

A review of rock studies for archaeologists, and an analysis of dolerite and hornfels from the Sibudu area, KwaZulu-Natal

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ABSTRACT

The physical requirements of stone tools tend to prescribe the choice of rocks for their production. Hardness, roughness and impact toughness dictate the ease of knapping as well as the durability of flaked tools, and these rock properties can be measured by mechanical tests described here. Geochemical and petrographic analyses of archaeological and geological samples can also characterise rocks and, under certain circumstances, they enable rock sources to be traced. Examples of how this can be achieved are provided from sites around the world. At Sibudu, KwaZulu-Natal, locally available dolerite and hornfels are the most common rock types employed to make flaked tools. Unfortunately, neither rock lends itself to being sourced, but mechanical tests demonstrate that these rocks have both desirable and undesirable properties for stone-tool manufacture and use. Coarse-grained (rough) dolerite is difficult to knap, but it ensures durable tool edges, whereas fine-grained hornfels is relatively easy to knap, but the sharp edges on its products are sometimes fragile, require resharpening, and have a tendency to break. Dolerite was thus more suited to tool manufacture than we initially realised.

KEY WORDS: Rocks, geochemical analysis, mechanical properties, petrography, stone tools, dolerite, hornfels, Sibudu.

WHY STUDY ROCKS FROM ARCHAEOLOGICAL SITES?

Rock has been used to create tools for more than two million years and selected use of the material has continued into historic times. Innumerable stone artefacts have been recovered from archaeological contexts and in many instances no other artefact types have been preserved in sites, so it is necessary to get as much information from them as possible. Rocks have the potential to answer questions not only about artefact production and discard, but also about people's movements and their relationships with each other across space. Geochemical characterisation is one way of tracking geological sources and such information can show where and how far people travelled to gather rocks or whether there were ancient exchange networks in place. For example, millstones from Cuicul (Djemila, Algeria) have a geochemical signature showing that the rock for their manufacture came from Italy (Antonelli & Lazzarini 2010). Sourcing rocks has not been attempted often in South Africa for reasons to be discussed shortly, but it is commonplace elsewhere. Knowing the origin of rocks used for manufacturing artefacts is sufficiently relevant for archaeologists that a map has been produced of places in Europe where it can be predicted that people in the past obtained supplies suitable for a variety of tasks (Duke & Steele 2010). Magnetic susceptibility is not as commonly used for sourcing rocks as geochemistry, yet it also provides a rapid and low-cost method that was successfully used to link greenschist and basalt polished artefacts and geological outcrops from Western Hungary and the Czech Republic (Bradák et al. 2009). As with most research, multiple sources of evidence allow the most reliable interpretations. It is advisable to supplement geochemical analyses with mechanical tests that measure

rock attributes such as hardness, abrasive hardness, surface roughness and elasticity. Such a project revealed that Roman lava quarries were used for millstone production in Germany (Glühak & Hofmeister 2009).

Most of the rocks found at archaeological sites are the result of knapping to produce a range of tool types. The emphasis here is therefore on flaked stone tools, which are particularly abundant at South African sites like Sibudu, KwaZulu-Natal, which will be the case study later in the paper. Sibudu's rich stone-tool assemblages contain large amounts of dolerite and hornfels. During the initial analyses of the tools we wondered why people selected coarse-grained, rough dolerite when fine-grained hornfels seems intuitively to be a far better product. Our initial hypothesis was that dolerite might be expediently used because it was readily available near the shelter, but we did not consider that its properties were inherently suitable for tool-making or use. It was therefore important for us to characterise dolerite and hornfels to test our hypothesis. Geochemical studies can characterise rock to provide clues to its selection for specific tasks, but there are also mechanical tests for quantifying rock properties. These were the basis of our study and we reviewed a variety of analytical techniques in order to find ones suitable for our local purposes. Some of the available techniques were either inappropriate or too expensive for our study, but we briefly review our overall findings for the benefit of other researchers who may want to answer questions about rocks.

Rocks need to be identified as accurately as possible in the first stage of analysis and petrographic analysis using thin-section microscopy is the best way to do this (Andrefsky 1998). Secure identifications can now and then solve archaeological enigmas without requiring further investigation.

PETROGRAPHIC STUDIES OF ROCKS

Magnificent archaeological artworks collected early in the last century were sometimes deposited in museum collections with scant record of their provenance. Clearly such situations create problems for museums and also for researchers wishing to examine the collections. Case studies abound, but we mention only two: petrographic observations of grain sizes revealed that previously unprovenanced granite sculptures, housed in the Egyptian Antiquity Museum of Turin, originated in the granite outcrops in the Aswan area of Egypt (Serra et al. 2010). Koh Ker sculptures stored by the National Museum of Cambodia and the Metropolitan Museum of Art are another good example of the way in which mysteries about identity can be solved. The source of the three main sandstone types used to make the tenth-century Cambodian sculptures was identified through petrographic analysis that involved counting, classifying and measuring detrital grains by means of a micrometric eyepiece (Carò et al. 2010). We adopted a similar method, not for sourcing, but for part of our hornfels and dolerite characterisation that will be described later. The method was ideal because grain size and therefore rock roughness can be measured on slides under the microscope. The slides used for such work are standard thin sections of rock with a nominal thickness of 30 mm; these are generally examined under a polarized light microscope.

Petrographic characteristics of rocks translate into mechanical properties that, in turn, affect the ability of rocks to perform adequately, first during artefact manufacture and,

secondly, during use. In addition to rock quality, the type of use and the morphology of the blank dictate wear and the potential need for rejuvenation of the tool (Collins 2008), but that aspect of rock use is beyond the scope of this paper.

