NEUTRON TOMOGRAPHIC ASSESSMENT OF INCISIONS ON PREHISTORIC STONE SLABS: A CASE STUDY FROM WONDERWERK CAVE, SOUTH AFRICA*

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This study presents the application of neutron tomography to the analysis of ironstone slabs found in a late Earlier Stone Age context (Fauresmith industry) at the back of Wonderwerk Cave, Northern Cape Province, South Africa. These slabs have markings on the surface that might be anthropogenic, and thus significant to understanding the emergence of human symbolic behaviour. Neutron tomography proved to be an effective tool for distinguishing surface incisions from lines that are the expression of internal fissures in the rock.

KEYWORDS: NEUTRON TOMOGRAPHY, SYMBOLIC ARTEFACTS, EARLIER STONE AGE, WONDERWERK CAVE, FAURESMITH, BANDED IRONSTONE

INTRODUCTION

In recent years, a range of non-destructive imaging techniques based on penetrating radiation has been developed for the non-invasive three-dimensional (3D) study of the internal structure of objects. Imaging with penetrating radiation entails the set-up geometry of source–sample–detector. Radiation from the source is collimated towards the sample and detector. As the radiation passes through the sample, it is attenuated (absorbed and/or scattered) to a higher or lesser degree due to characteristics related to the type of radiation used, as well as characteristics of the sample’s composition. A two-dimensional (2D) ‘shadow image’ of the sample is cast on the detector (in electronic and digital format), from where the image (2D-radiograph) is relayed for inspection and observation on a PC monitor. Among these methods, neutron tomography (NT)
has established itself as an important diagnostic tool for non-destructive examination and analysis of historical, archaeological and fossil objects (e.g., Schillinger et al. 1996; Schwarz et al. 2005; Rant et al. 2005; Fiori et al. 2006; Kardjilov et al. 2006; Kusche et al. 2007; Banhart 2008; de Beer et al. 2009). NT is a radiation-based analytical imaging technique that shares many features with other tomographic imaging methods: it uses serial slices and facilitates virtual reconstruction of both the internal and external structure of 3D objects on a 2D or 3D scale. That it is non-invasive is a critical factor, since many of the samples studied may be rare or unique, or alternatively breaking/cutting them will undermine the goals of the investigation (Rant et al. 2005). The specific importance of NT lies in the ability of neutrons to penetrate many materials, including metals, which other imaging techniques cannot (Johansen 2005). Moreover, NT has proved especially successful in providing high-resolution images, in the order of magnitude of tenths of a millimetre, for features within a rock sample that is several centimetres in size, and also of imaging hidden interior features that X-ray and gamma-ray imaging have failed to reveal (Schillinger et al. 1996). Although most applications of NT have focused on metals, several studies have centred on imaging the internal composition of geological samples (e.g., Winkler et al. 2002; Vontobel et al. 2005; de Beer et al. 2007; Longridge et al. 2009). Indeed, NT has proved to be an important complement to X-ray tomography in determining or validating existing data concerning some of the important physical properties of rock.

Given the success of these studies, we have applied NT to investigate surface modifications to several banded ironstone (BIF) slabs recovered from the site of Wonderwerk Cave (Northern Cape Province, South Africa; Fig. 1 (a)), which are suspected of having been incised by early hominins and, as such, may represent manifestations of early symbolic behaviour.

BACKGROUND

The stone slabs investigated here are all banded ironstone (BIF) and were recovered in archaeological deposits at the back (Excavation 6) of Wonderwerk Cave, a 140 m long phreatic cavity formed in dolostone, located in the eastern flank of the Kuruman Hills, in the Northern Cape Province of South Africa (Figs 1 (a) and 1 (b): see also Beaumont 2004; Beaumont and Vogel 2006; Chazan et al. 2008).

