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A high resolution and continuous isotopic speleothem record of paleoclimate and paleoenvironment from 90 to 53 ka from Pinnacle Point on the south coast of South Africa

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A B S T R A C T

Coastal South Africa draws interdisciplinary interests due to the co-occurrence of a rich record for early human behavioral modernity, hyper-diverse vegetation with very high endemism (the Cape Floral Region), and globally influential oceanic and climate systems. High resolution and continuous climate and environmental records are needed to provide the context for the evolution of behavioral modernity and this diverse flora. Here we present the first such record for climate and environmental change from 90 000 to 53 000 years ago from the southern Cape coast. This important time span covers a burst of expression of several indicators of human behavioral modernity, as well as several key cycles in global climate change. Our research location is ideally placed near the location of several critical archaeological sites, near the boundary of the winter and summer rainfall regimes, and close to isotopically distinct floral zones. We used isotopic analysis of precisely dated speleothems to document shifting vegetation and rainfall, and show that the presence of winter rain and C3 grasses waxes and wanes in response to Southern Hemisphere shifts in SSTs and global temperature. When proxies of global temperatures indicate warmer conditions, $\delta^{18}O$ and $\delta^{13}C$ indicate more winter rain and more C3 grasses, respectively, and vice versa. This record displays abrupt and short-term changes previously undocumented. It is often argued that the Cape Floral Region partially owes its high diversity to relative climatic stability. Our record shows isotopic variability that at least matches that displayed in the Levantine Mediterranean system, so climatic stability may not have characterized the south coast. One short-lived phase of human technological innovation (the Still Bay) associated with early evidence for behavioral modernity occurs synchronous with an abrupt environmental perturbation. Early modern humans in this region confronted a variable climate and adapted quickly in a manner similar to behaviorally modern humans.

1. Introduction

The south coast of South Africa is a focus of interrelated scientific studies of human evolution, floral diversity, and Southern Hemisphere climate mechanisms. The floristically hyper-diverse and unique Cape Floral Region (CFR), the world's smallest floral kingdom, is located here as a thin strip hugging the coast (Fig. 1).

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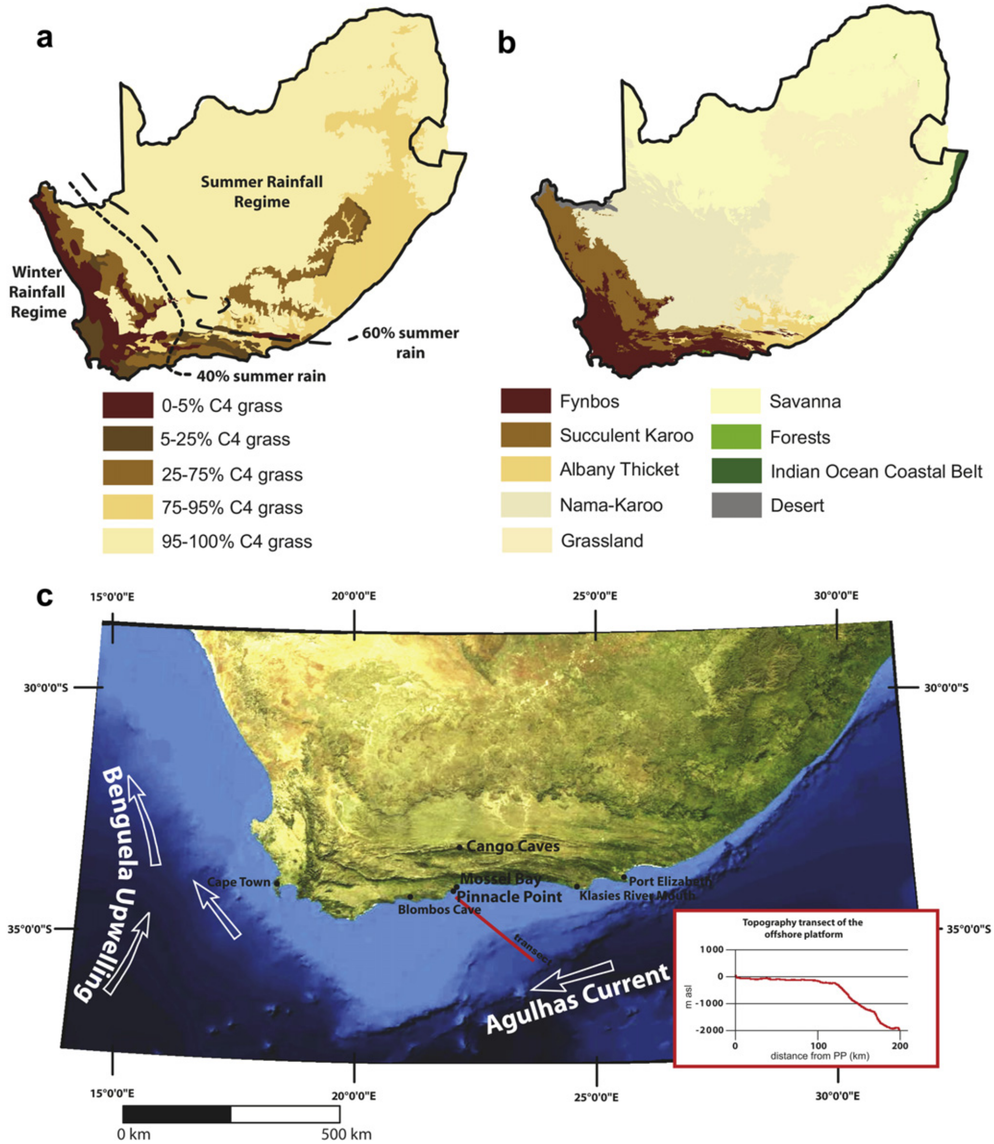

Fig. 1. Location of Crevice Cave (Pinnacle Point, South Africa), the major vegetation zones, distribution of C3 and C4 grasses and configuration of offshore platform. (a) The distribution of C4 grasses as a percentage of all grasses (Vogel et al., 1978) (b) distribution of vegetation biomes in South Africa (Mucina et al., 2006), (c) the location of sites mentioned relative to the coast and offshore platform. Base image of South Africa and oceanic topography from NASA World Wind, and the offshore platform transect was generated from the 3D Paleoscape model (Fisher et al., 2010). The distribution of the Cape Floral Region is broadly equivalent to the combined distribution of the Fynbos, Succulent Karoo, and Albany Thicket shown in (b).

The CFR is a Mediterranean vegetation that has the world's highest frequency of endemic plants (69%) and is extraordinarily speciose for its size, rainfall, and energy (Cowling and Lombard, 2002; Goldblatt and Manning, 2002; Manning, 2008; Cowling et al., 2009). It is a globally-recognized biodiversity hotspot (Myers et al., 2000). It is particularly diverse in geophytes (Proches et al., 2005, 2006), far exceeding other Mediterranean floral regions. This diversity and uniqueness, a focus of study and debate for many years, has been argued to result from regional climate and edaphic factors (Goldblatt and Manning, 2002), relative climatic stability and great age (Rebelo et al., 2006), the influence of fire (Cowling, 1992), progressive aridification since the late Miocene (Linder and Hardy, 2004), and gradual development of topo-edaphic heterogeneity (Cowling et al., 2009). Fynbos forms the largest component of the CFR, and it is dominated by small-leafed evergreen shrubs and rushes (restios). Fire is a key component of its regeneration, and it is typically found on nutrient-poor soils. Renosterveld is another major component, and it is typically found on nutrient-rich soils (often on shale) and includes a shrub and grass component (Manning, 2008). Thicket is an important plant community, always found where summer and winter rainfall are nearly equal, and has variable amounts of woody vegetation and grass (Vlok et al., 2003).

The south coast is near the confluence of two oceans (Atlantic and Indian) and two major oceanic systems influential to world climate – the cold Benguela Upwelling on the west coast and the warm Agulhas Current flowing down the east coast. Leakage of warm Agulhas Current waters into the South Atlantic is a key contributor to the global thermohaline system (Lutjeharms et al., 2001; Lutjeharms, 2006). This confluence of cold and warm waters contributes to a rich marine ecosystem, with dense and diverse shellfish communities in rocky and sandy intertidal zones and diverse fish and sea mammal communities (Branch and Branch, 1992; Branch, 1994; Bustamante and Branch, 1996; Branch and Menge, 2001).

The south coast is also at the juncture of a winter rainfall system to the west and summer to the east, and the relative positions of these systems in reaction to global climate change have long been a focus of study and debate (Van Zinderen Bakker, 1976, 1978, 1983; Deacon, 1983; Deacon and Lancaster, 1988; Meadows and Baxter, 1999; Stuut et al., 2004; Chase and Meadows, 2007). The integrated relation of the position of the winter and summer rainfall belts, and the location of the CFR, is widely accepted. The winter rainfall zone is thought to be the center of the CFR and fynbos, with diversity and endemism both being concentrated in the winter rainfall area and declining to the east in the summer rainfall area (Cowling and Lombard, 2002; Cowling and Proches, 2005). There is also a transition from C3 grass domination in the winter rainfall (Fig. 1) areas to the west to more C4 grass representation to the east in the summer rainfall areas (Vogel et al., 1978; Cowling, 1983).