MECHANICAL STUDIES OF ROCKS

Archaeologists who work with Stone Age assemblages need to know why people in the past selected certain rock types for making some classes of tools while other rocks were avoided. Mechanical properties of rocks seem crucial to the choices that people made. For stone-tool knappers two potentially important features of rocks are fracture predictability (the consistency with which a particular type of stone fractures) and durability (the ability of an edge to resist degradation by a static or dynamic force) (Braun et al. 2009). Rocks that fracture in an expected manner are most suitable for the process of knapping. When rocks are isotropic (exhibiting properties with uniform values measured along axes in all directions), they fracture relatively predictably because the path of fracture follows the direction of the applied force rather than that of the internal structure of the rock (Crabtree 1967; Domański et al. 1994). Elasticity, brittleness (often called fracture toughness) and hardness are mechanical properties of rocks that affect fracture. **Elastic** materials deform under force, but the change is reversible (Braun et al. 2009). Elasticity can be measured by using Young's modulus and Poisson's ratio (Tsobgou 2009). The **brittleness** of a rock refers to its tendency to fracture and this is defined by the ratio between the hardness and the toughness of the rock, a parameter that is linked to the rock's density (Tsobgou 2009). Brittle materials deform irreversibly under force and they break at, or near, yield stress (Braun et al. 2009). As brittle materials can undergo very little deformation, fracture occurs more quickly than in ductile (easily moulded or shaped) solids. **Hardness** (Hv) determines attributes such as resistance to scratching, wear, penetration and the ability to be cut (Rollason 1961: 3). Yonekura et al. (2008: 738) observe that Palaeolithic tools often display hardness values that are higher than average values for geological samples of the same rock type. Thus stone knappers consciously selected hard rock. The property of hardness can be measured by a variety of tests, such as the Vickers method, listed as one of the top four tests by Rollason (1961). This test involves applying a force onto the planar surface of a rock using an indenter, then measuring the imprint left after extraction of the indenter (Tsobgou 2009).

Brittle rock like obsidian meets knapping requirements well because it allows great accuracy during knapping. Neither obsidian nor flint is available in South Africa; instead there are cryptocrystalline silicates such as chert and chalcedony (Humphreys & Thackeray 1983) and they, like obsidian, are well suited to tool-making (Beck & Jones 1990; Andrefsky 1998). This is evident at Klasies River (Wurz 1999) and many other South African Middle Stone Age sites such as Rose Cottage (Wadley & Harper 1989).

In addition to properties that facilitate knapping, tool makers appear to have selected rocks suited to tool functions (Gould & Saggers 1985; Beck & Jones 1990; Byrne 2004). Crabtree (1967), Orton (2008), Webb and Domański (2008) and Yonekura et al. (2008) are amongst the researchers who have noted that rocks with micro-grains and smooth surfaces tend to be used for the production of sharp-edged blades or blade tools requiring fine retouch. Although obsidian produces superior cutting edges, it is

not appropriate for tasks such as boring or scraping because of its fragility (Beck & Jones 1990). At Arago Cave (France), convergent scrapers are generally found on flint or quartzite (Byrne 2004), and in the Western Desert of Australia, coarse-grained rocks seem suitable for scalar retouch (Gould & Saggers 1985). Thus rock composition can explain much of the variability in artefact classes and morphology (Webb & Domański 2008).

Whatever their use, stone tools eventually develop signs of wear, but hard rocks develop edge or surface wear at a slower rate than brittle rocks. The surface heterogeneity, or roughness, of some rocks particularly seems to slow down their rate of wear (Lerner et al. 2007). In contrast, artefacts made on rocks that are not hard-wearing, such as obsidian, have rapid edge attrition and high discard rates (Braun et al. 2008). Hominins creating an Oldowan Industry at Kanjera, East Africa, in the Late Pliocene, selected coarse-grained rocks, such as granite, for their durable edges and not for their ease of fracture (Braun et al. 2009).

GEOCHEMICAL STUDIES OF ROCKS

Sometimes the chemical components of a rock give a clue to its potential success for knapping and our own chemical tests were conducted for this purpose. Rocks with high silica content (like flint, which is 100 % silica) are brittle and can be suitable for flaking, but quartz (also silica-rich) often has so many faults that it is difficult to control.

Chemical analyses are more often used for sourcing rocks. A range of geochemical analyses is available to characterise rock samples and provide a statistical probability of provenance with a known geological source. Geochemical techniques measure the amount of radiation emitted or absorbed and this makes it possible to determine the elements that are present in a sample as well as their relative proportions (Andrefsky 1998). New and sometimes experimental methods are currently used in the chemical characterisation of artefacts and rock samples. Each method has merits and limitations. The primary methods include various forms of X-ray fluorescence spectrometry (XRF, PXRF, EDXRF and WDXRF), neutron activation analysis (NAA, INAA) and inductively coupled plasma-mass spectrometry (ICP-MS). Other methods are less commonly used, such as proton-induced X-ray emission-proton-induced gamma-ray emission (PIXE-PIGME) (Bellot-Gurlet et al. 2008), cold neutron prompt gamma activation analysis (PGAA) (Kasztovszky et al. 2008), and electron microprobe analysis (EMPA) (Tykot 1997; Mallory-Greenough et al. 1999).

Archaeologists need to know which techniques are destructive and which are not. PIXE, PGAA and EDXRF are non-destructive. PGAA, for example, has been used non-destructively to determine the provenance of flint, chert, radiolarite, felsitic porphyry, obsidian and hornstone stone tools in the Hungarian National Museum (Kasztovszky et al. 2008). This was done by detecting the major components (Si, Ti, Al, Fe, Mn, Ca, Mg, Na, K and H) as well as trace elements. Many of the other techniques are destructive, though only tiny samples are generally required.

Some rocks are more suitable for elemental compositional analysis than others. Obsidian is particularly useful because of its source-specific chemistry (Shackley 2008) and it has been widely studied, resulting, for example, in the MURR obsidian database that has characterised obsidian from more than 400 sources around the world (Glascock et al. 2007).

X-ray fluorescence spectrometry (XRF)

X-ray fluorescence spectrometry (XRF) is based on the emission of fluorescent X-rays from a material that has been excited by bombarding it with high-energy rays. This method allows for both the destructive and the non-destructive analyses of materials (Craig et al. 2007). XRF spectrometry does not penetrate the rock sample significantly; it primarily evaluates the surface, creating little or no damage, unless the sample is crushed to determine the relative proportion of elements (Andrefsky 1998). Variations in the XRF technique include portable XRF (PXRF), energy dispersive XRF (EDXRF) and wave dispersive XRF (WDXRF). Size limitations for samples examined by EDXRF range from 10 mm in diameter for the mid-Z elements to 25 mm for the light major elements (Lundblad et al. 2008).

