Ecosystem change during MIS4 and early MIS 3: Evidence from Middle Stone Age sites in South Africa

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1.1 ABSTRACT

Several Middle Stone Age (MSA) site in southern Africa present evidence of environmental changes during Marine Isotope Stages (MIS) 4 and 3 between 70ka and 50ka. Of these, Sibudu Cave, KwaZulu-Natal, has yielded a detailed record of how global-scale climate change events manifest locally. During MIS 4 (70ka to 60ka) conditions were similar to those during the Last Glacial Maximum. During the transition between MIS 4 and MIS 3 at around 60ka the Sibudu environment changed from a predominantly forested community to more open grass/woodland mosaic. Other MSA sites from across South Africa provide complementary palaeoenvironmental proxy data but imprecise dating presents a cross-correlation challenge. Archaeological sites on the western portion of South Africa appear to have been abandoned earlier and for longer than sites in the East, most likely as a result of adverse climatic conditions. Regional scale climate events in southern Africa are driven by ocean/atmosphere interactions, and at this time weakening of the palaeo-Agulhas Current and an eastward shift of the Agulhas Retroflection resulted in lower sea surface temperatures and a corresponding decrease in humidity and rainfall.

Key words: Middle Stone Age, palaeoenvironmental proxy data, MIS 4, environmental change

1.2 INTRODUCTION

The planet is currently warming (Trenberth *et al*., 2007) and climate change modelling is the means by which the impact of this warming is determined. The high level of complexity in ecosystems reduces the skill of models to forecast the future impact of these changes. An alternative approach is to examine past records of global climates where the associated ecosystem responses are documented. Evidence for past global warming change is derived from isotope analysis of marine cores and polar ice cores. The most recent of these global-

scale events took place at the end of the last glaciation commencing approximately 20ka ago and is known as Marine Isotope Stage 2 (MIS 2). The penultimate warming was between MIS 4 (70ka to 60ka) and early MIS 3 (60ka to 50ka), and is the subject of this analysis. While the warming is known to have taken place, little evidence has been presented for the associated terrestrial ecosystem response to this change.

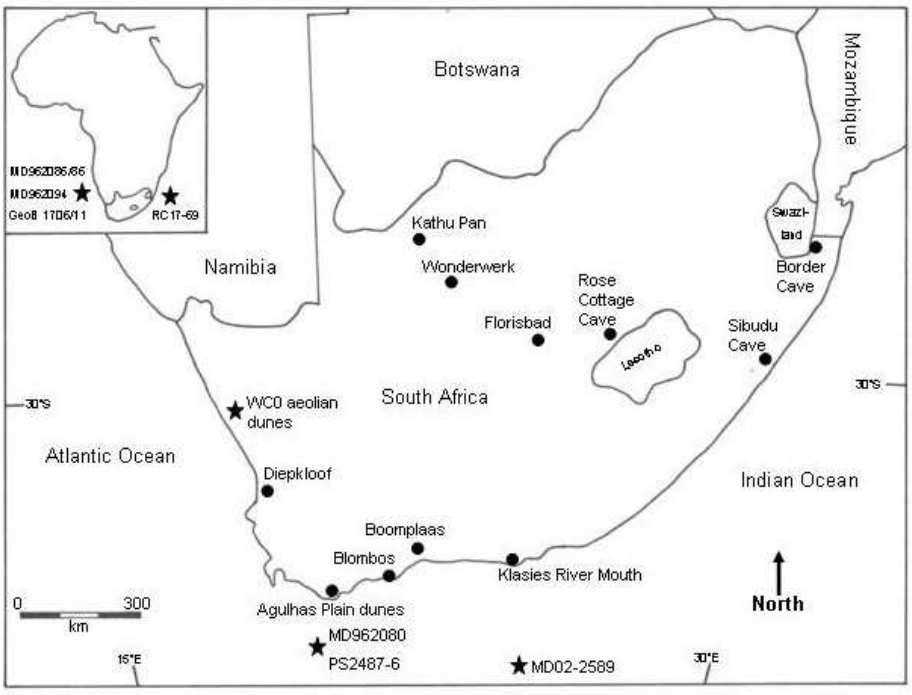

Figure 1. Map of southern Africa showing the locations of Middle Stone Age archaeological sites, deep sea cores and aeolian sediments mentioned in the text**.**

Through multi-disciplinary analysis of cultural, biological and geological material from middle and lower latitude terrestrial sites it is possible to reconstruct local environmental conditions through time. Seven South African Middle Stone Age (MSA) archaeological sites (Fig. 1) provide environmental evidence for MIS 4/early MIS 3. These are Sibudu Cave, Border Cave, Rose Cottage Cave, Klasies River Mouth, Boomplaas Cave, Blombos Cave, Diepkloof Rockshelter and Wonderwerk Cave. Between ~75ka-55ka there was a fundamental change in technological and cultural features compared with earlier and later MSA assemblages (Mellars, 2006; Mitchell, 2002, pp.71-106). The stone tool

industries of this time include the distinctive Still Bay and Howiesons Poort assemblages. Although the Still Bay has ages of ~75ka-70ka (Jacobs *et al*., 2008a, b; Tribolo *et al*., 2005) and the Howiesons Poort dates to between 65ka-60ka (Jacobs *et al*., 2008a, b; Tribolo *et al*., 2005) depending on the site and dating methods, the Still Bay is the older of the assemblages and always underlies the Howiesons Poort. There is associated evidence for modern human behaviour such as the use of composite stone tools, sophisticated hunting techniques and symbolic expressions (Mellars, 2006; Mitchell, 2002). The appearance of the Still Bay and Howiesons Poort in various MSA sites across South Africa is thought to be a response to sharply oscillating climatic conditions during MIS 4 and early MIS 3 (Mellars, 2006, Mitchell, 2002).

The ecosystem responses that took place at the archaeological sites in southern Africa are proxied in several lines of evidence including the macro-faunal, micro-faunal, botanical and sedimentological evidence that is preserved. It is possible that the environmental proxies themselves may be biased. Anthropogenic influences (e.g. choice of firewood), excavation, sampling methods and the differential preservation of material may complicate the situation (Allott, 2005). Nevertheless where distinctive environmental shifts are shown to occur, they should have regional manifestations, and they should be recorded in the other sites.

In this analysis the local and regional records are compared with palaeoclimatic data from a number of sites around the world to obtain a global perspective of climate change at this time. Lake sediments, speleothems, aeolian deposits and archaeological sites have become a source of palaeoenvironmental proxies at a local terrestrial scale. This paper compares records of climate change for the period 70ka to 50ka (MIS 4 and early MIS 3) from a number of ocean cores as well as archaeological, geological and other types of research sites from southern Africa.