Coastal South Africa is also the location for the richest archaeological record for early modern human behavior. On this coast are found early examples of material cultural complexity that pre-date by some 20 thousand years the "Human Revolution" of 50–40 ka (Mellars, 1973; Klein, 1998, 2000), now generally acknowledged to be inconsistent with the African record (McBrearty and Brooks, 2000; Henshilwood and Marean, 2003; Marean and Assefa, 2005). This material cultural complexity includes the production of bone tools such as points (Henshilwood et al., 2001a; d'Errico and Henshilwood, 2007; Backwell et al., 2008), beads (Henshilwood et al., 2004; d'Errico et al., 2005), large quantities of worked and unworked pigments (Watts, 1999, 2002), decorated ochre (Henshilwood et al., 2002; Mackay and Welz, 2008), and most recently lithic heat treatment (Brown et al., 2009). All these occur in Middle Stone Age (MSA) sites at least ~72 ka in age, and earlier as well. More recently, the world's earliest evidence for shellfish collection has been found at ~164 ka on the south coast, and it occurs with early evidence for pigment use and the production of chipped stone bladelets (Marean et al., 2007). The impact of climate and environmental change on this record for modern human origins continues to be debated (Deacon, 1989; Ambrose and Lorenz, 1990; Jacobs et al., 2008a). It has recently been hypothesized that the bottlenecked origin population for the modern human lineage (Ingman et al., 2000; Tishkoff et al., 2007; Gonder et al., 2007; Fagundes et al., 2007; Behar et al., 2008) may have found an ideal refuge here during the long cold MIS6 due to the co-occurrence of the diverse geophyte plants and rich intertidal mollusk communities (Marean, 2008).

All of these scientific lines of enquiry would benefit from long continuous climate and environmental records from this region. Since these are lacking (Meadows and Baxter, 1999; Chase and Meadows, 2007; Chase, 2010), we initiated a multi-proxy study to develop such records across the span of time associated with the origins and spread of modern humans and through several glacial cycles (~400–30 ka). We focused our efforts near Mossel Bay at the geographic center of the CFR, at the transition zone between the winter and summer rainfall belts, and centrally located near many of the archaeological sites displaying early modern human behavior. Central to our effort is the study of speleothems (stalagmites, stalactites, and flowstones) because they can be precisely and accurately dated with uranium–thorium (U–Th) dating and studied for several climate and environment proxies (McDermott, 2004). Here we report on a record we have developed from 90 to 53 ka that spans a significant Interglacial to glacial transition, the origin and spread of several stone tool technologies that are widely considered to be highly advanced for their time, and a florescence of several indicators of early modern human behavior. Our record provides a much-needed climatic and environmental yardstick to help constrain other studies of less well-dated and more temporally patchy evidence for the southern coast of South Africa, although for other parts of South Africa there are several new high resolution studies (Pickering et al., 2007; Holzkämper et al., 2009).

2. The regional setting

Our research location (Pinnacle Point, south coast near Mossel Bay, Fig. 2) is ideally placed. Its coastal location is exceptional for studying linkages with the Antarctic ice cores and deep sea cores and to examine the complex interplay of regional climate, environment, and flora relative to sea surface temperatures (SSTs). It is centrally positioned to the east-west CFR distribution (Fig. 1) and currently surrounded by fynbos vegetation. Rare limestone fynbos (mainly C3) currently covers the Pinnacle Point area. A south-to-north transect inland from Pinnacle Point passes through renosterveld vegetation, over fynbos-covered mountains, and into the Succulent Karoo Biome where the rare grasses are predominantly C4 (Fig. 1). At Pinnacle Point (average annual rainfall = 375 mm, average annual temperature = 17 °C) rains fall all year, but currently more rain falls in the summer (mostly from the east) than winter (mostly from the west), and the region is warmed by the Agulhas current. The prevailing wind and swell is from the southwest (Tinley, 1985). This placement at the intersection of rainfall and vegetation systems of such differing isotopic character facilitates studying temporal shifts in rainfall and vegetation since speleothems can record these isotopic shifts (Bar-Matthews et al., 1996; McDermott, 2004).

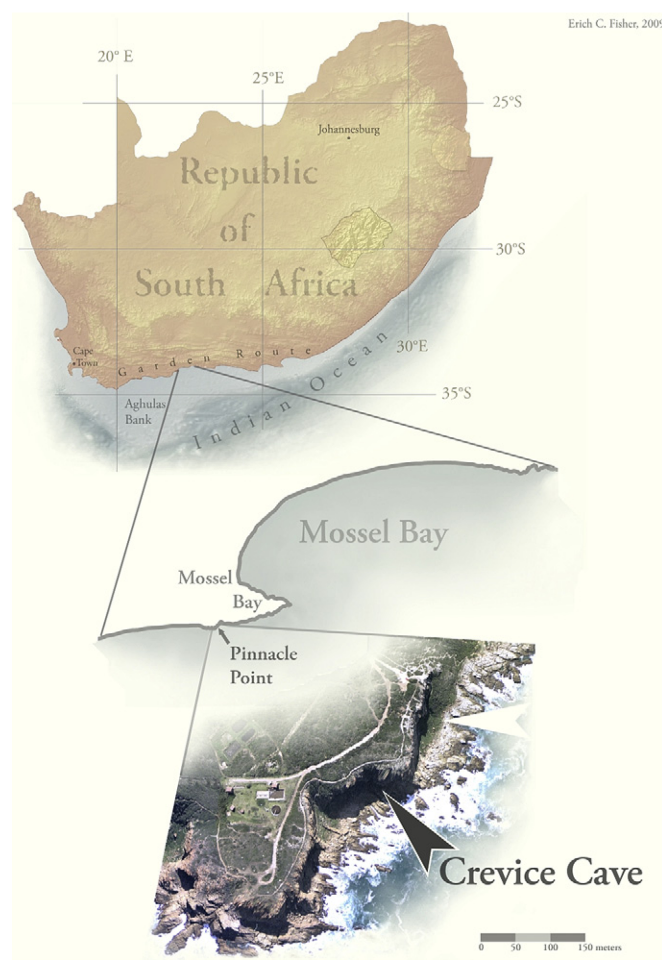

Fig. 2. The location of Pinnacle Point relative to Mossel Bay, and the location of Crevice Cave at Pinnacle Point.

Pinnacle Point is the area surrounding a small headland in a cliffed coast on the Indian Ocean on the central south coast of South Africa, approximately 10 km west of the Mossel Bay point (Fig. 2). The top of the cliffs is now the location of a large golf and resort development. We recognize it as a locality around which are concentrated a wide variety of archaeological, paleontological, and geological localities. From Pinnacle Point to the Mossel Bay point the heavily dissected coastal cliff displays caves, gorges, arches, and stacks that signal cliff dissection and retreat, a process enhanced by repeated high sea levels (Bird, 2000). The coastal cliffs are highly folded and faulted exposures of the Skurweberg Formation of the Paleozoic Table Mountain Sandstone Group (TMS). This formation comprises coarse-grained, light-gray quartzitic sandstone, with beds of varying thickness and consolidation. The dip varies strongly along the coast, ranging from 10 to 75 degrees (South African Geological Series 3422AA 1993). Shear zones with *boudinage* features cut through the TMS, fault breccias of varying thickness fill these zones, and the caves and rockshelters are found in these eroded fault breccias.

A large number of coastal caves and rockshelters (>20) occur in the nearly vertical coastal cliffs in the thicker shear zones where substantial fault breccias had formed, and the caves typically coincide with less steeply dipping beds (10–40 degrees). The primary mechanisms for cave development include the formation of the shear zones, followed by movement along these shear zones and erosion at the contact, cementation of the breccia, mechanical erosion by high sea levels, and in some cases collapse.

Unlithified dunes, aeolianites, calcarenites, and calcretes of the Bredasdorp Group cap the TMS throughout the area, and are mostly referable to the shallow marine Middle and Late Quaternary Klein Brak, and aeolian deposits of the Waenhuiskrans and Strandveld Formations (Malan, 1987; Malan, 1991; Viljoen and Malan, 1993). These are found in extant caves, in the remnants of collapsed caves, cemented to the cliff walls, and on the landscape. Sonar studies have shown that these dune systems are partially preserved on the submerged continental shelf and likely connected to the better preserved terrestrial systems at Sedgefield and Wilderness (Birch et al., 1978; Flemming et al., 1983; Flemming, 1983). At times they sealed the caves from occupation (Marean et al., 2007).

The edge of the continental shelf is approximately 120 km offshore in this area and the coastal platform is gradual in decline (Van Andel, 1989), so that extensive coastal landscapes formed during regressions of the Middle and Late Quaternary. The offshore platform was the source for much of the aeolian sands that comprise the extensive ancient dune systems on land (Illenberger, 1996), under sea (Dingle and Rogers, 1972; Flemming et al., 1983), and in the caves (Birch et al., 1978). While TMS is acidic and acidizes groundwater flowing through it, the water entering the caves has been buffered by these calcium carbonate-rich dune sands and calcretes that cap the TMS throughout the area. Abundant calcite formations are present in the caves and rockshelters, particularly along joints and bedding planes. Small (1–10 cm) to large (>1 m) stalactites and stalagmites are present in many of the caves, and flowstone formations are present in virtually all the caves, often intercalated with archaeological deposits, and almost always occurring behind aeolianite remnants. This means that the original parent material for the speleothems was mollusk remains from the dune sands. We believe this to be the first study of speleothems from a context of this type. The intercalation of speleothem with sediments affords the opportunity to conduct both uranium–thorium dating (U–Th) and optically stimulated luminescence (OSL) on intercalated sediments.

We studied speleothems and cemented dunes from Crevice Cave (34°12′23.315″ S, 22° 5′ 26.847″ E), a small sea cave at Pinnacle Point, to develop a life history of the cave and a speleothem isotopic sequence. The cave is set back ~45 m from the high tide mark and ~14 m at floor above mean sea level. Like most caves at Pinnacle Point, it is formed in a fault breccia, but in this case the shear plane is very steep, running nearly vertical. The result is that the floor is TMS and no archaeology is present. The opening is a slit in the cliff, approximately 2 m high, and one steps up into the cave and onto a small shelf, with the rest of the cave projecting upwards as a crevice (Figs. 3 and 4). This configuration provided a small opening that was easy to close by an abutting dune. Cemented dune remnants are found outside and inside the cave, and those outside reach nearly to the top of the TMS cliff ~50 m above the cave.