The BIF studied here occurs within the Neoarchaean Campbellrand carbonate platform sequence within the Transvaal Supergroup, and overlies limestones and lesser dolostone with cryptalgal laminae (Klein 2005; Knoll and Beukes 2009). Banded ironstone is a chemical marine sediment deposited in an ocean with dissolved Fe (II) formed during periods of low atmospheric O₂ and low concentrations of sulphate in seawater (Canfield 2005). The BIF in the Kuruman region has been exposed to burial temperatures estimated at 100–150°C (Klein 2005). BIF is characterized by alternate banding of Fe-rich and chert-rich lamina (Fig. 1 (c)). Scales of banding include mesobands (thickness less than 25 mm) and microbands (0.3–1.7 mm). The mineral composition of BIF includes chert, magnetite and hematite. Rebeckite and crocidolite are important components of the BIF in the Transvaal Supergroup, and siderite is the most common carbonate (Klein 2005). The iron content ranges from 20 wt% to 40 wt%, and SiO₂ ranges from 34 wt% to 56 wt%. The Al content is low, ranging from 0.09 wt% to 1.8 wt%.

The archaeological deposits in Excavation 6 at Wonderwerk Cave in which the slabs were found (Fig. 1 (b)) have been tentatively dated to between 780 and 187 ka, using U-series dating and palaeomagnetostatigraphy (Chazan and Horwitz 2009, Matmon et al. 2011). The stone slabs are associated with late Earlier Stone Age lithic artefacts belonging to the Fauresmith industry, which is characterized by the co-occurrence of blades, prepared core flakes and bifaces.
Banded ironstone is a raw material that is readily available in the area immediately surrounding Wonderwerk Cave (e.g., on the slope of the hill in which the cave sits), but not inside the cave, such that the slabs were introduced into the cave (Figs 1 (d) and 1 (e): see also Beaumont and Vogel 2006; Chazan and Horwitz 2009). Although detailed geological and taphonomic analyses of Excavation 6 are still in progress, it is clear that sedimentary deposition was accompanied by low-energy water activity, as attested to by silt pooling. There is, however, no
sedimentary, nor faunal or lithic taphonomic, evidence for high-energy geological processes that could have transported the heavy (>200 g) BIF slabs to the back of the cave (Matmon et al. 2011). Mapping of the interior of the cave in relation to the surface topography has ruled out the possibility of a buried entrance in proximity to Excavation 6 (Rüther et al. 2009). As such, the BIF slabs would have been intentionally introduced into the cave by hominins (Figs 1 (d) and 1 (e); see also Beaumont and Vogel 2006; Chazan and Horwitz 2009).

Ironstone slabs make up a significant component of the Earlier Stone Age archaeological assemblages at Wonderwerk Cave. Although some of these slabs have been flaked to form simple cores or core scrapers, most are unworked. Several of the slabs examined to date exhibit clear incisions/surface modifications. One of these ‘incised’ slabs, with a series of parallel incised lines visible on one aspect, was published by Beaumont and Vogel (2006, fig. 6), who concluded that the surface modifications were inconsistent with natural processes and point to intentional modification by hominins. However, Chazan and Horwitz (2009) questioned this conclusion, noting that the surface ‘modifications’ do not take the form of clearly defined symbols or images that are recognizable. More recently, Bednarik and Beaumont (2010) have published an additional incised slab from Excavation 5 at Wonderwerk Cave that they attribute to the Middle Stone Age, and which they identify as intentionally marked.

Given the amorphous and unclear nature of these surface incisions, it was deemed necessary to undertake an in-depth investigation in order to determine whether they represent intentional versus natural modifications. Given that it is a non-destructive, high-resolution 3D imaging technique suitable for otherwise impermeable materials, NT offers an innovative and appropriate method for a study of this kind.

This study has added importance, given the co-occurrence of several unusual features in the archaeological assemblage associated with the incised slabs in Excavation 6: (i) the absence of a complete knapping sequence, such that is likely that some of the flaked tools and bifaces were produced elsewhere and introduced into Excavation 6; (ii) the fact that the bifaces are of variable size, rather than the small size expected under the strict definition of the Fauresmith (Porat et al. 2010); (iii) the presence of a large unifacially flaked blade that has no clear parallel in other Fauresmith assemblages; and (iv) the presence of quartz crystals and small chalcedony pebbles, both representing non-utilitarian manuports that do not naturally occur within the cave. Given that this distinctive assemblage was found at the very back of Wonderwerk Cave, a relatively remote and poorly illuminated zone some 140 m in from the cave entrance, Chazan and Horwitz (2009) proposed that it represented a locality specifically chosen by early hominins for its special sensory properties. The ‘modified’ slabs may then represent another unique component of this collection.

