Archaeomagnetic evidence for climate change at Sibudu Cave

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ABSTRACT

In situ magnetic susceptibility (MS) measurements were undertaken on the north, south and east section walls of the trial trench in Sibudu Cave, KwaZulu-Natal, South Africa. All three sections show similar down-section variations in MS. Laboratory-based mineral magnetic measurements on sub-samples identified two major mineral magnetic zones (MMZB and MMZA). MMZB consists of coarser grained ferrimagnetic minerals and a larger proportion of anti-ferromagnetic haematite from spalling of the sandstone rock shelter during the arid, cold conditions of Oxygen Isotope Stage 4 (OIS 4). MMZA, which incorporates all layers from P1 (~60 ka) to BSV and BSS (~1100 AD), is dominated by fine- to ultra-fine-grained ferrimagnetic minerals (magnetite and maghaemite) that reflect the input of derived soils by aeolian activity. MMZA can be divided into three broad Climatic Zones (CZ3, CZ2 and CZ1) that reflect changes in the concentration of ferrimagnetic minerals during three age clusters. These are ~60 ka in OIS 4 and ~50 ka in OIS 3 and ~1100 AD in OIS 1. Optically stimulated luminescence (OSL) dating of the Middle Stone Age (MSA) sequence suggests hiatuses between the age clusters. Small-scale oscillations of MS in the sequence are thought to be due to varying amounts of intermixed anthropogenic material from hearths. Burnt material is identifiable by a unique mineral magnetic signature similar to that of burnt material from other archaeological sites in South Africa, but unlike that in other areas of the world. This is due to the long-term weathering and natural burning of the South African landscape. The transitional layers between OIS 4 (MMZB) and OIS 3 (MMZA) are associated with gypsum nodule formation that was probably post-depositional. It may have occurred during moister periods of climatic warming when no deposition took place in the Sibudu profile.

KEY WORDS: archaeomagnetism, mineral magnetism, OIS 4, 3 and 1, Sibudu Cave.

INTRODUCTION

Sibudu Cave is a sandstone rock shelter above the Tongati River in KwaZulu-Natal. Archaeomagnetic investigations examined sediment input and alteration in an attempt to reconstruct climate change and anthropogenic activity.

Archaeomagnetism is the study of the magnetic properties of archaeological sites and artefacts. In the past this term was mainly used to refer to the study of geomagnetic secular variation and its use for dating archaeological deposits and materials. However, due to recent advances in geomagnetism, the term has been expanded to include palaeomagnetism, environmental magnetism, mineral (rock) magnetism and certain geophysical exploration and survey techniques. The methods of mineral magnetism have, over the last 10 years, been increasingly used on archaeological sites for a variety of applications including taphonomy, sediment-source tracing, and environmental analysis (Dalan & Banerjee 1998; Herries & Latham 2003; Moringa et al. 1999; Peters et al. 2001).

Mineral magnetism is the magnetic character of sediments derived from the concentrations and grain-size of the magnetic minerals they contain; it is distinct from palaeomagnetism, which is the study of the magnetic direction fossilised within a rock by the Earth’s magnetic field at the time of the rock’s deposition or alteration. Thus, for mineral magnetic studies, samples need not be oriented and can be collected as a long core, if sediments are consolidated enough, or as individual samples in standard
archaeological sample bags or palaeomagnetic cubes—although individual samples result in a loss of stratigraphic resolution compared to continuous cores.

The frequency, size and shape of magnetic minerals determine the ease with which material can be magnetised by an external field. This is known as magnetic susceptibility (MS); it simply indicates the amount of Fe-bearing minerals present within a sample. It is the most widely-used environmental magnetic parameter in palaeoclimatic reconstruction.

South African cave sediments mainly comprise ferrimagnetic minerals with strong positive magnetic force, such as magnetite and maghaemite. Sometimes, however, they are in such small concentrations that the sediments are dominated by less magnetisable (canted) anti-ferromagnetic minerals with weak positive magnetic force, such as haematite and goethite (Herries 2003). Minor paramagnetic minerals (only magnetic within an applied field), such as clay minerals (for example, kaolinite) containing Fe$^{2+}$, also have a minor magnetic effect (Schreiner et al. 2002), while diamagnetic minerals might dilute the magnetic signal as well. Detailed in situ MS measurements of multiple sections can quickly identify the potential of a site for environmental analysis by identifying bulk changes in iron-bearing minerals. However, to understand fully the magnetic mineralogical changes, a suite of mineral magnetic measurements needs to be taken. Other analytical techniques for characterising mineralogy can most often not be used due to the small amounts of magnetic material within the samples. By applying magnetic fields in a variety of different ways the mineral type, grain-size and concentration can be calculated for an assemblage of grains within a soil or cave sediment. Previous magnetic-climate studies have mainly focused on windblown loess/palaeosol sequences (Maher & Thompson 1995) and lake sediments (Peck et al. 2004).

Preliminary archaeomagnetic work carried out at Sibudu is presented here; magnetic analyses are described and sediment alteration through time is examined in the light of changes in palaeoclimate and fire use.