Speleothem samples were taken from several areas in the cave, and we sought to sample speleothems that were as long as possible, so as to have long continuous sequences, as well as ones from different areas in the cave to sample the full range of potential speleothem formation. We took samples from the contact with the cemented dunes and also took samples that grew directly on the TMS behind the dune that sealed the cave. The largest most continuous samples were 3 large speleothems that formed on the top of the cemented dune that sealed the cave (Fig. 5). OSL samples were taken from within the cave as well as above the cave on the cliff (Crevice Cave Upper).

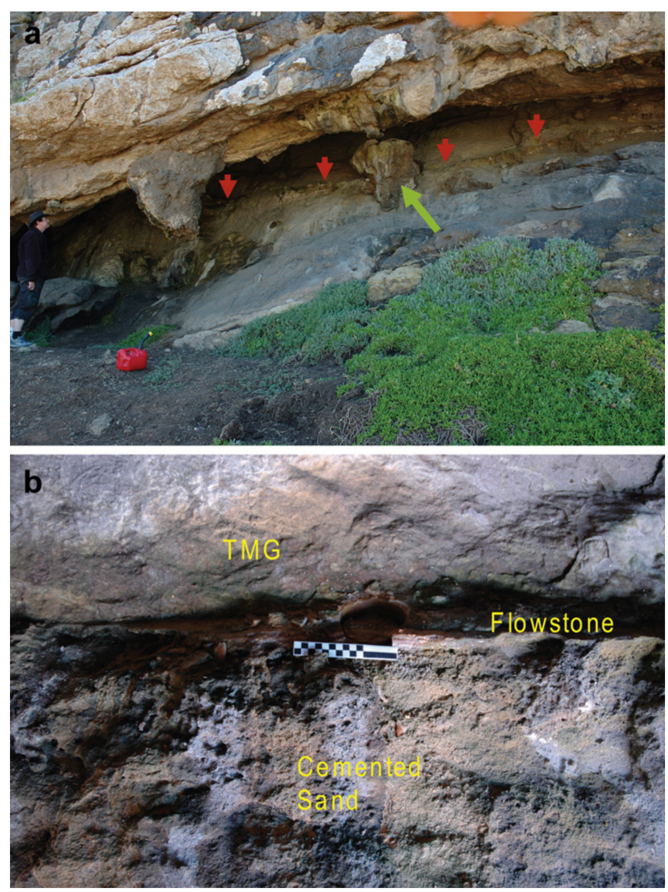

Fig. 3. Photographs of Crevice Cave from the outside. (a) The red arrows point to the flowstone ledge that formed on the surface of the sands that closed the cave and is shown in close-up in 3b. The boss between the 2nd and 3rd arrows from the left, indicated by the green arrow, is in Fig. 5. (b) A section of the remnant of the cemented sands with the flowstone capping. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

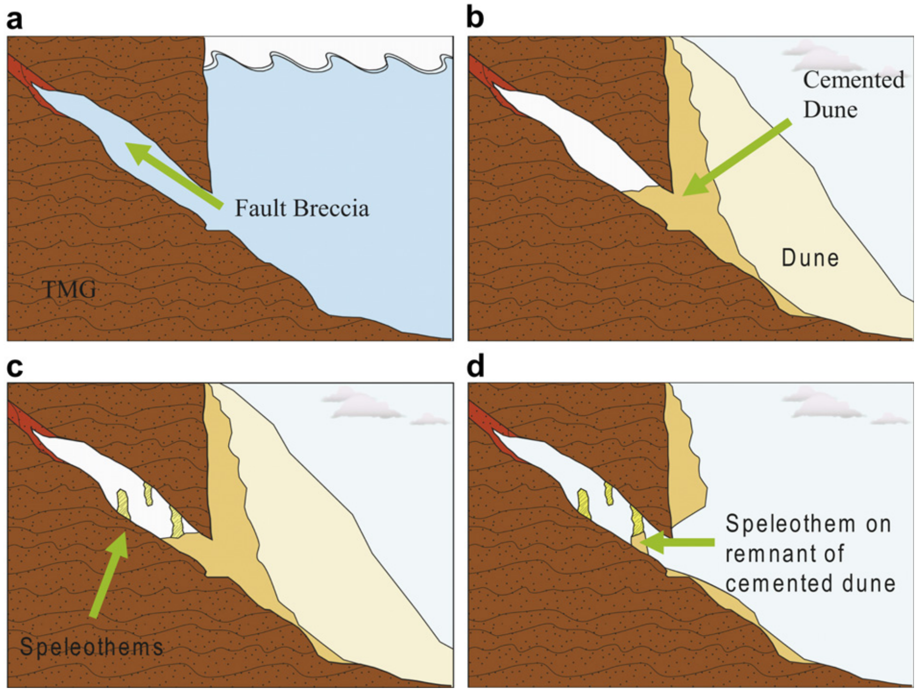

Fig. 4. Schematic of the Crevice Cave Life History. (a) The cave is cut by a high sea level into a fault breccia, (b) the cave is closed by a dune that abuts the cliff, and is cemented at the contact of the dune and the TMS cliff, (c) speleothems form within the cave, and (d) the cave eventually opens and the speleothems are revealed.

3. Materials and methods

3.1. Stable isotope analyses and uranium–thorium dating

U–Th dating of speleothem laminae was performed using the MC-ICP-MS (Vaks et al., 2006) at the Geological Survey of Israel. Each calcite lamina represents a growth period, and to determine the duration of the speleothem growth periods, the top and base of growth laminae were dated (Fig. 6). Where possible, several age determinations were performed across the lamina cross section.

A continuous isotopic record was obtained by assuming that the measured age represents the centre of the dated lamina, and that the growth rate from the centre to the margin of each lamina is constant. To obtain maximum resolution of the isotopic record we chose the speleothems with the fastest growth rate (7 out of 21 dated speleothems) and obtained a composite profile from these speleothems. In order to obtain a continuous record we compared the $\delta^{18}O$ and $\delta^{13}C$ profiles of several speleothems (Fig. S4) covering similar time intervals, which enabled us to extend the isotopic record by matching the oldest lamina of a younger speleothem with the youngest lamina of an older speleothem. Because the isotopic record includes no significant time intervals in which ages are absent, we consider the record of the Crevice Cave speleothems to be essentially continuous from 90 to 53 ka (Fig. 7). The composite isotopic record was determined for 7 different stalagmites and stalactites from various locations within the cave. We generated 146 U–Th ages and ~1100 oxygen and carbon isotopic measurements from which ~330 measurements (Supplementary Data) produced the composite $\delta^{18}O$ and $\delta^{13}C$ curves taken from multiple overlapping speleothems (Bar-Matthews et al., 2003). The Supplementary Video shows the location of the samples in the cave 3D model.

For $\delta^{18}O$ and $\delta^{13}C$ analyses, samples of 1–2 mg material were drilled using a 0.8–1 mm diameter drill, either along or across the growth axis (Fig. 6). Hendy tests (14 measurements of $\delta^{18}O$ and $\delta^{13}C$) were performed on representative samples (Hendy, 1971) and show lack of correlation between $\delta^{18}O$ and $\delta^{13}C$ indicating that the speleothems formed in isotopic equilibrium (Fig. S5). Much stronger evidence for isotopic equilibrium is that several speleothems (Fig. S4) from different locations within the cave deposited during the same time interval show similar isotopic profiles (Bar-Matthews et al., 2003; Dorale and Liu, 2009). High resolution measurements of $\delta^{18}O$ and $\delta^{13}C$ were performed using a Delta Plus Mass Spectrometer, $\delta^{18}O$ and $\delta^{13}C$ values of calcite are reported in per-mil (‰) relative to the VPDB standard (Supplementary Data).

We collected and measured between 2006 and 2007 at Mossel Bay (~6 km from Pinnacle Point) each rainfall event and the cumulative $\delta^{18}O$ and δD of modern rainfall (Ayalon et al., 1998) (Table 1 and Supplementary Data) showing that Mossel Bay winter rain is depleted in $\delta^{18}O$ relative to summer rain, consistent with GNIP isotope summaries (IAEA/WMO, 2002). For water analyses, hydrogen was measured by Thermo Finnigan High Temperature Conversion Elemental Analyzer (TC/EA). The measurements were carried out at a reaction temperature of 1450 °C (Nelson, 2000). Oxygen was measured by Finnigan Gas Bench II. $\delta^{18}O$‰ measurements relied on the CO_2–water equilibration technique (Epstein and Mayda, 1953). All water samples were analyzed in duplicate for $\delta^{18}O$ and δD. The results are reported in δ‰ units relative to the Vienna Standard Mean Ocean Water (VSMOW) standard. The precision of these methods was ±0.1‰ for $\delta^{18}O$ and ±1.5‰ for δD.

For dating purposes up to 0.8 g material was drilled using 0.8–4 mm diameter drill bits along the growth axis (Fig. 6). Depending on the uranium concentration, 100–800 mg calcite powder was dissolved in 7 N HNO_3. The sample was loaded onto mini-columns contained in 2 ml Bio-Rad AG 1X8 200–400 mesh resin. Uranium (U) was eluted by 1 N HBr and Thorium (Th) with 6 N HCl. The U and Th solutions were evaporated to dryness and dissolved in 2 ml and 5 ml of 0.1 N HNO_3 respectively. High precision U–Th dating was performed using a (Nu) Instruments MC-ICP-MS, equipped with 12 F cups and 3 ion counters. The

Fig. 5. Speleothems formed on the top of the cemented dune and wrapped prior to cutting. The speleothems are formed on the same boss that appears in Fig. 3, but in that figure the speleothems have been removed.

sample was introduced to the MC-ICP-MS through an Aridus® micro-concentric desolvating nebuliser sample introduction system. The instrumental mass bias was corrected using an exponential equation by measuring the $^{235}U/^{238}U$ atomic ratio and correcting with the natural $^{235}U/^{238}U$ ratio (0.0072) and comparing it with $^{235}U/^{238}U$ value of NBL-112a standard. The calibration of ion-counters relatively to Faraday cups was performed using several measurement cycles with different collector configurations in each particular analysis. The age determination was possible due to the accurate determination of ^{234}U and ^{230}Th concentrations by isotope dilution analysis using the ^{236}U–^{229}Th spike. The samples had a $^{230}Th/^{232}Th$ activity ratios of more than 100 and needed no age corrections. The reproducibility of the $^{234}U/^{238}U$ ratio was 0.11% (2σ).

