Cave and rock shelter sediments of southern Africa: a review of the chronostratigraphic and palaeoenvironmental record from Marine Isotope Stage 6 to 1

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Abstract

Caves and rock shelters contribute important records to local, regional and sub-continental reconstructions of environment and climate change through the southern African Quaternary. Against a backdrop of pronounced climate change, the archaeological record of the Marine Isotope Stage 6 to 1 period in southern Africa documents a remarkable time in the behavioural and technological evolution of anatomically modern humans. Significant evidence of this evolution is represented in diverse components of the sedimentary record in caves and rock shelters in the region. We present a catalogue of published caves and rock shelters in southern Africa that preserve temporally-relevant clastic and chemical palaeoclimatic proxies in order to: (1) facilitate the integration of cave and rock shelter sedimentary data into broader, regional chronostratigraphically-correlated palaeoclimatic sequences; and (2) identify possible areas and proxies that require focused research in the future. To demonstrate the complexity of the Marine Isotope Stage 6 to 1 stratigraphic record and use of palaeoenvironmental proxies, we present three case studies representing interior and coastal contexts: Border Cave, Klasies River Mouth and Pinnacle Point. These examples aptly demonstrate the challenges of these contexts, but also the opportunities for palaeoenvironmental research in southern Africa when conducted through integrated, multidisciplinary approaches. Published records of palaeoenvironmental research from cave and rock shelter sequences in southern Africa are heavily biased to the South African coastal areas and the record is temporally and spatially fragmented. However, there are interesting patterns in the chronostratigraphic record and in the distribution of sites within the context of the geology and vegetation ecology of southern Africa that require further exploration. There are also promising techniques in stable isotope analysis that can be applied to abundant sedimentary components found in the region's caves and rock shelters, and in its museums.

Introduction

Clastic and chemical sediments yielded from caves and rock shelters in southern Africa contribute important palaeoenvironmental records to local, regional and sub-continental reconstructions of climate change through the southern African Quaternary. In the period from Marine Isotope Stage (MIS) 6 to MIS 1, these data also contextualise the behavioural and technological evolution of anatomically modern humans (Marean et al., 2014; Wadley, 2015; Stewart and Mitchell, 2018). While much of the southern African interior has been prone to gradual denudation for millions of years, the nature of caves and rock shelters as clastic and chemical sediment traps means they have the potential to yield high-resolution records of climate change and biological evolution over long time periods (e.g., Butzer, 1984; Klein, et al., 1991; Jacobs et al., 2008a; Bar-Matthews et al., 2010; Matmon et al., 2012; Karkanas et al., 2021).

Biogenic components of clastic sediments include animal and human (anthropogenic) accumulations of fauna and flora and provide rich records that have been recognized as palaeoenvironmentally-informative archives for over 50 years (e.g., Butzer, 1964; Klein, 1970). Across southern Africa, archaeological excavations continue to generate the vast majority of chronological and palaeoenvironmental data from caves and rock shelters. Through the 1970's and 1980's, extensive excavations, mostly in South Africa, started to provide sufficient faunal and botanical assemblages to enable some of the first syntheses of Quaternary environmental change (e.g., Klein, 1974, 1980; Avery, 1982, 1987, 1988; Butzer, 1984; Prior and Williams, 1985; Thackeray, 1987; Deacon and Lancaster, 1988; Dowson, 1988). More recently, palaeoenvironmental records derived from caves have drawn on stable isotopes from a broad range of components found in the clastic sedimentary record, including terrestrial and marine shells (e.g., Johnson et al., 1997; Cohen et al., 1992; Loftus et al., 2019a), bone and enamel (Sealy, 1996; Sealy et al., 2016 respectively), sedimentary organic matter (Roberts et al., 2013), and leaf waxes (Collins et al., 2017), which have facilitated reconstructions of vegetation cover and composition, rainfall conditions (amount/seasonality), and temperatures across glacial-interglacial cycles. When anthropogenically accumulated assemblages are used for climatological reconstructions (e.g., the use of botanical remains, macrofauna, shellfish), they can produce records of ecological exploitation that help correlate human movement on the landscape to climatic conditions (e.g., Stewart et al., 2012). These records are invaluable, but in any one site tend to be punctuated glimpses, limited in completeness by diverse post-depositional processes or by the nature of irregular and ephemeral occupation.

Geogenic processes (i.e., processes that are geological in nature, e.g., fluvial, colluvial, aeolian) of cave sediment accumulation include allogenic and autogenic components that are also influenced by external climatological conditions (e.g., Karkanas et al., 2021). Consequently, host rock breakdown-derived sedimentation, speleothem deposition and secondary mineral accumulation have been used as proxies for environmental conditions and change (e.g., Butzer, 1973b, 1984; Butzer et al., 1978). Speleothem records from caves and rock shelters also provide important independent palaeoclimatic records and when inter-stratified with clastic deposits can add considerable chronostratigraphic control (e.g., Marean et al., 2010; Karkanas et al., 2021). Here, we draw on the available speleothem records as additional stratigraphic, chronological and palaeoenvironmental components in the southern African cave and rock shelter sequences from MIS 6 to 1. Geogenic processes of weathering, erosion and sedimentation affect the sequences found in cave deposits in diverse ways with complex ties to changing geomorphology, hydrology and climate over short and long timespans, leading to deposit deformation (e.g., Klasies River Main site), formation of significant unconformities (sedimentary hiatuses e.g., Bushman Rock Shelter, Sibudu, Wonderwerk Cave), and cave closure (e.g., Pinnacle Point 13B).

Here, we endeavour to provide an overview of cave and rock shelter stratigraphies and the utilisation of proxies pertinent to the study of southern African Quaternary climate change. This is motivated by a need to understand the source of biases in the current record resulting from the unequal distribution (and sampling) of sites through the region, and from changes in geochronological and palaeoenvironmental analytical capacity, procedures and resolution over many decades of research. In doing so, we hope to highlight opportunities for future re-sampling and re-analysis in light of under-utilised museum collections and an inclination in the archaeological discipline to frequently re-excavate sites. To this end, we present a catalogue of published caves and rock shelters that preserve temporally-relevant clastic and chemical palaeoclimatic and palaeoenvironmental proxies in southern Africa.

Table 1 presents a catalogue of 104 caves and rock shelters in southern Africa dated to the last 200 ka (MIS 6 to 1) that have published sedimentary sequences with palaeoenvironmental and paleoclimatic proxies. Archaeologically, this period spans the Middle Stone Age (MSA) (~300 ka to 20 ka), Later Stone Age (LSA) (~20 ka to historical period) and Iron Age (~2 ka to historical period). Figure 1 presents this data in a map of southern Africa. Individual maps of southern African sites and associated proxies through each Marine Isotope Stage are presented in the Supplementary Information (SI) Figures 1 to 6. (Supplementary data files are archived in the South African Journal of Geology repository (https://doi.org/10.25131/sajg.124.0052.sup-mat)). This catalogue draws on important syntheses of the archaeological record (e.g., Vogel and Visser, 1981; Thackeray, 1992; Wadley, 1993; Dewar, 2008; Lombard et al., 2012; Scott et al., 2021) and individual publications of sites from across southern Africa. It allows us to assess the geographical distribution of published deposits dated from MIS 6 to 1 inclusively, and comment on the availability and utilisation of different palaeoenvironmental proxies across southern Africa by country and South African province. The list is comprehensive, however, it must be noted that every site has been excavated, documented and analysed differently. In many cases, chronological data draw from 30-year-old publications and with new analyses, these dates may change. We are, however, confident that we have referred to the most recent dates available at the time of writing this contribution. It must also be noted that date ranges for deposits, and sequences of deposits, do not indicate sedimentary or occupational continuity and all sites document sedimentary and occupational hiatuses that may not be represented in the given dates. We have tried to document major sedimentary breaks in sites from original literature.

Although we have attempted to document all rock shelters and caves in southern Africa with published chronologies and published dedicated palaeoenvironmental analyses, there are two limitations to the list presented. First, there are many shelters containing deposits of Holocene age with Later Stone Age artefact assemblages in southern Africa (e.g., Deacon, 1974). While relatively few have published dedicated palaeo-environmental analyses, there is a chance we have missed examples of these in older literature, contract archaeological site reports or the grey literature. Second, there is a significant distributional bias resulting from political and logistical dynamics. For example, we could not find any records of sites satisfying our criteria for inclusion in Zimbabwe. We are aware of previous (e.g., Cooke, 1971; Deacon, 1974; Larsson, 1996) and ongoing work in rock shelters and caves in the country, and we await these important results. It must also be noted that there are many caves that have been documented in the speleological literature that do not contain anthropogenic deposits but may be of significant palaeoenvironmental value (e.g. Laumanns, 2017).

We also attempt to demonstrate the complexity of the MIS 6 to 1 stratigraphic record represented in cave and rock shelters by

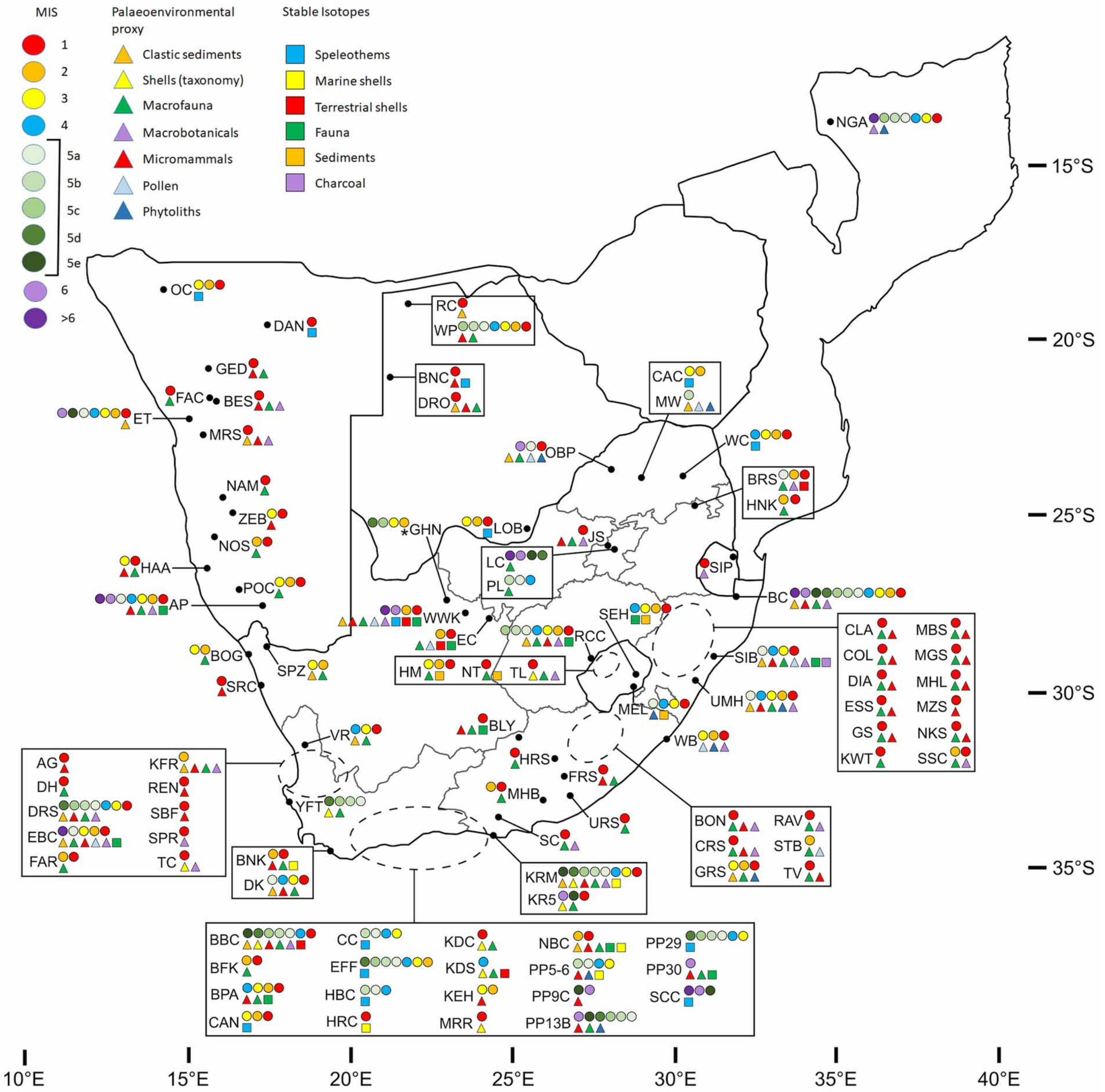

Figure 1. *Map of southern Africa with locations of caves and rock shelter sites with published dates and palaeoenvironmental data yielded from clastic sediments and speleothems between Marine Isotope Stage 6 and 1. Sites are listed in Table 1 and discussed in text. Table 1 includes site name abbreviations. The * associated with GHN represents the use of tuff deposit growth as a palaeoenvironmental proxy.*

Table 1. Catalogue of sites discussed in text and presented in Figure 1.

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Botswana and Mozambique					
Bone Cave, Botswana (BNC)	U-Th	0.37 to 0.02	1	Stable isotopes from speleothems; micromammals	Railsback et al., 2018; Pierce, 2020
Drotsky's Cave, Botswana (DRO)	^{14}C*	12.5 to 5.4	1	Macrofauna; micromammals; sediments; valley calcrete	Robbins et al., 1996a
Lobatse Cave, Botswana (LOB)	U-Th	50.9 to 21.4	3 to 1	Stable isotopes from speleothems	Holmgren et al., 1994, 1995
Ngalue Cave, Mozambique (NGA)	U-Th ^{14}C ESR	~470; 324; 251; 105 to 42; ~1	13; 9; 8; 5c to 3; 1	Starch granules; phytoliths	Mercader, 2009; Mercader et al., 2013
Rhino Cave, Botswana (RC)	^{14}C	5.5 to 0.9 (6.6 on organic content in shelter wall cupules)	1	Sediments	Robbins et al., 1996b; Brook et al., 2011
White Paintings Rock Shelter, Botswana (WP)	^{14}C TL OSL	~95 to ~20; 5 to 0.2	5c to 2; 1	Macrofauna; micromammals	Robbins et al., 2000
Eswatini					
Siphiso Rock Shelter (SIP)	^{14}C*	14 to 0.35	1	Macrobotanicals	Prior and Williams, 1985; Barham, 1989a
Lesotho					
Ha Makotoko (HM)	^{14}C	>42 to 7	3 to 1	Macrofauna; stable isotopes from sediments	Mitchell, 1993; Roberts et al., 2013; Mitchell and Arthur, 2014
Melikane Rock Shelter (MEL)	^{14}C OSL	83 to 27; 3.3 to 0.3⁺	5a to 3; 1	Phytoliths; stable isotopes from sediments	Jacobs et al., 2008a; Stewart et al., 2012, 2016, 2020; Stewart and Mitchell, 2018
Ntloana Tšoana (NT)	^{14}C OSL	14 to 6.8 (palaeoenvironmental data from MSA deposits are unpublished)	1	Macrofauna; stable isotopes from sediments	Roberts et al., 2013; Arthur, 2021

Sites are organised alphabetically by country and by province for South African sites. Dates for Marine Isotope Stage boundaries follow Lisiecki and Raymo (2005). Boundaries for MIS 5 substages follow Otvos (2015).

*Indicates sites for which some or all of the published ^{14}C dates are uncalibrated, have not been calibrated in subsequent publications, or it is not stated if the dates are calibrated.

⁺Indicates sites where debates about chronology continue.

Abbreviations: U-Th=Uranium Thorium radiometric dating; ^{14}C=Carbon-14 radiometric dating; ESR=Electron spin resonance; OSL=Optically stimulated luminescence; SG-OSL=Single-grain optically stimulated luminescence; IRSL=Infrared stimulated luminescence; TL=Thermoluminescence; AAR=Amino acid racemisation; PM=Palaeomagnetism; CNB=Cosmogenic nuclide burial dating; OES=Ostrich egg shell.