**Magnetism and Palaeoclimate**

Mineral magnetic analysis of sediment sequences can reveal a climatically driven signal for a number of reasons. Rock containing primary-reduced iron (Fe$^{2+}$) is broken down by weathering processes and oxidised to Fe$^{3+}$. This primary and secondary amorphous iron is transformed by various processes into secondary iron oxides (such as magnetite, maghaemite and haematite), hydroxides (such as goethite) and sulphides (such as pyrrhotite). Pedogenic processes such as fermentation, biologically-induced mineralisation and induced hydrolysis (Maher 1998) in the topsoil convert primary and secondary iron into magnetite, with later oxidisation to maghaemite through oxidisation/reduction cycles (Maher 1998; Tite & Linnington 1975). This is known as pedogenic enhancement and it produces a dominance of maghaemite in highly weathered soils. With prolonged weathering, this process may cause the formation of haematite and goethite. The degree of pedogenic enhancement is controlled by the local lithology, where different iron oxides, hydroxides and sulphides may already coexist with amorphous iron. In igneous landscapes magnetite is the dominant iron oxide, whereas sedimentary rocks may contain significant haematite. The greatest enhancement is often seen in rock types that do not contain large amounts of primary iron oxides (Shenggao 2000).
In Chinese loess/palaeosol sequences, MS can distinguish between un-weathered loess deposited during glacial periods (low MS values) and the in situ weathering and pedogenic effects seen in palaeosols (high MS values) that formed in interglacial periods (Liu et al. 1999). Maher and Thompson (1995) suggest that, in the Chinese example, maximum MS values (greatest pedogenic enhancement) correlate well with absolute rainfall. However, in certain circumstances, water-logging can result in depletion of magnetic minerals by processes such as gleying. In Alaskan loess this has been correlated to rainfall exceeding a particular threshold (Liu et al. 1999).

Pedogenic formation of ferrimagnets is driven by temperature and moisture; it appears to be favoured in well-drained, poorly-acidic soils on weatherable, Fe-bearing (but often not Fe-rich) substrates in a climate that produces wetting/drying cycles (Maher 1998). Excessively arid, waterlogged or acidic soils display little magnetic pedogenic enhancement. Southern Africa, owing to its strong seasonality of rainfall, is an ideal place to explore the effects of temperature and moisture on pedogenesis. South Africa has two main climate regimes: the Cape region has predominantly winter rainfall whereas most of the country experiences summer rainfall. Regionally specific climatic regimes and environmental differences have an effect on, for example, the soil type, its pH and its moisture content and this, in turn influences soil profiles. Environmental and climatic information must therefore be interpreted in the context of the influence of temperature versus moisture within summer and winter rainfall regimes. Regional variations in the effects of the last glacial cycle can be detected and these are linked to the complexity of climatic belt and monsoonal cycles, which, in turn, have been shown to cause changes in environmental thresholds (Partridge et al. 1998). Variations in the patterning of summer and winter rainfall regimes will thus have occurred in the past.

Mullins (1977) noted that a major mechanism of magnetic enhancement is through heating. Magnetic enhancement through pedogenesis or heating by fire will produce a strong MS signal in soils and sediment sequences. Fire is an important mechanism in the South African landscape because bushfires are common. Ultra-fine-grained magnetite is produced during heating, and maghaemite can also be formed by oxidation on cooling. The age of the South African landscape means that soils and sediments have undergone repeated burning to the extent that they now contain large quantities of ultra-fine-grained, ferrimagnetic minerals due to thermo-magnetic enhancement (Herries 2003). Consequently, many MS changes identified in South African cave sequences are governed by derived soils whose pedogenic alteration and enhancement is affected by variation, not only in rainfall and temperature, but also natural burning cycles. This is different from the Eurasian model of soil formation (Dearing et al. 1996; Maher 1998). A study of grain-size and mineralogy is thus important for understanding MS changes in archaeological deposits.

DEPOSITION AND ALTERATION

Numerous reconstructions of palaeoclimate have relied on mineral magnetism from lakes and marine sequences (for example, Peck et al. 2004; Williamson et al. 1998). Caves are less well studied because of their variable depositional input, their complex stratigraphy and the confusing signal that can be left by human and animal occupation (Ellwood et al. 1997; Herries & Latham 2003).
In loess sequences, pedogenic alteration occurs in situ. In cave sequences, by contrast, the non-anthropogenic deposits represent mainly material that was transformed in exterior soil profiles, eroded and later deposited within the cave, although material is also weathered from the rock in which the cave is located. If sediments are to preserve proxy mineral magnetic palaeoclimatic records after they are deposited in a cave, they must remain unaltered by environmental processes, such as pedogenesis and chemical alteration that continue to occur outside the cave. The degree of preservation will depend on the sediments’ location within the cave, ranging from the deep cave environment to the cave entrance. In some cave entrances and rock shelters, pedogenesis can occur in situ with the development of soil horizons. This is particularly the case in humid environments. However, even in deep cave environments, diagenesis can occur naturally or through anthropogenic processes, in particular, the use of fire. Caves are thus only partially closed systems.