1.3 SIBUDU CAVE

Sibudu Cave, located in KwaZulu-Natal, was the most recent of the MSA sites to be excavated in southern Africa, and has the advantages of being well-dated and the subject of multi-disciplinary studies. It has an MSA cultural sequence that contains pre-Still Bay, Still Bay, Howiesons Poort, post-Howiesons Poort, late and final MSA stone tool assemblages (Cochrane, 2006; Delagnes *et al*., 2006; Villa *et al*., 2005; Villa and Lenoir, 2006; Wadley, 2005, 2007, 2008). Optically Stimulated Luminescence (OSL) ages for 14 sediment samples (Table 1) from the three youngest lithic phases are available (Jacobs, 2004; Jacobs *et al*., 2008a, b; Wadley and Jacobs, 2004, 2006); these have weighted mean ages of 57.5 ± 1.4ka (post-Howiesons Poort), 47.6 ± 1.2ka (late MSA) and 35.1 ± 1.4ka (final MSA) (Jacobs *et al*., 2008a). Ages for the Pre-Still Bay, Still Bay and Howiesons Poort layers are based on seven OSL dates derived from additional sediment samples (Jacobs *et al*., 2008a, b; Jacobs and Roberts, 2008). Based on these results, the Howiesons Poort occupation falls

Table 1. Optically Stimulated Luminescence dates for the pre-Still Bay, Still Bay, Howiesons Poort, post-Howiesons Poort, late and final Middle Stone Age levels from Sibudu Cave (Jacobs and Roberts, 2008; Jacobs *et al.*, 2008a, b).

final MSA	Location	Level	Sample	Age (ka)
SIB11	East	Co	Sediment	34.7 ± 1.7
SIB10	East	Bu	Sediment	35.6 ± 2.0
SIB22	East	LBMOD	Sediment	48.9 ± 2.8
late MSA				
SIB14	North	MOD	Sediment	48.3 ± 2.0
SIB8	North	OMOD	Sediment	48.3 ± 1.8
SIB13	North	OMOD-BL	Sediment	47.0 ± 1.8
SIB7	North	RSp	Sediment	46.6 ± 1.9
SIB12	East	RD	Sediment	49.0 ± 2.0
post-HP				
SIB6	North	BSp	Sediment	58.0 ± 2.1
SIB4	North	SS	Sediment	53.6 ± 2.0
SIB9	North	P	Sediment	59.1 ± 2.2
SIB3	North	Ch2	Sediment	58.6 ± 1.9
SIB2	North	Y1	Sediment	58.2 ± 2.5
SIB1	North	B/Gmix	Sediment	57.8 ± 2.3
Howiesons Poort				
SIB15		GR2	Sediment	61.6 ± 1.5
SIB17		GS2	Sediment	63.8 ± 2.5
SIB19		PGS	Sediment	64.7 ± 1.9
Still Bay				
SIB20		RGS	Sediment	70.5 ± 2.0
Pre-Still Bay				
SIB21		LBG	Sediment	72.5 ± 2.0
SIB24		LBG2	Sediment	73.2 ± 2.3
SIB23		BS	Sediment	77.3 ± 2.2

between 65ka-62ka, the Still Bay dates to 70ka and the Pre-Still Bay to between 75ka-72ka (Jacobs *et al.*, 2008a, b; Jacobs and Roberts, 2008). The three broad age clusters, ~58ka, ~48ka and ~35ka and the Howiesons Poort are distinguished by differences in lithic assemblages, environmental characteristics and long hiatuses of 9.8 ± 1.3ka and 12.6 ±

2.1ka (Jacobs *et al*., 2008a, b; Wadley and Jacobs 2006). A third hiatus occurred after ~35ka occupation, lasting until about 1000 BP.

1.3.1 Sibudu environment during MIS 4

Sedimentological and mineralogical analyses of the Still Bay and Howiesons Poort layers show relatively high percentages of calcite and this suggests higher humidity (Pickering, 2006; Schiegl and Conard, 2006; Wadley, 2006). Magnetic susceptibility data from layers deposited at the end of MIS 4 (~58ka) imply a cold, glacial climate (Herries, 2006). The cold ~58ka layers contain gypsum growth within the sediments. However, the magnetic susceptibility data should be viewed with caution, as sedimentological analysis of the deposits indicate that the majority of the sediment is anthropogenic in origin and this may complicate interpretation (Goldberg *et al*., 2009; Pickering, 2006).

Tree species richness is well correlated with evapotranspiration across a wide range of ecosystems. Changes in evapotranspiration will thus have an influence on trees species composition and distribution on localised site level, as well as on a broad community level (Stephenson, 1998). Local levels of moisture availability at a site are dependent on effective evapotranspiration which is not only affected by precipitation, but a number of factors including aspect, slope, temperature, humidity, wind speed and direction, soil moisture content, depth and type and the presence of rivers (McDowell *et al*., 2008; Verstraeten *et al*. 2008). The carbonised seed assemblage prior to 58ka from Sibudu Cave is predominantly composed of evergreen taxa, implying the presence of closed forested environments (Sievers, 2006; Wadley, 2004). This interpretation is supported by the composition of woody taxa identified in the charcoal assemblage. Taxa such as *Podocarpus*, *Buxus* and *Curtisia*, evergreen forest species are noted. The presence of these species suggests that available moisture was high during this period, but not necessarily higher than present (Allot, 2006). Although the assemblage at this time is dominated by *Podocarpus* species (Allott, 2004, 2005) and the area appears to have been predominantly a forested one, there is evidence for a woodland/savanna community in the vicinity (Allott, 2006). Throughout the MSA occupations at Sibudu there is evidence that a mosaic environment existed around the site, partly due to the location of the site and the continual presence of the Tongati River (Wadley, 2006). Carbonised Cyperaceae (sedges) are present throughout the MSA sequence. Sedges grow in moist conditions and the occurrence of *Schoenoplectus* spp. seeds indicates open water, demonstrating that the Tongati River, that flows in front of the site was perennial during site occupations. Carbon isotope analyses of *Podocarpus* and *Celtis* charcoal from Howiesons Poort layers (65ka-62ka) indicate conditions of elevated levels of water availability and humidity (Hall *et al*., 2006, 2008).

The extensive faunal assemblage provides further evidence of environmental change through time in the Sibudu area. The Howiesons Poort faunal assemblage is dominated (91.4%) by small species preferring semi-closed or closed habitats, such as blue duiker, bushbuck, bush pig and vervet monkey (Clark and Plug, 2008). This supports the botanical evidence for the presence of an evergreen forested environment. In addition, a

small suite of species (8.6%), including buffalo and blue wildebeest show the occurrence of open savanna/woodland near the site (Clark and Plug, 2008), supporting the charcoal data (Allott, 2006). This provides further evidence for a mosaic of vegetation types in the area. A large variety of aquatic species including mammals, reptiles, water birds, fish, amphibians and molluscs have been identified (Plug, 2004, 2006) and these, together with the presence of *Schoenoplectus* spp. seeds, demonstrate that the Tongati River was perennial, even in the past.

The micromammal species composition provides further evidence for a cooler, humid forested environment. Two key species, *Cricetomys gambianus* (Giant rat) and *Rhinolophus clivosus* (Geoffroy's horseshoe bat) both require humid conditions. In addition *C. gambianus* cannot tolerate high overall temperatures (Glenny, 2006).

1.3.2 Sibudu environment during MIS 3

Palaeoenvironmental evidence from the post-Howiesons Poort layers (58.5 ± 1.4ka) indicates a general trend of oscillating warm/cool phases and drier conditions than seen during the Howiesons Poort. Magnetic susceptibility data suggest an initial (~58ka) very cold environment which became progressively warmer through MIS 4, alternating with brief cool phases (Herries, 2006). Sedimentological and mineralogical analyses reveal a high proportion of gypsum nodules in many of the layers (Pickering, 2006; Schiegl and Conard, 2006; Wadley, 2006). Such gypsum accumulations may be considered an indicator of arid conditions (Goldberg and MacPhail, 2006).

The vegetation patterns show a reduction of forested areas and an increase in more open woodland and grassland communities, reflecting the previous trend of a mosaic environment around the site. Pollen and phytolith data, although limited, reveal the presence of a grass-dominated community and the presence of savanna taxa such as *Acacia* (Renaut and Bamford, 2006; Schiegl and Conard, 2006; Schiegl *et al*., 2004). The seed assemblage is still dominated by evergreen forest taxa, but it also reveals an increase in the number of deciduous savanna/woodland taxa (Sievers, 2006; Wadley, 2004). The composition of the charcoal assemblage shows a similar trend with the presence of dry-adapted genera such as *Acacia*, *Celtis* and *Ziziphus* and cooler climate indicators such as *Erica* spp. (Allott, 2005, 2006). The presence of riverine forest taxa attest to the continued presence of a mosaic of vegetation communities around the site. A substantial change in the local environment is suggested by the occurrence of a pioneer shrub species, *Leucosidia sericea* (which at present does not occur near the coast) (Allott, 2006).