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Sehonghong (SEH)	^{14}C OSL	57.6 to 1	4 to 1	Stable isotopes from sediments and tooth enamel	Mitchell, 1996; Jacobs et al., 2008a; Loftus et al., 2015; Pargeter et al., 2017; Jacobs and Roberts, 2017
Tloutle Rock Shelter (TL)	^{14}C	9.6 to 6.9	1	Macrofauna; shellfish; macrobotanicals	Mitchell, 1990; Plug, 1993b; Esterhuysen et al., 1999
Namibia					
Apollo 11 Cave (AP)	^{14}C* AAR SG-OSL	~236; ~180; 80 to 8; 1.6 to 0.3	7; 6; 5a to 1; 1	Macrofauna; micromammals; macrobotanicals; stable isotopes from bone	Thackeray, 1979; Freundlich et al., 1980; Vogel and Visser, 1981; Vogel, 1983; Vogelsang et al., 2010; Murray-Wallace et al., 2015
Big Elephant Shelter (BES)	^{14}C*	3.1 to 1	1	Macrofauna; micromammals; macrobotanicals	Beaumont and Vogel, 1972; Wadley, 1976, 1979; Wadley, 2012
Dante Cave (DAN)	U-Th	4.6 to 0.01	1	Stable isotopes from speleothems	Sletten et al., 2013; Voarintsoa et al., 2017
Erb Tanks (ET)	^{14}C* AAR	30; ~85 to <5 1	6/5; 5a to 1	Sediments	McCall et al., 2011
Fackelträger (FAC)	^{14}C*	2.9 to 0.2	1	Macrofauna	Thackeray, 1979; Freundlich et al., 1980
Geduld (GED)	^{14}C*	2.3 to 0.8	1	Macrofauna; micromammals	Smith and Jacobson, 1995
Haalenberg Shelter (HAA)	^{14}C*	~40.1; 2.3 to 2.2	3; 1	Macrofauna; micromammals	Thackeray, 1979; Vogel and Visser, 1981
Mirabib Hill Shelter (MRS)	^{14}C*	8.4 to 1.5	1	Micromammals; macrobotanicals; sediments	Brain and Brain, 1977; Sandelowsky, 1977
Namtib (NAM)	^{14}C*	8.3 to 5.4	1	Macrofauna	Thackeray, 1979; Freundlich et al., 1980; Vogel and Visser, 1981
Nos (NOS)	^{14}C*	~22.1; 0.3 to 0.1	2, 1	Macrofauna	Thackeray, 1979; Vogel and Visser, 1981
Orumana (OC)	U-Th	47 to 0.1	3 to 1	Stable isotopes from speleothems	Railsback et al., 2016
Pockenbank (POC)	^{14}C*	49.5 to 19.3; ~6.9; ~0.3	3 to 2; 1	Macrofauna	Thackeray, 1979; Freundlich et al., 1980; Vogel and Visser, 1981
Zebrarivier Cave (ZEB)	^{14}C*	>48.2; ~11.9	3; 1	Micromammals	Vogel and Visser, 1981; Avery, 1983

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
South Africa by province					
Eastern Cape					
Blydefontein Rock Shelter (BLY)	^{14}C	12 to 0.8	1	Macrofauna; micromammals; stable isotopes from bone	Avery, 1988; Scott et al., 2005; Bousman, 2005
Bonawe Rock Shelter (BON)	^{14}C*	8.0 to 2.2	1	Macrofauna; micromammals; macrobotanicals	Opperman, 1987; Tusenius, 1989; Avery, 1990
Colwinton Rock Shelter (CRS)	^{14}C*	6.3 to 0.1	1	Macrofauna; micromammals; macrobotanicals	Opperman, 1987; Tusenius, 1989; Avery, 1990
Fairview Rock Shelter (FRS)	^{14}C*	3.7 to 2.4	1	Macrofauna; micromammals	Robertshaw, 1984
Grassridge Rock Shelter (GRS)	^{14}C* OSL	43.1 to 28; 13.5 to 11.6; 7.3 to 6.8	3 to 1	Macrofauna; phytoliths; sediments	Opperman, 1984, 1987, 1988; Ames et al., 2020
Highlands Rock Shelter (HRS)	^{14}C*	4.5 to 3.5	1	Macrofauna	Deacon, 1976; Klein, 1980;
Klasies River Cave 5 (KR5)	^{14}C* OSL/TL $\delta^{18}O$ on shell	137.4 to 115; 4.2 to 2.2	6 to 5e; 1	Macrofauna; shellfish	Singer and Wymer, 1969; Klein, 1976; Shackleton, 1982; Voigt, 1982; Hall and Binneman, 1987; Feathers, 2002
Klasies River Main site (KRM)	^{14}C* AAR ESR SG-OSL TL-OSL TL OSL IRSL U-series ESR $\delta^{18}O$ on shell	120.0 to 43; 4.7 to 2.5	5e to 3; 1	Macrofauna; micromammals; macrobotanicals; shellfish; stable isotopes from shell; sediments	See Grine et al., 2017; Langejans et al., 2017; Reynard and Wurz, 2020 for review
Melkhoutboom Cave (MHB)	^{14}C*	15.4 to 2.8	2 to 1	Macrofauna	Deacon, 1976; Klein, 1980
Ravenscraig Rock Shelter (RAV)	^{14}C*	10.2 to 0.4	1	Macrofauna; macrobotanicals	Opperman, 1987; Tusenius, 1989
Scott's Cave (SC)	^{14}C*	1.2 to 0.3	1	Macrofauna; macrobotanicals	Wells, 1965; Deacon and Deacon, 1963; Deacon, 1967; Klein and Scott, 1974
Strathalan Cave B (STB)	^{14}C*	29.3 to 20.9	2	Macrofauna; pollen	Opperman, 1992, 1996; Opperman and Heydenrych, 1990

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Te Vrede (TV)	^{14}C*	10.1 to 8.1	1	Macrofauna; micromammals	Opperman, 1987; Avery, 1990
Uniondale Rock Shelter (URS)	^{14}C*	6.3 to 2.1	1	Macrofauna	Brooker, 1989; Sadr and Samson, 2006
Waterfall Bluff (WB)	^{14}C OSL	37.6 to 10.5 (8.2 unmodeled)	3 to 1	Macrobotanicals; phytoliths; pollen	Esteban et al., 2020a; Fisher et al., 2020
Free State					
Rose Cottage Cave (RCC)	^{14}C OSL	95 to 15; 10 to 5⁺ (See Loftus et al. 2019b for site occupation phases in MIS 3)	5c to 2; 1	Macrofauna; micromammals; macrobotanicals; sediments; stable isotopes from tooth enamel	Butzer, 1984; Plug and Engela, 1992; Avery, 1997b; Smith et al., 2002; Pienaar et al. 2008; Loftus et al., 2019c; Lennox and Wadley, 2021
Gauteng					
Jubilee Shelter (JS)	^{14}C*	8.7 to 3.1; 1.8 to 1.3	1	Macrofauna; macrobotanicals; micromammals	Turner, 1986; Wadley, 1986; Dowson, 1988; Avery, 1993
Lincoln Cave (LC)	U-Th	252 to 115	9 to 5d	Macrofauna	Reynolds et al., 2007
Plovers Lake (PL)	U-Th ESR	88 to 61.6	5b to 4	Macrofauna	de Ruiter et al., 2008
KwaZulu-Natal					
Clarke's Shelter (CLA)	^{14}C*	2.1 to 1.5	1	Macrofauna; micromammals	Mazel, 1984a; Avery, 1991
Collingham Shelter (COL)	^{14}C*	1.9; 1.2; 0.6	1	Macrofauna; micromammals	Avery, 1991, 1992b; Mazel, 1992; Plug, 1992
Border Cave (BC)	^{14}C* ESR	238 to ~20; 2 to 0.6 (1 Brown Sand Upper remains poorly controlled)	6/7 to 2; 1	Macrofauna; micromammals; macrobotanicals; sediments	Klein, 1977; Butzer, 1978; Avery, 1992a; d'Errico et al., 2012; Villa et al. 2012; see Backwell et al., 2018 for review
Diamond 1 (DIA)	^{14}C*	4.9 to 2.8	1	Macrofauna; micromammals	Mazel, 1984a; Avery, 1991
eSinhlonhlweni Shelter (ESS)	^{14}C*	0.4 to 0.1	1	Macrofauna; micromammals	Mazel, 1986a; Avery, 1991
Gehle Shelter (GS)	^{14}C*	~5.7; 1.3 to 0.7	1	Macrofauna; micromammals	Mazel, 1984b; Avery, 1991
KwaThwaleyakhe Shelter (KWT)	^{14}C*	3.8 to 1.2	1	Macrofauna	Mazel, 1993; Plug, 1993a
Mbabane Shelter (MBS)	^{14}C*	1.5 to 0.4	1	Macrofauna; micromammals	Mazel, 1986a; Avery, 1991
Mgede Shelter (MGS)	^{14}C*	6.5 to 0.1⁺	1	Macrofauna; micromammals	Mazel, 1986b; Avery, 1990, 1991

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Mhlwazini Cave (MHL)	^{14}C*	~2.6 to 2.2; 0.5 to 0.2	1	Macrofauna; micromammals	Mazel, 1990; Plug, 1990; Avery, 1991
Mzinyashana Shelter 1 (MZS)	^{14}C*	4.2 to 0.6	1	Micromammals	Avery, 1997a; Mazel, 1997
Nkupe Shelter (NKS)	^{14}C*	6.6 to 2.4	1	Macrofauna; micromammals	Mazel, 1988; Avery, 1990, 1991
Shongweni South Cave (SSC)	^{14}C*	22 to 11.8; 4; 1.7 to 0.7	2 to 1	Macrofauna; macrobotanicals	Davies, 1975
Sibudu (SIB)	^{14}C* OSL	77.2 to 46.4; 0.9	5a to 3; 1	Macrofauna; micromammals; macrobotanicals; stable isotopes from charcoal and tooth enamel; pollen; sediments	Cain, 2004, 2006; Plug, 2004, 2006; Allott, 2006; Glenny, 2006; Herries, 2006; Renaut and Bamford, 2006; Reynolds, 2006; Sievers, 2006; Wadley and Jacobs, 2006; Wells, 2006; Clark and Plug, 2008; Jacobs et al., 2008a,b; Wadley, 2008; Val, 2016; Robinson and Wadley, 2018; Clarke, 2019
Umhlatuzana Rock shelter (UMH)	^{14}C* OSL	~71 to 10; 2.8^{+}	5a/4 to 1	Macrofauna; micromammals; macrobotanicals; phytoliths; sediments	Kaplan, 1990; Avery, 1991; Lombard et al., 2010; Sifogeorgaki et al., 2020
Limpopo					
Cold Air Cave (CAC)	U-Th	48 to 24.3; 6.5 to 0.1; 0.3 to 0.1 (multiple stalagmites represented)	3 to 2	Stable isotopes from speleothems	Repinski et al., 1999; Holmgren et al., 1999; Stevenson et al., 1999; Lee-Thorp et al., 2001; Holmgren et al., 2003; Sundqvist et al., 2013
Mwulu's Cave (MW)	OSL	~90	5b	Sediments; pollen; phytoliths	Tobias, 1949, 1954; de la Peña et al., 2019; Esteban et al., 2020b; Feathers et al., 2020
Olieboomspoort (also published as Olieboompoort) (OBP)	^{14}C* U-Th ESR	~150; 77; 0.8^{+}	6; 5a; 1	Macrofauna; phytoliths; pollen; sediments	Mason, 1969; Van der Ryst, 2006; Val et al., 2021
Wolkberg Cave (WC)	U-Th	57.8 to 39.7; 29.5 to 1.5	4 to 3; 3 to 1	Stable isotopes from speleothems	Talma et al., 1974; Holzkämper et al., 2009
Mpumalanga					
Bushman Rock Shelter (BRS)	^{14}C* OSL	~80; 14.1	5a; 2/1	Macrobotanicals; macrofauna; stable isotopes from snail shell	Vogel, 1969; Plug, 1978, 1981; Abell and Plug, 2000; Porraz et al., 2015, 2018; Puech et al., 2021
Heuningneskrans Shelter (HNK)	^{14}C	28.5 to 9.5	2 to 1	Macrofauna	Klein, 1984; Porraz and Val, 2019

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Northern Cape					
Boegoeberg 1 (BOG)	^{14}C*	>37.2 to 30⁺	3 to 2	Macrofauna	Klein et al., 1999
Equus Cave (EC)	^{14}C* AAR	29 to 10; AAR - 17 to 0	2 to 1	Macrofauna; stable isotopes from tooth enamel and OES; pollen	Scott, 1987; Klein et al., 1991; Lee-Thorp and Beaumont, 1995; Johnson et al., 1997; Sponheimer and Lee-Thorp, 1999
Ga-Mohana Hill (GHN)	^{14}C OSL U-Th	15; 31; 105 (U-Th indicates maximum age of deposits of 162)	5d to 5c; 3; 2	Presence of ex situ 'cascade' tufa dated to 113.6 to 99.7 ka	Wilkins et al., 2020; 2021
Spitzkloof A (SPZ)	^{14}C*	~52; 23.4 to 17.1	3; 2	Macrofauna; sediments	Dewar and Stewart, 2012, 2016
Spoeg River Cave (SRC)	^{14}C	3.5 to 1.3	1	Micromammals	Avery, 1992c; Vogel et al., 1997
Wonderwerk Cave (WWK)	^{14}C U-Th OSL PM CNB	2000 to ~500; 238 to 153; 16 to 0	76 to 13; 8 to 6; 2 to 1	Macrofauna; micromammals; macrobotanicals; sediments; stable isotopes from fauna, OES and speleothems; pollen	Chazan et al., 2008; Matmon et al., 2012; Horwitz and Chazan, 2015; Pickering, 2015; Chazan et al., 2020; Shaar et al., 2021
Western Cape					
Andriesgrond (AG)	^{14}C*	14.8 to 0.2⁺	1	Micromammals	Avery, 1990; Anderson, 1991
Blombos Cave (BBC)	^{14}C OSL SG-OSL TL	127 to 67; 2 to <1.8	5e to 4; 1	Macrofauna; micromammals; shellfish; stable isotopes from OES; macrobotanicals; sediments	Tribolo et al., 2006; Henshilwood, 2008; Henshilwood et al., 2011; Jacobs et al., 2013, 2020; Badenhorst et al., 2016; Nel and Henshilwood, 2016; Roberts et al., 2016; Reynard and Henshilwood, 2019; Haaland et al., 2020
Boomplaas Cave (BPA)	^{14}C AAR U-series	~66 to 34; 25 to >2.8	4 to 1	Macrofauna; micromammals; stable isotopes from tooth enamel	Faith, 2013; Sealy et al., 2016; Faith et al., 2018; Pargeter et al., 2018
Buffelskloof (BFK)	^{14}C*	>22.8 to 3.8	2 to 1	Macrofauna	Opperman, 1978
Byneskranskop (BNK)	^{14}C	17.1 to 1.7	2 to 1	Macrofauna; micromammals; stable isotopes from marine shell	Klein, 1981; Loftus et al., 2016, 2017; Faith et al., 2018
Cango Cave (CAN)	^{14}C U-Th	49.2 to 1.8	3 to 1	Stable isotopes from speleothems	Vogel, 1983; Talma and Vogel, 1992; Vogel and Kronfeld, 1997