Non-anthropogenic deposition within caves can be of fluvial and/or aeolian origin and both can cause changes in the magnetic mineralogy of the cave sequence. Non-local magnetic inputs to caves can vary in rate, source and grain-size, reflecting wind-speed and direction and changes in stream catchments. Local magnetic inputs vary with changes in the rates of magnetic depletion (loss of iron or conversion to less magnetic minerals), magnetic enhancement within the local soil horizons and erosion and depositional rates into the cave. Deposition can have a dramatic effect on the mineral magnetic sequence, especially if local and non-local input occurs, or if there is a change between these two sources.

Fluvial material is most likely to be derived from the immediate external environment or at least within the cave catchments. The simplest model is one where sediment is derived at a constant rate from local soil profiles developed on a single rock type. Sedimentary input therefore reflects changes in weathering regimes and pedogenic enhancement in external soil profiles and it should be identifiable by changes in the fine-grained ferrimagnetic fraction of the cave sediments. Weathering, erosion and increased pedogenesis occurs during warm periods, producing high MS values. Reduced pedogenesis and low MS values occur during cold, glacial periods. Fluvially introduced, local, authigenic magnetic input is the preferred depositional regime for analysts because it normally originates from the immediate area. It can thus provide good records of local climate change, as was shown at Rose Cottage Cave, in the Free State of South Africa (Herries & Latham 2003). In contrast, aeolian input can come from much farther afield than the immediate catchment. It is therefore more likely to exhibit mineralogy derived from non-local soil types or rock strata. Aeolian sequences in loess can, for example, contain MS changes attributable to variation in wind speed and direction during glacial and interglacial cycles (Begét 2001), with derived soils brought from different rock stratas with varying mineral magnetic signatures.

Another factor that has to be taken into account in cave sequences is material derived from the interior of the cave: spalling of the cave roof and walls adds to the derived sediment. The effects of this accumulation will depend on the mineralogy of the host bedrock. Non-magnetic detritus such as quartz can be introduced from the host rock and this will dilute the magnetic signal. Primary magnetic oxides may also be introduced. Diluting effects on the magnetic signal can be reduced by screening of the coarse-grained fraction or by magnetic extraction methods. Increased roof-spalling will
sometimes occur during cold, glacial periods as the result of freeze-thaw action, but it may also occur in wet or windy climates where there are increases in weathering and erosion (Butzer 1978).

Cave entrances often do not act as closed systems because human and animal behaviour can have complex mineralogical and stratigraphic effects (Woodward & Goldberg 2001). The most pronounced anthropogenic effect on magnetic mineralogy comes from making fires. In the majority of cases, heating of sediments has a localised effect and such sediments can be avoided during sampling for the reconstruction of environments. However, it is important to identify fireplaces by using a suite of mineral, magnetic and other comparative analyses. Magnetic measurements are sensitive to fire histories because burning causes the transformation of trace iron within the fuel source itself or/and within sediments associated with the heating (Peters et al. 2002). Changes between different minerals and different grain sizes can occur; these are dependent on the temperature, longevity and atmosphere of heating (Herries & Kovacheva in press). As with magnetic enhancement in soils, the effect of heat on sediments is determined primarily by their initial magnetic makeup.

In most cases, heating causes the formation of fine- to ultra-fine-grained ferrimagnetic particles, such as magnetite and maghaemite (Peters & Thompson 1999), which produce elevated concentrations of magnetic minerals and relatively high MS. The grain sizes formed by heating can normally be detected easily by frequency dependence MS (Walden et al. 1999). South African cave sediments already contain large amounts of fine to ultra-fine grains. In some instances these appear to cause problems with the MS method because of the formation of high concentrations of ultra-fine super-paramagnetic grains (Herries 2003). Thus, burnt material has a unique magnetic character with high MS and low frequency-dependent MS values. Burnt sediments from Rose Cottage Cave and Pinnacle Point Cave 13b (Western Cape) all show this character. Different fuel sources can often be determined from the MS of ash residues. A number of factors can affect the thermo-magnetic enhancement of ash, including the type of combustion process used, contaminant mineralogy and fuel chemistry (Peters et al. 2002). Mineralogically complex fuel-ash is normally confined to fuels such as coals and peat. Pure wood-ash, which would be expected to dominate MSA hearths, should cause no thermo-magnetic enhancement because wood itself is non-magnetic, but magnetic enhancement does occur due to small amounts of burnt sediment within the ash.

Mineral magnetic studies thus examine the nature of the sedimentary magnetic input into the cave and the various processes that have acted on that material before and after its deposition in the cave.