Micromammal evidence for a significant environmental shift at the same time is derived from the identification of another habitat specific pioneer species, *Mastomys natalensis* (Natal multimammate mouse) which does not inhabit forested areas (Glenny, 2006). Carbon isotope values from *Podocarpus* and *Celtis* charcoal from ~58ka layers are less negative than those from the earlier Howiesons Poort layers, suggesting that both species were responding to more arid conditions at ~58ka (Hall *et al*., 2006, 2008).

The faunal species composition of the ~58ka layers (post-Howiesons Poort) shows a dramatic shift in response to the changing environment. At this time the highest proportion of large grazing species are recorded indicating an open environment with increased grass cover (Wadley *et al*., 2008). Small bovid species are less frequent and larger savanna/woodland species such as giraffe, zebra, blue wildebeest and red hartebeest dominate the assemblage (Cain, 2005, 2006; Clark and Plug, 2008; Plug, 2004; Wadley *et al*., 2008; Wells, 2006). A recent analysis of the fauna (Clark and Plug, 2008) shows that during the youngest post-Howiesons Poort layers there was predominantly open savanna/woodland with large grazers. Prior to this, there was still a riverine forest community, along with the savanna/woodlands. The occurrence of a riverine forest faunal community during the early phase of the post-Howiesons Poort suggests that the transition between forest and grassland during MIS 4 and MIS 3 was gradual, rather than abrupt.

1.4 ARCHAEOLOGICAL EVIDENCE OF ENVIRONMENTAL CHANGE FROM OTHER MSA SITES IN SOUTH AFRICA

Improvements in OSL, electron spin resonance (ESR) and uranium-series (U-Th) dating should allow correlations between available environmental proxies from Sibudu and other MSA sites. However there are complications. When comparing the chronologies for the distinctive stone tool technical complexes between sites, it is clear that there are some discrepancies. An underlying assumption is that these stone tool assemblages would be ubiquitous and autochthonous, and that the timing of their rise and demise should be well matched. The transition from Still Bay to Howiesons Poort is not synchronous across MSA sites, and the assemblage that precedes the Howiesons Poort is not always designated Still Bay. This may be because the Still Bay is of very short duration and does not always occur in all sequences. However, it is likely that the problem lies with the precision and accuracy of the dating techniques. The dating conundrum complicates attempts to fine-tune palaeoenvironmental evidence across space or through time. For consistency in this study, the most recently published luminescence ages are used (where available), but earlier published dates based on other methods have been noted (Table 2).

A summary of palaeoenvironmental evidence from Sibudu Cave and these sites is presented in Figure 2 and Table 2. The majority of these sites are located on or near to the coast, particularly in the southern Cape. Exceptions are Rose Cottage Cave, Border Cave and Wonderwerk Cave which are located in the South African interior.

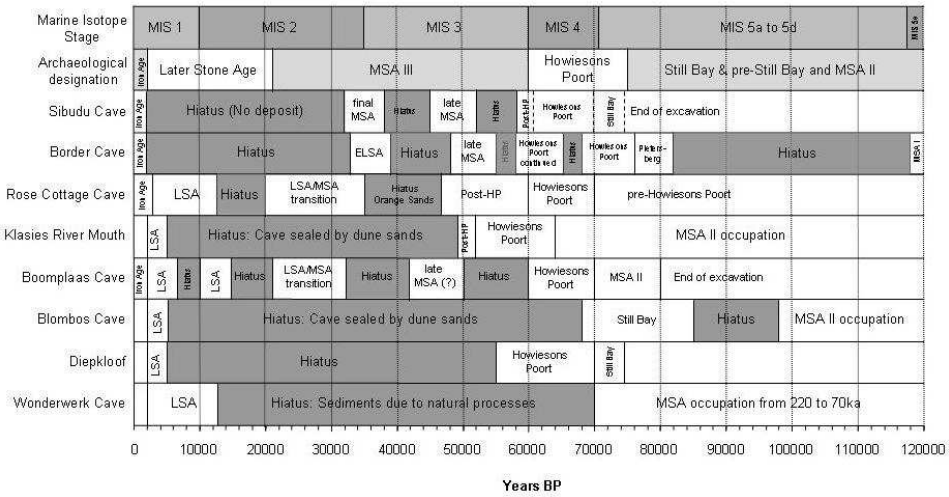

Figure 2. Summary graph of Marine Isotope Stages 1 to 5, archaeological designations and occupation/hiatus periods for Sibudu Cave and other Middle Stone Age sites from South Africa during the last 120ka.

Table 2. Summary table for Sibudu Cave and other Middle Stone Age sites cited. The age range, dating techniques and dating references is provided for each site.

Site	Age range	Dating techniques	Dating references
Sibudu Cave	Iron Age: ~1000 BP	Radiocarbon (^{14}C)	Wadley and Jacobs, 2004
	final MSA: ~35ka	OSL	**Jacobs, 2004**
	late MSA: ~48ka	OSL	**Jacobs and Wadley, 2006**
	post-HP: ~58ka	OSL	**Jacobs et al., 2008a, b**
	HP: 65ka-62ka	OSL	**Jacobs and Roberts, 2008**
	Still Bay: 70.5ka	OSL	
	Pre-Still Bay: 77ka-72ka	OSL	
Border Cave	Iron Age	Radiocarbon (^{14}C)	Butzer et al., 1978; Beaumont et al., 1978
	ELSA: ~38ka	AAR	Miller et al., 1993
	Howiesons Poort: ~55-75ka	ESR	**Grün et al., 1990a**
	MSA II		**Grün and Beaumont, 2001**
Rose Cottage Cave	LSA	Radiocarbon (^{14}C)	Wadley & Vogel 1991
	ELSA: ~29-40ka	OSL	Jacobs, 2004; Pienaar et al., 2008
	post-HP: 56ka	TL	Tribolo et al, 2005; Woodborne & Vogel 1993
	Howiesons Poort: 65ka-63ka		**Jacobs and Roberts, 2008**

Klasies River	MSA III: ~>45-50ka	Radiocarbon (^{14}C)	Vogel, 2001
	Howiesons Poort: 65ka-63ka	AAR	Bada & Deems, 1975
	Pre-HP: 72ka-71ka	OIS correlation	Deacon & Geleijnse, 1988; Shackleton, 1982
	MSA II: ~75-94ka	Palaeoenviro-proxies	Butzer, 1978; Deacon, 1989
	MSA I: ~90-115ka	Uranium series	Vogel, 2001
		OSL	Feathers, 2002; Tribolo et al., 2005
		ESR	Grün et al., 1990b
			Jacobs and Roberts, 2008
Boomplaas Cave	LSA	Radiocarbon (^{14}C)	Fairhall et al., 1976
	ELSA: ~21ka	Palaeoenviro-proxies	Deacon et al., 1984
	post-HP: >40ka	U-Th	Vogel, 2001
	Howiesons Poort: ~55-65ka	AAR	**Brooks et al. 1993; Miller et al, 1999**
Blombos Cave	LSA: ~2ka	Radiocarbon (^{14}C)	d'Errico et al, 2001
	3 MSA phases, including	OSL	Henshilwood et al., 2001; Vogel et al., 1999
	Still Bay: 85ka-76ka, 73ka		**Jacobs, 2004, 2005;**
	MSA 2: ~99-143ka		**Jacobs et al. 2003a, 2003b, 2006**
		ESR	Jones, 2001
		TL	**Tribolo et al., 2005, 2006**
Diepkloof	LSA: ~1800 BP	Radiocarbon (^{14}C)	Parkington & Poggenpoel, 1987;
	Howiesons Poort: 63ka-58ka	Radiocarbon (AMS)	Parkington, 1990
	Still Bay: 73ka-71ka	OSL	Parkington, 1999
		TL	Parkington et al, 2005
			Tribolo, 2003, Tribolo et al., 2005
			Jacobs and Roberts, 2008
Wonderwerk Cave	MSA (incld Howiesons Poort):	U-Th	Johnson et al, 1997
	~70-220ka	AAR	Johnson et al, 1997
			Beaumont & Vogel, 2006