3.2. OSL dating

OSL dating provides an estimate of the time elapsed since luminescence minerals, such as quartz, were last exposed to sunlight (Huntley et al., 1985; Aitken, 1998; Lian and Roberts, 2006; Jacobs and Roberts, 2007). Buried grains will accumulate the effects of the nuclear radiation flux to which they are exposed, and the burial dose ('equivalent dose', D_e) can be measured using the OSL signal. The burial ages were calculated from the equivalent dose divided by the total dose rate due to ionizing radiation. Here we provide an abbreviated description of the methods, with more details provided in Supplementary Data.

Twelve samples (Fig. S6) were collected for OSL dating from within Crevice Cave, the cliff face above Crevice Cave (Crevice Cave Upper) and from two large blocks of aeolianite that were found on the floor and near the entrance of the cave, the latter derived from inside the cave. The *in situ* samples were obtained by either drilling the cemented outcrops inside the cave with a core drill or by hammering lumps of sediment off with a hammer. Each specimen was studied through micromorphology to better understand the relationship between the OSL ages and the formation processes. For the core-drilled samples, a sub-sample was chosen for OSL dating based on the presence of visible colour or texture changes. If the samples were homogeneous, but overlain by a flowstone, then the sample was taken furthest away from the flowstone to overcome any complexities with dosimetry due to the presence of the flowstone. The outer light-exposed grains were removed in the laboratory under dim red light illumination using concentrated hydrochloric (HCl) acid to dissolve the carbonate, holding the grains together. The samples for which lumps were hammered off, were very thin and small and were totally dissolved in HCl acid, which introduced the likelihood of zero-age grain contamination in these samples. Quartz grains of 180–212 μm diameter were isolated for OSL dating and purified using standard procedures (e.g., Aitken, 1998), including etching by hydrofluoric acid to remove the external alpha-dosed layer.

D_e values were estimated from multi-grain aliquots (~30 grains per aliquot) for all samples. For those samples that contained zero-age contamination, individual grains were also measured to enable rejection of zero-age grains. OSL data were obtained and analysed using the single aliquot regenerative-dose (SAR) protocol, experimental apparatus and statistical models described elsewhere (Galbraith et al., 1999; Bøtter-Jensen et al., 2000; Wintle and Murray, 2006). We used the central age model (Galbraith et al., 1999) to determine the relative spread in D_e values remaining after making allowance for measurement uncertainties (i.e., the overdispersion). Burial doses and OSL ages were calculated from the weighted mean of the independent estimates of D_e, using the central age model, for each of the samples.

The total dose rate for each sample was calculated as the sum of the beta and gamma dose rates. Account was also taken of the cosmic-ray contribution, which was adjusted for site altitude, geomagnetic latitude, the density and thickness of rock and sediment overburden (Prescott and Hutton, 1994) as well as the $\cos^2 \Phi$-zenith angle dependence (see Smith et al., 1997) and the changing overburden of dune sands through time. The effective alpha dose rate from radioactive inclusions internal to the quartz grains (estimated from measurements made previously on quartz grains from the southern Cape coast (Jacobs et al., 2003)) was also included. The D_e and dose rate information are presented in Supplementary Data, together with the optical ages for all samples. The error on the weighted mean is reported at the 68% confidence interval.

4. Results

4.1. The closing of Crevice Cave and formation of the speleothem

The dual OSL and U–Th dating coupled to micromorphologic and field observation allows us to develop a robust understanding of the sequence of events that led to the formation of the speleothems. The OSL ages for the sandstones and micromorphologic and petrographic analysis document three phases of dune formation (Fig. 8): a) two samples (46618 and 46619) provide a weighted

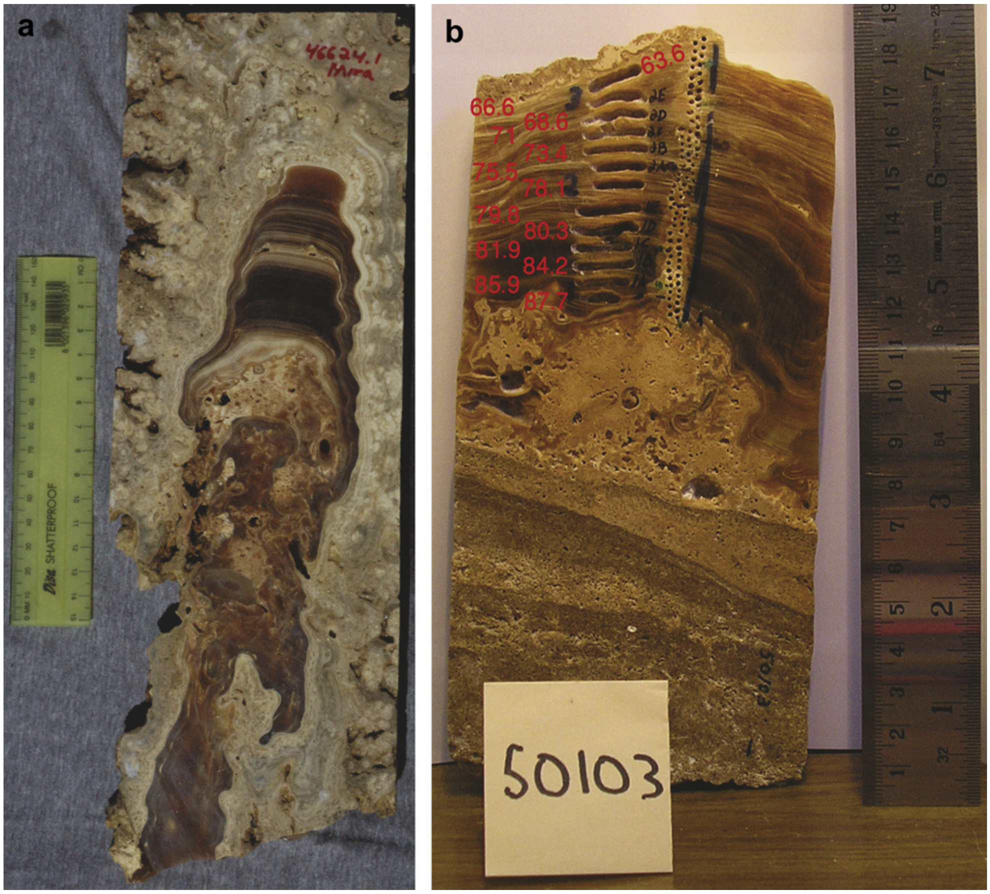

Fig. 6. Speleothems (two separate samples) from Crevice Cave sliced lengthwise by diamond saw. (a) showing tufa on the outside and clean speleothem on the inside, and (b) speleothem from Crevice Cave analyzed for U–Th ages (large drillings on left) and oxygen and carbon isotopes (small drillings to right). The U–Th ages for this specimen are shown on the sample.

mean age estimate of 144.4 ± 5.6 ka, b) six samples (46617, 46665, 46621, 46606, 50103A and 50103B) provide a weighted mean age estimate of 126.5 ± 3.4 ka, and c) five samples (46608, 46673, 46674, 46454 and 20702) provide a weighted mean age estimate of 90.1 ± 2.4 ka. These first two phases resulted in a partially closed cave, tufa formation, and substantial biogenic activity. The final phase of dune formation at ~90 ka is followed by the deposition of detritus-free low magnesium calcite speleothem, until ~50–40 ka when the cave re-opened. The optical ages for the final dune sand is concordant with the age of a similar dune sand dated to 90.0 ± 3.0 ka in Pinnacle Point Cave 13B (PP13B) and the earliest U–Th age estimates of 91.6 ± 1.0 ka for a flowstone overlying the dune sand in PP13B (Marean et al., 2007). The Supplementary Video provides a 3D model and illustrates the life history of the cave.

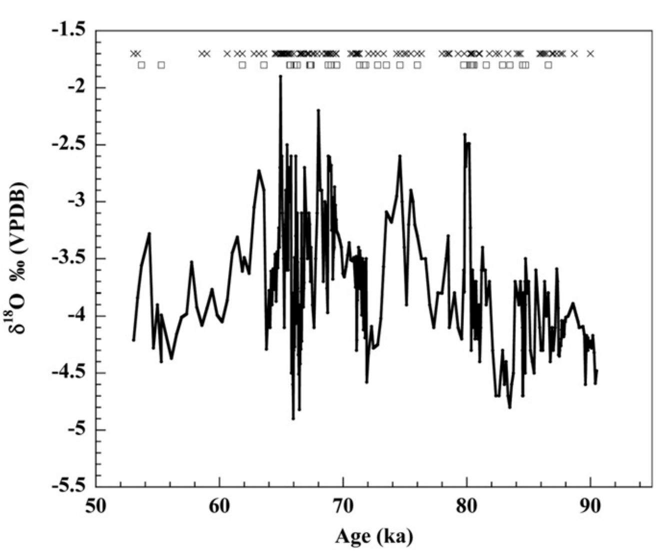

Fig. 7. Composite δ^{18}O profile of Crevice Cave speleothems from 90 to 53 ka. The MC-ICP-MS ages are indicated on top of the diagram: open square symbols are the ages of the speleothems that are part of the composite profile; X symbols are the ages of all other dated speleothems from Crevice Cave that are not part of the composite record.