The technique is often used to characterise obsidian (Hughes 1994; Negash & Shackley 2006; Carter & Shackley 2007; Craig et al. 2007; De Francesco et al. 2008; Eerkens et al. 2008) and to a lesser extent chert (Evans et al. 2007). It is also used as a sourcing method. XRF and laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) analyses of obsidian samples from the Late Chalcolithic 2 levels at Tell Hamoukar and Tell Brak, north-east Syria, linked them to sources in the eastern Taurus (Khalidi et al. 2009). Iranian obsidians from Chalcolithic sites were analysed using WDXRF and were found to have originated from three geological sources (Niknami et al. 2010). At Jiskairumoko, in Peru, both XRF and PXRF analysis determined that the inhabitants ignored suitable local sources of obsidian; instead they obtained most of their rock from far distant Chivay (Craig et al. 2007). An EDXRF study of obsidian artefacts from Catalhöyük in Turkey revealed that they had travelled more than 190 km (Carter & Shackley 2007). Deeper in the past, at the Middle Stone Age site of Port Epic in Ethiopia, obsidian artefacts (aged about 77 ka ago) were sourced using WDXRF and EDXRF (Negash & Shackley 2006) to outcrops 150 km and 250 km distant.

While most geochemical work is done on obsidian, rocks such as basalt can also be characterised using XRF (Lebo & Johnson 2007; Lundblad et al. 2008). Selected samples of volcanic rocks like pumice from sites in Tunisia and Turkey were analysed by XRF and ICP–MS to determine the concentration of major and selected trace elements (Lancaster et al. 2010).

Neutron activation analysis (NAA)

NAA converts some atoms of a sample's elements into artificial radioactive isotopes by irradiation with neutrons. The radioactive isotopes decay to form stable isotopes at a rate determined by their half-life. Measurement of the decay enables types and amounts of elements to be determined (Pollard et al. 2007).

While this method is expensive, it is precise and can measure more elements than either XRF or PIXE-PIGME (Shackley 2008). Neutron activation analysis (NAA) is also effective in measuring small samples (<5 mm in diameter), though the method is destructive (samples are usually powdered) and it renders the sample radioactive for a number of years. The distinct chemical groups of transparent obsidian artefacts from the northern Lake Titicaca Basin, Peru, were identified using instrumental neutron activation analysis (INAA), combined with portable X-ray fluorescence (PXRF) (Craig et al. 2010). The provenance of sandstone used in the construction of the Khmer monuments in north-east Thailand was discovered using INAA together with inductively coupled plasma

emission spectrometry (ICP) (Uchida et al. 2010). Sampson and colleagues conducted a large-scale project in the Karoo, South Africa, comparing elements from geological outcrops of hornfels with archaeologically recovered stone tools made on hornfels. One thousand six hundred hornfels geological sources were mapped in the Karoo. Unfortunately the archaeologically recovered hornfels tools could not be successfully sourced because the INAA readings demonstrated a large amount of variation in the elements, even within a single hornfels outcrop (Sampson & Youngblood 2006).

NAA is no longer as readily available as it once was, due to the decommissioning of research reactors in the United States, Britain and Canada (Speakman & Glascock 2007), but these facilities are still available in South Africa. NAA has largely been replaced by ICP–MS.

Inductively coupled plasma–mass spectrometry (ICP–MS) and laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS)

ICP–MS applications are variable, the main differences being, first, whether the sample is introduced into the plasma as a solution or by laser ablation of a solid sample and, secondly, in the type of magnetic separation applied to the ions (Pollard et al. 2007). The plasma is maintained at 10 000°C and, at this temperature, molecular species are broken down, and positive ions are transferred to the mass spectrometer by means of a special interface (Pollard et al. 2007). ICP–MS requires crushed samples and is therefore destructive.

The advantages of laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) are numerous. The process requires little sample preparation, samples remain solid, and even samples smaller than 1 mm can be analysed (Eerkens et al. 2008). It is also a fairly quick process, with Eerkens et al. (2008) reporting a throughput of about six artefacts per hour, making it relatively cost-effective. Notwithstanding the small sample size required for its use, LA–ICP–MS is able to detect more source-discriminating elements than methods like PIXE. Ambrose et al. (2009) used the method to trace obsidian sources on Timor, SW Pacific, for archaeologically recovered artefacts. As is the case with XRF, obsidian is most often the subject of ICP–MS and LA–ICP–MS analyses, but they have also been attempted on other rock types. A pilot study of black chert in northern England used ICP–MS and LA–ICP–MS (Evans et al. 2007). Chert is not as easily characterised and sourced as obsidian; it often forms a single, continuous bed that may outcrop in a number of places. Even so, four geological sources of the black chert were sampled and could be successfully differentiated, though with some degree of overlap amongst elements.

ICP–MS, together with optical emission plasma–mass spectrometry (ICP–OES) and atomic absorption spectroscopy (AAS), was profitably used to source the geological outcrops for vitreous dacite and/or rhyodacite artefacts from Formative period archaeological sites in the upper Salado River Basin in the Atacama Desert, northern Chile (Seelenfreund et al. 2009). In Tito Bustillo Cave and the Monte Castillo Caves, in northern Spain, petrography, XRD, SEM–EDS and ICP–MS were used in archaeological pigment characterization studies (Iriarte et al. 2009).

ICP–MS and LA–ICP–MS facilities are available in South Africa, but thus far have primarily been used by geologists (Lombard et al. 2003; Marsh 2004).

X-ray diffraction (XRD)

X-ray diffraction uses X-rays of known wavelengths to determine the lattice spacing in crystalline structures and therefore to identify chemical compounds directly (Pollard et al. 2007). Powder diffraction is the simplest method; this requires a powdered sample, but only a small quantity (5–10 mg) is required, reducing the extent of destruction to the artefact.

XRD was one of the techniques used to create a database of some of the most important black limestone quarries used in Roman times, for example those in Tunisia and Greece (Brilli et al. 2010). XRD, together with modal mineralogy, petrographic texture, SEM–EDS and whole-rock chemistry, was used to recognise three different petrographic groups for soapstone (talc-bearing schists) and garnet chlorite schist artefacts found in some Medieval archaeological sites in Tuscany (Central Italy) (Santi et al. 2009).

Proton-induced X-ray emission (PIXE)

Protons can be used instead of X-rays or electrons in the method called proton-induced X-ray emission (PIXE). A high-intensity, highly focused beam of protons is produced by a Van de Graaff accelerator (Pollard et al. 2007). One advantage of the technique is that the beam can be focused on a portion of an artefact so that sampling and destruction are avoided.