STRATIGRAPHY AND SAMPLING

Layers YA2 to BSS in the Sibudu Cave trial trench are the focus of this study. YA2 has an age of ~60 ka and BSS has a calibrated age range of AD 1030–1130 (Pta-8015, Pta-9196, Pta-9202), but there is not a continuous sequence between these two ages (Jacobs et al. submitted; Wadley & Jacobs 2004, this volume). The Sibudu layers analysed here appear to have been deposited at the end of Oxygen Isotope Stage 4 (OIS 4) (at ~60 ka) and during OIS 3 (~60 ka and ~50 ka) and OIS 1 (~1100 AD). There was no deposition in OIS 2. The uppermost layers BSS and BSV contain an Iron Age (IA) occupation (Wadley & Jacobs 2004). No Later Stone Age layers have been identified
(Wadley & Jacobs 2004, this volume) and so the IA horizons lie directly on the most recent MSA layers, which, in the trial trench, have ages of ~50 ka (Wadley & Jacobs this volume). The MSA layers are often only a few centimetres thick and are distinct and highly coloured. Multiple occupation horizons have been identified in the trial trench, which has reached a depth of over three metres. However, few horizons cover the entire excavation grid, which measures 21 m². A number of depositional hiatuses are suggested by the age clusters (Jacobs et al. submitted; Wadley & Jacobs this volume). Evidence for supposed heating events occurs throughout the deposits, some as definable hearths and others as ash-spreads and associated burnt horizons (Schiegl et al. 2004).

Since enhanced values of MS can be caused by a variety of mechanisms, including burning and pedogenesis, the methodology reported here aimed to identify their discrete MS signals by comparing sediment from established hearths with that from correlatable positions on each of three section walls of the trial trench. The Sibudu layers are not only thin, but also friable, which makes collection from every layer for laboratory analysis difficult. It was thus decided to undertake in situ magnetic susceptibility measurements in the trial trench to identify whether the same trend in MS could be established for several separate sequences. Small sub-samples of sediment were also extracted for laboratory analysis to confirm the origin of magnetic mineralogical change throughout the MSA section from YA2 (~60 ka) to MOD (~50 ka). Additional samples were taken from interesting layers, which were then analysed for in situ MS.

Samples were taken using a combination of plastic cubes, sample bags and bulk excavation. In the laboratory the samples were air-dried, crushed with a pestle and mortar, homogenised and packaged into measurement cubes. Tests were performed to obtain the magnetic mineralogy of the samples (after Walden et al. 1999): these include frequency-dependent magnetic susceptibility (X_{FD}, \%), low-temperature magnetic susceptibility (RS ratios), saturation anhysteretic remanent magnetisation (SARM), saturation isothermal remanent magnetisation acquisition curves and backfields (SIRM and S-ratios), hysteresis loops and thermomagnetic curves (Curie points: Tc). Most of

![Fig. 1. In situ magnetic susceptibility (MS [SI]; Standard International Units) showing similar trends for layers YA2 to RSp from the east, south and north section walls of square B5 in Sibudu Cave.](image-url)
the tests aimed to identify ferrimagnetic versus anti-ferromagnetic minerals on the basis of their magnetic hardness or coercivity. The most common ferrimagnetic minerals (soft, with low coercivity) are magnetite and maghaemite; the most common anti-ferromagnetic minerals (hard, with high coercivity) are haematite and goethite. Some tests aimed to identify the particular magnetic grain-size of the various minerals from ultra-fine, single-domain or super-paramagnetic grains to larger, single-domain grains and coarse-grained, multi-domain grains.

MAGNETIC MINERALOGY RESULTS

Magnetic records from three section walls (the north, south and east walls of square B5 in the trial trench) were compared and combined. In Figure 1, in situ MS measurements show a similar trend for all three sections between layers YA2 (at 300 to 290 cm) and RSp (at 220 cm).

Laboratory-based mineral magnetic measurements (Fig. 2a) show a decrease with depth in the frequency-dependent MS ($X_{\text{FD}}$ %) in fine- to ultra-fine-grained (viscous) ferrimagnetic minerals. A drop in $X_{\text{FD}}$ % occurs between layers P1 and G1 from a mean of 4.8 % above layer G1 to 2.0 % below G1 (Fig. 2a). A slight difference in mean $X_{\text{FD}}$ % can also be seen between layers RSp and SPCA (means of 5.1 % and 3.4 %, respectively).

A comparison of magnetic susceptibility at room temperature and at liquid nitrogen temperatures (see the RS ratio profile on Fig. 2b) shows the quantity of ultra-fine-grained, super-paramagnetic ferrimagnetic minerals in the samples compared to larger,
fine-grained ferrimagnetic minerals. The low-temperature MS measurements show a large difference in RS ratios between layers P1 and G1, but no change between the RS ratios of layers RSp and SPCA. This shows that the ultra-fine-grained, superparamagnetic grain-size content of the zone between P1 and SPCA remains constant and is the dominant component of the MS signal in this upper section. Below layer P1 the magnetic mineral signature changes, with a reduction in the ultra-fine-grained ferrimagnetic mineralogy, and overall is much more variable between layers. The large reduction in both grain sizes below layer P1 is due to a decrease in pedogenic enhancement outside the rock shelter where the grain sizes are formed; and possibly also to a change in sediment source. Above P1 the magnetic mineralogy does not show great variability; this suggests that the sediment input mechanism and source may have been relatively constant and that small changes in pedogenesis occurred, together with variation in the amount of magnetic material deposited.