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Crevice Cave (CC)	U-Th	90.5 to 53	5b to 3	Stable isotopes from speleothems	Bar-Matthews et al., 2010
De Hangen (DH)	^{14}C*	1.9 to 0.1	1	Macrofauna	Parkington and Poggenpoel, 1971
Die Kelders Cave 1 (DK)	^{14}C* ESR OSL TL IRSL	79.7 to 50.6; 2 to 1.4⁺	5a to 3; 1	Macrofauna; micromammals; sediments	Schweitzer, 1970; Tankard, 1976; Avery, 1982; Feathers and Bush, 2000; Goldberg, 2000; Klein and Cruz-Uribe, 2000; Schwarcz and Rink, 2000
Diepkloof Rock Shelter (DRS)	^{14}C SG-OSL TL/OSL	107 to 49.1; 1.5 to 0.4⁺	5d to 3; 1	Macrofauna; micromammals; macrobotanicals; sediments	Parkington and Poggenpoel, 1987; Avery, 1990; Jacobs et al., 2008a; Cartwright, 2013; Miller et al., 2013; Steele and Klein, 2013; Tribolo et al., 2013; Feathers, 2015; Jacobs and Roberts, 2015; Collins et al., 2017
Efflux Cave (EFF)	U-Th	114 – 20 ka	5d - 2	Stable isotopes from speleothems	Braun et al., 2020
Elands Bay Cave (EBC)	^{14}C OSL TL IRSL	~236; ~83.0; ~38 to 19; 16.9 to 9.6; 5.3 to 3.5; 1.3 to 0.8	7; 5a; 3 to 2; 2 to 1; 1	Macrofauna; micromammals, macrobotanicals; pollen; stable isotopes from tooth enamel; sediments	Matthews, 1999; Parkington, 2000; Cartwright et al., 2016; Klein and Cruz-Uribe, 2016; Miller et al., 2016; Stowe and Sealy, 2016; Tribolo et al., 2016
Faraoskop Rock Shelter (FAR)	^{14}C*	16.5 to 10.8; 4 to 2; 0.6	2 to 1	Macrofauna	Manhire, 1993
Herolds Bay Cave (HBC)	U-Th	93 to 62	5b to 4	Stable isotopes from speleothem	Braun et al., 2020
Hoffman's/Robberg Cave (HRC)	^{14}C	4.0 to 3.3	1	Stable isotopes from marine shell	Kyriacou, 2009; Loftus et al., 2017
Klipdrift Cave (KDC)	^{14}C	13.7 to 10.7	1	Macrofauna; shellfish	Ryano et al., 2017, 2019; Discamps et al., 2020
Klipdrift Shelter (KDS)	SG-OSL	71.6 to 51.7	4	Macrofauna; shellfish; stable isotopes from OES	Henshilwood et al., 2014; Reynard et al., 2016; Roberts et al., 2016
Klipfonteinrand (KFR)	^{14}C	22.3 to 13.4	2	Macrofauna; micromammals; macrobotanicals; sediments	Avery, 1990; Mackay et al., 2020
Knysna Eastern Heads Cave 1 (KEH)	^{14}C	39 to 18	3 to 2	Micromammals	Matthews et al., 2020

Table 1. Catalogue of sites discussed in text and presented in Figure 1. (*Continued*)

Site (site name abbreviation)	Dating	Age of deposits (ka)	MIS	Palaeoenvironmental proxy used	Reference
Matjes River Rock Shelter (MRR)	^{14}C*	11.3 to 2	1	Shellfish	Döckel, 1998; Sealy et al., 2006
Nelson Bay Cave (NBC)	^{14}C	29.8 to 4.7	2 to 1	Macrofauna; micromammals; stable isotopes from bone, tooth enamel and marine shell; sediments	Klein, 1972; Butzer, 1973a; Sealy, 1996; Loftus et al., 2016, 2017; Faith et al., 2018; Sealy et al., 2020
Pinnacle Point 5-6 (PP5-6)	OSL Tephro-chronology	98 to 50	5c to 3	Micromammals; phytoliths; stable isotopes from marine shell	Loftus et al., 2017; Esteban et al., 2020c; Matthews et al., 2020
Pinnacle Point 9C (PP9C)	OSL	130 to 120	6 to 5e	Micromammals	Matthews et al., 2011, 2020
Pinnacle Point 13B (PP13B)	OSL, U-Th, ^{14}C*	~165 to 40; 2.3	6-3; 1	Macrofauna; micromammals; phytoliths	Rector and Reed, 2010; Esteban et al., 2020c; Matthews et al., 2020
Pinnacle Point 29 (PP29)	U-Th	112.3 to 42.7	5d to 3	Stable isotopes from speleothems	Braun et al., 2019
Pinnacle Point 30 (PP30)	OSL	~151	6	Macrofauna; micromammals; stable isotopes from bone	Rector and Reed, 2010; Matthews et al., 2020; Williams et al., 2020
Renbaan (REN)	^{14}C*	5.4 to 1.1	1	Micromammals	Kaplan, 1984, 1987; Avery, 1990
Spring Cave (SPR)	^{14}C*	3.5 to 0.4	1	Macrobotanicals	February, 1992; Jerardino, 1996
Staircase Cave (SCC)	U-Th	330.2 to 130.2	9 to early 5e	Stable isotopes from speleothems	Braun et al., 2019
Steenbokfontein (SBF)	^{14}C*	8.4 to 2.2	1	Micromammals	Avery, 1999; Jerardino and Swanepoel, 1999
Tortoise Cave (TC)	^{14}C*	7.7 to 0.7	1	Shellfish; macrobotanicals	Robey, 1987; February, 1992; Jerardino, 1993
Varsche Rivier 003 (VR)	^{14}C	61.4 to 41.7; 2 to 0.2	4 to 3; 1	Macrofauna; sediments	Steele et al., 2016
Ysterfontein 1 (YFT)	OSL Sea level curves	110 to 71 (see Avery et al., 2008 for discussion of ages)	5d to 5a	Macrofauna; shellfish	Avery et al., 2008

presenting three case study sites, Border Cave, Klasies River Main site and the Pinnacle Point site complex. The case study sites present three of the most complete sedimentary sequences of the period in southern Africa, represent interior and coastal contexts, and provide useful examples of the utilisation of different sedimentary components as palaeoenvironmental proxies.

Case study 1: Border Cave

Border Cave is one of a handful of non-coastal caves and rock shelters in southern Africa with a long clastic sedimentary sequence spanning the last 250 000 years – MIS 7 to MIS 1 (Figure 2; Table 2). Although only 82 km west of the Indian Ocean, the site occupies a non-coastal ecological and geomorphological context – located 600 m above mean sea level on the west-facing steep slope of the rhyolitic Lebombo Mountains of northern KwaZulu-Natal, overlooking the plains of the Eswatini lowveld. Precipitation in the area fluctuates greatly due to the highly variable topography but the mountains presently receive between 550 to 1 000 mm per year (Schultz and Lynch, 2007). The geomorphological and climatological variability of the area also results in a diverse mosaic of local vegetation with numerous vegetation types close to the cave, including the Lebombo Summit Sourveld (SVI 17), Northern and Southern Lebombo Bushveld (SVI 15 and 16 respectively) (Mucina and Rutherford, 2006), and riverine and lowveld vegetation in Eswatini. The potential for significant ecological variability in this area can be extended to its past. Extensive excavations at the site led by four different archaeologists since 1934 have yielded a rich record of human occupation and exploitation of the local landscape that includes a human burial, examples of ornamentation (Cooke et al., 1945), and bone tools (d'Errico et al., 2012). Exceptional preservation of organic matter has led to discoveries of plant exploitation beyond 170 000 years ago (Wadley et al., 2020a, b).

Chemical sedimentation at Border Cave is minimal. The sedimentary sequence consists of a mixture of autogenic and allogenic clastic sediments including some anthropogenic and biogenic inputs. Larger allogenic clastic particles are generally anthropogenic in nature, accumulated through flora and fauna collection and burning activities. Minor components of allogenic soils incidentally accumulated by people and animals are also present, although prolonged or regular occupation of the cave by large numbers of animals is unlikely given the precipitous access route into the cave (Butzer et al., 1978). Geogenic autogenic clastic material comprises granulometrically variable rhyolitic and sandstone components formed through decay of the host rock and potentially minor aeolian inclusions into thick units of minimally mobilised sediments (Butzer et al., 1978; Backwell et al., 2018).

The stratigraphy of Border Cave (Figure 2 and Table 2) was briefly described by Cooke (Cooke et al., 1945) and following Beaumont's earlier excavations (Beaumont, 1973) has been described as a sequence of alternating units of 'White Ash' and 'Brown Sand'. These units vary in thickness and lateral continuity, but White Ash units can generally be described as

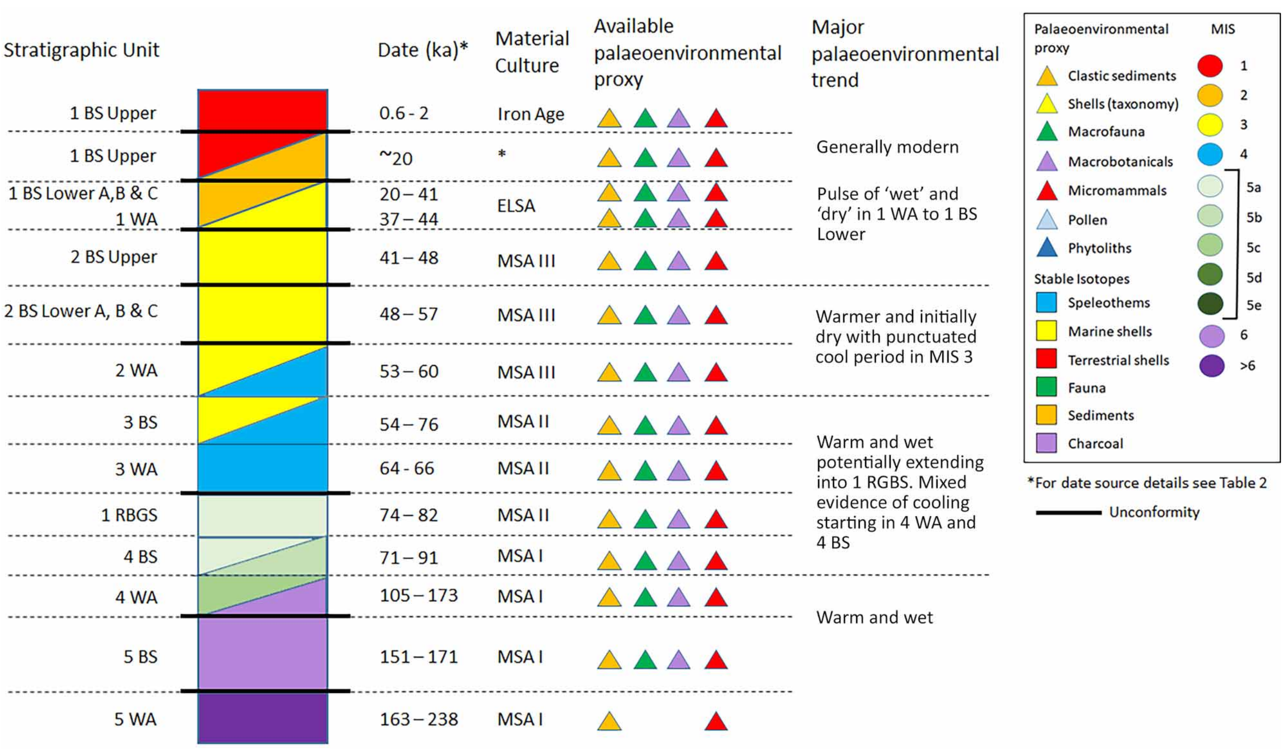

Figure 2. *Composite stratigraphic profile of the Border Cave deposits with dates, material culture associations, available palaeoenvironmental proxy and major palaeoenvironmental trend interpretations. Table 2 includes major dating references for the deposits. Marine Isotope Stages are represented as colours in the column and follow Figure 1 in sequence. 1 Brown Sand (BS) Upper remains poorly controlled.*

Table 2. Stratigraphic, cultural and chronological sequence at Border Cave.

Material Culture	Member	Method	Age of deposits (ka)	MIS[e,f]	References
Iron Age	Pits and rubble in 1 BS Upper[a]	^{14}C on bone charcoal, vegetation, and ceramic typology	0.6 – 2	1	1, 2
*	1 BS Upper	^{14}C on charcoal	(poorly controlled)	1 - 2	1, 2
Early LSA	1 BS Lower A, B &C	^{14}C on charcoal	~20 – 41	2 – 3	3, 4
	1 WA	^{14}C on charcoal	37 – 44	3	3, 4
MSA III	2 BS Upper	^{14}C on charcoal and ESR	41 – 48	3	3, 4
	2 BS Lower A,B & C	^{14}C (uncal) on charcoal and ESR	48 – 57	3	3, 4
	2 WA	^{14}C (uncal) on charcoal and ESR	53 – 60[†]	3 – 4	3, 4, 5
MSA II	3 BS	ESR	54 – 76	3 – 5a *(5a)*	6, 7, but see 8
MSA II	3 WA	ESR	64 ± 2	4 *(5a)*	6, 7
MSA II	1 RGBS	ESR	74 – 82	5a	6, 7, 8
MSA I	4 BS[b]	ESR	71 – 91	5a – 5b *(5b)*	6, 7, 8
MSA I	4 WA	ESR	105 – 173	5c – 6 *(5c-e)*	6, 7, 8
MSA I	5 BS[c]	ESR	151 – 171	6 *(5c)*	6, 7, 8
MSA I	5 WA[d]	ESR	163 – 238	6 – 7 *(5d)*	6, 7, 8[‡]

References: Butzer et al., 1978 (1); Beaumont, 1980 (2); d'Errico et al., 2012 and references therein (3); Villa et al., 2012 and references therein (4); Bird et al., 2003 (5); Grün and Beaumont, 2001 (6); Grün et al., 2003 (7); Millard, 2006 (8). [a]Previously named Layer 1a (Butzer et al., 1978); [b]Previously named 1GBS (Butzer et al. 1978); [c]Previously named 1GBS.LR.B (Beaumont 1978) and BACO A and B Upper (Butzer et al., 1978); [d]Previously named BACO B Lower (Butzer et al., 1978). [e]Dates for Marine Isotope Stage boundaries follow Lisiecki and Raymo (2005). Boundaries for MIS 5 Substages follow Otvos (2015). [f]Italicised and bracketed Marine Isotope Stages follow Avery (1992a) where these differ from Lisiecki and Raymo (2005) and Otvos (2015). 'BS' is an abbreviation of Brown Sand and 'WA' is an abbreviation of White Ash, the major alternating units of the stratigraphic framework defined by Beaumont (1973) and currently used. *considered 'sterile' by Beaumont (1980). [†]References 3, 4, 5 and Backwell et al. (2018) generally propose an age of about 60 Ka for 2 WA. [‡]Significant error margins are found on some ESR samples from stratigraphic unit 5 WA. 1 BS Upper remains poorly controlled.

interdigitating the Brown Sands. Different geometries of the two deposits suggest slightly different depocenter locations (Beaumont, 1978). Significant stratigraphic complexity is present across major unit contacts but also at the sub-unit scale where White Ash units in particular are often comprised of many sub-cm lenses and strata (Cooke et al., 1945; Beaumont, 1973; Butzer et al., 1978). More recently, closer inspection has revealed great intra-unit stratigraphic complexity and sub-unit unconformities (Backwell et al., 2018; Wadley et al., 2020).

It is clear from Table 2 that some significant sedimentary hiatuses are present in the depositional sequence at Border Cave (Figure 2). Butzer et al. (1978) identified eight such hiatuses. Of particular importance is the long hiatus in 1 Brown Sand Upper that may span 18 ka and date to between about 20 ka to 2 ka (d'Errico et al., 2012; Villa et al., 2012), resulting in an absence of an LSA-age assemblage at the site. Part of the stratigraphic and chronological challenge in this part of the sequence is a result of disturbance of the 1 Brown Sand Upper deposit by Iron Age use of the cave for both small livestock management and storage pits (Beaumont, 1978). This is perhaps the most significant gap in the record given its importance in reconstructing the local MIS 2 to MIS 1 climate change. The cause of the other hiatuses in the Border Cave sequence is unclear, but recent research suggests erosional and depositional processes occurred at multiple temporal and spatial scales (Backwell et al., 2018).