Our study of paleoclimate and paleoenvironment from the speleothem at Crevice is restricted to this interval when the detritus-free speleothem is forming. As far as we are aware, this is the first climate and environment study of speleothems from

Table 1
Summary of the δ^{18}O by month and season collected in Mossel Bay just 6 km from Pinnacle Point during 2006–2007 (δ^{18}O in ‰ VSMOW).

Season	Month	Mean	Min	Max
Summer	January	0.13	−0.48	1.08
Summer	February	−0.84	−2.05	0.55
Summer	March	−1.58	−7.48	3.82
Fall	April	−2.99	−7.51	1.32
Fall	May	−0.96	−2.41	0.49
Winter	June	−2.86	−11.49	4.25
Winter	July	−6.05	−12.09	−2.02
Winter	August	−3.31	−4.42	−1.20
Summer	December	−1.35	−1.35	−1.35

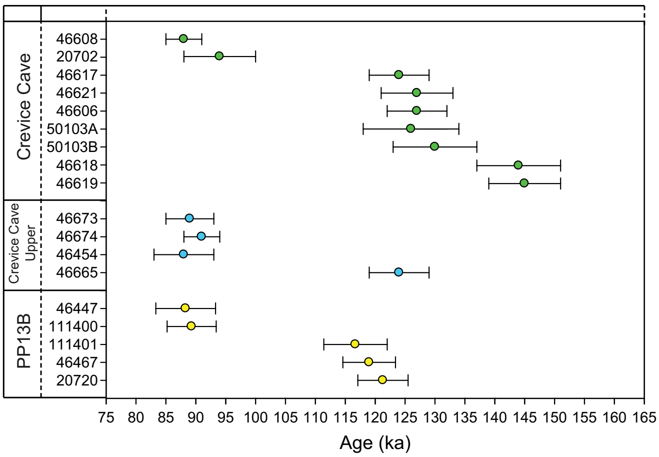

Fig. 8. Optically stimulated luminescence ages from Crevice Cave, Crevice Cave Upper (the cliff face above), and PP13B (Marean et al., 2007) showing the dune pulses that closed the caves.

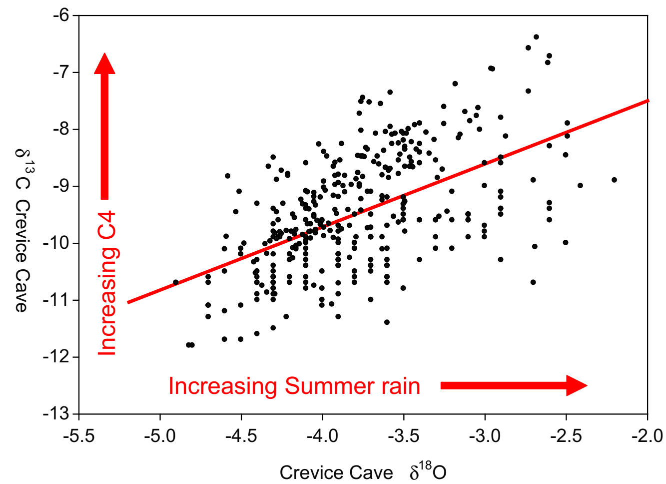

Fig. 9. Crevice Cave (Pinnacle Point) δ^{13}C plotted against δ^{18}O, with least squares line (red line $y = -5.2984 + 1.1006x$, PMCC $r = 0.5502$, $p = < 0.0001$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a context of this type where the cave is a sea cave formed in quartzite, the calcium carbonate is provided by dune sands, and the latter provide the sealant for the caves.

4.2. Climate and environment sequence from 90 to 53 ka in coastal South Africa

4.2.1. The determinants of the changes in δ^{18}O and δ^{13}C at Crevice Cave

The Crevice Cave isotope records (henceforth δ^{18}Occ and δ^{13}Ccc) are highly variable from ~ -5.0‰ to -2.5‰ and ~ -11.5‰ to ~ -6.5‰, respectively (Supplementary Data). As noted above, the coastal platform is gradual in decline so that extensive coastal landscapes formed during sea level regressions, and the slope break-point is ~ 110 km offshore (Fig. 1). Coastal retreat during lowered sea levels is insufficient to drive the changes in δ^{18}O observed here since topographic obstructions are lacking on the Agulhas bank (Fisher et al., 2010), therefore we interpret the shifts in δ^{18}O to be primarily driven by fluctuations in relative summer and winter rainfall (Cruz et al., 2005) as documented by the GNIP map (IAEA/WMO, 2002) and our modern rainfall collections (see above). δ^{18}Occ shows more frequent oscillations, probably reflecting short-term oscillations in the influence of winter and summer rainfall.

In the semi-arid CFR, the main cause of δ^{13}C environmental variation is the amount of C4 grass (Talma and Netterberg, 1983), although other processes can be important contributors to the speleothem δ^{13}C signal (Bar-Matthews et al., 1996; McDermott, 2004). Succulents following the CAM pathway are abundant in the Succulent Karoo, now largely restricted to the arid interior and west coast in a winter rainfall area. Fossil faunal assemblages from the south coast suggest that even the coldest glacial cycles failed to cause an expansion of the Succulent Karoo onto the south coast, though through MIS5-3 the faunas cycle shows a pattern of greater amounts of grazers and open range species during cooler periods, and greater amounts of browsers during warmer periods (Klein, 1972, 1976, 1983).

The good correlation between the δ^{18}Occ and δ^{13}Ccc ($r = 0.55$, $p < .0001$, Fig. 9) could suggest that kinetic isotope effects may be operating (Mickler et al., 2004, 2006). However, similar isotopic profiles obtained from several speleothems located from different locations in the cave (Fig. S4) and Hendy tests (Fig. S5) show that kinetic isotope effects are negligible. Although there is significant correlation between δ^{18}Occ and δ^{13}Ccc, the variation is not equal between points, and therefore the scatter is substantial and the residuals in some cases are large (Fig. 9). This is the outcome of larger δ^{18}Occ variations compared with δ^{13}Ccc.

The relationship between δ^{18}Occ and δ^{13}Ccc (Fig. 9) shows a strong tendency for depleted δ^{18}O (suggesting a greater component of winter rain) to occur at the same time as depleted δ^{13}C (suggesting more C3 grasses), and vice versa. This is the expected relationship given the modern geographic pattern where C3 grasses are more common under strong winter rain to the west, and C4 grasses are more common under strong summer rain to the east (see above, and Fig. 1). The consistency between the pattern in our temporal record with the modern geographic relations between season of rain and dominant grass type, coupled with our modern rainfall collections, strongly suggests that we can use δ^{18}Occ and δ^{13}Ccc as proxies for the influence of season of rain and relative amount of C3 and C4 grass in the Pinnacle Point area, respectively. Furthermore, the speleothem from the Cango Caves (~ 92 km almost due north and inland from Pinnacle Point) is from an area that today has about 40% C4 grass, significantly more than the limestone fynbos vegetation at Pinnacle Point today. This speleothem records a broken sequence from 50 to 12 ka and then from ~ 5 to 0 ka, the latter documenting the appearance of the known modern vegetation regime. The ~ 5–0 ka sequence records δ^{13}C ranging from ~ -4.9‰ to -9‰ (Talma and Vogel, 1992) – we use that as a benchmark for comparison to the changing Crevice Cave δ^{13}C record.

4.2.2. The Crevice Cave record described and compared to other records

A key focus of Quaternary studies is the relation between global proxies of climate change and their regional and terrestrial expression. To investigate this, we compared the Crevice Cave record to a variety of climate and oceanic proxy records, and conducted these comparisons at various scales to reflect the varying resolution of climate proxy records. We smoothed the δ^{18}Occ and δ^{13}Ccc data to 1000 year increments to help indentify long-term trends and allow easier comparisons to lower resolution ice core (EPICA Dome C) and deep sea core (MD97-2120, MD85-674, MD96-2077) records. MD96-2077 (33.17 °S, 31.25 °E) is a local core within the Agulhas Current off the east coast of South Africa. Its resolution is relatively low (1000 years) and it is missing data from 82 to 79 ka (Bard and Rickaby, 2009). MD85-674 (3.11 °N, 50.26 °E) samples the Indian Ocean further north, but also has relatively low resolution (Bard et al., 1997). Farther afield, but at higher-resolution, is core MD97-2120 from Chatham Rise, east of New Zealand (45°32.06 °S,174°55.85 °E), that provides a second SST record from the southern latitudes (Pahnke et al., 2003). Surprisingly, there is no clear relationship between the Crevice Cave record and those from the Agulhas Core (MD96-2077). In contrast, the smoothed δ^{18}Occ and δ^{13}Ccc pattern tracks MD97-2120 SSTs (New Zealand) very closely and somewhat less closely MD85-674 (North Indian Ocean) and EPICA Dome C ice core (Fig. 10). We examined the correlation of the smoothed output and found a powerful fit between the δ^{18}Occ and δ^{13}Ccc records and the MD97-2120 SST record, and somewhat less strong correlations with MD85-674 and EPICA Dome C (Fig. 10 and Supplementary Data). When EPICA Dome C shows warmer conditions, and SSTs from MD97-2120 are higher, δ^{18}Occ and δ^{13}Ccc suggest a larger influence of winter rain over summer rain and more C3 grass over C4, and vice versa. It is important to remember for these comparisons that the accuracy of the globally tuned ice cores may be restricted to ±5 ka (Petit et al., 1999), so substantial offsets from our more accurate and precise speleothem record are possible. Despite this caveat, our results suggest that the broad patterns in δ^{18}Occ and δ^{13}Ccc are driven by Southern Hemisphere climate mechanisms, so below as we describe the specific patterns in δ^{18}Occ and δ^{13}Ccc, we will relate them to MD97-2120 SST and EPICA Dome C.