1.4.1 Palaeoenvironmental evidence from archaeological sites during MIS 4

Evidence from Border Cave, northern KwaZulu-Natal, suggests fluctuating environmental conditions between 80ka and 60ka. Proxy data from cave sediments (Butzer *et al*., 1978), microfauna (Avery, 1982, 1992) and macrofauna (Deacon and Lancaster, 1988; Klein,

1977) indicate that conditions were cooler and moister than present. Local vegetation communities comprised extensive *Podocarpus* dominated forest and thick bush towards the end of MIS 4. As with Sibudu Cave there is evidence for a hiatus from about 58ka. Evidence of spring activity and rock spalling from the Howiesons Poort sediments of Rose Cottage Cave, eastern Free State Province, suggest that conditions in this area were also colder and moister than present (Deacon and Lancaster, 1988). Charcoal and pollen analyses indicate that there were complex changes in the vegetation. Prior to the Howiesons Poort occupation the local vegetation comprised riverine and other well-watered communities. Vegetation diversity decreased during the Howiesons Poort suggesting a drying trend (Wadley *et al*., 1992). Wonderwerk Cave, in the Northern Cape Province, has yielded non-archaeological evidence from sedimentary (Beaumont and Vogel, 2006; Butzer, 1984a, b; Butzer *et al*., 1979) and faunal (Avery, 2006; Beaumont, 1990) analyses of the cave deposits. The site was not occupied from 70ka until 12.5ka, but sediment layers were formed by natural processes. These non-archaeological data suggest that prior to 30ka the local environment was drier and colder than present, with grazers present throughout the sequence. This is thought to be due to very low rainfall conditions in the interior of South Africa between MIS 4 and MIS 2, when it has been estimated that rainfall was about 60% lower than present values (Johnson *et al*., 1997).

Klasies River Mouth, a complex of caves and overhangs on the southern Cape coast has provided faunal, botanical and geological evidence from the MSA II, Howiesons Poort and post-Howiesons Poort levels, suggesting a shift from cooler in MSA II to more moderate conditions in the post-Howiesons Poort. Environmental interpretations from this site are complicated by rising and falling sea levels under interstadial and stadial conditions, respectively, and there are some inconsistencies amongst the ages and cultural designations of the various levels, so interpretations should be made with care. The MSA II faunal assemblage is dominated by browsers (86%) indicating a bushy/wooded terrestrial environment. The presence of Antarctic/sub-Antarctic marine mammals suggests a colder marine environment than seen during the Holocene (Deacon and Lancaster, 1988). During the Howiesons Poort there is an increase in grazing species suggesting the presence of grasslands (Deacon, 1989, 1995; Deacon and Lancaster, 1988; Singer and Wymer, 1982) and cooler, possibly drier conditions than recorded for the MSA II levels (Avery, 1992, Klein, 1976, 1983; Thackeray, 1992, Thackeray and Avery, 1990). The $\delta^{18}O$ values of shell samples from MSA I through the Howiesons Poort and MSA III deposits also suggest a cooling trend (Deacon and Lancaster, 1988) through MIS 4. Palaeoenvironmental reconstructions from the Howiesons Poort levels of Boomplaas Cave, southern Cape, are based on faunal assemblages (Avery, 1982; Deacon *et al*., 1984) and charcoal and pollen analyses (Scholtz, 1986). During MIS 4 environmental conditions were extremely harsh, being much colder and drier than present. The site of Blombos Cave on the southern Cape coast has no Howiesons Poort occupation, only evidence of the earlier Still Bay and MSA II phases. The site was sealed by dune sands from ~70ka until 2000BP (Jacobs *et al*., 2006). Proxy data from marine fauna and shellfish assemblages and geological analyses indicate a transition between warm conditions during MIS 5a to colder conditions during MIS 4 (Henshilwood *et al.*, 2001). Faunal (Parkington *et al*., 2005), charcoal (Cartwright and

Parkington, 1997) and sedimentological (Butzer, 1979) analyses from Diepkloof rock shelter in the north-western Cape indicate that during the Howiesons Poort occupations the climate was cooler and moister than present. Charcoal assemblages from this period contain afromontagne species such as *Podocarpus* and *Kiggelaria* which require year-round moisture (Cartwright and Parkington, 1997).

1.4.2 Palaeoenvironmental evidence from archaeological sites during early MIS 3

Evidence from sites in the interior of South Africa is presented first again, followed by evidence from the coastal sites. Based on proxy data from Border Cave, the local vegetation shifted from dense woodland communities to more open woodland savanna with variations in the amount of grass versus bush at the beginning of MIS 3 (Avery, 1982; Butzer *et al*., 1978; Klein, 1977). These shifts are in-line with the Sibudu environmental records. At Rose Cottage Cave the environment appears to have become colder than in MIS4 and there is evidence of more mesic conditions (Wadley *et al.*, 1992). There is a hiatus after the post-Howiesons Poort occupation indicated by a layer of almost culturally sterile orange sand that lasted from ~48ka-~35ka (Harper, 1997). Although no archaeological evidence is available from Wonderwerk Cave during this time, sedimentary evidence (Beaumont and Vogel, 2006; Butzer, 1984a, b) indicates that the environment was generally dry.

At Klasies River Mouth, faunal evidence from post-Howiesons Poort levels shows a further increase in grazing species compared with the Howiesons Poort levels. This indicates a continuation in the shift to more open grasslands and cooler conditions in early MIS 3. After 50ka the sites were sealed by dune sands (Butzer, 1978; Deacon and Lancaster, 1988; Singer and Wymer, 1982). Oxygen isotope data from shell samples from this period confirm the cooling trend (Deacon and Lancaster, 1988). At Boomplaas Cave charcoal studies indicate that during early MIS 3 (60ka-50ka) a cold, very dry harsh climate prevailed, based on the range of woody species reflected (Scholtz, 1986). From ~55ka to 40ka conditions began to ameliorate (Deacon and Lancaster, 1988). In general, evidence from Boomplaas suggests that MIS 3 was cooler and moister than the subsequent Last Glacial Maximum (Deacon *et al*., 1984). A series of occupational hiatuses occurred after the Howiesons Poort (Deacon, 1979). No environmental evidence is available from Blombos Cave because the site was sealed by dune sands during this time (Henshilwood *et al*., 2001). Charcoal data from Diepkloof indicates a change in the selection of firewood species composition at this time suggesting a shift to drier conditions (Cartwright and Parkington, 1997; Parkington *et al*., 2005). This shift to drier conditions is supported by the dominance of larger grazing species in the faunal assemblage (Parkington *et al*., 2005).

During MIS 4 and early MIS 3, climatic conditions were extremely variable and resulted in the majority of the sites being abandoned for prolonged periods when conditions were unsuitable for human occupation (Fig. 2). Assuming that the landscape was abandoned by people due to environmental conditions, it is interesting that occupation at sites in the eastern summer-rainfall region of South Africa (Sibudu Cave, Border Cave and

Rose Cottage) persisted after the western (including the winter-rainfall zone) sites were abandoned. Environmental evidence from the various sites suggests that the eastern regions experienced greater precipitation than the more arid western regions. Towards the end of MIS 3 and through MIS 2 the environment over much of central South Africa was extremely harsh and sites in this area were unoccupied for periods of up to 60 000 years. During MIS 2 western South Africa appears to have been wetter than present conditions (Chase and Meadows, 2007). Climatic conditions in the eastern regions were more favourable for longer periods, but during MIS2, most sites show intermittent occupations or an absence of occupation.