Palaeoenvironmental proxies and interpretations

In the absence of isotope-yielding chemical precipitates at Border Cave, palaeoenvironmental reconstructions have drawn on other suitable proxies from the clastic sedimentary components. These include particles accumulated through a range of geogenic and allogenic biogenic and anthropogenic processes. Three key studies at Border Cave establish the palaeoclimatic interpretation for the site. Butzer et al. (1978) utilises 'éboulis' (rubble lenses and strata, or 'horizons') presence and frequency to propose a sequence of frost-weathering deposits formed in colder periods at Border Cave from MIS 6 to 1. Avery (1992a) utilises micromammal remains yielded from excavations at Border Cave to propose proportions of local climatically diagnostic vegetation through the Border Cave sequence. In addition, Avery (1992a) proposes mean temperatures, precipitation and general prevailing climate from 5 White Ash to 1 Brown Sand. Klein (1977; also synthesised in Butzer et al., 1978) uses mammalian fauna (macrofauna) from 4 Brown Sand (MSA I) to 1 Brown Sand Lower (ELSA) to propose not only human subsistence strategies but also the prevailing climate. It should be noted that Klein (1977) calibrates his sequence to material culture, not MIS and so his sequence starts with MSA I as represented in the lower part of 4 Brown Sand (Previously 1 GBS). Preliminary analyses of seeds and charcoal yielded from a new series of excavations sampling the whole sequence provide tentative new palaeoenvironmental information (Backwell et al., 2018). Dedicated publications of these proxies are emerging (e.g., wood charcoal from 1 RGBS; Zwane and Bamford, 2021) and phytolith and pollen analyses are forthcoming.

The published studies can be synthesised as follows: Sediments, micromammal and macrofaunal proxies indicate warmer, wetter conditions during the earlier phases of deposition at Border Cave, during accumulation of units 5 White Ash, 5 Brown Sand, 4 White Ash and 4 Brown Sand - MIS 6 through 5a and b (MSA I and Figure 2). This has been further supported by anthracological analyses focusing on the 1 RGBS unit (MIS 5a), which also suggest microenvironmental variability in the vicinity (Zwane and Bamford, 2021). However, woody species' representation in the vicinity of the cave as evidenced by anthropogenically-gathered charcoal recovered from 5 Brown Sand and 4 White Ash (Backwell et al., 2018) suggests a similar vegetation regime to today and challenges Avery's (1992a) proposal that miombo woodland or miombo savanna woodland occupied the Lebombo Mountain during early phases of Border Cave occupation. Both the micromammal (Avery, 1992a) and sedimentary data (Butzer et al., 1978) identify a cooling period in 3 White Ash and 3 Brown Sand spanning the early MIS 5a stages to the MIS 4 to 3 transition (MSA II), with micromammal data indicating a reduction in rainfall during this period. From the upper 3 Brown Sand unit into 2 White Ash and 2 Brown Sand Lower deposit (MIS 4 transitioning into 3; about 76 to 50 ka), both sediments and micromammal data identify a warming of the climate with an initially dryer phase. In the same period, macrofaunal remains suggest a prevailing climate largely similar to today's (Klein, 1977). Recently, seed and charcoal data suggest that a mosaic of vegetation similar to that of today existed around the site before 100 ka (Backwell et al., 2018). Butzer et al. (1978) propose a short colder period within a 2 Brown Sand lower sub-unit (within MIS 3), which potentially correlates with a similar cooler period identified by Avery (1992a), although the micromammal data indicate this to be a period of higher rainfall. Butzer et al. (1978) also identify a cold 'wet' and 'dry' period in the 1 White Ash and 1 Brown Sand Lower deposits and correlate this to MIS 3 to 2. We await new information from current research at the cave to augment these interpretations with more botanical evidence.

Case study 2: Klasies River Main site

Klasies River Main site (KRM) represents a complex of closely associated caves and rock shelters on the southern coast of the Eastern Cape Province (Figure 1) that have yielded evidence for human occupation from MIS 5e to 3 and again in MIS 1 (Tables 1 and 3). The sites are hosted within a quartzarenite cliff, with cave openings at elevations between 6 m and 18 m above mean sea level (Deacon and Geleijnse, 1988). The area has a mild, temperate climate with relatively high rainfall (~1000 mm per year; Schultz and Lynch, 2007), and the natural vegetation is a mosaic of different biomes, including species from Mucina and Rutherford's (2006) Southern Afrotemperate Forest (FOz 1), Southern Coastal Forest (FOz 6), Subtropical Dune Thicket (AZs 3), Gamtoos Thicket (AT 4), Cape Seashore Vegetation (AZd 3), Algoa Dune Strandveld (AZs 1), and Southern Cape Dune Fynbos (FFd 11) biomes (Van Wijk et al., 2017). KRM is one of a group of significant sites in the Greater Cape Floristic Region (GCFR) of the southern and western Cape that records early utilisation of coastal resources by human populations (Marean et al., 2014). This behaviour (along with other complex subsistence behaviours) has been suggested to be a significant step in the evolution of modern human cognitive abilities (e.g., Marean, 2014; Wadley, 2015; Will et al., 2016), and it has not been recorded outside of this region until after 100 ka, except for potential evidence at a group of sites around East London (Morrissey et al., 2020) and a single occurrence in Eritrea (Walter et al., 2000). The occupation of KRM took place during multiple isotope stages, in an area with significant climatic and environmental differences from most of the other GCFR sites, including a steeper coastal shelf and the site's location in the year-round rainfall zone (Deacon, 1992; Fisher et al., 2010; Langejans et al., 2017; Reynard and Wurz, 2020). Therefore, understanding the palaeoenvironmental context of the human behaviour recorded at KRM is useful not only for site-specific reconstructions of human-environment interactions, but also for elucidating the impact of spatial and temporal changes in palaeoenvironmental conditions on human subsistence behaviours across the GCFR and southern Africa more generally.

Broadly speaking, the clastic deposits at KRM can be divided into discrete anthropogenic deposits (such as hearths and shell middens) and the surrounding geogenic deposits (including sands and colluvial rubble). Anthropogenic inputs (also found in geogenic deposits as reworked components or isolated *in situ* particles) include palaeoenvironmental proxies such as faunal remains exploited for subsistence (e.g., bovids and marine shellfish) and carbonised plant material (e.g., charcoal) (Deacon, 1993; Langejans et al., 2017; Larbey et al., 2019; Reynard and Wurz, 2020).

The ocean played a significant role in the earliest phases of deposition, starting with the formation of beach deposits in the caves (Butzer, 1978). Beach deposits outside the caves then provided the main source of sand, likely through aeolian processes, for some time (Deacon and Geleijnse, 1988). A marked shift occurred when the colluvial transport of sediments from the Geelhoutboom palaeodune above the site became the main source of geogenic inputs. This eventually led to the formation of sloped deposits in Cave 1, which are rich in secondary-context anthropogenic materials eroded from deposits in Cave 1A (Deacon and Geleijnse, 1988). The main biogenic input was the deposition of micromammal bones by owls, a significant palaeoenvironmental proxy (Nel et al., 2018).

Chemical deposits at Klasies include dripstone and flowstone ('crusts'), and tufa (Deacon and Geleijnse, 1988; Wurz et al., 2018). Their presence or absence in particular deposits has been used to identify wet and dry phases in the sedimentary sequence (Butzer, 1978). Isotopic analysis of the speleothems, an important palaeoenvironmental proxy at other sites in the region (e.g. Braun et al., 2019), has been unsuccessful due to partial dissolution and recrystallisation of these deposits.

A single stratigraphic system (Figure 3) is applied across the KRM complex. Individual lithostratigraphic units (sometimes just millimetres thick) are grouped into named members and sub-members based on broad lithological similarities (Deacon and Geleijnse, 1988; Wurz et al., 2018). However, the grouping of units both within and between caves has been heavily influenced by cultural stratigraphy. There are seven recognised cultural phases – defined based on lithic (stone tool) technologies – consisting of five MSA and two LSA industries (Wurz, 2002). The major stratigraphic groupings and their ages are presented in Table 3. Several hiatuses have been inferred based on sedimentary structures, speleothem growth, dating, and cultural stratigraphy (Deacon and Geleijnse, 1988). These are discussed below with the palaeoenvironmental data. The chronology of the deposits is somewhat unclear, with overlapping ages for many phases (Table 3). This is due in part to the impacts of the geochemistry of the site on the accuracy and interpretation of some dating techniques and their results (Vogel, 2001; Feathers, 2002). However, there are broad ages available for the entire sequence. For more detailed reviews of the stratigraphy and dating see Wurz (2002) and Grine et al. (2017).

Palaeoenvironmental proxies and interpretations

The basal beach deposits (MIS 5e; MSA I) in Cave 1 indicate a sea-level highstand up to +7 m (Butzer, 1978). Speleothem formation between the gravels and the overlying deposits has been suggested to represent a hiatus in clastic sedimentation (Hendey and Volman, 1986). The dominance of beach sand in the Light Brown Sand Member (LBS) deposits (MIS 5e to 5d; MSA I), that overlie the basal beach deposits, indicates that the shoreline was close to the site (Deacon and Geleijnse, 1988). This is supported by the taxonomic composition and $\delta^{18}O$ values of anthropogenically-accumulated marine shell assemblages, which suggest relatively high contemporary sea surface temperatures (SSTs) and sea levels (Shackleton, 1982; Langejans et al., 2017; Thackeray, 2018). Reconstructions of SSTs suggest they were 5°C cooler (14°C average) and had 1.8°C lower seasonal amplitude (4.9°C) than the present (Loftus et al., 2017). The mammalian assemblages suggest a mosaic of vegetation, but a dominance of open grassland, and a relatively dry climate (Klein, 1976; Nel et al., 2018; Reynard and Wurz, 2020). Correspondingly, dry conditions inside Cave 1 are evidenced by a lack of speleothem formation (Butzer, 1978). An unconformity between the LBS and the overlying Shell and Sand Member (SAS) deposits across the site corresponds with the change in sand source from beach deposits to the Geelhoutboom dunes (Deacon and Geleijnse, 1988; Rightmire and Deacon, 1991).

Butzer (1978) interpreted the presence of beach cobbles in the SAS (MIS 5c to 4; MSA II) as representing a coeval sea-level highstand up to +5 m. However, the cobbles were almost certainly anthropogenically introduced and there is no other evidence for this highstand (Singer and Wymer, 1982; Deacon and Geleijnse, 1988). Sea levels were initially relatively high, but decreased through the period in which the SAS was deposited (Langejans et al., 2017; Thackeray, 2018). Average SSTs increased

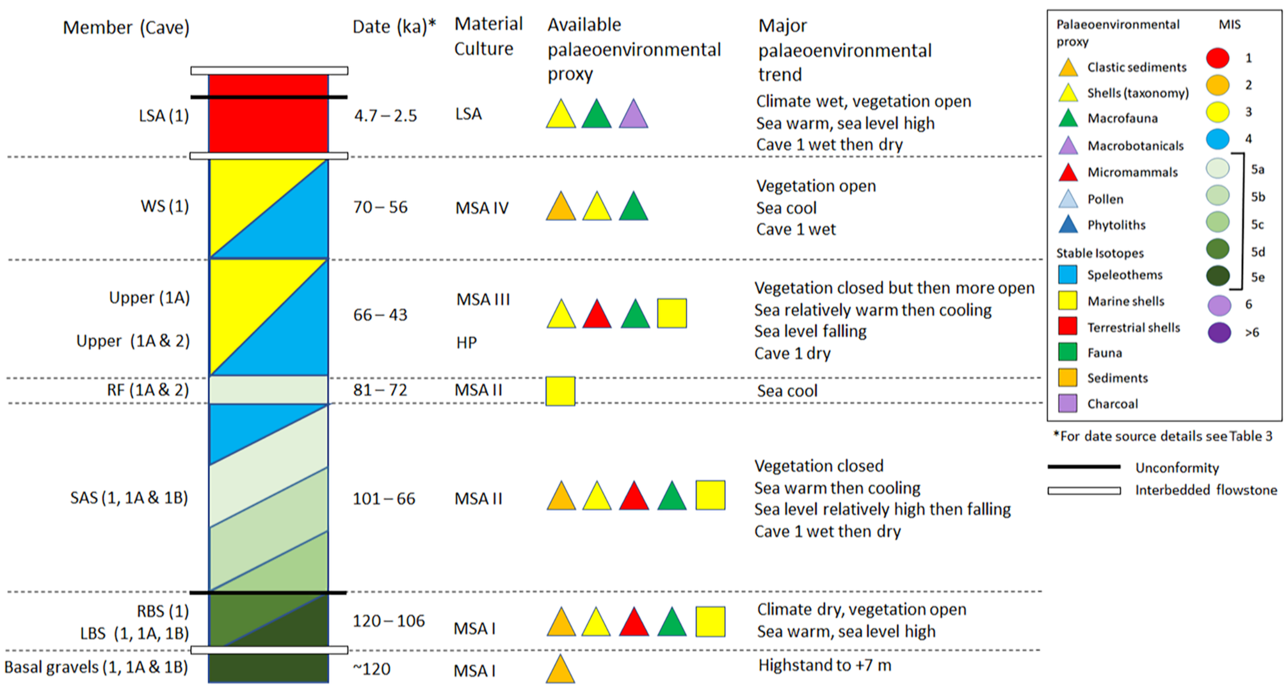

Figure 3. Composite stratigraphic profile of the deposits at Klasies River Main site with dates, material culture association, available palaeoenvironmental proxy and major palaeoenvironmental trend interpretation. Major dating references for the deposits are provided in Table 3. Marine Isotope Stages are represented as colours in the column and follow Figure 1 in sequence.

Table 3. The major stratigraphic groupings at Klasies River Main site, including both the cultural stratigraphy (Singer and Wymer, 1982; Wurz, 2002) and the members (Deacon and Geleijnse, 1988).

