

Vegetation history inferred from pollen in Late Quaternary faecal deposits (hyraceum) in the Cape winter-rain region and its bearing on past climates in South Africa

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Abstract

Pollen analysis shed light on vegetation community structure over the last 23,000 year in the western Cape. The pollen from dated hyrax faecal accumulations (hyraceum) relates to the evolution of climate and contributes to proxy records in southern Africa. Principal components analyses of the pollen data and $\delta^{13}\text{C}$ values of the hyrax dung samples show millennial and shorter scale temperature, moisture and seasonality variations in the winter rain region. The moisture availability at times do not parallel that in previously studied proxy records in the summer rain region showing an asynchronous moist event in the early Holocene and drier conditions in the Middle Holocene. Anomalies in climate between the two regions may depend on the degree of northward or southward shifting of winter- and summer-rain circulation systems. Scenarios with winter-rain or cool growing seasons mostly typify the dung sequence but do not exclude the possibility of southward displacement of the westerly belt under precessional strength with slight summer rain increases during the Last Glacial Maximum. Limited southward displacement is also possible during the Mid Holocene.

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1. Introduction

The pervasive climate model used to explain rainfall variations through time in southern Africa is that presented by Tyson (Tyson, 1986; Cockcroft et al., 1987). Tyson (1999) refined the model that comprises a series of oceanic and atmospheric scenarios based on observations of modern circulation patterns. It accommodates variations in the key drivers of rainfall in the modern weather system in three spatial dimensions and by extrapolation may explain variations in climate through time (Muller and Tyson, 1988). The diachronous drivers include the north/south displacement of the westerly belt that is responsible for the winter rainfall in the western Cape, as well as the intrinsic waveform in the westerly system that also effectively imposes a north/south displacement of the incident air in the region (Tyson, 1999). The east/west displacement of the tropical easterly winds that are

responsible for advecting moisture from the Indian Ocean over the subcontinent plays a very important role in the summer rainfall areas. Sea surface temperatures and the intensity of the low-pressure cell that dominates the subcontinent during summer, strongly influence the import of moist air from the Indian Ocean. Tyson (1999) tested the model against the 200,000 year moisture record from the Tswaing impact crater record (Partridge et al., 1997), and against Late Holocene speleothem proxy data for rainfall from Cold Air Cave in the Makapansgat Valley (Holmgren et al., 2003) near Pietersberg. Deviations of the moisture and precession signals in the younger section of the Tswaing sequence seem to indicate that precessional forcing became weaker and were overridden by other factors after ca 50,000 yr BP (Tyson, 1999; Tyson and Partridge, 2000). On a shorter time scale, the Makapansgat Valley study also highlighted the local expression of the Medieval Warm Epoch and Little Ice Age in southern Africa that had been previously addressed using the Tyson model (Tyson and Lyndesay, 1992).

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Testing of the model has relied largely on correlations between temperature and rainfall using proxies from the summer rainfall area. While some proxies for rainfall and temperature do exist for the winter rainfall area, we cannot link them directly to the regional scale model for climate change. Indeed, in Tyson's (1999) model the changes in any one of the variables have the opposite effect on summer and winter rainfall. Typically, northerly displacement of the westerlies will increase precipitation in the winter rainfall area and reduce it in the summer rainfall, as will the eastward displacement of the tropical easterlies. The range of possible scenarios is, however, wide especially when considering the circulation changes under cold Last Glacial Maximum (LGM) conditions or precessional variations. Depending on the degree of northward or southward displacement of the circulation system, the rainfall amounts may vary in harmony or in opposite directions. Only when there is a synchronous southerly displacement of the westerlies with an eastward displacement of the easterlies will arid conditions prevail across the entire subcontinent. Conversely, the region will experience ubiquitous increase in precipitation when the circulation over the subcontinent intensifies by a westward displacement of the easterlies combined with a northward displacement of the westerlies. In order to test the Tyson model it is necessary to assess both summer- and winter-rainfall area palaeodata to determine the extent of synchronous and asynchronous climate change manifestations.