1.5 OTHER TERRESTRIAL RECORDS OF PALAEO-CLIMATE CHANGE

In South Africa terrestrial palaeoclimatic records from numerous caves, lacustrine, spring, fluvial and coastal systems provide proxy data from different climate zones across the country. Butzer (1984a, b) compiled a series of proxy records based on sedimentological and lithostratigraphic analyses from a number of such sites. During MIS 4 and early MIS 3, the southern Cape region experienced humid to sub-humid conditions, the south-western Cape was semi-arid, south-central and eastern South Africa was initially cold and humid during MIS 4, becoming warmer and humid during MIS 3 and the northern portions of the country were cold and arid. Palynological and sedimentological evidence from Agulhas Plain lunette dune accretion from two pans in the southern Cape region (Fig. 1) suggest that from the end of MIS 4 and early MIS 3 conditions became slightly drier or similar to present conditions (Carr *et al*., 2006). Indications of arid and cold conditions in the northern regions are supported by a range of pollen data from the sites of Florisbad, Wonderwerk Cave and Kathu Pan, located in the northern and north-central parts of South Africa (Fig. 1). The pollen data suggests that between ~75ka-64ka this area was extremely arid and cold (Van Zinderen Bakker, 1995).

The Pretoria Saltpan (Tswaing Crater), a meteorite impact north-east of Tshwane in the Gauteng Province, provides a rainfall record for the last 200ka (Partridge, 1999; Partridge *et al*., 1997; 1999). The rainfall data show a decrease between 70 and 60ka associated with decreasing insolation (Fig. 3), however the interpretations should be made cautiously as relative dating methods were used at the site. The data show that the eastern summer rainfall area of South Africa was becoming drier at this time. This would have affected the vegetation communities around Sibudu Cave and Border Cave. The forested environments would have been reduced to river/stream margins and an expansion of woodland and grassland savanna communities would have occurred.

Oxygen isotope time series from U-Th dated speleothems from two sites in South America, Bahia State (NE Brazil) and Botuvera Cave (SE Brazil) provide a record of oscillating temperatures and aridity (Fig. 4). During MIS 4, conditions were cool and wet followed by warmer and drier environments during early MIS 3 (Cruz *et al*., 2005; Wang *et al*., 2004).

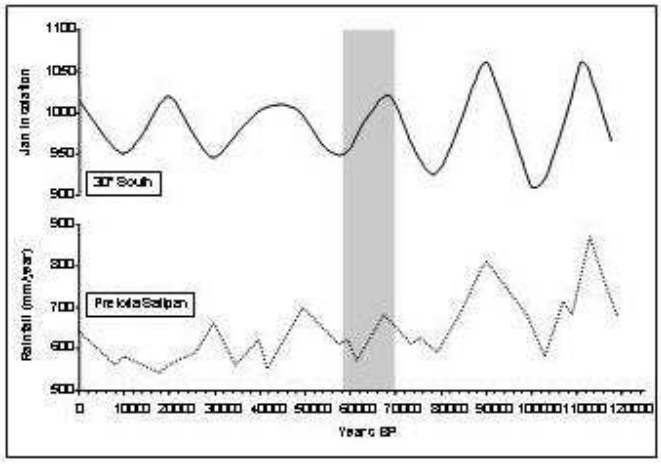

Figure 3. Southern African January insolation, 30° south (Partridge *et al*., 1997) and Pretoria Saltpan (Tswaing Crater) tuned rainfall (mm/year) time series (Partridge *et al*., 1997). The shaded area indicates the period of interest for this study.

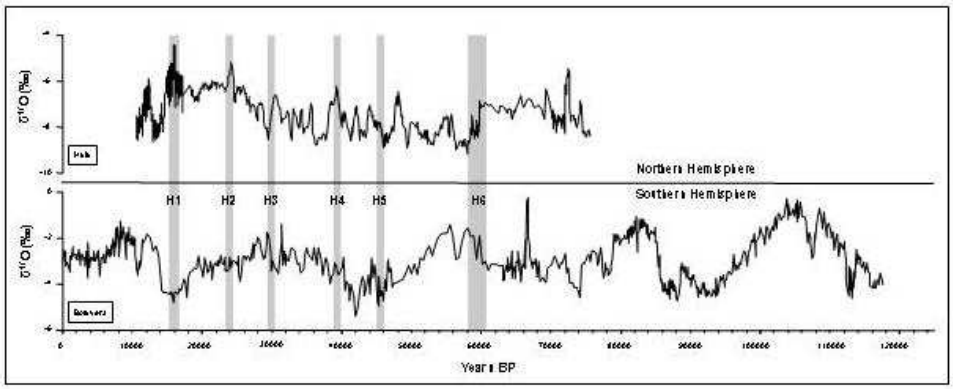

Figure 4. High-resolution $\delta^{18}O$ time series from northern and southern hemisphere speleothems for the last 120ka. Dansgaard/Oeschger events 20-17 (numbered) and Heinrich events 1-6 (shaded areas) are presented. Top: Combined oxygen isotope ratios from five speleothems from Hulu Cave, China (Wang *et al.*, 2004). Bottom: Oxygen isotope ratios from speleothems from Botuvera Cave, southeastern Brazil (Cruz *et al.*, 2005).

The Botuvera speleothem $\delta^{18}O$ record shows a notable spike at ~70ka indicating a very wet period and then an abrupt shift to an arid period, suggesting a shift to glacial

conditions in MIS 4. This is in contrast to results from the $\delta^{18}O$ records (Fig. 4) from the northern hemisphere Hulu Cave speleothems, which show that between 70ka and 55ka conditions were warm and dry before abruptly becoming cool and wet (Wang *et al*. 2001).

The long term variability of East African climates has been reconstructed using a series of drill cores from Lake Malawi and Lake Tanganyika (Cohen *et al*. 2007, Scholz *et al*., 2007). Between 135ka-70ka these regions experienced episodic periods of extremely arid conditions. After 70ka the climate seems less variable and overall conditions became more humid and general moisture availability increased. This is thought to be due to diminished precessional scale variability (Cohen *et al*., 2007). These post 70ka conditions are similar to those indicated by the Hulu speleothems and suggest that the East African climate was more likely influenced by changes occurring in the northern hemisphere.