Lithic Culture	Member	Cave	Method	Age of deposits (ka)	MIS	References
LSA II	*	1	^{14}C on charcoal and shell	2.8 to 2.5†	1	1, 2
LSA I	*	1	^{14}C on charcoal	4.7 to 3.4†	1	1, 2, 3
MSA IV	White Sand (WS)	1	AAR on bone, TL-OSL, SG-OSL	70 to 56	4 – 3	2, 4, 5
MSA III	Upper	1A	TL, OSL, SG OSL, LU ESR on teeth	60 to 43†	4 – 3	5, 6, 7, 8, 9
Howiesons Poort	Upper	1A, 2	TL-OSL, TL, SG OSL, LU-ESR on teeth, U-series on calcite crust, combined U-series and ESR on teeth	66 to 46	4 – 3	5, 6, 8, 9, 10, 11, 12
MSA II (Mossel Bay Sub-Stage)	Rockfall (RF)	1A, 2	OSL/IRSL, SG OSL, $\delta^{18}O$ on shell	81 to 72	5a	5, 8, 13
	Shell and Sand (SAS)	1, 1A, 1B	AAR on bone, TL-OSL, LU ESR on teeth, U-series on speleothem and calcite crust, combined U-series and ESR on teeth, $\delta^{18}O$ on shell	101 to 66	5c – 4	4, 5, 6, 10, 11, 13, 14
MSA I (Klasies River Sub-Stage)	Rubble Brown Sand (RBS)	1	AAR on bone	~90†	5b	4
	Light Brown Sand (LBS)	1, 1A, 1B	AAR on bone, TL-OSL, U-series on speleothem, $\delta^{18}O$ on shell	120 to 106	5e – 5d	4, 5, 10, 13, 14
	Basal Gravels*	1, 1A, 1B	Sea level†	~120†	5e	15

References: Singer and Wymer, 1982 (1); Nami et al., 2016 (2); Binneman, 1995 (3); Bada and Deems, 1975 (4); Feathers, 2002 (5); Grün et al., 1990 (6); Tribolo, 2003 (7); Jacobs et al., 2008a (8); Tribolo et al., 2013 (9); Vogel, 2001 (10); Eggins et al., 2005 (11); Tribolo et al., 2005 (12); Deacon et al., 1988 (13); Shackleton, 1982 (14); Butzer, 1978 (15). *Neither the LSA deposits nor the basal gravels have been included in Deacon's members. †Several dates require brief discussion. MSA III: the results of $\delta^{18}O$ shell analysis suggest an upper age limit in MIS 5a or 5b (Shackleton, 1982; Deacon et al., 1988) but this is considered unlikely. RBS (MSA I): AAR dating on bone is considered unreliable (Miller et al., 1999). Basal gravels (MSA I): these deposits could relate to an earlier event than the MIS 5e highstand as a flowstone crust and stalagmites formed on the surface of the gravels prior to the formation of the LBS Member, suggesting a hiatus in clastic deposition (Hendey and Volman, 1986).

slightly from 13.2°C to 13.3°C over the same period, with seasonal amplitude increasing from 4.9°C to 5.9°C (Loftus et al., 2017), but some data suggest a gradual decrease in SSTs at the end of the SAS (Thackeray, 2018). The interior of Cave 1 was wetter than during the LBS period, but gradually dried through the phase (Butzer, 1978). The vegetation appears to have been relatively closed (more forested), with the presence of a wetland environment near the site (Klein, 1976; Nel et al., 2018; Reynard and Wurz, 2020). Deposition in Cave 1 ceased following the formation of the SAS due to sediments in Cave 1A blocking the entrance of Cave 1 (Deacon and Geleijnse, 1988). It only resumed with the formation of the White Sand Member (WS).

Marine shell isotopic values from the overlying Rockfall Member (RF) in Cave 1A (MIS 5a; MSA II) suggest particularly low SSTs (Thackeray, 2018), but little specific information is available for these deposits.

The Upper Member (MIS 4 to 3) includes the Howiesons Poort (HP) and MSA III cultural phases. SSTs were initially warmer than the RF, but lower temperatures and/or sea levels followed during the MSA III (Langejans et al., 2017; Thackeray, 2018). The interior of Cave 1 was dry throughout this period (Butzer, 1978). Mammalian assemblage composition suggests a relatively closed environment during the early parts of the HP, followed by a shift to markedly more open conditions in the later HP and the MSA III (Avery, 1987; Reynard and Wurz, 2020). There is also evidence for the presence of both a wetland and dunes around the site during the MSA III. It is unclear if this is due to changing conditions or a mix of contemporaneous local environments (Reynard and Wurz, 2020).

The WS deposits (MIS 4 to 3; MSA IV) in Cave 1 were initially interpreted as a regressional aeolian deposit, indicative of a fall from a highstand (Butzer, 1978). However, they are more likely the product of colluvial deposition, and they cannot be assumed to provide any information on local sea-level change (Deacon and Geleijnse, 1988). Evidence for ponding at the rear of Cave 1 indicates a relatively wet environment inside the cave (Butzer, 1978). The shellfish and large mammal assemblages suggest relatively low SSTs (Voigt, 1982), and fairly open vegetation (Klein, 1976). There was a significant hiatus of ~40 ka between the deposition of the WS and the formation of the LSA deposits. The only surviving deposits from this period are archaeologically sterile screes in Cave 1A (Deacon and Geleijnse, 1988) and a late Holocene age flowstone separating the WS and LSA deposits in Cave 1 (Vogel, 2001), neither of which have received much research attention. This hiatus is likely due to shoreline regression in MIS 2, reducing the attractiveness of the site for coastal hunter-gatherers, and/or the filling up of the shelters rendering them unusable (Deacon, 1995).

The Holocene deposits (MIS 1; LSA I and II) are indicative of relatively high sea levels, including an estimated +1 m to +2 m highstand evidenced by an erosional unconformity in the LSA II (Butzer, 1978), while the shellfish assemblages suggest warmer SSTs (Voigt, 1982; Binneman, 1995). Cave 1 was relatively wet during the LSA I, followed by a drier LSA II (Butzer, 1978). However, the tree species identified from charcoal fragments suggest wet conditions around the site during LSA II (Zwane, 2018), suggesting that moisture conditions inside the cave did not necessarily correlate with the hydroclimate of the broader landscape. The large mammal assemblage is characteristic of a mosaic of vegetation, but with relatively open conditions (Klein, 1976). A capping flowstone marks the end of the archaeological sequence (Butzer, 1978).

Case study 3: Pinnacle Point

Pinnacle Point is a rocky headland about 10 km west of Mossel Bay on the south coast of South Africa (Figure 1). The present-day climate is mild with year-round rainfall. Vegetation on top of the cliffs is mainly Canca Limestone Fynbos (FFl3) and Groot Brak Dune Strandveld (FS9) grows along the slopes (Mucina and Rutherford, 2006). The area is most well-known for two archaeological sites, PP13B and PP5-6, which preserve archaeological deposits dating to the period between MIS 6 and early MIS 3. However, smaller excavations have investigated a number of sites at Pinnacle Point and their geogenic deposits. Sea levels are an important influence for the sedimentological and anthropogenic environment at Pinnacle Point. High sea levels are responsible for the initial formation of the caves with some higher lying sites (>20 m above sea level) having deposits dating back as far as 1.0 to 1.1 Ma (Pickering et al., 2013). Lower lying sites in the coastal cliffs are also affected by the erosional forces of high sea levels (Marean et al., 2010; Karkanas et al., 2021). Much of the Pleistocene, however, had lower sea levels than the present-day and during these times the wide and gently sloping shelf to the south of Pinnacle Point was exposed in varying degrees, with a maximum distance to the ocean of 90 km during the Last Glacial Maximum (~21 ka ago; Fisher et al., 2010). Glacial-interglacial changes in climate, environment and sea levels affected geogenic clastic and chemical processes such as beach formation, spring water infiltration, aeolian activity, roofspalling, speleothem formation and root encrustation, and cementation at the caves (Karkanas et al., 2021). These factors also had a major impact on the resources available for hunter-gatherers inhabiting the caves (Marean et al., 2007, 2020).

Anthropogenic deposits at Pinnacle Point have been excavated mainly at PP13B and PP5-6 (Marean et al., 2010; Karkanas et al., 2015; Smith et al., 2018). Smaller excavations were also conducted in PP13A, PP9A and PP9C (Marean et al., 2004; Matthews et al., 2011). The stratigraphy of the main archaeological excavations at Pinnacle Point was subdivided into units based on macroscopic criteria like sediment texture and colour. These stratigraphic units were later grouped into stratigraphic aggregates (StratAggs) based on general geogenic and/or anthropogenic characteristics such as the proportion of sand and roof spall and the density of anthropogenic elements like shells or hearths (Figure 4 and Table 4).

The oldest archaeological deposits at Pinnacle Point were excavated at PP13B and the stratigraphy is summarized here from Marean et al. (2010). OSL ages are drawn from Jacobs (2010). The back of the cave preserves a boulder beach at the base of the sequence that is overlain by a laminated freshwater seep deposit. The Laminated Facies consists mainly of roof spall and dates to MIS 11 (Marean et al., 2010, Jacobs, 2010). While there is a continued contribution of roof spall throughout the sequence at PP13B, the proportion of aeolian silt and sand is generally higher in levels above the Laminated Facies (Marean et al., 2010). Human occupation layers are intercalated between these mixed aeolian-roof spall layers. The oldest human occupation layers date to MIS 6 (~164 ka) and the transition between MIS 6 and MIS 5e (~135 to 130 ka, Marean et al., 2010; Jacobs, 2010). Proxies for past climates and environments have mainly been recovered from these levels and OSL dating efforts focussed on occupation layers. The ages of sediments in between occupation layers therefore are based on their stratigraphic position leaving some uncertainty with respect to the continuity of sedimentation at PP13B. There is evidence of sediment deformation and slumping near the front of the cave at about the time of the sea level highstand during MIS 5e (122 to 127 ka, Marean et al., 2010; Jacobs, 2010). Rather than erosion by the waves removing sediment, slumping was probably caused by sea spray wetting the sediment (Marean et al., 2010). Clastic sedimentation with little evidence of human occupation continued after the highstand into MIS 5d with variable proportions of aeolian sand and roof spall in different parts of the cave (Marean et al., 2010). Intense human occupation marks the MIS 5c levels of PP13B before the site is closed by an aeolian dune at ~91 ka (Marean et al., 2010; Jacobs, 2010). A flowstone that formed on top of this dune suggests that the cave was closed until at least ~39 ka (Marean et al., 2010). U-Th ages of this flowstone were used to constrain the closing dates of the cave, but no palaeoclimate proxies were analysed on these samples. The erosion of the closing dune and re-opening of the cave was also associated with removal of some sediment from the front of the cave and the deposit forming from the erosional truncation mainly consisted of reworked MSA material from within the cave (Marean et al., 2010). A radiocarbon date from a charcoal fragment within this truncation fill yields an age of ~35 ka, suggesting it formed shortly after the opening of the cave (Marean et al., 2010). Smaller erosional features in the deposits have fills of late Holocene and modern ages (Marean et al., 2010).

The sequence of archaeological occupation that ends abruptly in PP13B due to closure of the cave by the dune making the site inaccessible continues at PP5-6. The stratigraphy of PP5-6 is summarized from Karkanas et al. (2015) and an age model based on OSL ages and tephrostratigraphy is published in Smith et al. (2018). The base of the deposits at PP5-6 consists of a thick sterile aeolian sand that dates to 96 ± 6 ka and overlaps in age with the dune that closed PP13B (Karkanas et al., 2015; Smith et al., 2018). Above this dune deposit, aeolian deposition continued and was mixed with roof spall. Human occupation during MIS 5b and 5a is mainly represented by isolated combustion features that probably represent several burn events in short succession (Karkanas et al., 2015). Although there are a large number of these combustion features in random locations around the site, they are usually separated from subsequent combustion features by sand layers and show little disturbance from trampling or raking (Karkanas et al., 2015). This suggests that people used the site frequently but for short periods (Karkanas et al., 2015). The upper sections of the PP5-6 sequence dating from the beginning of MIS 4 (72 ± 3 ka) to early MIS 3 (51 ± 2 ka) maintained high but episodic aeolian input intercalated with layers of ashy and burnt material and a few hearths remaining in situ (Karkanas et al., 2015; Smith et al., 2018). This change suggests that human occupation was longer lasting and intensive, with trampling and raking destroying hearth structures (Karkanas et al., 2015). The change in site use intensity and density of ashy deposits is also associated with a marked shift in the preferred lithic raw material from quartzite to heat-treated silcrete (Brown et al., 2009). Erosion and reworking by debris flows affected mainly the youngest deposits at PP5-6 dating to the latter part of MIS 4 and early MIS 3 (Karkanas et al., 2015).

PP9 consists of a number of small cavities that have been much less extensively excavated (Marean et al., 2004). PP9C is a small tunnel about 5 m long located near the south side of the main opening of PP9 and about 7 m above its cave floor. Small excavations were conducted near the front of the site, where sediment fill causes a constriction, and in the back of the cave. The deposits have not been formally described, but they are rich in micromammal remains that were accumulated by owls during the MIS 6-5 transition (Matthews et al., 2011).

A rescue excavation was conducted at PP30 when large mammal bones were discovered during trenching to install piping for development. The deposits most likely accumulated as part of a hyena den over a short period of time in MIS 6 (~151 ka). The stratigraphy shows no major subdivisions (Rector and Reed, 2010).

Palaeoenvironmental proxies and interpretations

At Pinnacle Point, palaeoclimatic and environmental proxy records were recovered from the archaeological sequences as well as from sites that have not been formally excavated. The main findings of these proxy records from PP5-6, PP9C, PP13B, PP29, PP30, Crevice Cave and Staircase Cave are briefly summarized here. As the Pinnacle Point records were compiled from multiple sites, we present the information based on MIS and sub-stages rather than organized by stratigraphic units. Micromammal assemblages were analysed from sequences at all excavated sites described here, but their applicability as a palaeoenvironmental proxy is hampered by their large ecological niches and behavioural flexibility (Matthews et al., 2020).

Staircase cave is a collapsed cave located along a staircase that was built for easier access to PP13B between PP13B and PP5-6. The stable oxygen and carbon isotopes of speleothems from Staircase Cave suggest that the seasonality of rainfall and the abundance of C_3 and C_4 plants in the vegetation are related to rainfall amount in the interior summer rainfall area of southern Africa during MIS 8 and 7 (Braun et al., 2019). The speleothem record from Staircase Cave covers the interval between 195 and 163 ka in early-middle MIS 6. Rainfall seasonality continues to change in phase with inland rainfall, however the vegetation composition does not show considerable variations and indicates a mixed vegetation with a slight dominance of C_3 plants over C_4 grasses (Braun et al., 2019). Large mammal faunas dating to the later parts of MIS 6 and possibly MIS 5 between 174 and 117 ka (Lightly cemented-MSA Lower and Dark Brown Sand 4a) have low numbers of individuals but suggest a consistent presence of grasslands near Pinnacle Point (Rector and Reed, 2010). Phytoliths from PP13B (Dark Brown Sand 4c) indicate overall shrubby vegetation near the cave probably Limestone or Sand Fynbos with dominant C_3 plants (Esteban et al., 2020c). The large mammal faunas from PP30 dated to ~151 ka suggest Pinnacle Point was located either in a mosaic of grassland and shrubland vegetation types, or that the current coastline represented an ecotone between shrublands on the coastal lowlands and grasslands on the currently flooded shelf (Rector and Reed, 2010). Stable isotope analyses of small and large mammal remains from PP30 suggest C_4 grassland within the foraging radius of the hyenas that accumulated the bones whereas local microhabitats were dominated by C_3 plants (Williams et al., 2020).

Part of the transition from the glacial MIS 6 to the interglacial MIS 5e is covered by the Staircase Cave speleothems (137 to 130 ka). A steep increase in $\delta^{18}O$ and $\delta^{13}C$ to the highest recorded values of any speleothem record in the region suggests a dominance of summer rainfall and C_4 vegetation, but part of this signal could also be generated by kinetic isotope effects due to the opening cave (Braun et al., 2019). Micromammal assemblages from PP9C date to between 130 and 120 ka and suggest a shift from somewhat more open grassy environments to warm and humid conditions with dense vegetation (Matthews et al., 2011). High sea levels during MIS 5e probably caused the collapse of Staircase Cave and slumping of sediments in PP13B (Braun et al., 2019; Marean et al., 2010).