The Crevice Cave speleothem record displays dramatic changes in both δ^{18}O and δ^{13}C, with both long-term trends and short abrupt shifts (Fig. 10). Major cycles are most pronounced in the δ^{13}Ccc record with minimum values at ~84 ka, a gradual increase towards maximum values at ~75 ka, and a decline at ~66 ka. The δ^{18}Occ approximates this pattern. Starting at ~90 ka the δ^{13}Ccc values are more C3 grass-dominant than the Holocene Cango record (Fig. 10), with a trend toward increasing C3, while the δ^{18}Occ is more depleted suggesting strong winter rain. EPICA Dome C shows a warming trend during this time that peaks at ~84.5 ka, while our directly dated speleothem suggests this peak is at ~83.4 ka. From

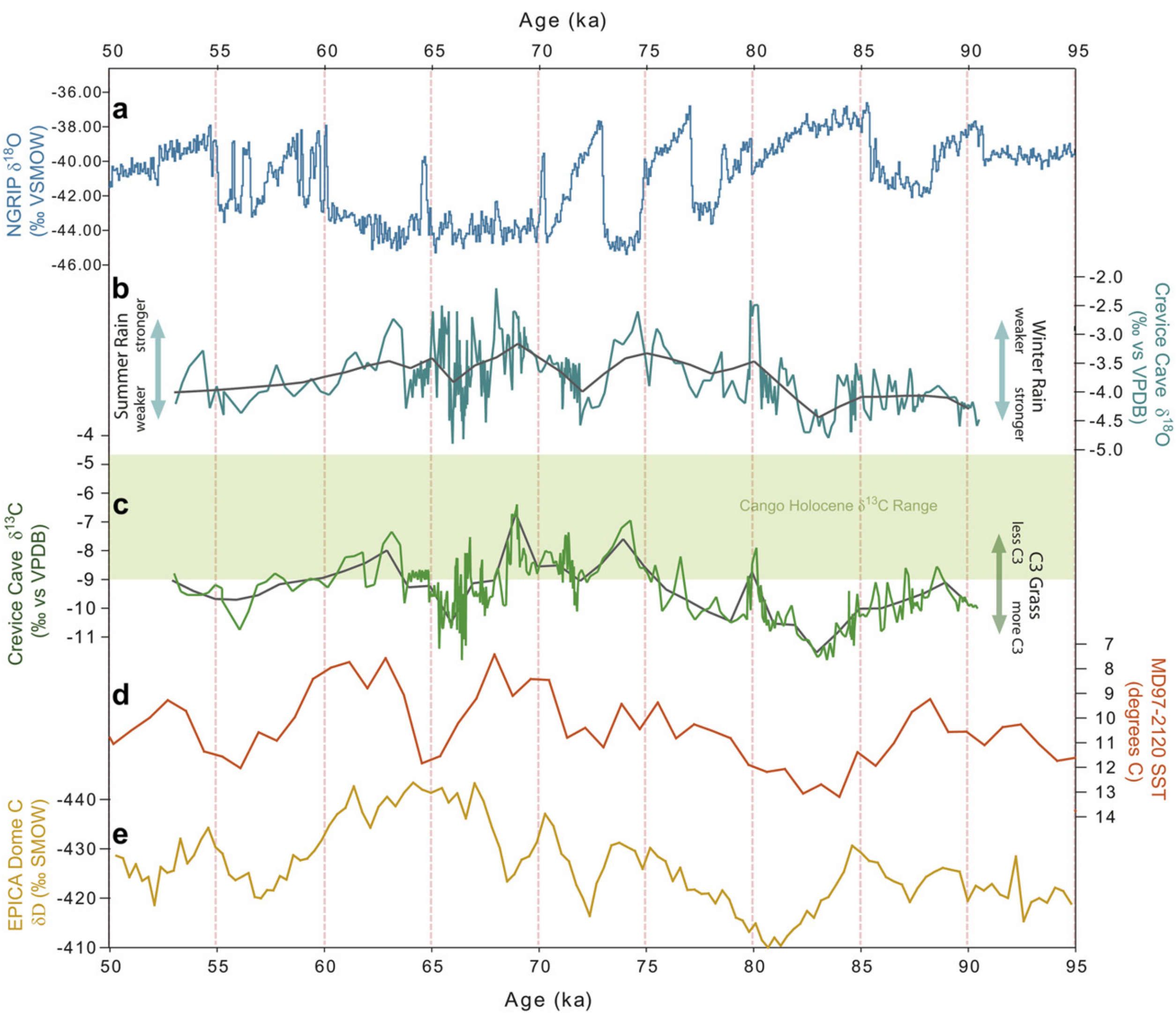

Fig. 10. Stable oxygen and carbon isotope data from Crevice Cave speleothems in comparison to other indicators of global and regional climate, ordered north to south. (a) the NGRIP δ^{18}O (‰ VSMOW) (North Greenland Ice Core Project Members, 2004), (b) the Crevice Cave (Pinnacle Point) δ^{18}O record showing the raw (blue) and smoothed (black) records, (c) the Crevice Cave (Pinnacle Point) δ^{13}C raw (green) and smoothed (black) records plus the range of the Cango Holocene record, (d) the MD97-2120 deep sea core record SST record oriented with colder temperatures up (Pahnke et al., 2003), and (e), and the EPICA δD record (EPICA Community Members, 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

~84 ka both δ^{18}Occ and δ^{13}Ccc display a coupled trend toward enrichment coincident with a decrease in SSTs and temperatures, and both δ^{18}Occ and δ^{13}Ccc show a millennium-long spike in summer rain and δ^{13}C values consistent with more C4 grass at ~80 ka that is hitherto unrecognized in any Southern Hemisphere record. This spike overlaps strongly with the more C4 Cango Holocene range. Near the boundary with MIS4 there is a peak in very grassy C4 conditions ~74 ka. Radiometric age estimates for the Younger Toba super-eruption place that event at ~74 ka (Oppenheimer, 2002). This may suggest a correlated impact on coastal South African environments, but it is important to note that our record also registers a short dramatic isotopic excursion centered at ~72 ka. In Fig. 11 we compare the higher resolution EPICA EDML curve (EPICA Community Members, 2006) to our δ^{13}Ccc results, and a clear high amplitude isotopic excursion is present in the EDML curve centered at ~72.5 ka. We suggest the EDML excursion at ~72.5 and the δ^{13}Ccc excursion at ~72 ka may represent a significant Southern Hemisphere climate anomaly that had a strong terrestrial impact. However, it is difficult to confidently correlate these events to Toba, because of the potential temporal discrepancy between the globally tuned ice cores and our more accurate speleothem record.

From ~75 ka to 67 ka the Crevice record shows δ^{13}C well within the more C4 grass Cango Holocene range, and during this time both SSTs and EPICA Dome C suggest cooler Southern Hemisphere conditions. Both δ^{18}Occ and δ^{13}Ccc show a short spike in summer-rain and C4 vegetation at ~69 ka, and then in the middle of MIS4 the δ^{13}Ccc records a trend toward more C3 conditions with a great deal of variability in both δ^{18}Occ and δ^{13}Ccc. EPICA Dome C shows increasingly colder conditions without displaying this variability, while MD97-2120 records a single prolonged peak in SSTs at ~64.5 ka. The higher resolution EPICA EDML curve shows similar variability at this time, further suggesting that this higher resolution Southern Hemisphere ice core record and our terrestrial record are recording similar hemispheric events of variability. From ~66 to ~50 ka the isotopic variability diminishes while δ^{18}Occ and δ^{13}Ccc suggest more summer-rain and C4 grass than today.

5. Discussion

5.1. Significance for the CFR and rainfall regimes

The geographic distributions of the proportions of C4 and C3 grasses in South Africa are currently correlated to the distribution of summer and winter rain, respectively (Fig. 1). The precise causal relationships are complicated, with temperatures during the growing season argued to be the driving force (Vogel et al., 1978). Our record, well-positioned at the east-west center of the C3–C4 grass distribution, suggests that the broad east-west geographic coupling between season of rainfall and predominant type of grass in coastal South Africa continued into the past, with the combined presence of winter rain and C3 grasses waxing and waning in concert with Southern Hemisphere climate. When conditions cool, summer rain expands into the Pinnacle Point region, and C4 grasses