As with the other geochemical techniques, obsidian tends to be most often the subject of PIXE analyses (for example, Gazzola et al. 2010; Poupeau et al. 2010), but Langejans (2007) used PIXE to characterise the elements present in plant and animal residues from stone tools found at Sterkfontein and Sibudu. This novel use of the method unfortunately requires that the residue is removed from the stone tool.

BEHAVIOURAL INTERPRETATIONS OF ROCK SELECTION AND TRANSPORT

Archaeologists have studied and interpreted rock selection by people in the past in many ways. Most have concentrated on functional analyses that seek chemical and physical relationships between rocks and their potential for flaking and retaining durable working edges; these approaches have already been discussed. Some archaeologists have looked at ways that people in the past could have manipulated rock to improve its qualities, for example through heat treatment (e.g. Brown et al. 2009). Others have emphasised the social and even symbolic potential of rock procurement and use. We do not deal with these approaches here. Neither dolerite nor hornfels used at Sibudu would have been deliberately heat treated; they could not be beneficially altered through heating because it is not possible to effect recrystallisation of these rocks using the low temperatures characteristic of camp fires.

More relevant to our Sibudu study is the transport of rocks from the surrounding landscape to the site. There is no agreed definition for archaeologists' use of the terms 'local rocks' versus 'non-local rocks', but here we arbitrarily use a 20 km radius around a site to indicate 'local' rock use. Greenschists in Central Europe moved within a radius of about 500 km (Bradák et al. 2009) and soapstones were exchanged between the Central Alps and Middle Adriatic coastal sites in the fifth to fifteenth centuries AD (Santi et al. 2009); these transactions were unquestionably non-local to the beneficiaries.

Further examples of rocks travelling long distances have been mentioned in earlier sections of this paper.

Based on models of embedded procurement, rocks can be transported as part of people's seasonal round (Blair 2010) rather than as trade items. Changes in a seasonal round may then result in changed rock use. In turn, this might imply altered relationships between groups and territories. A related argument is made by Ambrose and Lorenz (1990) who point especially to Klasies Main site, where fine-grained quartz and silcrete (interpreted as non-local rocks) were commonly used in the Howiesons Poort Industry of the Middle Stone Age, but not in other Klasies assemblages where locally available coarse-grained quartzite was more common (Singer & Wymer 1982; Wurz 1999). Such changes in rock type during the Howiesons Poort were, for a long time, thought by some archaeologists to be a defining attribute of that industry in southern Africa, possibly linked to temporary changes in social and even symbolic behaviour. If this belief is still held, it can only be applied to the Cape because Rose Cottage (eastern Free State) and Sibudu data demonstrate that there is no change in rock use at these sites between the Howiesons Poort and previous industries (Soriano et al. 2007; Wadley & Mohapi 2008). Fine-grained rocks (opalines) occur in high frequencies throughout the Middle Stone Age and Later Stone Age sequence at Rose Cottage, while at Sibudu dolerite and hornfels are used as much during the Howiesons Poort as anywhere else in the sequence (Wadley & Mohapi 2008), save in the immediate post-Howiesons Poort assemblage (~58 ka) where quartz and quartzite are the predominant rock types (Cochrane 2006). Changes in rock use are therefore not uniform through time in southern Africa. Change or continuity in rock use must be examined on a site-by-site basis. This is the appropriate time to introduce the case study of Sibudu and the rock-collecting strategy of its inhabitants during the Middle Stone Age.

ROCKS AND ROCK ATTRIBUTES FROM THE SIBUDU LOCALITY

Local geology

Sibudu rock shelter, north of Durban and about 15 km inland of the Indian Ocean, is carved into a steep cliff that geologically is within the Mariannhill Formation of the Natal Group (Clarke et al. 2007; Fig. 1). The site preserves a cultural sequence, ~77 ka to ~38 ka, that includes pre-Still Bay, Still Bay, Howiesons Poort and post-Howiesons Poort industries, as well as what are informally described as late and final MSA assemblages (Wadley & Jacobs 2006).

The geology of the Verulam area was studied and mapped by Clarke et al. (2007). Abundant dolerite in the vicinity of Sibudu originates from intrusive Jurassic volcanism. Most dolerite occurs as sills, though close to Sibudu is a true dolerite dyke (Clarke et al. 2007). Dolerite sills in the area include the prominent, fine-grained Mhlasini sill, which outcrops extensively inland of the Indian Ocean (Clarke et al. 2007). Silica values from several Mhlasini sill core samples are comparable, ranging between 51.05 and 50.58 wt%. The Verulam sill, only a few kilometres from the Mhlasini sill, is generally coarse-grained with silica values that range widely amongst its samples—between 48.95 and 52.61 wt% (Clarke et al. 2007). Effingham dolerite sills occur along the Indian Ocean coastal belt and they are characterised by particularly high silica contents (sometimes in excess of 63 wt%). Notwithstanding these differences, dolerite is chemically similar