A series of coercivity measurements enable an examination of the acquisition and stability of remanence that the samples possess. During IRM acquisition, saturation of either very fine-grained (viscous single-domain grains) or very coarse-grained (multi-domain grains) ferrimagnetic minerals occurs at 100mT, while complete saturation of ferrimagnetic minerals occurs at 300mT. Above 300mT only the anti-ferromagnetic component contributes. Samples throughout the sequence are dominated by ferrimagnetic minerals (magnetite and maghaemite), but the less magnetic anti-ferromagnetic minerals (haematite and perhaps goethite) also exist, as shown by non-saturation of IRM backfields (see the S-ratio on Fig. 2c). Coercivity measurements (the -100mT and -300mT profiles in Fig. 2c) show that the mineralogy is relatively constant from P1 (at 280 cm) to MOD (at 170 cm). Furthermore, the mineralogy is dominated by ferrimagnetic minerals in a variety of grain sizes. However, S-ratios (-100mT) confirm that a slightly higher proportion of viscous single-domain or multi-domain ferrimagnets occurs in layers RSp to MOD (as shown by the higher mean values of -0.8) than in layers P1 to SPCA (mean -0.9). However, the presence of multi-domain grains is not suggested by other tests. Some variation is also seen in anti-ferromagnetic material as shown by variation in the S-ratio (-300mT). At the base of the sequence, YA2 to G1, the concentration of ultra-fine-grained ferrimagnetic minerals decreases, as shown by both X_{rpa} % and RS (Figs 2a, 2b). A greater contribution from coarser ferromagnetic minerals is shown by a change in S-ratio (-100mT) (Fig. 2c). Anti-ferromagnetic minerals also increase, as shown by the change in the S-ratios (-300mT) from mean values of -0.94 in layers above P1 and -0.79 below G1 (Fig. 2c).

Thermomagnetic curves were produced to identify the Curie Point (the temperature at which magnetic ordering is randomised) of the dominant mineral in the samples. These show a range of behaviours (Fig. 3). A hearth from MOD is dominated by magnetite which undergoes no alteration on heating to 700°C (Fig. 3a), showing that this transformation probably occurred during ancient heating to a temperature of at least 450°C. Thermomagnetic curves show that the base of the sequence is dominated by maghaemite (see YA1 in Fig. 3d), while layers higher in the sequence are dominated by magnetite (see SPCA and BM in Figs 3b, 3c). Nonetheless, there is some variation between layers and both magnetite and maghaemite occur in most layers. Burnt layers are dominated by magnetite or thermally stable maghaemite. These data are consistent with information from the palaeomagnetic directions preserved within burnt rocks; and
suggest a temperature of between 400°C and 500°C for heated rocks from various Sibudu layers (work in progress).

Eurasian studies of hearths suggest that an increase in MS is normally followed by an increase in $X_{\text{FD}}$ %, but the opposite occurs at Sibudu. Hearths in Sibudu have a distinct character with very high MS values (up to 3555 SI for sample Sn), but low $X_{\text{FD}}$ % values (less than 3%) (Table 1). This pattern of behaviour is repeated at other archaeological rock shelter and cave sites in South Africa, such as Rose Cottage Cave and Pinnacle Point. This is possibly due to the high proportion of viscous grains present in the samples. These lie outside the range recorded by the magnetic susceptibility equipment, but lie completely within the ultra-fine, super-paramagnetic grain-size range. The formation of these super-paramagnetic grains seems to be due to the high proportion of viscous grains in the samples due to repeated long-term burning of the South African landscape (Herries 2003). This behaviour makes it quite easy to identify burnt material at the sites.

Fig. 3. Thermomagnetic curves for selected samples from Sibudu Cave showing (a) magnetite from a hearth in layer MOD (Curie Point of 580°C; note higher magnetisation); (b) magnetite in layer SPCA (MMZA; CZ2; Curie Point of 580°C); (c) magnetite in layer BM (MMZA; CZ3; Curie Point of 580°C); (d) maghaemite in layer YA1 (MMZB; CZ4; Curie Point of 620°C and drop in magnetisation on cooling). The three curves that are not parts of a hearth show high alteration. Cooling curve ends at 100°C.
The full sequence of in situ MS measurements (Fig. 4) shows an increasing general oscillation from the base to the top of the sequence, with small steps at layers G1 to P1, SPCA to RSp and MOD to BSV. When the magnetic susceptibility behaviour for the entire sequence is examined and compared to the changes in magnetic mineralogy, different mineral magnetic zones, with different mineral magnetic signatures, can be identified. Only the large differences in MS between G1 and P1 and between MOD and BSV (Fig. 4) are due to major changes in sediment input and sourcing. The lowest group of layers, YA2 to G1, have low proportions of ultra-fine ferrimagnets, mainly maghaemite, and high proportions of anti-ferromagnets. The layers between P1 and MOD have much higher proportions of ultra-fine ferromagnets (super-paramagnetic and viscous single-domain grains), both magnetite and maghaemite, and lower anti-ferromagnetic (haematite) material. The most marked change in the MS signal in the upper layers is between layers SPCA and RSp and this is probably also climatically significant with a minor change in ferrimagnetic content.