Speleothem deposition commenced in PP29 (about 200 m west of PP13B) during MIS 5d and the stable isotopic records suggest high summer rainfall with mixed vegetation. The transition from MIS 5d into MIS 5c shows a peak of C_4 vegetation followed by intermediate year-round rainfall and C_3 dominated vegetation during MIS 5c (Braun et al., 2019). Phytolith assemblages from the latter part of MIS 5c at PP13B (StratAggs Upper Roof Spall and Shelly Brown Sand) on the other hand suggest a mix of coastal thicket, riparian, fynbos and grassland vegetation with substantial C_4 grass presence near the cave (Esteban et al., 2020a). Large mammal communities from PP13B in MIS 5c (Dark Brown Sand 2 and 3) also support the presence of grasslands, probably on the partly exposed Palaeo-Agulhas Plain with somewhat wetter conditions than in MIS 6. The latter part of MIS 5c (Upper Roof Spall) might have been somewhat drier based on the PP13B fauna (Rector and Reed, 2010). The end of MIS 5c at ~92 ka is associated with a major phase of dune mobility at Pinnacle Point, which led to

PP13B west	PP13B east	PP13B northeast	MIS	PP5-6	PP9C	PP30	Speleothems	Palaeoenvironment
NE Cut Fill; South Pit Fill			1					
South Pit Fill			2					
South Pit Fill	Truncation Fill	LC-MSA Upper Flowstone	3	RBSR; BBCSR			PP29; Crevice Cave	Mixed vegetation; year-round rainfall
cave closed by dune		LC-MSA Upper Flowstone	4	BBCSR; OBS2; DBCS;SGS; OBS1; SADBS: ALBS			PP29; Crevice Cave	Increased summer rain; high C4 grass in veg
cave closed by dune		LC-MSA Upper Flowstone	5a	ALBS; LBSR; YBSR			PP29; Crevice Cave	variable environment; mosaic vegetation
LB-Sand1		LC-MSA Upper Flowstone/ **Upper Dune**	5b	LBSR; YBSR			PP29; Crevice Cave	variable environment; mosaic vegetation
LB Sand1-2; DB Sand 2 - 3; LGB Sand 1	**SBS**; URS	**LC-MSA Upper Dune**	5c	**YBS**			PP29	year-round rain; mixed vegetation
LBG Sand 1	LRS	LC-MSA Upper Lower Dune	5d				PP29	Summer rain; mixed vegetation
LBG Sand 1; DB Sand 4a; LBG Sand 2		LC-MSA Middle	5e		OYCS; BYDS; BYSS; BYCS			Erosion/cave collapse Shift from more open to more dense veg
DB Sand 4a-c; LBG Sand 2-4; LB Silt			6 160-130 ka		BYCS	PP30	Staircase Cave	Mixed vegetation; increasing moisture; summer rain
		LC-MSA Lower	6 165-162 ka					Open grasslands
			6 195-165 ka				Staircase Cave	Changing rainfall seasonality; C3 vegetation dominant

Figure 4. *StratAggs for archaeological sites that were excavated at Pinnacle Point sorted by Marine Isotope Stages and substages for the time period between MIS 6 and MIS 1. Caves with speleothem deposition are listed for each stage/substage and a palaeoclimatic summary is given. StratAggs in bold represent aeolian sands belonging to a phase of dune formation that closed PP13B (period of closure is indicated) and Crevice Cave. Table 4 gives references for dating of each StratAgg. Colours of Marine Isotope Stages and symbols for palaeoproxies follow the legend in Figure 1. Red triangles=Micromammals, green triangles=Macrofauna, blue triangles=phytoliths, green square=stable isotopes from fauna.*

Table 4. List of StratAggs identified in excavations and the respective cave location, dating method and results.

StratAgg	Cave	Method	Age of deposits (ka)	MIS	Reference
Northeast Cut Fill	PP13B (west)	OSL	2 - 3	1	1, 2
South Pit Fill	PP13B (west)		0 - 39*	1 - 3	1
Truncation Fill	PP13B (east)	^{14}C†	35 - 39	3	1
Lightly cemented MSA Upper Flowstone (LC-MSA Upper)	PP13B (northeast)	U-Th	39 - 92	3 - 5b	1
Reddish Brown Sand and Roof Spall (RBSR)	PP5-6	OSL	52 - 45	3	3
Black and Brown Compact Sand and Roof Spall (BBCSR)	PP5-6	OSL	62 - 50	3 - 4	3
Black Ashy Sand (BAS)	PP5-6	OSL	63 - 60	4	3, 4
Orange Brown Sand 2 (OBS 2)	PP5-6	OSL	65 - 61	4	3, 4
Dark Brown Compact Sand (DBCS)	PP5-6				
Shelly Gray Sand (SGS)	PP5-6	OSL	68 - 62	4	3, 4
Orange Brown Sand 1 (OBS 1)	PP5-6	OSL	71 - 65	4	3, 4
Shelly Ashy Brown Sand (SADBS)	PP5-6	OSL	73 - 68	4	3, 4
Aeolian Light Brown Sand (ALBS)	PP5-6	OSL, tephro-stratigraphy	76 - 71	5a	3, 4
Light Brown Sand and Roof Spall (LBSR)	PP5-6	OSL	89 - 75	5a - b	3, 4
Light Brown Sand 1 (LB Sand1)	PP13B (west)	OSL	94 - 91	5b - c	1, 2
Yellow Brown Roofspall and Sand (YBSR)	PP5-6	OSL	95 - 84	5b - c	3, 4
Lightly cemented MSA (LC-MSA Upper) Upper Dune	PP13B (northeast)	OLS	98 - 91	5b - c	1, 2
Yellow Brown Sand (YBS)	PP5-6	OSL	98	5c	3
Shelly Brown Sand (SBS)	PP13B (east)	OSL	98 - 92	5c	1, 2
Upper Roof Spall (URS)	PP13B (east)	OSL	98 - 92	5c	1, 2
Dark Brown Sand 2 (DB Sand 2)	PP13B (west)		102 - 91*	5c	1
Light Brown Sand 2 (LB Sand 2)	PP13B (west)		102 - 91*	5c	1
Dark Brown Sand 3 (DB Sand 3)	PP13B (west)	OSL	102 - 91	5c	1, 2
Lower Roof Spall (LRS)	PP13B (east)	OSL	114 - 106	5d	1, 2
Olive Yellow Cave Sand (OYCS)	PP9C (front)	OSL	120 ± 7	5e	5
Brown Yellow Dune Sand (BYDS)	PP9C (front)	OSL	126 ± 9	5e	5
Brown Yellow Surface Sand (BYSS)	PP9C (rear)		*		5
Brown Yellow Cave Sand (BYCS)	PP9C (rear)	OSL	130 ± 9	6 - 5e	5
Lightly cemented MSA Upper (LC-MSA Upper) Lower Dune	PP13B (northeast)	OSL	133 - 115	6 - 5e	1, 2
Lightly cemented MSA Middle (LC-MSA Middle)	PP13B (northeast)	OSL	130 - 120	6 - 5e	1, 2
Light Brown Grey Sand 1 (LBG Sand 1)	PP13B (west)	OSL	134 - 94	6 - 5c	1, 2
-	PP30	OSL	151	6	6
Dark Brown Sand 4a (DB Sand 4a)	PP13B (west)		166 - 117*	6 - 5e	1
Light Brown Grey Sand 2 (LBG Sand 2)	PP13B (west)		166 - 117*	6 - 5e	1
Lightly cemented MSA Lower (LC-MSA Lower)	PP13B (northeast)	OSL	174 - 153	6	1, 2
Dark Brown Sand 4b (DB Sand 4b)	PP13B (west)	OSL	199 - 152	6	1, 2
Light Brown Grey Sand 3 (LBG Sand 3)	PP13B (west)		349 - 152*	11 - 6	1
Dark Brown Sand 4c (DB Sand 4c)	PP13B (west)	OSL	349 - 152	11 - 6	1, 2
Light Brown Grey Sand 4 (LBG Sand 4)	PP13B (west)		349 - 152*	11 - 6	1
Light Brown Silt (LB Silt)	PP13B (west)	OSL	349 - 152	11 - 6	1, 2
Laminated Facies	PP13B (west)	OSL	414 - 349	11	1, 2
Boulder Facies	PP13B (west)		Unknown-349*	11	

References: Marean et al., 2010 (1); Jacobs, 2010 (2); Smith et al., 2018 (3); Karkanas et al., 2015 (4); Matthews et al., 2011 (5); Rector and Reed, 2010 (6); *age was determined based on the stratigraphic position and measured ages on over- and under-lying StratAggs rather than by direct dating. † Radiocarbon age was not calibrated.

the closure of PP13B to human occupation (Marean et al., 2010). Crevice Cave, which is located between PP13B and PP5-6 at Pinnacle Point, was also closed by a dune of similar age enabling speleothem deposition inside the cave (Bar-Matthews et al., 2010; Karkanas et al., 2021) and dune sands of this age are also deposited near the bottom of the sequence in PP5-6 (Karkanas et al., 2015).

The speleothem records from PP29 and Crevice Cave show somewhat different trends in MIS 5b and 5a. In MIS 5b, PP29 records increased summer rain and C_4 grasses followed by mixed rainfall and C_3 vegetation in MIS 5a (Braun et al., 2019). Crevice Cave speleothem stable isotopes suggest winter rain and mixed vegetation with more C_3 plants in MIS 5b and an increase of summer rain and C_4 grasses in MIS 5a (Bar-Matthews et al., 2010). Phytolith assemblages from PP5-6 during MIS 5b (Yellow Brown Roof Spall and Sand and Light Brown Sand and Roof Spall) represent a mosaic of Fynbos and Renosterveld vegetation types with a high grass component dominated by C_3 grasses as well as coastal thicket (Esteban et al., 2020c). Overall, this points to a variable environment with a mosaic of vegetation types. Temperature reconstructions based on stable isotope analyses of the opercula of marine snail *Turbo sarmanticus* from PP5-6 suggest a coastal sea surface temperature decrease relative to the present day of about 3.2°C in MIS 5b and a (Loftus et al., 2017).

The phytolith record from PP5-6 suggests an increase in the abundance of C_4 grasses during MIS 4 (Aeolian Light Brown Sand and Shelly Ashy Brown Sand) and a mixture of coastal thicket, riparian vegetation and fynbos being present in the surrounding of the site (Esteban et al., 2020c). Both speleothem records support an increase in C_4 vegetation alongside an increase of summer rainfall for much of MIS 4 (Bar-Matthews et al., 2010; Braun et al., 2019). Stable isotope analyses of *T. sarmanticus* from the MIS 5-4 transition and MIS 4 layers at PP5-6 (Aeolian Light Brown Sand, Shelly Ashy Brown Sand, Orange Brown Sand 1, Dark Brown Comact Sand) indicated reductions of coastal sea surface temperatures by between 4.6 and 6.0°C (Loftus et al., 2017).

Phytolith records from early MIS 3 levels at PP5-6 (Black Ashy Sand, Black and Brown Compact Sand and Roof Spall; 63 to 51 ka) indicate a continued abundance of C_4 grasses with grassy fynbos growing on top of the cliffs and coastal thicket along the slopes (Esteban et al., 2020c). Both speleothem records show a shift of rainfall systems to mixed/winter rainfall conditions and a mixed vegetation with a slight dominance of C_3 plants (Bar-Matthews et al., 2010; Braun et al., 2019).

Trends in the chronostratigraphic record

As can be seen in Figures 1 and 5 and Table 1 (and SI Figures 1 to 6), representation of chronostratigraphic units is not evenly distributed temporally or spatially. MIS 1 age deposits with published palaeoenvironmental records are the most abundant, represented in 33% of the sites documented. This abundance is heavily biased towards the coastal regions, while the interior is poorly represented (Wadley, 2000), particularly in the western regions (i.e., Namibia and the Northern Cape province of South Africa; Mitchell, 1997; Lombard et al., 2012; Loftus et al., 2019b). Consequently, interior climatological reconstructions for this period rely on chemical precipitate-derived isotope records from a few key caves (e.g., Cango Cave and Cold Air Cave; Table 1) and proxies deriving from surficial records (e.g., Lyons et al., 2014). Limited studies in Eswatini and the Lebombo Mountains (e.g., Price-Williams, 1981; Price-Williams et al., 1982; Deacon and Lancaster, 1988; Barham, 1989a; Wadley, 2000) provide a little information on this poorly represented area.

A rapid decrease in deposit frequency is seen in MIS 2 with an equal number of sites with deposits dating to MIS 3 across southern Africa. Many of the caves with longer sequences from coastal and interior southern Africa are missing MIS 2 age deposits from their stratigraphic records (Table 1 and Figure 5b) – as recognised by Klein (1974; 1984), who noted that a significant and recurrent sedimentary hiatus is found between the Middle Stone Age and Later Stone Age deposits at many shelters throughout South Africa. Examples of this MIS 2 age sedimentary hiatus can be seen at the sites of Nelson Bay Cave, Bushman Rock Shelter, Klasies River, Olieboomspoort, Sibudu, Kangkara Cave, Melikane Rock Shelter, Ngalue Cave, and briefly at Border Cave and Sehonghong. Important Later Stone Age shelter sites have been excavated in Gauteng (e.g., Cave James, Hope Hill Shelter; Wadley, 1986, 1987, 1996), but no dedicated palaeoenvironmental studies have been published to date.

The frequency of deposits with palaeoenvironmental records continues to decrease beyond MIS 3. With the exceptions of Eswatini and Zimbabwe, all countries have sites with deposits that have published palaeoenvironmental data spanning MIS 4 and 1 (178 deposits in 100 sites with at least one deposit dating to between MIS 4 and 1) and South Africa contributes the greatest proportion of those deposits (n = 126; 70%). South African sites contribute the largest number of deposits with palaeoenvironmental data dated to older than MIS 5a (n = 76, 85% of the southern African sample [n = 89]). Outside South Africa, only Namibia has deposits of MIS 6 age, from the sites of Apollo 11 and Erb Tanks.

Within South Africa, sites in the Western Cape, Eastern Cape and KwaZulu-Natal document the most deposits with palaeoenvironmental data spanning MIS 6 to 1 (number of sites = 63, number of deposits = 158) (Table 1 and Figure 5b), while no sites with published palaeoenvironmental data were documented in the North West Province. The Western Cape documents more deposits with palaeoenvironmental data in this age range and arguably more complete sequences (96 deposits in 33 sites) than the Eastern Cape and KwaZulu-Natal (62 deposits in 30 sites; 29 deposits in the 15 Eastern Cape sites; 33 deposits in the 15 KwaZulu-Natal sites). Interior South African provinces have only sporadic palaeoenvironmental records dated to MIS 5 and older. Gauteng has two sites (Lincoln Cave and Plover's Lake) dating to 5d and 5b respectively. MIS 5c is represented at Rose Cottage Cave in the Free State and in the Northern Cape at Ga-Mohana, dated to 5b and 5c. Wonderwerk Cave's MSA palaeoenvironmental records date to MIS 6.

Trends in the spatial distribution of sites

The spatial distribution of caves and rock shelters with published palaeoenvironmental data dating to between MIS 6 and 1 is far from even (Figure 1 and SI Figures 1 to 6). The absence of adequately researched sites from a large area of the region – across most of Botswana, all of Zimbabwe, and through Mozambique to the isolated Ngalue Cave – is the most significant geographical gap. There are sites in these parts of southern Africa (e.g., Deacon, 1974; Larsson, 1996) for which palaeo-environmental research is yet to be conducted or published. Figure 6 presents the distribution of the 104 catalogued cave and rock shelter sites within the geological context of southern Africa.