1.6 PALAEOENVIRONMENTAL EVIDENCE FROM SOUTHERN AFRICAN DEEP SEA CORES

Deep sea cores along the western, southern and eastern coasts of southern Africa provide evidence of the local manifestation of global climatic changes during MIS 4 and early MIS 3. Cores from the Walvis Ridge and Namibian continental slope along the western coast of southern Africa (Fig. 1) provide a record of climatic variability regulated by shifting climatic fronts during glacial and interglacial periods (Little *et al*., 1997; Pichevin *et al*., 2005; Stuut *et al*., 2002). The $\delta^{18}O$ records of *Globorotalia inflata*, a pelagic foram (Fig. 5A) and the proportion of aeolian dust (Fig. 5B) from MD962094 indicate intensified south-east trade winds and enhanced winter rainfall during MIS 4 and relatively arid conditions during MIS 3 (Stuut *et al*., 2002, 2004). Several cores, MD962094, GeoB1706, 1711, and MD962086/87 provide records of variation in upwelling events of the cold Benguela Current that flows northwards along the western coast of southern Africa. Upwelling is controlled by the relative position of the Subtropical Convergence Zone which affects the heat flux into the southern Atlantic Ocean from rings of warm water spawned from the Agulhas Current Retroflection (Little *et al*., 1997). Geochemical, micropalaeontological and isotope records from GeoB1706 and 1711 show that during MIS 4-3 increased upwelling of cold nutrient-rich water occurred (Little *et al.*, 1997). Weaker trade winds during MIS 3 resulted in warmer water from the Agulhas Current to move into the colder Benguela region (Pichevin *et al*., 2005). South-east trade winds show increased intensity during glacial periods resulting in increased upwelling (Pichevin *et al*., 2005; Stuut *et al*., 2002). Dust grain-size (Fig. 5C) data from MD962087 and alkenone-based sea surface temperatures from MD962086/87 (Fig. 5D) indicate a similar pattern. Evidence for humid conditions during glacial periods and drier conditions during interglacials is derived from OSL dated cores (WC03-1, 2, 5, 10, 11 and 18) taken from aeolian dune sands along the west coast of South Africa (Fig. 1) (Chase and Thomas, 2006, 2007). Changes in the sediments were related to variations in moisture, wind strength and sediment supply. There were periods of increased activity/deposition of aeolian sands during MIS 4 associated with increased humidity (Chase and Thomas, 2006, 2007). The study area is within the winter

rainfall zone of South Africa. Rainfall in this area is influenced by westerly temperate frontal systems and these are thought to be more vigorous during glacial periods, resulting in wetter conditions (Barrable *et al*., 2002).

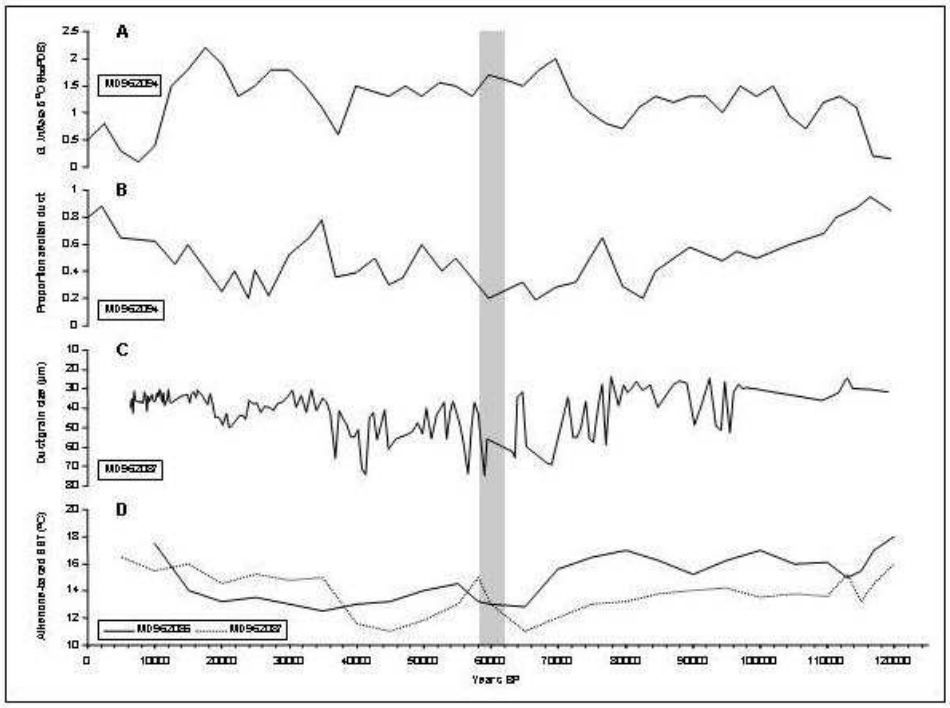

Figure 5. Palaeoenvironmental proxy data sets from deep sea cores of the western coast of southern Africa for the last 120ka. Age models and stratigraphy of the cores are mostly created by correlating $\delta^{18}O$ records of selected planktonic and/or benthic foraminifera with the SPECMAP record developed by Imbrie *et al*. in 1984. The shaded area indicates the period of interest for this study. A: $\delta^{18}O$ record for *Globorotalia inflata* from deep sea core MD962094 (Stuut *et al*., 2002). B: The proportion of aeolian dust from deep sea core MD962094 (Stuut *et al*., 2002). C: Time series of dust grain size (µm) from deep sea core MD962087 (Pichevin *et al*., 2005). D: Alkenone-based sea surface temperatures (SST) for deep sea cores MD962086 and 87 (Pichevin *et al*., 2005).

Cores PS2487-6 from the Agulhas Retroflection and MD962080 from the Western Agulhas Bank (Fig. 1) provide records of variation in the frequency and intensity of Agulhas warm water leakages, responses to shifts in the STCZ and global changes (Flores *et al*., 1999, Rau *et al*., 2002). $\delta^{18}O$ and $\delta^{13}C$ records, foraminifera species assemblages and sediment composition and texture show that during glacial periods (MIS 2, 3, 4) there was a northwards displacement of the STCZ and an eastward movement of the Agulhas Retroflection (Flores *et al*., 1999; Rau *et al*., 2002). Further evidence for changes in ocean

current circulation patterns comes from core MD02-2589 on the southern Agulhas Plateau, where isotopic and grain-size data indicate a northward shift of the Antarctic Circumpolar Current (Molyneux *et al*., 2007) which would have had an impact on the Agulhas Current. An eastward shift of the Agulhas Retroflection would have an impact on environmental conditions along the eastern coast of southern Africa and may be a factor determining the environmental changes seen in the local Sibudu environment at around 60ka. It has been demonstrated that the Agulhas Current has a significant influence on the summer rainfall patterns of the eastern coast at a variety of timescales (Cook *et al*., 2004).

Core RC17-69, off the eastern coast of KwaZulu-Natal (Fig. 1) was influenced by the warm Agulhas Current. Foraminifera assemblages from this core suggest that during glacials, the Agulhas Current was weakly developed in summer months and may have been replaced by cooler subtropical waters during winter months (Hutson, 1980). During the LGM the current was seasonably variable and heat transport from tropical latitudes was reduced (Prell and Hutson, 1979; Prell *et al*., 1980a, b). The cooling or reduction of the Agulhas Current during MIS 4 (~60ka), coupled with glacial conditions, would have had a significant impact on the environment of the east coast of southern Africa (Reason and Mulenga, 1999). Oxygen isotope records from core MD 73-025, south of Madagascar, and RC17-69 do indicate a cooler period during MIS 4 (Prell and Hutson, 1979; Shackleton, 1977; Tyson, 1991).

1.7 DISCUSSION AND CONCLUSION

Oxygen and deuterium isotope sequences from Greenland (GRIP, N-GRIP, GISP2) and Antarctic (Vostok, Epica, Byrd) ice cores (Fig. 6) show that MIS4 was a period during which the earth emerged from near glacial conditions (the ice core data for 65ka are almost analogous to those of 22ka, which is considered to be the height of the last glacial). The problem of mid-latitude ecosystem responses is complicated by differences between the northern and southern hemisphere records, particularly regarding the timing of major events (e.g. Blunier *et al.*, 1998; Blunier and Brook, 2001; Jansen *et al*., 2007; Leuschner and Sirocko, 2000; Petit *et al*., 1999; Schmittner *et al*., 2003). This makes it difficult to determine whether ecosystem changes are responding to Northern or Southern Hemisphere forcing, or whether low- to mid-latitude forcing of climate change took place. Earlier studies (e.g. Blunier *et al*., 1998; Blunier and Brook, 2001, Leuschner and Sirocko, 2000, Petit *et al*., 1999) suggested that the timing of large southern hemisphere climate events lead the northern hemisphere by 1500-3000 years. More recent research suggests that the south leads the north by approximately 400-500 years (Schmittner *et al*., 2003).