**DISCUSSION**

The overall trend for the site (Fig. 4) is an oscillating, but steady increase in magnetic susceptibility MS values from the base to the top of the sequence. This is due to a decrease, with depth, in fine- to ultra-fine-grained ferrimagnets. Three clusters of ages occur in the sampled section (Jacobs et al. submitted; Wadley & Jacobs 2004, this volume): layers YA2 to SPCA have an age of ~60 ka; layers YSp/RSp to MOD have an age of ~50 ka; and layers BSS and BSV have an age range of AD 1030–1130. The sequence thus divides by age cluster into distinct zones; further subdivision can be made on the basis of the mineral magnetic analysis. Table 2 shows the relationship between groups of layers, ages, climatic zones and mineral magnetic zones.

**Mineral Magnetic Zone B (MMZB)**

The deeper levels (YA2 to G1) sampled here have very low MS values (mean 41 SI) and distinctly different magnetic characteristics from the upper sequence. Mineral magnetic analysis suggests a high proportion of coarser grained, single-domain ferrimagnetic minerals and considerable influence from remanence-bearing, non-ferrimagnetic minerals. In South African soils, haematite often occurs in an amorphous or ultra-fine-grained state and acts as a pigment causing bright-red colouration of the sediments (Herries 2003). In this state, haematite does not hold a remanence and has no

### TABLE 1

<table>
<thead>
<tr>
<th>Layer</th>
<th>K_{LF} (10^{-5}) SI</th>
<th>X_{FD} %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hearth White Ash</td>
<td>1100</td>
<td>2.48</td>
</tr>
<tr>
<td>Hearth Brown Ash</td>
<td>601</td>
<td>3.00</td>
</tr>
<tr>
<td>Hearth Orange Ash</td>
<td>991</td>
<td>2.87</td>
</tr>
<tr>
<td>Sn Lower</td>
<td>1757</td>
<td>2.56</td>
</tr>
<tr>
<td>Sn Upper</td>
<td>3555</td>
<td>1.62</td>
</tr>
<tr>
<td>White above Ch 3</td>
<td>2185</td>
<td>1.88</td>
</tr>
</tbody>
</table>

A comparison between low frequency magnetic susceptibility (K_{LF}) and frequency-dependent magnetic susceptibility (X_{FD} %) for excavated hearth samples and suspected hearth layers from the trial trench at Sibudu. Burnt layers all display high K_{LF} and low X_{FD} %.
effect on IRM curves, thus the haematite identified in the experiments reported here appears not to have come from derived soils. The sandstone into which Sibudu Cave has been eroded belongs to the Newspaper Member of the Natal Group (Bell & Lindsey 1999). This group consists of well-bedded, reddish-grey sandstone beds that are well-cemented with low porosity, together with subordinate siltstones, shale and conglomerates. The sandstone contains a large amount of feldspar and as such it can be considered arkosic sandstone. The sandstone itself is very weak magnetically. Thermo-magnetic curves and demagnetisation spectra suggest that haematite is the main magnetic mineral present, forming grain coatings and acting as partial cement. The Natal Group supplies parent material to sediment and soil horizons; mechanical breakdown of the rock shelter will therefore add to the percentage of anti-ferromagnetic, remanence-
bearing haematite in the rock shelter sediments, as noted in the layers below G1. MMZB is thus thought to reflect haematite, derived, first, from spalling of the sandstone shelter and, secondly, from a mixed aeolian sediment source containing small concentrations of fine-grained maghaemite from local soil horizons.

**Mineral Magnetic Zone A (MMZA)**

The sequence above G1 (P1 to BSV) is characterised by a high proportion of ultra-fine magnetite and maghaemite, derived from local soil horizons outside the rock shelter. Oscillations occur in the sequence; these are probably related to the intermixing of anthropogenically altered material and are not thought to be completely due to a climatic signal. At the top of MMZA a large step in MS is seen from layer MOD to layers BSS and another step is seen between layers SPCA and RSp. No major mineralogical change is seen and the increase in MS is mainly due to an increased concentration of fine-grained ferromagnetic minerals. The steps coincide with the hiatuses between the age clusters.

**Climatic implications of MMZB and MMZA**

Magnetic mineralogy parameters indicate a pronounced shift from higher coercivity magnetic minerals in MMZB to lower coercivity minerals in MMZA. Studies of marine and lake sediments around Africa have documented an increase in higher coercivity magnetic minerals in colder, glacial sediments (Bloemendal & DeMenocal 1989; Peck et al. 2004). During cold, arid periods it is thought that strong winds carry material from farther afield. Such events would have been compounded at Sibudu Cave during very cold periods because increased spalling of the host rock would have caused the addition of even more high-coercivity haematite. No fluvial action is suggested at Sibudu (Pickering this volume) and non-anthropogenic deposition in the rock shelter is mainly due to aeolian activity, along with weathering of the host rock. Thus the sequence at Sibudu is less complex than lake sequences where material deposited is derived not only from long-distance aeolian activity, but also from local fluvial activity. The non-anthropogenic deposits thus suggest variations between cold glacial versus warmer interstadial conditions; the evidence is contained in the magnetic mineralogy altering due to changing wind speed and direction, the transport of soils from different sources and distances, local weathering regimes and changing pedogenesis in a single source outside the rock shelter. However, due to frequent burning of the South African landscape, as discussed earlier, the effects of pedogenesis may be much reduced. Changes in all these mechanisms are partially responsible for the large change observed between MMZB and MMZA. Taken as a whole, the mineral magnetic evidence can be interpreted as a change from a cold, dry, glacial phase (MMZB) to a warmer, moister, interstadial phase (MMZA). Changes in aeolian input are mostly responsible for the smaller-scale changes seen during both MMZB and MMZA.