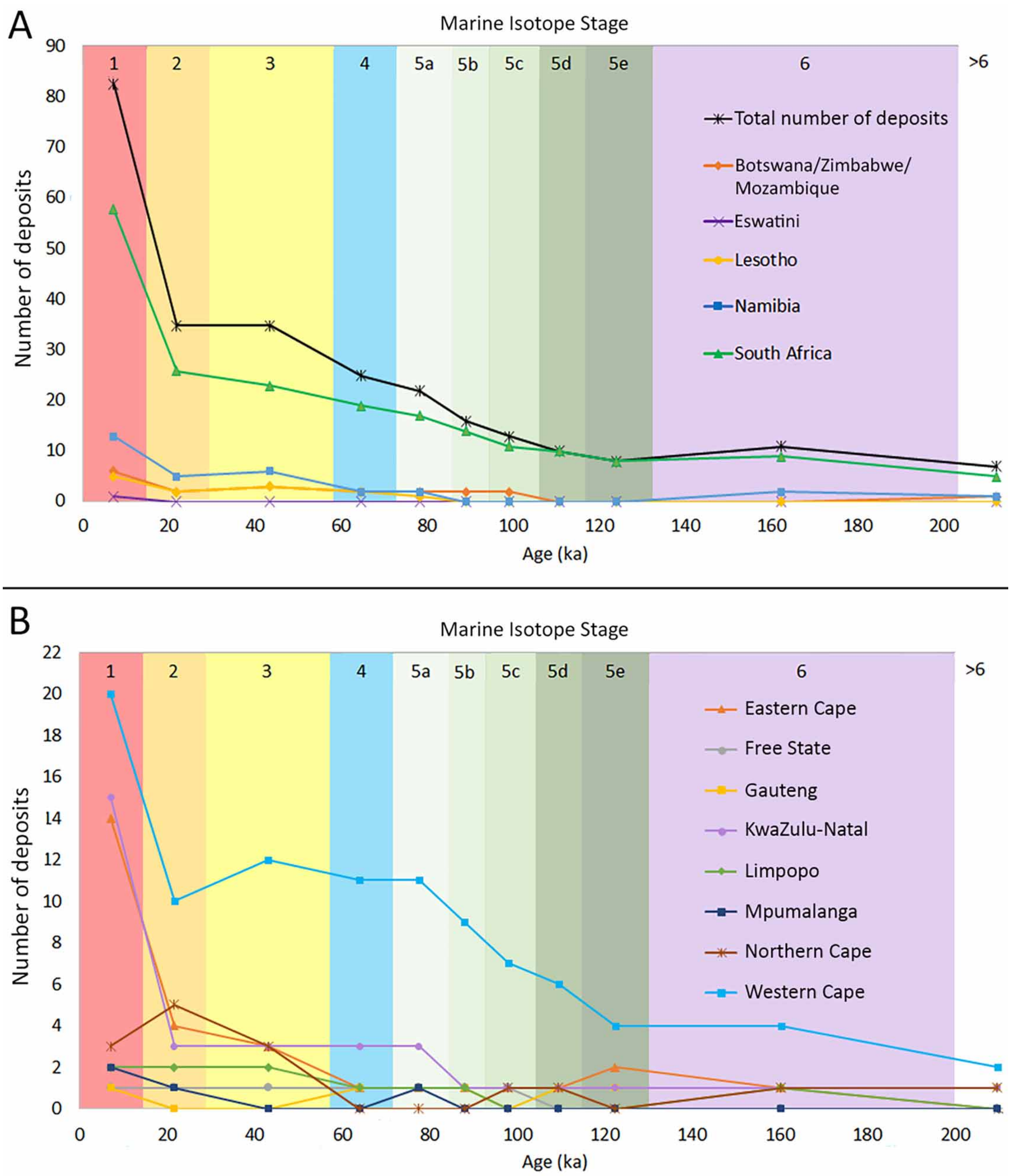

Figure 5. *Number of deposits in southern Africa (**A**) and in South African provinces (**B**) with published dates and palaeoenvironmental proxies per Marine Isotope Stage.*

The scale of the map limits the geological resolution (to mitigate this issue SI Table 1 provides a list of major contributing lithologies to each unit presented in the map), and there are clearly challenges relating to consistency of geological mapping across national borders, but a number of major trends can be clearly observed. First, most caves and shelter sites are hosted within sedimentary rocks, in which the region is extremely rich. However, the distribution of sites across major sedimentary complexes is not uniform and is correlated with the local topographic and geomorphological context, and, by extension, geological history. For example, the majority of sites hosted within the enormous Karoo Supergroup sedimentary complex are associated with the Drakensberg/ Lesotho mountain area and not the interior of the Western Cape or the western and coastal Eastern Cape, areas worthy of further exploration. Contrastingly, there is an abundance of sites in the Cape Fold Mountains, where dramatic geological contortion creates opportunities for fault-guided cave and rock shelter formation locally assisted by coastal erosion. Second, very few sites with the relevant data are documented within the carbonates of the Transvaal Supergroup that stretches through the South African interior and into Botswana, despite the abundance of karstic caves known from this area. A similar observation can be made for the Damara Complex in western and central Namibia, where speleological surveys have documented many caves (e.g., Marais and Irish, 1997; Pickford and Senut, 2010; Laumanns, 2017), and the Cheringoma and Grudja Formations in central Mozambique (Pena et al., 2019).

Figure 7 presents the distribution of the 104 catalogued cave and rock shelter sites within the modern vegetation context of southern Africa. Each of the three case studies presented here demonstrates the capacity for local-scale climate and environmental conditions to develop within larger climate fluctuations. Each biome, and associated local and regional ecology, responds to climatological drivers at different temporal and geographical scales, making intra- and inter-biome correlations across areas of variable topography and hydrology difficult. Changing ecologies have significant human implications for resource availability, technological adaptation and population movement. Prevailing vegetation and precipitation also tangibly affects the availability and preservation potential of different proxies. It is evident from Figure 7 that many sites occupy areas near current boundaries of major vegetation biomes, while large central areas remain underrepresented. The available data distribution (as presented here) demonstrates the limitations of the current record and opportunities for future research. Limitations include:

- challenges in isolating changes within single biomes, without the influence of nearby expanding and contracting ecotones, and

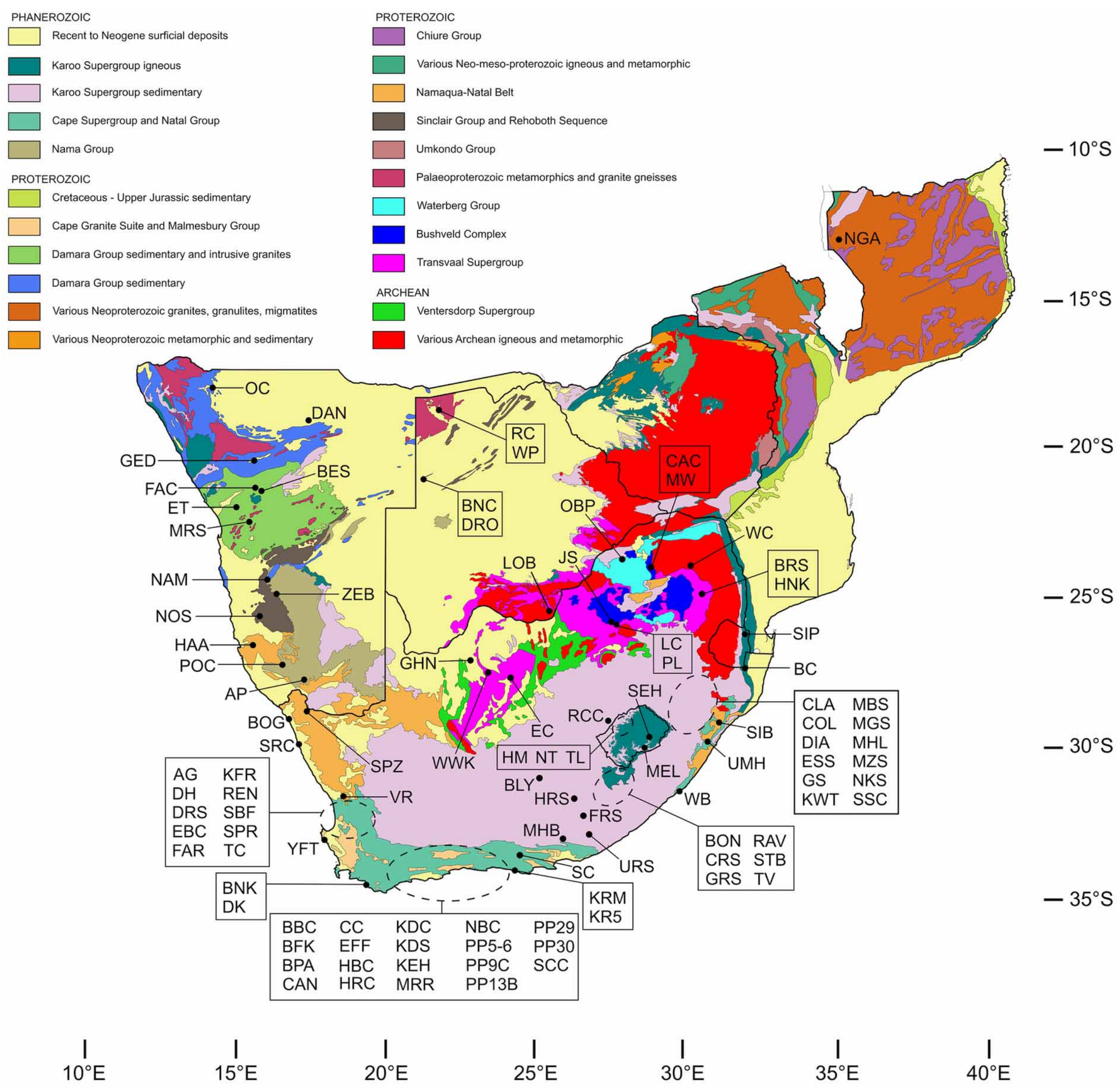

Figure 6. *Simplified geological map of southern Africa with the locations of the 104 cave and rock shelter sites discussed in this paper. Map is based primarily on simplified geological maps published by Schlüter, 2008 and McCourt, 2016 (see SI Table 1 for associated lithologies and additional sources, and methodology for the map assembly and limitations).*

- difficulties in building representative intra-biome records for any period that enable local topographical and hydrological influences to be explored.

Opportunities include:
- exploring human resource exploitation choices and technological responses to changes within ecotones, and
- human mobility patterns in extreme periods of climatological change (e.g., MIS 2), a subject that continues to be explored in the Lesotho Highlands (e.g., Stewart et al., 2012; Roberts et al., 2013; Pargeter et al., 2017).

Palaeoenvironmental proxy availability and utilisation across southern Africa

The most widely used palaeoenvironmental proxies are faunal assemblages (macrofauna and micromammals), representing 52% of utilised proxies in sites across southern Africa (Figure 8a) and across South African provinces (Figure 8b), aptly demonstrating the abundance (and suitability of preservation conditions) of this form of evidence in caves and shelters of all ages. However, stable isotope analyses on fauna (bone or tooth enamel) represents only 5% of proxies published. This may be due to limited access to specialist analytical equipment and skills, or preservation issues of suitable tissue (for discussion see Koch et al., 2001; Trueman et al., 2004; Koch, 2007), but suggests there is great potential for this technique across southern Africa both in primary research and in the resampling of the abundant faunal assemblages curated in museums and universities across the region.

Botanical remains in general, including macrobotanicals, pollen, phytoliths and stable isotope analysis of charcoal, are the next most abundantly published palaeoenvironmental proxy (n = 43; 20% of all proxy publication in southern Africa). South African studies utilise these more than any other southern African country (n = 36; 16% of all proxy publication), with caves and rock shelters of the Eastern and Western Cape provinces publishing the bulk of data (n = 19; 52% of the South African botanical proxy record). Several factors may play a role in the spatial distribution of data. First, plant taphonomy is complex, with chemical and mechanical processes in the shelter often leading to differential preservation of charcoal, pollen and phytolith remains based on size, shape and taxon (e.g., Esteban et al., 2020b). Consequently, host rock lithology and local hydrology may play a role in regional preservation bias. Second, approaches to the collection and sampling of botanical remains

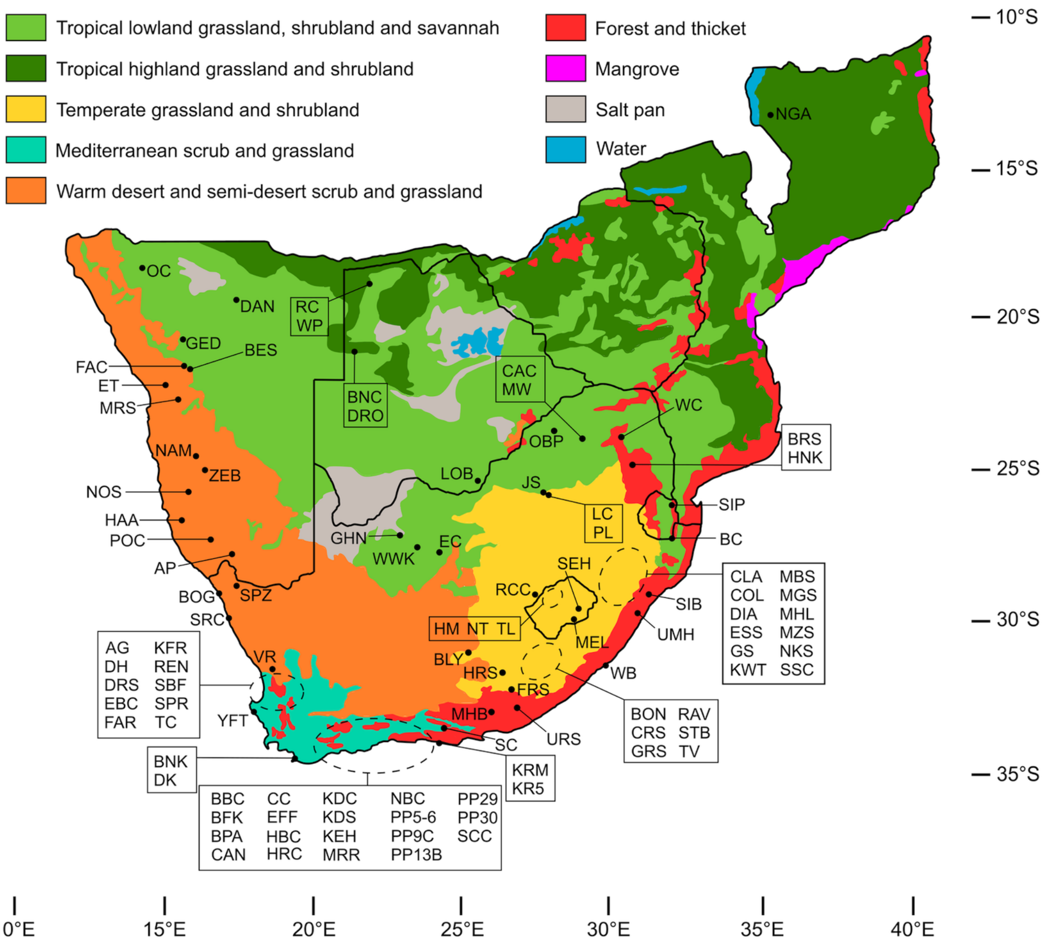

__Figure 7.__ Simplified map of different vegetation formations of southern Africa with the locations of the 104 cave and rock shelter sites discussed in this paper (redrawn from Biondi et al., 2015 with vegetation classifications based on Sayre et al., 2013).