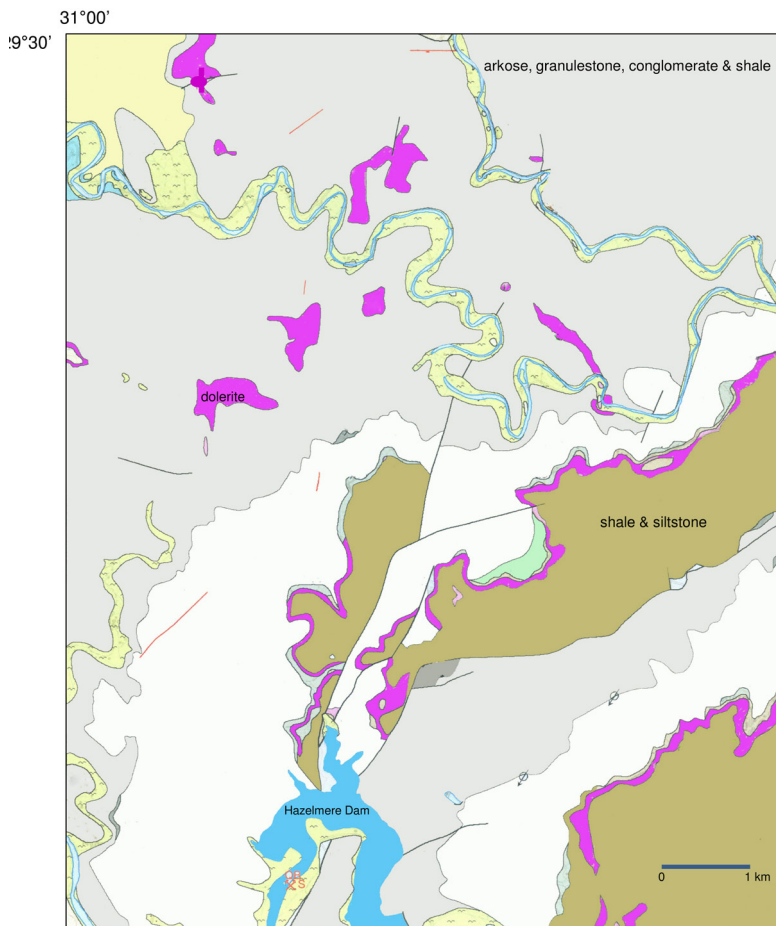


Fig. 1. Simplified geology map of the Sibudu area. Sibudu is not shown on the map in order to protect it, but the area included is within easy walking distance of the site. Rocks represented here are: undifferentiated dolerites (purple), Pietermaritzburg horizontally laminated carbonaceous and micaceous shale and siltstone (light brown) and Mariannhill flat- and cross-bedded medium- to coarse-grained arkose, granulestone and small-pebble conglomerate with sub-ordinate shale (light grey). The geology map is a redrawn portion of the Council for Geoscience's 2006 1:50 000 sheet, 2931CA Verulam.

across large regions and as a result we have been advised that it is unlikely that it will ever be possible to source dolerite artefacts from archaeological sites in KwaZulu-Natal.

Quartz is relatively rare within a few kilometres of Sibudu where it occurs only as small, rounded nodules in rivers and exposed river-terrace gravels. Small-pebble conglomerates in the area are also a source of tiny quartz and cryptocrystalline nodules. Mudstones and shales occur widely and, along the margins of dolerite intrusions into the shale, bands of hornfels of varying qualities are sometimes created. Sources of good-quality hornfels are elusive in the area, but one occurs in the Verulam district on the Black Mhlasini River, within 15 km of Sibudu (Cochrane 2006). This hornfels is found as thin slabs (just a few centimetres thick) and it is often poorly metamorphosed.

A piece of hornfels that eroded from the talus slope of the shelter was subjected to an elemental analysis by XRF (R. Uken pers. comm. 2004; Wadley 2005). Its high silica content (63.8 %) and low magnesium (1.4 %) and calcium (0.7 %) content (relative to that of dolerite) confirms that it is metamorphosed shale (hornfels) from a contact zone with a dolerite intrusion. Varying temperatures occur in the zone of thermal metamorphism where a dolerite intrusion occurs. Consequently, there are different grades of metamorphic hornfels and igneous dolerite and, on occasion, they are difficult to discriminate using only a hand lens. Both dolerite and ‘chilled dolerite’ (which looks somewhat like hornfels) occur locally in the Sibudu valley (R. Uken pers. comm. 2004; Wadley 2005).

A survey along the Thongathi River by HK in 2011 showed that hornfels nodules are not present there. The river is, however, a source of weathered and river-rolled dolerite as well as of small quartz and quartzite pebbles. The rounded cortex on some Sibudu cores and flakes does imply a waterborne origin for some rocks brought to the site, but tabular dolerite pieces are also evident and the dolerite dyke within 200 m of the shelter seems likely to have been the source of much of this dolerite.

The use of rock at Sibudu

At Sibudu stone tools are generally made from hornfels and dolerite (Fig. 2), though quartz, and quartzite are represented and, on rare occasions, these become prominent



Fig. 2. Left: Sibudu Still Bay bifacial tool made of dolerite. The specimen was found in layer RGS. Right: Sibudu late MSA point made of hornfels. Note the broken tip. The specimen was found in layer Oreo. The scale bars indicate 1 cm.

TABLE 1

Sibudu rocks used for whole flakes, whole blades and retouched tools in the Still Bay Industry (~70 ka), the post-Howiesons Poort (~58 ka) and the final MSA (~38 ka), and blades in the late MSA. H=hornfels, D=dolerite, Qtzt=quartzite, SS=sandstone, Q=quartz. Post-Howiesons Poort data from Cochrane (2006); late MSA data from Villa et al. (2005); Still Bay and final MSA data from Wadley (2005, 2007). The final MSA data exclude broken retouched tools.

	H	D	Qtzt	SS	Q
Still Bay					
flake	261	813	32	40	21
blade	14	42	1	0	0
retouched tool	24	36	11	0	4
Total	299	891	44	40	25
post-Howiesons Poort					
flake	3857	3698	169	80	229
blade	133	139	4	1	1
retouched tool	173	62	5	0	1
Total	4163	3899	178	81	231
late MSA					
blade	93	66	1	0	0
Total	93	66	1	0	0
final MSA					
flake	2294	632	262	86	530
blade	91	24	13	6	26
retouched tool	139	29	14	1	39
Total	2524	685	289	93	595

in the sequence. Both fine-grained and coarse-grained dolerites are used. Some change through time is evident. Dolerite is the most common rock used for flakes, blades and retouched tools in the pre-Still Bay of about 77 ka and the Still Bay at about 70 ka; hornfels flakes comprise only about a third as many as dolerite flakes (Table 1). Proportions are different in the post-Howiesons Poort layers (~58 ka) where dolerite and hornfels flakes and blades are of similar frequencies, though more retouched tools are made on hornfels (Table 1). In the late MSA (~48 ka) hornfels is favoured for blade production, too, but not to the same extent as in the later phase of occupation. Here, in the final MSA (~38 ka), dolerite flakes are only a third of the frequency of hornfels flakes, and hornfels is also preferred for retouched tools and blades (Table 1).

Cochrane (2006) found that, at least in the ~58 ka occupations, retouched tools are almost three times more likely to be made of hornfels than unretouched flakes, but that far more hornfels retouched tools are broken than dolerite retouched tools. This fits our prediction that dolerite tools hold their edges more successfully than those made on hornfels. Blades, which are flakes with length at least twice the breadth dimension, are often made of dolerite at Sibudu, notwithstanding the predictions and observations made by archaeologists elsewhere in the world (examples were introduced earlier in this paper). Sibudu bladelets (length <26 mm) are more usually made of hornfels than dolerite, perhaps because of the small size of available hornfels nodules or because of the knapping requirements of bladelet production (Cochrane 2006). The survey

presented earlier in this paper suggests that hornfels and dolerite are most likely to have been selected for specific tool types because of their chemical and mechanical attributes. We explore this possibility further below.