The repeated, though intermittent, occupation of Sibudu Cave (Wadley & Jacobs this volume) and the significant anthropogenic content of the sediments (Pickering this volume) suggest that some variations in the MS signal are due to altered sediments and ash throughout the rock shelter deposits. However, *in situ* MS values of the three section walls from Sibudu Cave all showed similar trends and these imply that small-scale diagenetic effects, local disturbances and anthropogenic effects were not sufficient to
influence the overall signal, which appears to have a climatically controlled component from aeolian input. However, the anthropogenic signal cannot be completely removed from the MS curve as it is intermixed with aeolian sediments. Therefore only large changes in mineralogy or MS are securely interpreted as a climatic signal.

Climatic Zones (CZ4, CZ3, CZ2, CZ1)

MS can be used as a proxy record for climate and it has been shown to correlate well with other data such as oxygen isotope records. The mineral magnetic data clearly point to MMZB and MMZA as representatives of two distinctly different climates (Table 2). MMZB appears to lie within the cold glacial climate represented by OIS 4 and it is placed here within Climatic Zone 4. MMZA is largely encompassed by the interstadial environment of OIS 3. The MS oscillating signal in the long sequence of MMZA layers (P1 to BSS) may be thought of as representing a continuously fluxing climatic signal, which represents an overall warming in climate within OIS 3. These layers can be further separated into three broad periods, or climatic zones, based on a combination of the ages of the deposits, the presence of hiatuses and on the peaks and troughs in mean values of MS. Two subdivisions seem possible within OIS 3, while the youngest, Climatic Zone 1, belongs to OIS 1 (Table 2).

Climatic Zone 4

MMZB (layers YA2 to G1) represents the cold, glacial climate of OIS 4 and it is classified here as Climatic Zone 4 (CZ4) in the Sibudu sequence. These layers have a weighted mean age of 60.1 ± 1.5 ka (Jacobs et al. submitted; Wadley & Jacobs this volume) and this suggests that they were formed close to the end of OIS 4. A major change in magnetic mineralogy occurs above layer G1 (layer P1) and this is thought to represent the OIS 4 to OIS 3 transition. OSL ages (Jacobs et al. submitted; Wadley & Jacobs this volume) do not suggest a significant hiatus between G1 and P1. The ages

<table>
<thead>
<tr>
<th>Mineral Magnetic Zone</th>
<th>Oxygen Isotope Stage</th>
<th>Climatic zone</th>
<th>Age cluster</th>
<th>Sibudu layers sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMZA</td>
<td>OIS 3</td>
<td>CZ2</td>
<td>~50 ka</td>
<td>MOD, OMOD, OMOD2, RSp</td>
</tr>
<tr>
<td>MMZB</td>
<td>OIS 4</td>
<td>CZ4</td>
<td>~60 ka</td>
<td>G1, Ch2, BG/mix2, YA1, YA2</td>
</tr>
</tbody>
</table>
for these layers are consistent with the ~59 ka age for the OIS 4 to OIS 3 transition from the Vostok ice core (Petit et al. 1999). The Vostok ice core shows a sharp transition from OIS 4 to OIS 3, as appears to be the case at Sibudu.

Other palaeoenvironmental data from Sibudu show noticeable changes between MMZB layers YA2 to G1 and MMZA layers P1 to MOD (see Wadley this volume). There are, for example, conspicuous changes in the types of seeds found in the older layers YA1 to Ch2 and those found in younger layers (Sievers this volume; Wadley 2004). Studies of mammalian communities have shown that fauna from the older layers imply cool, dry, open woodlands while the upper layers have higher frequencies of forest-dwelling species (Plug 2004; Reynolds this volume).

Climatic Zone 3

Layers P1 to SPCA form the first subdivision within MMZA (Table 2). The ~60 ka ages of these layers suggest that the transition from MMZB in OIS 4 to MMZA in OIS 3 is continuous and that it occurred within the ~60 ka age cluster identified by Jacobs et al. (submitted; Wadley and Jacobs this volume). Layers P1 to SPCA have much higher MS values, with a mean of 194 SI, than the underlying MMZB layers, where the mean is 41 SI. Layers P1 to SPCA are thus classified as Climatic Zone 3 (CZ3) (Table 2, Fig. 4).