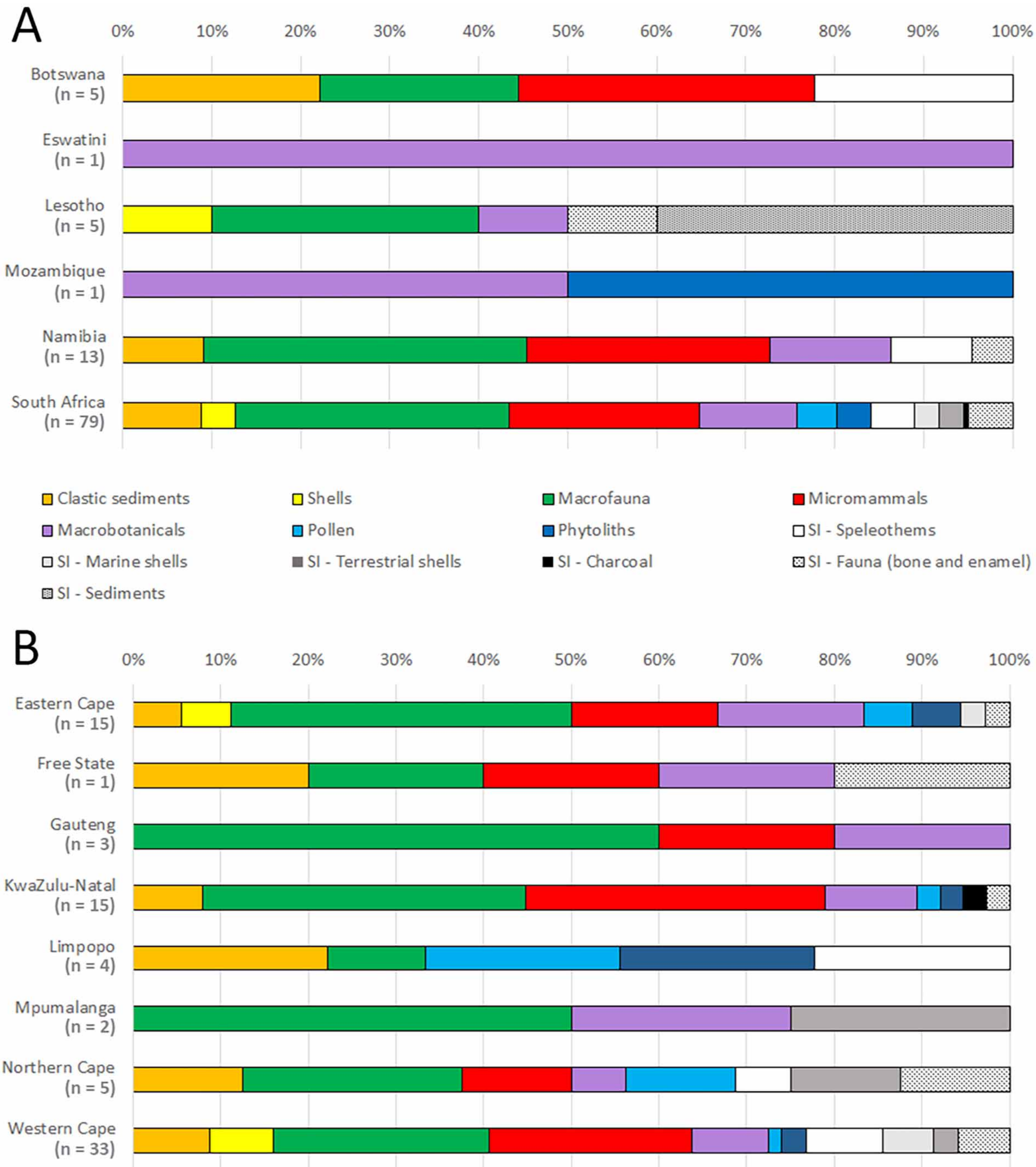

Figure 8. *Relative frequency of published palaeoenvironmental proxy use in southern Africa (**A**) and South African provinces (**B**). 'SI' represents stable isotope studies. N=number of sites with published chronologies and palaeoenvironmental proxy use.*

vary greatly across excavated sites and through the history of excavation and debate continues about sampling strategies for macrobotanical remains (e.g., Puech et al., 2021). Studies of microbotanical remains (pollen and phytoliths) are rare in southern Africa (n = 16; n = 15 in South Africa). This may be because these proxies are susceptible to contamination through mixing and during sampling, and large reference collections and specialist knowledge are needed for their analysis.

Stable isotope analysis on a range of clastic and chemical sediments represents 17% of the published palaeoenvironmental record from caves and rock shelters, with speleothems, bone and tooth enamel representing the most frequently used materials. Stable isotope analysis of sedimentary organic material has been applied in the Lesotho Highlands and provides an encouraging example of the potential of systematic and coordinated regional palaeoenvironmental research (e.g., Roberts et al., 2013), where similar methods have been applied between relatively close sites with chronostratigraphically correlated deposits. Apart from faunal material, which is well represented through caves and rock shelters of all regions and periods, availability of stable isotope-suitable materials is also potentially spatially and temporally biased. For example, speleothem growth is limited to particular geological contexts, while the presence of shellfish is limited to coastal and near-coastal sites, and organic remains are particularly prone to cumulative mixing or destruction within increasingly old deposits.

Clastic sediment type and stratigraphy as an environmental proxy has been utilised relatively infrequently (n = 20; 9%) and mostly by geoarchaeologist Karl Butzer (e.g., Butzer, 1973a,b; Butzer et al., 1978), who proposed several regional scale correlations between clastic sedimentation rates and climate changes (e.g., Butzer et al., 1978 at Border Cave). More recently, specialist multiscale sedimentological studies have focused on the patterns in anthropogenic and non-anthropogenic sediment accumulation at Pinnacle Point (Karkanas et al., 2015, 2021).

Discussion

Limitations and stratigraphic completeness of the record

At the landscape scale, Figures 1 and 6 (and Supplementary Information Figures 1 to 6) demonstrate the uneven distribution of sites across southern Africa. Regionally, this reflects many factors from the geological and geomorphological context, to logistical constraints and the political and economic environment.

In every site, it is evident that dynamic depositional and post-depositional processes have affected the stratigraphic and sedimentary record differently, as exemplified in the multiple minor and significant hiatuses evident in the three presented case studies. At Border Cave, up to eight significant hiatuses are documented, with one potentially spanning 18 ka (based on dates from 1 Brown Sand Lower; d'Errico et al., 2012; Villa et al., 2012) from the middle of MIS 2 to MIS 1. At Klasies River, a major hiatus lasting perhaps as long as 40 ka, resulted in no representation of MIS 2 age deposits, and is attributed to either a lack of occupation, or the caves being closed by sediments. At the Pinnacle Point site complex, PP13B was closed for perhaps as long as 30 ka during MIS 5a and 4, a period documented by clastic deposits in nearby caves PP 5-6, and speleothems in PP29 and Crevice Cave. Minor sedimentary hiatuses and complex processes that impact the integrity of the stratigraphic sequence and the deposits are abundant, spatially highly variable within sites and potentially of great significance for sampling and stratigraphic correlation, as has been demonstrated through micromorphological studies (e.g., Karkanas and Goldberg, 2010). When considering the implications of a hiatus, attempts should be made to distinguish between occupational hiatuses and sedimentary hiatuses (unconformities) because their distinction is of primary importance to interpretations of the completeness of the stratigraphic (as opposed to archaeological) record. The nature of hiatuses in the archaeological literature is not always clear.

Although hiatuses are spatially and temporally irregularly distributed, even in closely associated cave complexes like Pinnacle Point, the widespread absence of MIS 2 age deposits in coastal and interior sites warrants further study and expanded landscape-wide sampling. Generally, records from rock shelters and caves should be considered snippets of fragmented records. Various palaeoenvironmental proxies are deposited through different processes and preserved under specific conditions. This can lead to disparate signals from stratigraphically and chronologically correlated proxies on intra-site, local and broader scales – as seen in speleothem and clastic sedimentary components from all three case studies presented here. For example, charcoal is generally only deposited abundantly during human occupation of a cave or rock shelter and so inter-site and regional-scale correlations of single proxy data are difficult if occupational periods cannot be correlated. Anthropogenic components also generally represent not only the environmental resources and conditions around the cave but also human behaviour. For example, the taxonomic and elemental composition of a macrofauna assemblage found inside a cave will depend on which animals live in the surrounding areas, which of these animals humans exploit, and how and where these animals are butchered.

In all of the cave and rock shelter sites listed here, and in many cave sites documented in the speleological literature, non-anthropogenic clastic sediments represent significant components of deposits, or entire units in sequences. The correlation between clastic cave sedimentation and different spatial scales of environmental change has been explored in Europe and beyond (e.g., Zhou et al., 2000; Courty and Vallverdu, 2001; Karkanas, 2001; Woodward and Goldberg, 2001; White, 2007) and authors consistently comment on the difficulty of proposing deterministic correlations between sedimentation and climate. Although these sediments have generally not received dedicated chronological and palaeo-environmental research attention in southern Africa, they provide interesting opportunities to explore sedimentary processes, palaeo-environments (e.g., Karkanas et al., 2021) and potentially address the phenomenon of the missing MIS 2 age deposits through systematic sampling.

When considering the completeness of the stratigraphic record derived from caves and rock shelters, the reduction in abundance of older deposits (n = 49, 18% of cave and rock shelter deposits in southern Africa with palaeoenvironmental records date beyond MIS 5b) is not surprising given the increasing probability of record destruction resulting from cumulative post-depositional processes. However, several alternative causes could be suggested, for example:

- fewer caves and shelters were open before MIS 5b, with erosion over the last 90 ka contributing to the destruction or collapse of older caves, or the formation or opening of new shelters;
- older deposits are preserved but remain buried, beyond the extent of excavations;
- older deposits have been eroded and replaced by younger units;
- older deposits are preserved in non-anthropogenic cave deposits and so have escaped dedicated chronological and palaeoenvironmental study.

Dedicated geoarchaeological and chronological research is needed to test these hypotheses, any one of which may bias the sedimentary record from caves and rock shelters. Testing these hypotheses is particularly pertinent in the interior of southern Africa, where incomplete stratigraphic records may erroneously insinuate an absence of humans between MIS 6 and 3 and limit our understanding of the palaeoclimatic conditions during this important period. Recent publication of new archaeological deposits dated to MIS 5c and 5d in the Northern Cape (Wilkins et al., 2020) associated with wetter inland conditions (Wilkins et al., 2021) indicates the presence of people inland during at least some periods of MIS 5 and suggests intermittently wetter environmental conditions.

Implications of chronological resolution

Chronological resolution also plays an important role in limiting fine-scale correlations across space and time, with many sites reporting large errors on their dates (see Feathers et al., 2020 for a discussion of variability of OSL data interpretation in Middle Stone Age sites). In areas where sites with palaeoenvironmentally-informative sedimentary sequences are known, the depositionally isolated nature of cave deposits means that chronological control remains the only tangible way to correlate stratigraphic units, assemblages and associated proxies across the landscape. The resolution and reliability of that record is crucial and easily affected by analytical procedural refinements (e.g., changing calibrations for radioisotopic methods – see asterisks associated with 14C data in Table 1) or the innovation of new methods (e.g., U-series dating), considerations that are particularly pertinent for an archaeological record built over the last five decades. This is not a simple issue to mitigate because every cave deposit will be more or less suitable to different dating methods, each with their own inherent sampling and analytical idiosyncrasies influencing the resolution of the result. Significant efforts have been made to synthesise chronological records (e.g., Deacon, 1974; Jacobs et al., 2008a; Loftus et al., 2019b) and ideally these should be expanded on in a systematic way, while bearing in mind that a date range for a deposit or sequence of deposits does not necessarily represent continuity in sedimentation or occupation. Relatively large errors on dates, differing analytical techniques and taphonomic processes all serve to distil the palaeoenvironmental record into variably time-averaged mosaics that draw on differently biased proxies, and it is clear that many sites require resampling and chronological re-assessment using modern methods and calibrations. This is particularly true for the abundant MIS 2 to 1 age sites bearing Later Stone Age deposits, which in many cases haven't been revisited in the last 30 years or longer (e.g., Deacon, 1974).

From a historical perspective, the data presented provides some interesting insights into where, when and who contributed to the development of the palaeoenvironmental record and how it has been diversified over the last 50 years. Publications of 25 years old or older are unsurprisingly dominated by faunal studies during prolific research activity by Avery, Klein, Mazel, Opperman and Thackeray through the late 1970's to early 1990's. This work has formed the backbone of palaeoenvironmental interpretation throughout the region and has seen limited augmentation in some provinces. For example, publications of palaeoenvironmental research on chronologically controlled sites have only increased by 7% in the Eastern Cape, and 13% in KwaZulu-Natal in the last 25 years, while no new work has been published from Eswatini. Conversely, in the Western Cape, publications of palaeoenvironmental research on chronologically controlled sites have increased by 67% in the last 25 years, indicating a significant focus in this area and associated bias in the chronological and palaeoenvironmental resolution of those records. This bias can be attributed partly to the discovery of archaeological evidence for modern (or near-modern) cognitive abilities in early human populations at sites on the Cape coast (e.g., Marean et al., 2007; Henshilwood et al., 2011), which has driven multi-disciplinary palaeoenvironmental and palaeoclimatic studies aimed at contextualising these finds (e.g., Cleghorn et al., 2020). In comparison, the ostensible lack of this evidence at interior sites has resulted in less potential for, and research interest in, studies of inland conditions. Additionally, as a cautionary note for the future of palaeoenvironmental research, it is clear that the frequency of publications focused on faunal analyses have fallen radically in the last 25 years.

Conclusions

Clastic and chemical sediments from caves and rock shelters provide important and potentially multi-proxy and multi-faceted perspectives of climate change in southern Africa between MIS 6 and 1. The record is not complete, and is heavily geographically biased to South Africa, and coastal areas within South Africa. There are important sites in Namibia and Botswana and the landlocked Lesotho, and it is unlikely that the dearth of publications of dated cave and rock shelter deposits in Eswatini, Zimbabwe and Mozambique reflects an absence of these sites and records given their geological and topographical contexts (see Barham, 1989b; Figure 6). There are also ongoing studies of rock shelters and caves in these regions as part of both academic and contract archaeology projects and the publication of this data will help augment the record in the coming years. As demonstrated in the case studies and the 104 sites presented here, all sedimentary sequences in sites spanning beyond MIS 3 contain major to minor occupational and sedimentary hiatuses. These are related to a wide range of processes, some of which include local and regional environmental changes (e.g., Butzer et al., 1978), and some of which relate to in situ biogenic or anthropogenic activity.

Of particular interest in the reconstruction of a southern African palaeoenvironmental record is a consistent MIS 2 age sedimentary hiatus observed in many caves and rock shelters throughout the region. The conspicuous absence of MIS 2 age sedimentary data limits our capacity to assess the environmental context of human behaviour and resource exploitation across the region at a key period in our technological and cultural evolution. The processual implications of this period on sedimentation, erosion and occupation of caves and rock shelters is an important aspect to explore, but limited by an absence of data in comparative sedimentary sequences. This period coincides with significant climatological changes associated with the last glacial maximum, and systematic chronological and palaeoenvironmental sampling of the many non-anthropogenic cave and rock shelter deposits in southern Africa would be an important endeavour to address this dearth of data. It is also important to expand comparable sedimentological and palaeoenvironmental studies out of the caves and rock shelters and onto the landscape to help span the geographical and ecological gaps (e.g., Blydefontein Rock Shelter; Scott et al., 2005).

The advantage of cave and rock shelter clastic sedimentary records is the diversity of included evidence suitable for palaeoenvironmental analyses. Fauna, a temporally and regionally abundant form of evidence in cave and rock shelter sediments, has been the most widely used proxy in southern Africa and one drawn on for over 40 years, providing a long and broad record across the region. Although not extensively applied yet, modern stable isotope studies focusing on faunal remains (e.g., Williams et al., 2020) have a very large, well-distributed and temporally extensive sample with which to work. Exploration of the palaeoenvironmental record through stable isotope analysis of sedimentary organic material has proven to be effective in the Lesotho Highlands (e.g., Roberts et al., 2013) where sites with correlatable stratigraphic records are relatively closely situated. It is difficult to assess the distribution of botanical remains through southern Africa due to a significant spatial bias in the application of modern analyses.

There is a long history of archaeological research across southern Africa that has used cave sedimentary components for palaeoclimate reconstructions with great success. Spatial, temporal and analytical inconsistency in the published record leads to interpretations drawn on data with different, not necessarily comparable, resolutions. Ideally, palaeoenvironmental specialists should endeavour to align the resolution of research questions with the resolution of the evidence to most appropriately utilise the available data, but also identify where additional resolution is most needed (Faith et al., 2021). There remain important opportunities to advance our understanding of past climates in southern Africa by gathering data from underrepresented areas and deposits, and applying emerging methods on existing and new evidence from across the region.

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