated use of weapon tips that remain undamaged after initial impacts. As with impact fracture location, the co-occurrence of impact fractures can be used to dramatically reduce the number of taphonomically related fractures in an analysis. While this pattern may be the case with certain impact fracture scenarios, single impact fracture occurrences have been recorded on specimens associated with hunting activities at various southern African archaeological sites (see Villa et al., 2010; Lombard and Pargeter, 2008) and in hunting experiments (Lombard and Pargeter, 2008).

At present, these results test an original assumption of the macrofracture method that impact fracture formation, if not frequency, is independent of rock type (Lombard, 2005). These results have shown that impact fractures can and do occur on all of the rock types analysed, but in relatively low frequencies, and that there are few statistically significant differences between the rock types tested. This suggests that use-related factors and the effects of lithic taphonomy have a greater role to play in impact fracture formation than does rock type variation. Not withstanding the need for further investigation of this point, impact fracture frequencies are valuable data for inter-site and analyst comparisons when the contexts of comparison are not identical. A surprising outcome of the experiment was that exceptionally fine-grained rock types such as obsidian do not record higher knapping-related impact fractures than coarser-grained rock types. The glass-like qualities of obsidian do, however, make conducting macrofracture analysis easier and preserve other important macrofracture-related features, such as velocity-dependent micro-fracture features, more readily (see Hutchings, 2011). Heat-treating silcrete appears to increase its grain quality and reduces its impact fracture variability, although the small sample sizes for un heat-treated silcrete may be a variable here. These factors make obsidian and heat-treated silcrete potentially useful case studies for investigating more detailed aspects of macrofracture formation such as velocity dependency and impact fracture directionality. Future experiments will need to investigate these properties further as well as the fracturing of all of the rock types discussed in this paper under hunting, trampling and knapping conditions in order to further assess and compare these patterns.

6. Conclusions

Through observations of the impact fracture patterns left behind by hunting, trampling and now knapping, an effort has been made at tightening the way the macrofracture method is employed. These studies are showing that impact fracture patterning, that is the type, co-occurrence, relationship to retouch and ventral location of impact fractures are together more important for diagnosing weaponry than any one single 'diagnostic' impact fracture is alone. The results of this knapping experiment have, most importantly, shown that rock type variation plays less of a role in impact fracture formation than do variables associated with use and lithic taphonomy. All of the rock types used in this experiment accrued impact fractures in similar frequencies when they were knapped. Obsidian and heat-treated silcrete stand out amongst the African rock types used in this experiment in terms of being fine-grained and relatively easy to diagnose impact fractures on, but not in terms of mean impact fracture probabilities. Assemblages that are rich in obsidian and heat-treated silcrete might therefore represent interesting case studies to explore the more nuanced aspects of impact fracture formation such as fracture propagation velocity, which require fine-grained and homogenous rock types. The ongoing experimental work in this project will examine fracture patterns on the rock types discussed in this paper when they are trampled (obsidian) and used for hunting purposes and will investigate the role of variations in knapping techniques on the formation of impact fractures on African rock types. The macrofracture method, when carefully applied, can be used to generate a robust, quantifiable and comparable line of evidence in the interpretative framework for understanding the use of stone artefacts as weapon components. Moreover, macrofracture analysis is time efficient, can be used to analyze assemblage-level use-traces and is therefore one of the few solutions to directly comparing the statistical results of any use-trace analyses, macro or micro, between analysts. Individually, none of the suggestions provided in this discussion alone provide a clear solution for finding un-ambiguous weapon-related fracture signals in the archaeological record. However, taken together, they help to tighten the way we use the macrofracture method and provide a more robust platform from which to initiate discussions about the use of stone artefacts as weapon components.

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