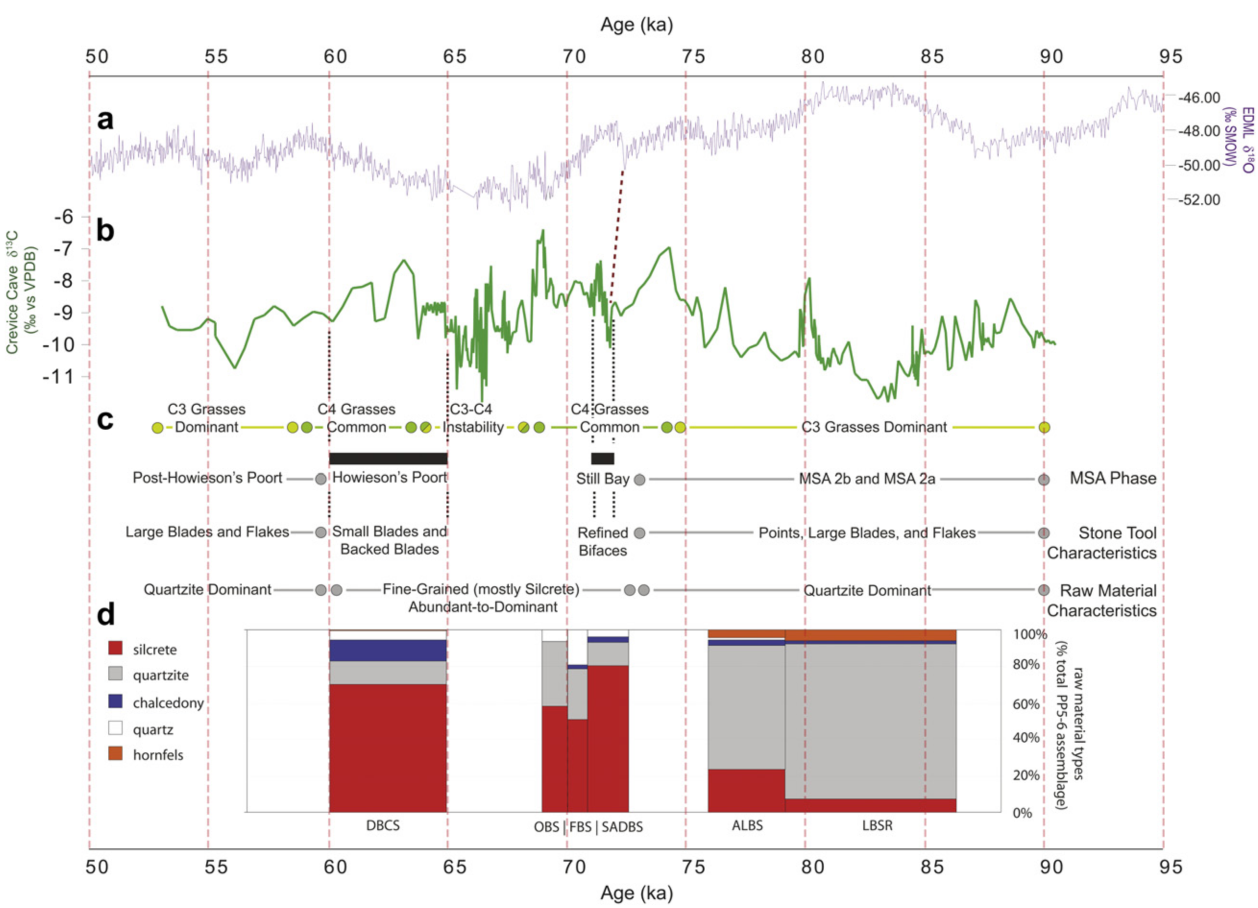

Fig. 11. The inferred vegetation sequence from the Crevice Cave speleothem relative to southern hemisphere temperature change and major phases in the production of stone tools and use of raw materials in the southern Cape of South Africa. (a) The EPICA EDML δ^{18}O record (EPICA Community Members, 2006), (b) the Crevice Cave (Pinnacle Point) δ^{13}C (green) records with inferred grass regimes above as in Fig. 2, (c) the major changes in stone tool phase, stone tool type, and raw material abundance in the southern Cape, and (d) the raw material abundances at archaeological site PP5-6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

do as well. Conversely, when conditions warm, winter rain increases in frequency and C3 grasses follow. Part of the casual mechanism may be that low CO_2 levels during cool periods favor C4 grasses (Bond et al., 2003). Vegetation responses to climate change are often subject to thresholds and tend not to be linear (e.g., Maslin, 2004). However, the general trend in Crevice Cave $\delta^{18}O$ and $\delta^{13}C$ suggests that the response of vegetation to rainfall change is rather fast but also complex.

The position of the winter rainfall belt relative to global climate change, and particularly glacial advances, has been debated for many years. A recent review provides a useful summary of the most influential hypotheses for this relationship (Chase and Meadows, 2007). While Pinnacle Point is just one location and one record, and most of these models were originally advanced for Holocene versus Last Glacial Maximum conditions, the Pinnacle Point record is strategically placed, long, continuous, and extremely well dated. While it does not span the Holocene and LGM, it does span a major Interglacial to glacial transition (MIS5 to 4), and thus we examine the fit of this record to the published predictions for the reaction of the winter–summer rainfall belts relative to glacial advances and retreats.

Cockcroft et al. (1987) modeled winter rainfall as being substantially increased across South Africa with glacial conditions, declining in abundance to the north and east, but with the area of Pinnacle Point receiving greater amounts of winter rain. Our record is inconsistent with the predictions for the south coast. Heine (1982) predicted winter rainfall as dominating the southern portion and south coast of South Africa during glacial maxima, and our results are inconsistent with this prediction. The first scientist to propose a specific model for the relation of glacial events and the position of the winter rainfall belt (Van Zinderen Bakker, 1976, 1978, 1983) predicted that the south coast would receive less winter rain during glacial maxima, and our record is consistent with this prediction. Overall, models that propose a general expansion of winter rainfall in reaction to global cooling are not supported by our results. Our results are consistent with Sealy (1996), who interpreted carbon isotopes from Last Glacial Maximum fauna from Nelson Bay Cave on the south coast to indicate mixed summer and winter rain.

The amplitude in δ^{18}Occ shifts equal those recorded from the eastern Mediterranean as recorded at Soreq Cave, while the δ^{13}Ccc shifts exceed that record (Bar-Matthews et al., 2003) (Supplementary Data). As noted, relative climatic stability has been hypothesized as an important factor in the development of the hyper-diversity of the winter-rainfall region of the CFR, particularly for the west coast (Goldblatt and Manning, 2002; Rebelo et al., 2006; Cowling et al., 2009). Our record documents changes in rainfall and climate on the south coast that equal or exceed those recorded in the Soreq Cave eastern Mediterranean record. CFR diversity is greatest to the southwest (Cowling and Lombard, 2002), and its been argued that the southwest remained climatically stable and thus a potential refugium (Cowling et al., 2009). If this proves to be the case (currently there are no long continuous high resolution speleothems records from the west coast from this time span), then it may be that the south and west coasts responded differently to global climate change.

Our record supports early summaries of the fossil faunal record that recognize dramatic Quaternary environmental change throughout the fynbos region from the west to south coast (Klein, 1983: 135). There is some evidence, mostly from the last 20,000 years, that winter rainfall remained in the southwest in glacial periods (Meadows and Baxter, 1999; Chase and Meadows, 2007), perhaps supporting fynbos, but it is critical to get longer more continuous records from throughout coastal South Africa. Also, it may be that the definition of “climatic stability” among botanists would encompass the variations we see in the Pinnacle Point record and represented in the fossil fauna, and if so then it is important for paleo-scientists and modern botanists to reach precision and correspondence in the definition of “climatic stability” relative to temporal variation in paleo-archives.

The exact composition of the vegetation is impossible to reconstruct from speleothem records alone. However, it is useful to construct hypotheses that can then be tested with multi-proxy data, for the precise reconstructions of the vegetation are essential for a proper understanding of the long-term human and animal evolutionary histories in this region. The modern vegetation of the CFR and immediately surrounding areas has some rather tight structural linkages to abiotic and edaphic features such as season of rain, annual rainfall, altitude, geology, and soils that allow us to make some reasonably informed hypotheses of the major shifts that occurred. As noted above, the speleothem record oscillates between cooler-more summer rain-more C4 conditions to warmer-more winter rain-more C3 conditions. In Table 2 we have summarized the major vegetation communities and their characteristics in the CFR and immediately surrounding areas, and provided some summary statements as to the likelihood that these vegetation types characterized the *end points* of these isotopic oscillations. It is important to recognize that paleo-vegetation systems may not have any direct modern analog, and this is made even more possible due to the importance of fire to the modern fynbos, the regional extinction of many large ungulates, and the possible increase in fire coincident with the introduction of pastoralism in the late Holocene.

As noted before, fossil faunas sampling the glacial cycles on the south coast do not suggest an expansion into this area of Succulent Karoo vegetation, but are consistent with significant expansion of grasslands and open range (Klein, 1972, 1976, 1983). Furthermore, the Succulent Karoo is characterized by extremely arid summers and receives most of its low rainfall in the winter, and this is completely inconsistent with the coupled summer rain-C4 signal in the Pinnacle Point record. Our record suggests that through most of the cooler phases of MIS4-3, the south coast had a stronger summer rain-C4 signal. Large bodied open-habitat grazing ungulates are abundant at Klasies River (~180 km east) in layers dating to MIS4-3, and also at Boomplaas Cave (90 km north and inland). This open habitat grazing signal is further amplified in the Last Glacial Maximum faunas at Nelson Bay Cave (~120 km east) and Boomplaas (Klein, 1972, 1976, 1983). This would suggest that the MIS4-3 summer rain-C4 grass cool climate signal at Pinnacle Point must accommodate substantial open habitats that could support gregarious grazing species. Following Table 2, the best possibilities during glacial phases are Grassy Fynbos and Thicket, and probably a mosaic of the two, because only these vegetation types of the Cape are found in summer rain and have the substantial C4 grass components that would accommodate the δ^{13}Ccc and the presence of large-bodied gregarious grazing species. Grassy Fynbos, Thicket, and C4 grasses are more typical of the Eastern Cape, and it may be that during glacials Eastern Cape vegetation expanded into the south coast. During warmer phases when the speleothem signal suggests stronger winter rain-C3 grass vegetation, the most likely vegetation communities are those present today such as Proteoid and Restiod Fynbos. Further coupled studies of fauna, isotopes on fauna, pollen, charcoals, and phytoliths currently underway at Pinnacle Point will likely help us narrow this range of possibilities.

Finally, if both the fossil faunal records throughout the current fynbos distribution suggest glacial conditions were coupled to expansions of grasslands, and our speleothem record documents an expansion into the south coast of summer-rain and C4 conditions, then an obvious question is where were the other fynbos communities? During cooler periods substantial areas of land were

Table 2
The major vegetation types and communities in the CFR with some of their important characteristics summarized. Under "Speleothem Signal", we show the likelihood for the presence of these vegetation types during the major isotopically recognized oscillations. The vegetation characteristics are summarized from Cowling, 1992; Vlok et al., 2003; Mucina et al., 2006; Manning, 2008).