Within CZ3, a number of oscillations are observed. A distinct double peak occurs at the base of CZ3 and this is also visible in the Vostok ice core; thus, part of the oscillating signal might be a function of climate. However, in the Sibudu sequence it could also be partially a product of anthropogenic variation between layers, although these peaks do not fit this signature. White to yellow nodules in layers Ch2 to P1, which fall within the OIS4 to OIS 3 transition, were identified as gypsum by X-ray Diffraction (XRD) and Fourier Transform Infrared spectroscopy (FTIR). The identification is confirmed by Schiegl et al. (2004) and Schiegl & Conard (this volume). These gypsum nodules could represent a hiatus in the sequence, with post-depositional build-up of gypsum during periods when there was no deposition or occupation. Gypsum (CaSO₄·2H₂O) is formed by a number of mechanisms that involve increased moisture and the introduction of sulphur in some form, perhaps from sea mists, aerosols or from the local rock (pyrite: FeS₂). Identical gypsum nodules form in sea caves at Pinnacle Point. Sibudu is presently located about 15 km from the sea, but the gypsum nodules may have formed from aerosols and sea mists during phases of climatic warming between colder glacial and more interstadial periods. During such transitional warming episodes, moister conditions may have occurred in conjunction with higher sea-levels than those in cold, glacial periods.

Climatic Zone 2

The MSA layers RSp to MOD have a weighted mean age of 49.7 ± 1.2 ka (Jacobs et al. submitted; Wadley & Jacobs this volume) and they have a mean MS value of 352 SI, which is considerably higher than the mean value of the underlying layers in CZ3, but lower than that of the overlying Iron Age strata of BSS and BSV. They show no evidence of a lowering in MS values—as would be expected after ~51 ka, based on isotope data from the Vostok ice core. Gypsum formation occurs in association with layers RSp, OMOD and MOD and this may be associated with moist, warming periods as is suggested by the higher MS signal.
Climatic Zone 1

The uppermost horizons of MMZA (Table 2) contain IA occupations (layers BSS and BSV) with an age range of AD 1030–1130. These deposits are distinct from the underlying ~50 ka MSA layers, but no geological hiatus has been noted, notwithstanding the long archaeological hiatus. The hiatus is represented by the large step in MS values from 365 SI in layer MOD to a mean MS of 675 SI in layers BSS and BSV. The higher MS values for the IA horizons reflect a greater concentration of ferrimagnetic minerals due to the warmer climate of the Holocene (OIS 1).

CONCLUSIONS

Mineral magnetic data from the trial trench of Sibudu Cave suggest that the sequence can be divided into two distinct mineral magnetic zones, MMZB and MMZA. MMZB, the oldest zone that incorporates layers YA2 to G1 with an age of ~60 ka, has low mean MS values (41 SI). It is classified as Climatic Zone 4 (CZ4) and it represents the cold, glacial climate of OIS 4 where there is a low input of fine- to ultra-fine-grained ferrimagnets. Maghaemite is predominant and there is extensive erosion of the haematite-rich, sandstone host rock. The age of ~60 ka suggests that the boundary between OIS 4 and OIS 3 is represented. This is supported by the seamless shift and increase in MS to MMZA at ~60 ka in layers P1 to SPCA.

MMZA incorporates the age clusters ~60 ka, ~50 ka and AD 1030–1130 and is also sub-divisible into three climatic zones, CZ3, CZ2 and CZ1. Layers P1 to SPCA (~60 ka) belong to CZ3, where the mean MS value is 194 SI. Layers RSp to MOD (~50 ka) belong to CZ2, where the mean MS value is 352 SI. The different mean values of MS are caused by varying rates of input of fine-grained ferromagnetic material. These two periods fall within OIS 3 and show an overall warming in climate with relatively brief, small-scale oscillations. CZ3 and CZ2 represent two distinct age clusters separated by a hiatus that is not geologically recognisable (Jacobs et al. submitted; Wadley & Jacobs this volume).

A long hiatus separates CZ2 from CZ1 (Jacobs et al. submitted; Wadley & Jacobs this volume). The IA horizons, BSS and BSV, have an age range of AD 1030–1130 and they belong to CZ1, where the highest mean MS values of 675 SI occur. The mineral magnetic change is due to high concentrations of pedogenic ferrimagnetic material. CZ1 represents the warm climate of our current Holocene interglacial, OIS 1.

Layers with large proportions of anthropogenic material can be identified with mineral magnetic and palaeomagnetic analysis of sediment sub-samples. Well-defined hearths that are easily recognised can and must be avoided in sampling. Notwithstanding such precautions, background anthropogenic indicators may still occur in the MS signal and this will complicate the results. Thus only large-scale trends in mineral magnetic parameters should be viewed as climatically determined. The large, double peak in MS readings at the base of MMZA, and other large-scale trends, are probably not caused by artificial heating from fires because they are repeated in the three separate MS sequences from the site. Furthermore, these MS readings do not fit the pattern of readings (low XFD % and high MS) from burnt material elsewhere in the site. The MS values reported here reflect a partially climatically determined signal. These are caused by changes in sedimentary input
from aeolian activity, differential breakdown of the sandstone host rock due to changes in weathering patterns and changes in pedogenesis caused by the shift between cold, arid glacial periods and warmer, moister interstadials.

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