Incised ochre from the Middle Stone Age site of Blombos Cave (Western Cape, South Africa), dated to c. 70 ka, and incised chert nodules from Qafzeh Cave (Israel) and Berekhat Quneitra (Golan Heights), dated to c. 100 and 60 ka, respectively, are currently the earliest widely accepted evidence of intentional marking of materials by hominins (Marshack 1995; Hovers et al. 1997; Henshilwood et al. 2009). There is evidence for grinding of ochre for pigment from Blombos Cave (c. 100 ka) and Pinnacle Point Cave 13b (Eastern Cape, South Africa), dated to 164–91 ka (Watts 2010; Henshilwood et al. 2011). If the Wonderwerk slab incisions are intentional, they would antedate these examples.

MATERIALS

Two ironstone slabs, collected from the slopes of the hill in which Wonderwerk Cave sits, were analysed by NT [External Sample #23 (Fig. 2; 9.9 × 6.8 × 2.4 cm) and External Sample #22...
These slabs serve as ‘standards’ representing natural ironstone slabs that have no anthropogenic context. The archaeological samples examined in this analysis are four ironstone slabs from Excavation 6, selected to represent the range of markings visible on slabs from this context. Slab X149 (7.6 × 6.5 × 3.6 cm) has a series of deep sinuous lines on one aspect. On the basis of the depth of these lines, the irregularity of their distribution and the presence of visible fissures in the rock, it appeared likely that the lines were the surface expression of internal fissures. Slab BB147 (Fig. 3; 10.6 × 7.2 × 4.2 cm) has a grid-like pattern of deep lines on one aspect. The visual identification of fissures in the rock raised the possibility that these lines were the surface expression of internal fissures. Slab W146 (Fig. 4; 6.5 × 4.7 × 2.6 cm) is one of the slabs identified as incised (Chazan and Horwitz 2009). ESEM
examination of this slab showed both a series of intersecting lines as well an area covered by shallow parallel lines (FEI XL30 environmental scanning electron microscope; Fig. 4 (b)). Scanning was under low-vacuum mode using BSE at pressures of 0–1.5 Torr, with nitrogen or water vapour in the microscope chamber for charge neutralization, since this is suitable for solid, dry specimens that do not need to be coated. Image recording was digital, with output to a hard drive. On the basis of visual examination, there are no deep fissures that penetrate this slab. Slab AA149 (Fig. 5; 10.8 × 7.3 × 4.4 cm) has a series of shallow lines that, on the basis of ESEM analysis (Figs 5 (b) and 5 (c)), appear consistent with incised lines; however, visual inspection suggested that there might be thin fissure lines in the rock.

Figure 3  Slab BB147 from Excavation 6. (a) A photograph showing a grid of lines visible on the surface. (b) A cutaway midway through the slab, showing that the lines continue as fissures (visible as white lines) through the slab. (c) Slices at 4, 8, 10 and 12 mm from the surface, showing the persistence of the grid pattern through the slab.
METHODS

Neutron- and X-ray radiography of all six slabs being investigated was carried out at the South African Neutron Radiography (SANRAD) facility, 40 km west of Pretoria, which is hosted by The South African Nuclear Energy Corporation (Necsa). This facility is equipped with a 100 kV X-ray source and utilizes the same digital electronic imaging equipment, and is currently being

Figure 4  Slab W146 from Excavation 6. (a) A photograph showing lines visible on the surface. (b) An ESEM image of lines on the surface of the slab. (c) An image of the surface, generated by NT. (d) A cutaway midway through the slab: the bedding characteristic of BIF is visible, but there are no fissures apparent in this slab.

applied in series, with neutron radiation. Both neutron- and X-ray radiography and tomography investigations were conducted at beam tube No-2 on the beam port floor of the SAFARI-1 nuclear research reactor at Necsa (for a detailed description of the facility and its characteristics, see De Beer 2005).