Vegetation Type	Community	Bedrock and soils	Altitude masl	Annual rainfall mm	Season of rainfall	Grass type			Fires	Speleothem signal	
						C3	C4	CAM		C4-summer rain	C3-winter rain
Sub-tropical thicket	Dune	Calcretes and Aeolianites	0–200	900–1500	Winter–summer nearly equal	Rare	Present	Present	No	Possible	Unlikely
	Valley	Mainly fine-grained soils	0–200	300–650	Winter–summer nearly equal	Rare	Dominant	Present	No	Possible	Unlikely
	Arid Thicket	Mainly fine-grained soils	0–400	200–300	Winter–summer nearly equal	Rare	Dominant	Present	No	Possible	Unlikely
	Thicket	Mainly fine-grained soils	400–1000	500–800	Winter–summer nearly equal	Rare	Dominant	Uncommon	No	Possible	Unlikely
Fynbos	Grassy Fynbos	Quartzites and shale, fertile lower slopes	0–200	600–800	Strong summer	Present	Present	No	Yes	Likely	Unlikely
	Proteoid Fynbos	Quartzites and deep fertile soils on lower mountain slopes	0–1000	600–1000	Winter to Bimodel	Dominant	Rare	No	Yes	Unlikely	Likely
	Ericaceous Fynbos	Quartzites and acidic humic soils in high mountains	1500–2000	1400–1800	Winter	Dominant	Rare	No	Yes	Unlikely	Unlikely
	Restiod Fynbos	Varied geology, soils unsuitable for deep rooted shrubs	Variable	Dry 100–350, Wet 1400–1600	Winter to Bimodel	Dominant	Rare	Present	Yes	Unlikely	Likely
	Asteraceous Fynbos	Calcareous and shallow soils of inland mountains	Variable	100–800	Winter to Bimodel	Dominant	Rare	No	Yes	Unlikely	Unlikely
Strandveld		Varied	0–200	200–500	Winter to Bimodel	Present	Present	No	Yes	Unlikely	Possible
Renosterveld		Shale	0–200	250–600	Winter to Bimodel	Present	Present	No	Yes	Unlikely	Unlikely
Succulent Karoo		Varied	0–1500	20–300	Winter, extreme summer aridity	Present	Rare	Yes	Yes	Unlikely	Unlikely

exposed by regressing sea levels (Van Andel, 1989), and our 3D model of the coastal platform off Pinnacle Point (Marean et al., 2007; Fisher et al., 2010) shows that at times from 90 to 53 ka the coast was as much as ~29 km distant, and even more during other glacial cycles. We hypothesize that the now submerged coastal platform was a likely refuge zone for fynbos vegetation, which may have followed the retreating coast during glacial regressions, while current coastal locations were enveloped in more mixed C3–C4 vegetation. This hypothesis is testable through studies of cored coastal sediments on the now submerged Agulhas bank.

5.2. Significance for modern human origins

Periods of rapid climate and environmental change provide challenging periods for human behavioral adaptation. It has been suggested that non-behaviorally modern humans display technological monotony (Klein, 1998, 2000), while others have argued that rapid technological change in the face of environmental change is an indicator of behavioral modernity (Deacon, 1989; McBrearty and Brooks, 2000). In South Africa two important archaeological entities (the Still Bay and Howieson's Poort) that are often cited as displaying evidence for early modern human behavior (Deacon, 1989; McBrearty and Brooks, 2000; Henshilwood et al., 2004; Wurz, 2008) date to the time span covered by our record and are well known on the south coast (Fig. 1).

During both the Still Bay and Howieson's Poort there are several additions to the material cultural repertoire that have been pointed to as potential indicators of early behavioral modernity. Both regularly have large associated assemblages of pigments, typically ochre, often including hundreds and even thousands of pieces, many modified through grinding (Watts, 1999, 2002; Henshilwood et al., 2001b). At Blombos and Klein Kliphuis there are engravings on ochre that have been interpreted as being symbolic (Henshilwood et al., 2002; Mackay and Welz, 2008), and in the Howieson's Poort layers at Diepkloof there is decorated ostrich eggshell (Parkington et al., 2005). Shell beads that were used as ornaments occur at Blombos (Henshilwood et al., 2004; d'Errico et al., 2005). Both the Still Bay and Howieson's Poort have technological characteristics that have been argued to be advanced. For example, bone tools have been found with both (Henshilwood et al., 2001a; Wadley, 2008), and the special defining tools – the production of refined bifaces and lanceolates (Still Bay) and small blades and backed blades and bladelets (Howieson's Poort) – are sometimes regarded as illustrating advanced lithic technologies (McBrearty and Brooks, 2000; Deacon, 2001). The Still Bay and Howieson's Poort document a temporal shift in choices people made for raw material procurement for stone tool production (Fig. 11). Both record an increase in preference for fine-grained raw materials, such as silcrete, particularly for the production of the special tools that characterize these phases. This focus on silcrete has been argued to indicate broadened trading networks reflective of modern exchange systems (Deacon, 1989) and symbolic behavior (Wurz, 1999). More recently, it has been documented that silcrete was intentionally heat treated to improve its flaking characteristics (Brown et al., 2009). Our studies of raw material at archaeological sites at Pinnacle Point precisely document this shift to silcrete, and the commitment to heat treatment, at ~72 ka (Brown et al., 2009) (Fig. 11), a finding consistent with the rest of the Cape record (Thackeray, 1992; Wurz, 2002; Henshilwood, 2008).

This coalescence of evidence for symbolic and technological complexity has been repeatedly pointed to as a clear indicator of behavioral modernity (McBrearty and Brooks, 2000; Marean and Assefa, 2005; Mellars, 2006). Recent results show that in the southern Cape the Still Bay dates between ~72–~71 ka and the Howieson's Poort to ~65–~60 ka (Jacobs et al., 2008a), time spans far shorter than originally proposed. Our speleothem record provides the first record from this region that is continuous enough, and appropriately highly resolved, to test the hypothesis that these precocious and rather unique expressions of material culture correlate to specific periods of climatic and environmental change. Overall, the Crevice Cave speleothem record shows that both the Still Bay and Howieson's Poort occur during a time when summer-rain and C4 grasses are more abundant in this region relative to today. Fossil faunas at surrounding sites suggest faunal communities dominated by large-bodied, open-habitat, gregarious and grazing ungulates (Klein, 1972, 1976, 1983). As we noted above, the modern vegetation types that could accommodate this pattern include Grassy Fynbos and Thicket, or a mosaic of the two. At Pinnacle Point Site 5–6, the time span of the Still Bay (~72–71 ka) and the Howieson's Poort (~65–60 ka) displays a shift from quartzite to silcrete coincident with the shift from winter rain-C3 grass to stronger summer rain-C4 grass (Fig. 11). Chase (2010) has recently suggested that MIS4 along the south coast was more humid than today. However, the large bodied open-habitat gregarious ungulate communities documented at this time, combined with the speleothem record, are accommodated with a Grassy Fynbos and Thicket vegetation regime without appeal to more humid conditions. From ~72 to 63 ka there is a period of climatic and environmental instability, within which the Still Bay is embedded and the Howieson's Poort begins. Particularly intriguing, our record documents a high amplitude climate and environmental event at ~72 ka concordant with the Still Bay. The short span of the Still Bay and its overlap with a high amplitude environmental change suggests a rapid technological innovation in response to a punctuated shift in climate and environment, a response highly consistent with the abilities of behaviorally modern humans.

6. Conclusions

The speleothem record from Crevice Cave at Pinnacle Point is the first long, continuous, and well-dated Late Quaternary record of climate and environmental change from the south coast of South Africa. This record provides a proxy record of the changing influence of winter and summer rainfall systems originating from the west and east, respectively. It also documents shifts in the composition of C3 and C4 grass in this area. Between 90 and 53 ka increasing amounts of winter rainfall correlate with increasing amounts of C3 grass vegetation, and conversely, increasing amounts of summer rainfall correlate to increasing amounts of C4 grassy vegetation. The broad shifts in the Crevice Cave record track changes in SSTs and shifts in Southern Hemisphere temperatures as recorded in deep sea cores and ice cores in a visually obvious manner (Figs. 10 and 11), and with strong statistical support (Figs. S1 and S2, see analysis above). This suggests that broad changes in terrestrial climate and environment along the south coast moved in concert with global climate change from 90 to 53 ka.

This record suggests that winter rainfall along the south coast did not expand in distribution during glacials, as has been suggested by several climate models, but rather at this location cooler conditions resulted in an increase in summer rain, consistent with predictions made long ago (Van Zinderen Bakker, 1976, 1978, 1983). During these cooler periods C4 grasses expanded into the south coast, and contemporary faunal assemblages document gregarious open range ungulate communities during these cooler periods. Taken together, this evidence suggests an expansion into the south coast of vegetation more typical of the Eastern Cape. The range of $\delta^{13}C$ at Crevice Cave, if taken as an indicator for the CFR along the south coast, suggests that the south coast CFR was subjected to levels of climate and environment change through 90–53 ka similar to those in the Eastern Mediterranean.

Embedded within this broad relation between the Pinnacle Point speleothem record and global climate change are a series of short periods of rapid climate and floral change that are not reflected in terrestrial lake cores further north in Africa (Scholz et al., 2007; Cohen et al., 2007), or the fossil fauna from coastal South Africa (Klein, 1974, 1980, 1983; Avery, 1999). Their absence in these other records may be due to the lower resolution of these records. This shows that during this critical time in modern human origins the southern Cape was a dynamic environmental setting with rapidly changing environments. One widespread stage of technological innovation, locally called the Still Bay, dates to ~72–71 ka (Jacobs et al., 2008b) when our record documents a short abrupt climate and environment anomaly that may correlate to a similar anomaly in the EDML ice core. Between ~90 and 72 ka prehistoric humans in the Cape relied on quartzite as their preferred lithic raw material at a time that our record suggests winter rain-C3 dominated vegetation. At 72 ka prehistoric people abruptly shift to heat treated silcrete as a preferred lithic raw material, coincident with a shift to greater amounts of summer rain and C4 grass vegetation. These early modern humans shifted their technological strategies in reaction to these environmental changes, sometimes quickly. The short and striking climatic and environmental perturbations may have provided the stresses and stimuli for the expression of behavioral complexity in the rich archaeological record in coastal South Africa.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in online version at doi:10.1016/j.quascirev.2010.05.009.

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