Where very fine-grained dolerite pieces occur at Sibudu, it can be difficult to distinguish these from hornfels using a hand-lens only. Consequently XRF analysis of thin sections (Wadley & Jacobs 2006) was used to determine which rock type was used. The hornfels results were referred to earlier. A thin section of a fine-grained dolerite that is especially well represented in the pre-58 ka layers at Sibudu was subjected to a petrographic analysis. The constituent minerals include 45 % clinopyroxene, 44.5 % plagioclase and small percentages of opaque minerals, quartz, limonite and goethite (Wadley & Jacobs 2006). Performing chemical analyses on small numbers of ancient stone tools is relatively unproblematic, though it is clearly necessary to obtain permits from the local heritage agency when destructive techniques are required. Where archaeologically recovered tools are used, these should preferably be taken from collapsed sections or other unprovenanced contexts. Testing the mechanical attributes of stone tools is not as easy as the chemical characterisation; indeed, many mechanical techniques available cannot be used because Sibudu's tools are not large enough. Blocks of rock are required for some tests, so it is best to use geological samples with a likely relationship to those from the archaeological site. Geological samples tested by us have a known provenance (Table 2).

TABLE 2

Sample numbers of dolerite and hornfels geological samples tested, their provenance and the tests carried out on them. The Ndwedwe quarry is about one kilometre from Sibudu.

Sample #	Rock type	Provenance	Test
1a	Dolerite	Thongathi River	Whole rock XRF
1b	Dolerite	Thongathi River	Hardness, roughness, thin section
2a	Dolerite	Sibudu dyke	Whole rock XRF
2b	Dolerite	Sibudu dyke	Hardness, roughness, thin section
3a	Hornfels	Black Mhlasini River	Whole rock XRF
3b	Hornfels	Black Mhlasini River	Hardness, roughness, thin section
4a	Hornfels	Shale quarry, Ndwedwe	Whole rock XRF
4b	Hornfels	Shale quarry, Ndwedwe	Hardness, roughness, thin section
12a	Dolerite	Thongathi River	Whole rock XRF
12b	Dolerite	Thongathi River	Hardness, roughness, thin section
13a	Dolerite	Thongathi River	Whole rock XRF
13b	Dolerite	Thongathi River	Hardness, roughness, thin section

Mechanical and chemical tests on dolerite and hornfels from Sibudu and its surrounds

Vickers Hardness Test

Because rock hardness affects both the knapping qualities of a core and the rate of edge wear attrition of the finished tool, it is an important property to quantify. Yonekura et al. (2008) used the Vickers method for their rock studies, and it is listed as one of the four most important and reliable hardness tests by Rollason (1961), so this is the test that we elected to use. Four dolerite and two hornfels geological samples, together

with one dolerite and ten hornfels tools from Sibudu, were sectioned and mounted in 25 mm epoxy moulds for the Vickers Hardness Test, which measures resistance to penetration. The hardness values (Hv), which are average readings, show that there is overlap in dolerite and hornfels Hv values (Fig. 3). This is partly because rocks are not homogeneous materials; they can contain inclusions and fault planes that can cause variable readings during testing. The Hv values achieved during our tests ranged between 551 and 210 for hornfels and between 538 and 272 for dolerite. The higher the Hv value the harder the rock. When considering geological samples only, dolerite has higher Hv values than hornfels. When looking at just archaeological samples there appears to have been selection for good-quality hornfels with high Hv values. These high values for the good-quality hornfels place it within the range of the dolerite high Hv values.

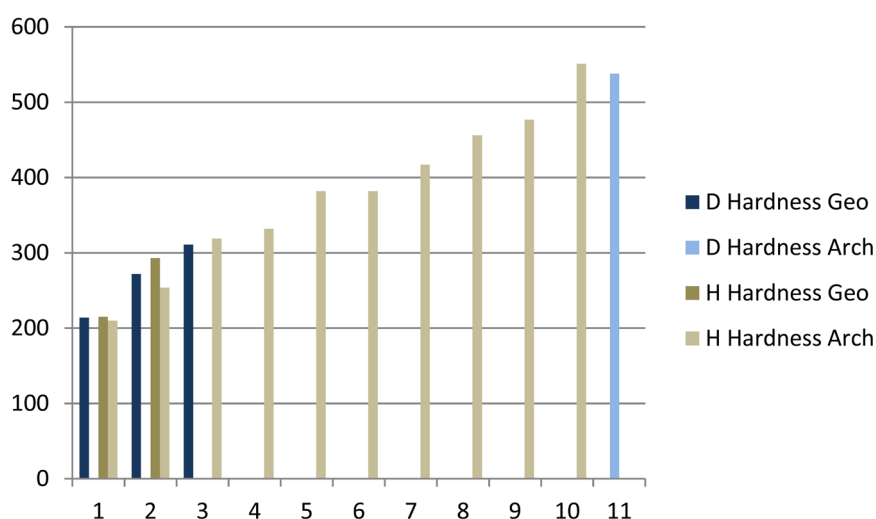


Fig. 3. Hardness values (Hv) derived from the Vickers Hardness Test of geological and archaeological samples of hornfels (H) and dolerite (D). Hv values are on the Y axis. Note the overlap in Hv values between hornfels and dolerite.