Where global climatic changes are synchronous in the northern and southern high latitude records, they should manifest in low latitude regional and local palaeoenvironmental records. In both Greenland and Antarctic ice cores, rapid increases in air temperatures of 5-10°C (Landais *et al*., 2007; Rahmstorf, 2002) are followed by a rapid return to cold (stadial) conditions. Notable cold phases called Dansgaard/Oeschger (DO) events (Dansgaard *et al.*, 1984; Oeschger *et al.*, 1984) occur with 1000, 1450 and 3000 year

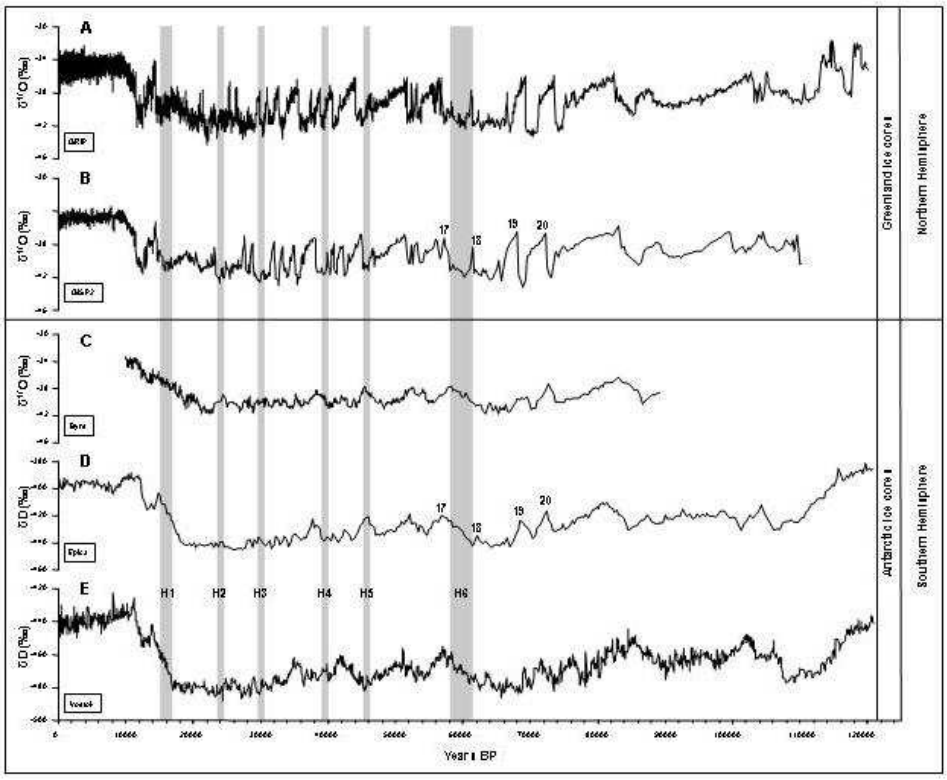

Figure 6. High-resolution $\delta^{18}O$ and δD time series from northern and southern hemisphere ice cores for the last 120ka. Dansgaard/Oeschger events 20-17 (numbered) and Heinrich events 1-6 (shaded areas) are presented. A: Oxygen isotope ratios from GRIP, Greenland (Blunier and Brook, 2001). B: Oxygen isotope ratios from GISP2, Greenland (Blunier and Brook, 2001). C: Oxygen isotope ratios from the Byrd ice core, Antarctica (Blunier and Brook, 2001). D: Deuterium isotope ratios from the Epica ice core, Antarctica (Jouzel *et al.*, 2004). E: Deuterium isotope ratios from the Vostok ice core, Antarctica (Petit *et al.*, 2001).

cyclicities (Leuschner and Sirocko, 2000). Twenty-two DO events have been identified in the Greenland ice cores and nine corresponding DO events have been identified in the Antarctic cores (Bender *et al*., 1994). Antarctic DO events are characterised by slower warming and cooling than Greenland events (Bender *et al*., 1994). Significant DO events are followed by massive episodic discharges of icebergs from the Laurentide and Scandinavian ice-sheets and are called Heinrich events (Bond *et al*., 1993; Heinrich, 1988; Leuschner and Sirocko, 2000; Rahmstorf, 2002). Heinrich events always occur during cold stadials and are followed by an abrupt shift to warmer climatic conditions (Bond *et al*.,

1993; Rahmstorf, 2002). Between ~70ka and 50ka (MIS 4 and 3) Greenland oxygen and deuterium isotope records (Fig. 6A and B) from the GRIP (Blunier and Brook, 2001; Grootes *et al*., 1993), GISP2 (Blunier and Brook, 2001) and N-GRIP (Landais *et al*., 2007; Jouzel *et al*., 2005, 2007) ice cores, and Antarctic records from the Byrd (Blunier and Brook, 2001), Epica (Jouzel *et al*., 2005) and Vostok (Petit *et al*., 1999) ice cores (Fig. 6C, D and E) show that DO events 20-17 and H6 are documented in both the Northern Hemisphere and Southern Hemisphere. The isotopic excursions are not as great in Antarctica and the changes are not as abrupt as those in Greenland (Bender *et al*., 1994). This can be clearly seen during H6, between DO 18 and DO 17 in Antarctica where $\delta^{18}O$ and δD values gradually become less negative indicating a slower warming trend than that seen in the Greenland records. The changes should therefore have an environmental impact at low latitudes.

Linking the terrestrial ecosystem and environmental proxies to climate change proxies requires consideration of the Earth System, and in particular the role of ocean currents in heat distribution. The difference in the rate of change in the Northern and Southern Hemispheres is possibly due to changes in the global thermo-haline circulation (Schmittner *et al*., 2003). A change in the northward circulation of warmer water from the southern oceans (reduction of the warm Agulhas Current eddies) into the Atlantic Ocean would result in a cooling of the northern latitudes and warming in the southern latitudes (Blunier *et al*., 1998; Blunier and Brook, 2001; Rahmstorf, 2002; Schmittner *et al*., 2003; Stocker, 2000, 2002). The Agulhas Current plays a significant role in determining the weather patterns over southern Africa, and hence DO events should be recognisable in the palaeoenvironmental records of the region. However the correlation may not be as simple as a teleconnection. Palaeoclimatic data from core MD97-2120, east of New Zealand, suggests that southern hemisphere mid and low latitude climates were more variable than can be inferred from the Antarctic ice core data (Pahnke *et al*., 2003; Pahnke and Zahn, 2005). This highlights the need to examine a range of proxy data sets derived from both marine and terrestrial sites to improve understanding of regional and local climatic variability through time.

Focussing on the Southern Hemisphere, an important observation in the Antarctica data sets is the similarity between the climatic conditions during MIS 4 and MIS 2, the Last Glacial Maximum (LGM). This is not limited to the $\delta^{18}O$ and δD records. The dust, Fe, Ca and other chemical flux records from the Vostok and Epica ice cores (Fig. 7) are proxies for sea ice extent (sodium (Na) flux); marine biological productivity (sulphate (SO_4) flux); aridity of surrounding continents (Iron (Fe), calcium (Ca), dust, methane (CH_4)); aerosol fluxes of marine, volcanic, terrestrial, cosmogenic and anthropogenic origin and direct records of changes in atmospheric gas (CO_2) composition (Petit *et al.*, 1999; Wolff *et al*., 2006). The data all suggest that during MIS 4 conditions were as severe as those during the cold and dry MIS 2, but not as prolonged. By gathering more evidence for the environmental manifestations this may contribute to a better understanding of why a shift to interglacial conditions occurred at the end of MIS 2, but did not occur at the end of MIS 4 despite the apparent similarity in precursive conditions.