Tomography imaging entails the taking of many radiographs at different angles of the sample. Therefore, the great power of tomography lies in its ability to unfold this absorption data taken from many different angles and then produce a map of local radiation absorption at all points inside an object. The initial data, which are acquired in the form of intensity measurements, must be converted to projection data, which approximate the line integral of the linear attenuation coefficients characterizing the material within the object. Thermal neutrons, emerging from beam tube No-2, penetrated the slab sample and cast a radiographic image containing information of

Figure 5  Slab AA149 from Excavation 6. (a) A photograph of the slab, showing the position of lines that appear to be incised (red) and a line that is more sinuous and apparently a fissure: the area shown in (b) is indicated by the black box. (b) A detailed view of the lines on the surface: the area shown in (c) is indicated by the black box. (c) An ESEM image, showing the lines on the surface of the slab. (d) A cutaway of the slab at a depth of 3 mm, showing the persistence of the lines to this depth. (e) One of the lines shown in cross-section, with depth measurement indicated. (See online for a colour version of this figure.)
the sample’s internal structure onto a scintillator screen. This screen changes the neutron image into a 2D visible image that can be detected by a CCD camera (1024 × 1024 pixel array), which captures the visual image from the scintillator and displays it on a computer screen. Multiple radiographs of each slab, taken at different angles of rotation, are captured. For scanning of the slabs, a spatial resolution of 100 µm was achieved. This was obtained by rotating the samples through 360° and taking 375 projections with a field of view (FOV) of 10 × 10 cm. The images were projected onto the CCD camera chip with an array of 1024 × 1024 pixels. Computer algorithms and software processing (Octopus software; Masschaele et al. 2007) generated a 3D virtual image, which was visualized through the VGStudio specialized computer software (Volume Graphics 2006).

RESULTS

Because of the density of the raw material, X-ray imaging was not effective at the 100 kV potential available. At this potential, the matrix of the slabs has a relative high X-ray linear attenuation coefficient, of the order of 1.25 cm\(^{-1}\) and thus no penetration of X-rays through thick samples is possible when Fe-rich materials with a high X-ray attenuation of 12.1 cm\(^{-1}\) are embedded in the matrix of the sample. However, NT produced excellent images, due to the fact that the linear attenuation coefficients of neutrons for the matrix- and Fe-stone-rich areas are 0.19 cm\(^{-1}\) and 0.73 cm\(^{-1}\), respectively, and allow easy penetration of neutrons through relatively thick samples. The results showed that NT was able to clearly identify fissures, both in cases where lines are visible on the surface and in cases where there is no surface expression of internal fissures. NT was also able to identify one archaeological case where lines on the surface of a slab were not associated with internal fissures.

The two external samples (from the hillside) both show clear evidence of internal fissures. In the case of external Sample #23 (Fig. 2), no lines were apparent on the surface on the basis of visual inspection, but NT showed multiple, irregular internal fissures. Cutaways show that the cracks propagate from the midplane of the slab out towards the surface, resulting in an increase in fissure lines moving from the midplane (Fig. 2 (c)) towards the surface (Fig. 2 (d)). Tomography also allows for quantitative analysis and, as illustrated in Figures 2 and 3, the fissures are 0.1 mm or less in width, with straight edges.

NT analysis of Slab X149 from the excavation clearly shows that, as expected, the lines visible on the surface continue as fissures well into the slab. The fissures do not travel the entire thickness of the slab but, rather, appear to propagate within the slab, increasing in number as one moves outwards towards the aspect with lines on the surface.