Surface Roughness

A novel method, devised by Professor Cawthorn of the Geology Department at the University of the Witwatersrand, was used to measure surface roughness. The method is not unlike the petrographic analysis described earlier by Carò et al. (2010). Grain sizes were measured on thin sections of rocks and the average of these provided a measure of surface roughness. Petrographic thin sections were first ground from geological specimens comprising two hornfels (numbers 3b, 4b) and four dolerite samples (numbers 1b, 2b, 12b and 13b); these were glued to glass slides so that the total thickness of each section was about 0.03 mm (30 microns). The thin sections were examined under a petrographic microscope with a measuring scale embedded in the eyepiece. The thin sections initially confirmed the hornfels and dolerite identifications. Then, 5x and 10x objective lenses were used to measure grain sizes on the dolerite and hornfels sections. First, the largest

crystal in the field of vision was selected and its longest dimension was measured; secondly, the lengths of the nine next largest neighbouring crystals were measured and the average of the ten crystal lengths was calculated for each slide. The long axes of plagioclase crystals were measured on dolerite samples, while the maximum dimensions of quartz crystals were measured on the hornfels samples. Average grain sizes of dolerite and hornfels geological samples from the Sibudu area are highly significantly different ($p < 0.0001$; $t = 1.7$, $df = 58$), with dolerite grain sizes being larger than those of hornfels. Dolerite has an appreciably rougher surface than hornfels (Table 3) because the platy plagioclase grains within it are larger than the quartz grains in the hornfels samples (Fig. 4). The greater the surface roughness of rock types, the less the attrition of tool edges, so roughness is a critical attribute that is likely to influence the rate of wear of a tool.

TABLE 3

Roughness rankings of dolerite (D) and hornfels (H) geological samples from the Sibudu area. Roughness rankings were measured by average grain sizes (GS). When ranking the roughness of rocks, 1 is the roughest. Note that there is no overlap between hornfels and dolerite readings.

See also Figure 4.

Sample	Rock	Objective Lens x	Total units	Average GS in mm	Roughness rank
3b	H	10	37	0.0185	6
4b	H	10	49	0.0245	5
12b	D	5	97	0.097	4
1b	D	5	134	0.134	3
13b	D	5	182	0.182	2
2b	D	5	351	0.351	1

Fracture Toughness

Brittle solids are not ductile and absorb relatively little energy before fracture occurs. Tough materials are those where fracture, once it occurs, is not easily propagated. Various V-notch tests can be used to determine the amount of energy absorbed by a specimen during fracture by impact, such as the Charpy and Izod V-notch tests. In our tests, a low energy Charpy pendulum impact testing machine (Alfred J. Amsler & Co machine, Amsler 125/74 with a Charpy 0,4 kpm scale according to DIN 51222) was used. The machine has a rated initial potential energy of 50 J or less. In such tests a notched bar is impacted and the energy transferred to the material is inferred. The fracture toughness is measured in joules/mm² when fracture is initiated. Fracture toughness (brittleness) readings were measured for four dolerite and four hornfels samples (Fig. 5). Note that there is no overlap between the readings of the dolerite and hornfels samples and that the dolerite sample readings are higher than those of the hornfels samples. The greater toughness of dolerite over hornfels is part of the reason why dolerite is so much more difficult to knap than hornfels.

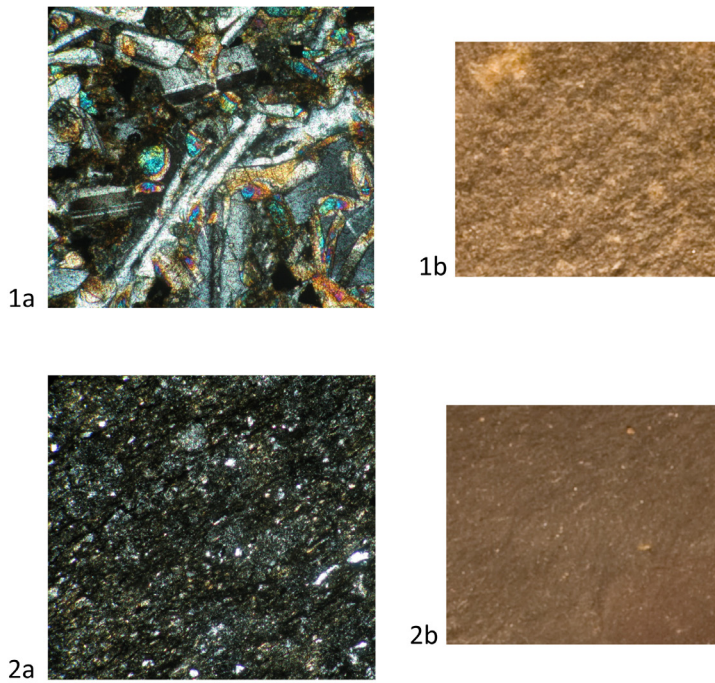


Fig. 4. Geological samples of dolerite and hornfels. 1a. Petrographic slide of dolerite (x8). Note the large, platy plagioclase grains. 1b. Dolerite block (x1) showing rough surface. 2a. Petrographic slide of hornfels (x8) showing small quartz grains. 2b. Hornfels block (x1) showing relatively smooth surface.

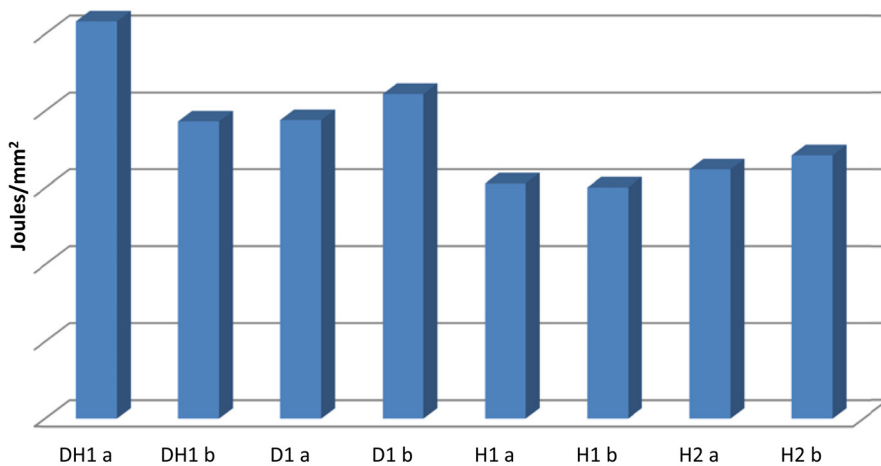


Fig. 5. Fracture toughness readings in joules/mm² for four dolerite samples (DH1a, DH1b, D1a and D1b) and four hornfels samples (H1a, H1b, H2a and H2b). Note that there is no overlap between the readings of the dolerite and hornfels samples.

XRF

XRF methodology was described earlier. Wave dispersive XRF (WDXRF) was used for the Sibudu samples which were processed with a PANalytical PW2404 WDXRF.