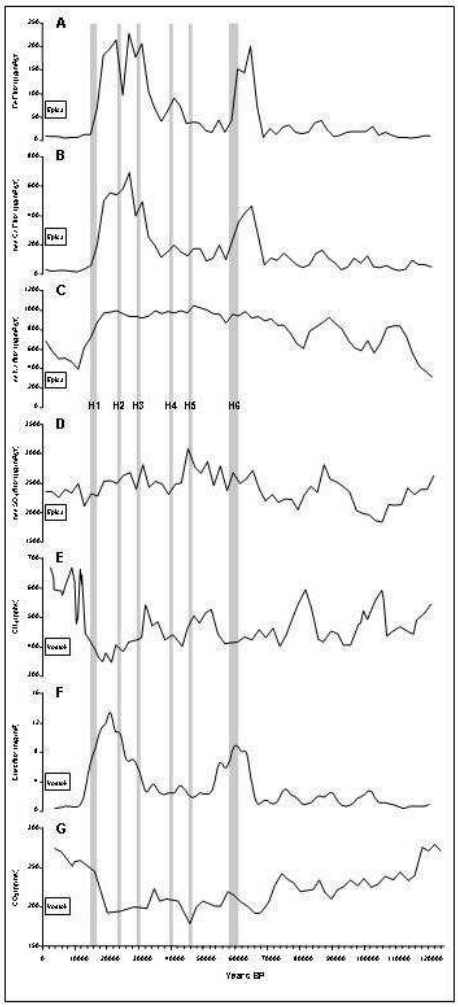

Figure 7. Chemistry data time series from the Epica and Vostok ice cores, Antarctica for the last 120ka. The shaded areas indicate Heinrich events 1-6. A: Iron (Fe) flux from Epica (Wolff *et al.*, 2006). B: Non sea salt calcium (nssCa) flux from Epica (Wolff *et al.*, 2006). C: Sea salt sodium (ssNa) flux from Epica (Wolff et al., 2006). D: Non sea salt sulphate ($nssSO_4$) flux from Epica (Wolff *et al.*, 2006). E: Methane (CH_4) variability from the Vostok ice core (Chappellaz *et al.*, 1990). F: Dust flux record from the Vostok ice core (Petit *et al.*, 1990). G: Carbon dioxide (CO_2) concentrations from the Vostok ice core (Barnola *et al.*, 1987).

The local manifestation of the global-scale climate events has been reviewed in this paper. Sibudu Cave has yielded the most comprehensive record for the region. Faunal and botanical assemblages, cave sediments, magnetic susceptibility of sediments, geology

and carbon isotope analysis of charcoal show that at the end of MIS 4 the environment around Sibudu Cave was humid and cooler than present, supporting a substantial evergreen forest with patches of drier, open woodland/savanna (Table 2). The shifts seen in the plant and animal communities preserved in the ~58ka layers provide evidence for oscillating climatic conditions into MIS 3. Evidence from more recent layers implies alternating cooler and warmer conditions with an overall warming trend, although temperatures remained lower than present (Herries, 2006). The forested area that existed in the pre-60ka period may have been reduced by ~58ka, allowing more open woodland and grassland communities to develop during the cooler and drier phase. During the warmer phases of MIS 3, grasslands decreased and woodland savanna predominated. Indirect evidence for a dramatic climate change between the ~58ka and ~48 ka occupations is suggested by a hiatus of 9.8 ± 1.3ka between these two occupational phases (Jacobs *et al*., 2008a, b; Jacobs and Roberts, 2008). This hiatus coincides with a period of colluviation between 56ka-52 ka, an indication of arid conditions or transitional climates with reduced vegetation cover, recorded from a series of well-dated stratigraphic sequences from erosion gullies in KwaZulu-Natal (Botha, 1996, Botha and Partridge, 2000, Botha *et al*., 1992, Clarke *et al*., 2003, Wintle *et al*., 1995). Environmental conditions were likely unsuitable for the use of the shelter as a permanent dwelling during hiatus periods, perhaps because of a particularly arid phase (Jacobs *et al*., 2008a, b).

The predominant forest type in KwaZulu-Natal is classified as part of the Indian Ocean coastal belt biome (Mucina *et al*., 2006) and it requires high moisture levels (rainfall, humidity). Forested communities are also constrained by the local substrate and therefore migration over time to more suitable areas is not a viable option (Eeley *et al*., 1999). During colder and drier periods such as during early MIS 3 the forested areas would have been reduced.

Evidence for glacial conditions in the southern hemisphere during MIS 4 and a shift to an ameliorating climate in MIS 3 has been recovered from Antarctic ice cores, deep sea cores and speleothems. These are similar to the harsh cold conditions seen in the LGM (MIS 2). The proxy environmental data from deep sea cores and other sites from the eastern region of South Africa indicate that between 70ka and 60ka the prevailing climatic conditions were colder and wetter than present. However, during MIS 3 temperatures began to slowly rise. Rainfall data from the Tswaing Crater indicate that rainfall began to decrease during this time, in response to decreasing insolation. On the western portion, proxy data from deep sea cores and aeolian dune sand deposits indicate colder and humid conditions with increasing wind strengths associated with lower Sea Surface Temperatures (SST) and increased cold water upwelling along the western coast during MIS 4 and MIS 3. Prior to 70ka, the south-western proxy data suggests that relatively arid conditions persisted. Records of local and regional climate changes from southern Africa show that during the period 70ka-50ka, conditions were overall colder and drier in the eastern regions and colder and wetter in the western regions. Western, south-western MSA sites abandoned earlier and for longer than MSA sites on the eastern region of South Africa as the local environments were less suitable for human occupation than in the east. Studies utilising a range of palaeoenvironmental proxies (e.g. pollen sequences and speleothems) and modern

meteorological records combined with various Global Circulation Models have indicated that the eastern portion of South Africa responds differently to climate change from that of the western regions (Barrable *et al*., 2002; Cook *et al*., 2004; Scott *et al*., 2008) . The eastern portions are influenced by moisture circulation patterns from the South West and tropical Western Indian Ocean affected by the position of the ITCZ and sea surface temperatures of the Agulhas Current (Cook *et al*., 2004). The western regions are affected by the degree of upwelling of the Benguela Current (Reason and Mulenga, 1999) and the northward movement of anticyclonic high-pressure systems which bring in moisture-rich westerly winds (Barrable *et al*., 2002).

Such a profound change was possibly due to a change in the strength or temperature of the Agulhas Current or an eastward shift of the Agulhas Retroflection. Summer rainfall along the south eastern coast of KwaZulu-Natal is influenced by the proximity and temperature of the Agulhas Current. Alongshore variations in the rainfall gradient are related to the distance between the coast and the current at the continental shelf edge and this influence extends up to 50km inland (Jury *et al*., 1993), and includes the Sibudu region. A weaker/cooler Agulhas Current and an eastward shift of the Agulhas Retroflection would lower SST's along the eastern coast, resulting in a decrease in summer rainfall and also lower humidity levels (Jury *et al*., 1993; Reason, 2002; Reason and Mulenga, 1999; Tyson, 1999). If SST's are cool in the western southern Indian Ocean (along the southeast coast of South Africa) and warmer in the eastern areas, the air over south-eastern Africa is drier and rainfall decreases (Reason, 2002; Reason and Mulenga, 1999). Proxy evidence from core RC17-69 suggests that a weakening of the Agulhas Current occurred towards the end of MIS 4 and that there was a corresponding decrease in rainfall as indicated by the Tswaing record.

This study highlights the necessity to examine multiple strands of palaeoenvironmental evidence and the connections between global climate change events and the impact of these changes on local environments and human populations during this time. It also indicates the need to ensure that dating of sites is secure before these strands of palaeoenvironmental evidence can be convincingly linked.

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