Slab BB147 (Fig. 3) from the excavation shows a very clear pattern of deep lines, which show a degree of regularity in layout. The very first neutron tomogram of the lines raised the possibility that the cracks in the sample could be filled with water, as water is a high neutron scatterer. The sample was dried in an oven for 2 days at 50°C and scanned again. The white lines were still present, as bright as the scan before heating. NT clearly shows that the lines on the surface of this slab are actually cracks that run through the entire slab. Figure 3 (c) shows a series of slices taken along the plain of the face of the slab. These slices show that the orientation of the lines remains consistent to a depth of 10 mm from the surface and there is no real change in the density of fissure. A graphic summary of this data is shown in Figure 3 (b), in which the NT virtual volume of the slab is cut away to reveal the interior. The continuation of the lines through the body of the slab can be seen here in three dimensions. These results are inconsistent with surface incisions by hominins, and it is clear that the lines on the surface of this piece are the result of internal fissures within the ironstone.
Slab W146 is one of the pieces suspected of being incised (Fig. 4). Here, NT analysis clearly picks up the bedding of the banded ironstone but does not detect any internal fissures in the slab (Fig. 4 (d)). NT analysis of Slab AA149 produced more ambiguous results. The bedding of the slab is clearly apparent (Fig. 5 (d)) and the lines are clearly apparent on the surface. A shallow cutaway shows the lines continuing to a depth of 3 mm, but not deeper (Figs 5 (d) and 5 (e)). However, the quality of the image does not allow clear determination of whether these are incised lines or cracks in the material.

DISCUSSION

Tomography is not a chemical quantitative analytical tool and thus it is not possible to determine the chemical composition of the white lines that correspond to fissures in the slabs through radiation imaging. The lines show up white in the neutron tomograms and thus indicate higher thermal neutron absorbing elements than the total matrix. Due to the drying procedure used in this analysis, we do know that there is no free water in those cracks, but certainly there can be bound hydrogen or other elements with neutron attenuations larger than that of Fe in the matrix, which allows for the high attenuation. This study also raises interesting questions about the propagation of fractures in banded ironstone. In two cases (External Sample #23 and X149), the fissures appear to propagate outwards from within the slab, becoming denser towards the surface. The bedded nature of the material appears to result in a lack of symmetry in the propagation of fissures and it might be that fissures are bounded by bedding planes. Alternatively, the fissures may relate to ancient shrinkage cracks located within the chert mesobands, which became filled with fine-grained iron minerals in a chert matrix (Beukes 1984), or they may represent fissures filled with quartz crystals and carbonate (Hanekom 1966, 127).

This study has shown the important contribution of neutron tomography to the analysis of surface markings on ironstone slabs found in Wonderwerk Cave, by providing a method with which to distinguish surface markings that are the expression of natural, internal fissuring, and so exclude these pieces from further investigations relating to hominin symbolic behaviour. The results show that in the case of BB147, the grid pattern on the surface of the slab is the continuation of fissures that run through the entire piece, and thus are not the result of hominin action. In the case of W146, although one surface is covered with lines, there are no internal fissures. This result does not confirm that these are in fact lines incised by humans, since other natural processes might have caused the patterns evident on the surface of the slab. Notably, glacial striations often produce a dense network of lines such as those found on slab W146 (see, e.g., De Wit 2004, fig. 9; Eriksson et al. 2006, fig. 11b). The density of lines on the surface of W146 is consistent with abrasion that might have resulted from grinding to produce pigment. The use of ochre for this purpose is well documented in the Middle Stone Age of Blombos Cave and Pinnacle Point (Watts 2010; Henshilwood et al. 2011).

The ability of NT to create 3D images of the internal structure of dense material has other potential applications for Palaeolithic archaeology. This investigation opens the door to the possibility of examining controversial examples of modified stones, such as the Tan-Tan or Berekhat Ram figurines, to determine whether the lines seen on the surface are actually the expression of internal fissures (Marshack 1997; d’Errico and Nowell 2000; Bednarik 2001). As illustrated here, SEM examination, as undertaken on the Berekhat Ram object, only provides a high-resolution image of the object’s surface, while NT offers examination of all depths—from its innermost core to the surface.
Another possible application may be in the study of stone tool manufacture. NT has the potential to allow an exploration of the fracture planes that develop in cores during knapping, which are otherwise not visible. The same method also holds promise for detecting microfractures that have developed in stone tools due to use. This data could complement insights from use-wear analysis, which is limited to surface features related to abrasion.

As in the case study described here, one of the strengths of tomography is that it can be applied to both archaeological artefacts and experimental control samples. Most importantly, it is a non-invasive method, permitting the researcher an 'insider's' view of the material being studied.

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