The four dolerite samples that were chemically analysed are part of a relatively homogeneous group because of their similar weight percentages of SiO_2 (quartz), Al_2O_3 (aluminium oxide), Fe_2O_3 (iron oxide), MgO (magnesium oxide) and CaO (calcium oxide) (Table 4). The components of dolerite samples from the broader Sibudu area submitted for XRF testing by Clarke et al. (2007) compare well with those reported here. The chemical compositions of the Black Mhlasini hornfels and the Sibudu shale quarry hornfels demonstrate their similar origins. Relative to the dolerite, the higher SiO_2 and Al_2O_3 , but lower Fe_2O_3 , MgO and CaO compositions of the hornfels, distinguish them from the dolerite samples (Table 4).

CONCLUDING REMARKS

Important behavioural information can be garnered from the study of rocks from archaeological sites, especially when combining techniques from petrography, mechanical and geochemical studies. Petrography is most useful for rock identification. Mechanical tests provide valuable information about the physical conditions (for example, hardness, roughness and fracture toughness) of rocks that make them useful or unsuitable for certain tasks. Geochemical studies most often provide information about provenances of archaeologically recovered rocks. Unfortunately not all rocks are amenable to sourcing; amongst these is dolerite, commonly used at Sibudu. Sampson and Youngblood's (2006) negative experience with the sourcing of Karoo hornfels suggests that it will not be possible to source Sibudu hornfels either.

The review at the beginning of this paper demonstrates that a number of parameters are shared by rock-using communities, regardless of their era, their level of technology, or the continent on which they lived. Rock properties determine the potential for creating and maintaining artefacts from them. In the case of flaked rocks it seems that the ones that are readily worked often break easily or produce sharp edges that wear rapidly. In contrast, rough rocks that are difficult to knap generate long-lasting tools. As a result, such rocks are sometimes preferred as a compromise solution to tool needs.

At Sibudu, many flakes and blades were produced from dolerite. This is notwithstanding the observation by Crabtree (1967) and Yonekuro et al. (2008) that smooth rock surfaces with small grain sizes (which provide sharp cutting edges) are deliberately selected for use as blades. Nonetheless, retouched tools were more often made from hornfels (or even quartz when small tools were required) than from dolerite. The XRF test on Sibudu-area rocks was useful for securely distinguishing them. For example, dolerite has relatively low silica and aluminium weight percentages compared with hornfels, but it has high iron oxide, magnesium oxide and calcium oxide weight percentages in comparison with hornfels. XRF could not, however, explain entirely satisfactorily the different use of the rocks in the past. Mechanical tests were more useful to that end. Dolerite is tough and rigid and has a rough surface, whereas hornfels is brittle (has a lower fracture toughness than dolerite) and is more fine-grained than dolerite. Thus, dolerite flakes are more difficult to produce than hornfels ones, but, once produced, they are likely to retain usable edges more

TABLE 4a
XRF results for major elements (wt%) from geological samples collected near Sibudu. D=dolerite; H=hornfels.

Sample	Rock	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	L.O.I	Total
		wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
1a	D	50.85	1.12	14.60	13.00	0.20	5.84	9.12	2.58	0.74	0.16	1.15	99.36
2a	D	51.97	1.50	13.33	13.99	0.22	4.81	9.04	2.47	0.98	0.26	2.14	100.71
12a	D	51.35	1.35	14.59	13.35	0.21	5.17	9.08	2.50	0.96	0.22	0.67	99.45
13a	D	51.03	1.60	13.56	14.65	0.20	4.72	8.28	2.50	0.84	0.23	2.30	99.91
3a	H	63.36	0.79	20.63	4.12	0.02	0.96	0.36	1.06	2.17	0.24	6.38	100.09
4a	H	62.35	0.79	20.45	4.59	0.02	0.94	0.57	1.04	1.94	0.34	6.15	99.18

TABLE 4b
Trace elements (ppm) from geological samples collected near Sibudu. D=dolerite; H=hornfels; LLD is lower limit of detection.

Sample	Rock	Rb	Sr	Y	Zr	Nb	Co	Ni	Cu	Zn	V	Cr	Ba
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
		LLD 3	LLD 3	LLD 3	LLD 8	LLD 3	LLD 6	LLD 6	LLD 6	LLD 6	LLD 12	LLD 12	LLD 20
1a	D	40	184	35	141	12	36	54	125	114	287	148	485
2a	D	33	181	32	129	9	42	53	73	108	245	129	512
12a	D	47	188	38	155	13	38	39	144	120	307	149	484
13a	D	32	230	38	171	13	41	6	11	130	310	41	316
3a	H	137	126	47	202	17	16	53	40	115	134	96	798
4a	H	123	115	42	202	18	17	47	40	106	136	92	708

successfully and with less damage than hornfels flakes. This prediction is correct because Cochrane (2006) demonstrated that, in the ~58 ka layers of Sibudu, fewer dolerite tools are broken than hornfels ones. Hornfels is relatively easy to knap, and produces sharp, thin edges, particularly desirable for blades that are cutting tools, but its products are more prone to breakage than those made from dolerite. One reason for the larger number of hornfels retouched pieces at Sibudu seems to be the need to re-sharpen the readily weakened edges of hornfels flakes or blades during their use. Yet, we demonstrated that there was considerable overlap between the hardness values of the hornfels and dolerite samples tested here, particularly amongst the archaeological samples. This suggests that stone knappers in the Middle Stone Age selected hard, good quality hornfels and avoided some of the geological products that we collected.

Rocks that are simultaneously tough and coarse-grained may be unsuitable for retouch because the flake edges are more likely to crush than to fracture, though the coarse-grained crystalline structure of these rocks sometimes produces a naturally denticulated flake edge (Jones 1979) that can be useful with no further modification. It is true that in the pre-Still Bay occupations of Sibudu, where dolerite is very commonly employed, there are many naturally denticulated edges on flake and blade products. When we began this project, our hypothesis was that dolerite was inferior to hornfels. We thought that dolerite was used expediently because of its proximity to the shelter. We were wrong. Dolerite is an excellent product for stone tools; it is merely difficult to knap.

Since choice of rock type is closely associated with both flaking quality and edge durability, the methods described in this paper have the potential to add to our knowledge of behaviour not only at Sibudu, but at other Stone Age sites in KwaZulu-Natal and farther afield in southern Africa. Experimental knapping and use of dolerite and hornfels flakes will, in future, test the suggestions made here.

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