Swamp pollen sequence from the Cederberg in the western Cape winter-rain region (Meadows and Sugden, 1991, 1993) suggests subtle changes over the terminal Pleistocene/Holocene transition and new data can place this record in perspective. In this paper, we derive the vegetation and climate development of the western Cape Fynbos region, from pollen in a sequence of hyrax dung (hyraceum) deposits (Scott and Woodborne, 2006). We compare this with vegetation development during the Late Quaternary in the summer-rain region to the north and east (Fig. 1). Key data include the well-known isotope records from the Cango Caves (Talma and Vogel, 1992) in the southern Cape region and the Makapansgat Valley in the Limpopo Province (Holmgren et al., 2003). The Blydefontein pollen results from the karoo region are based on various types of sediments and do not represent a continuous sequence of this period (Scott et al., 2004). A relatively complete sequence from the Wonderkrater spring in the Savanna Biome of the Limpopo Province (Scott et al., 2003) is a valuable record that compliments the speleothem isotope records from the summer rainfall region.

The dated dung middens (hyraceum) are from the hyrax species *Procavia capensis* (Scott and Woodborne, 2006). Dung samples contained an average of 0.9 million pollen grains per gram (Scott and Woodborne, 2006), representing the pollen from the rocky-slope vegetation (fynbos) in the Pakhuis Pass area. Here, we interpret the pollen

sequence in detail in terms of regional climate change of the southern African sub-continent. The species richness in the fynbos of the western Cape floristic region is enormous and a high speciation rate could be due to orbitally forced species' range dynamics (ORD) (Dynesius and Jansson, 2000) that imply relatively moderate glacial/interglacial changes in the Cape region. However, in view of the low taxonomic resolution of pollen identification we are unable to observe variations in plant species in the area. In stead, we use broad groups at family or genus level to infer environmental changes. The combined pollen sequence from several blocks of hyrax dung, where detailed enough, show marked variation at a millennial to centennial scale. Over the whole sequence, the most prominent change in pollen composition occurs just after 16 ka when a sudden decline of fynbos elements in favour of an increase of woody *Dodonea* pollen took place (Scott and Woodborne, 2006).

2. Setting

The shelter is situated at an altitude of 460 m on the eastern foothills of the Cederberg Range (32°06'S 19°04'E) (Fig. 1). Scott and Woodborne (2006) briefly described the site, which is on the eastern dry side of the mountain range with an estimated total rainfall of ca 200 mm per annum that falls in winter (Schulze, 1997). Only at a distance of hundreds of kilometres to the northeast, does the general precipitation pattern gradually shift to summer rains and increases. Winter-rain to the south and west in the higher Cederberg area above ca 1000 m is ca 700 mm and increases further southwards (Schulze, 1997). At the high altitudes at least 6 km to the south and west in the Cederberg, Mesic Mountain Fynbos occurs showing restioid, ericoid and proteoid elements (Moll et al., 1984) in several phytosociology communities (Taylor, 1996). The vegetation at the site is Dry Mountain Fynbos (Low and Rebelo, 1996) and supports Asteraceous Fynbos (Moll et al., 1984; Cowling et al., 1997). It is in a transitional area to dry Lowland Succulent Karoo vegetation that occurs to the north and east (Low and Rebelo, 1996). Pollen from the site may therefore register past shifts in climate and vegetation along this gradient efficiently.

Vegetation with Asteraceae like *Elytropappus rhinocerotus* (renosterbos that produces *Stoebe* type pollen) and restioids like *Ischyrolepis* spp. grows on an intermediate plateau immediately above the site. The rocky, sandy site occurs as shelters along vertical cliffs of a narrow west-to-east ravine that descends eastwards (Scott and Woodborne, 2006). The vegetation near the site includes mainly Asteraceae like species of *Euryops*, *Eriocephalus* and *Cotula*, succulents of the families Crassulaceae, Aizoaceae and Mesembryanthemaceae, restioids like *Restio* spp., and medium-high shrubs and trees of several species of *Rhus*, *Diospyros*, *Euclea*, *Dodonea*, etc. Thicket occurs in protected areas between rocks and along a lower lying stream with *Melianthus*, *Olea* and *Brabejum*.

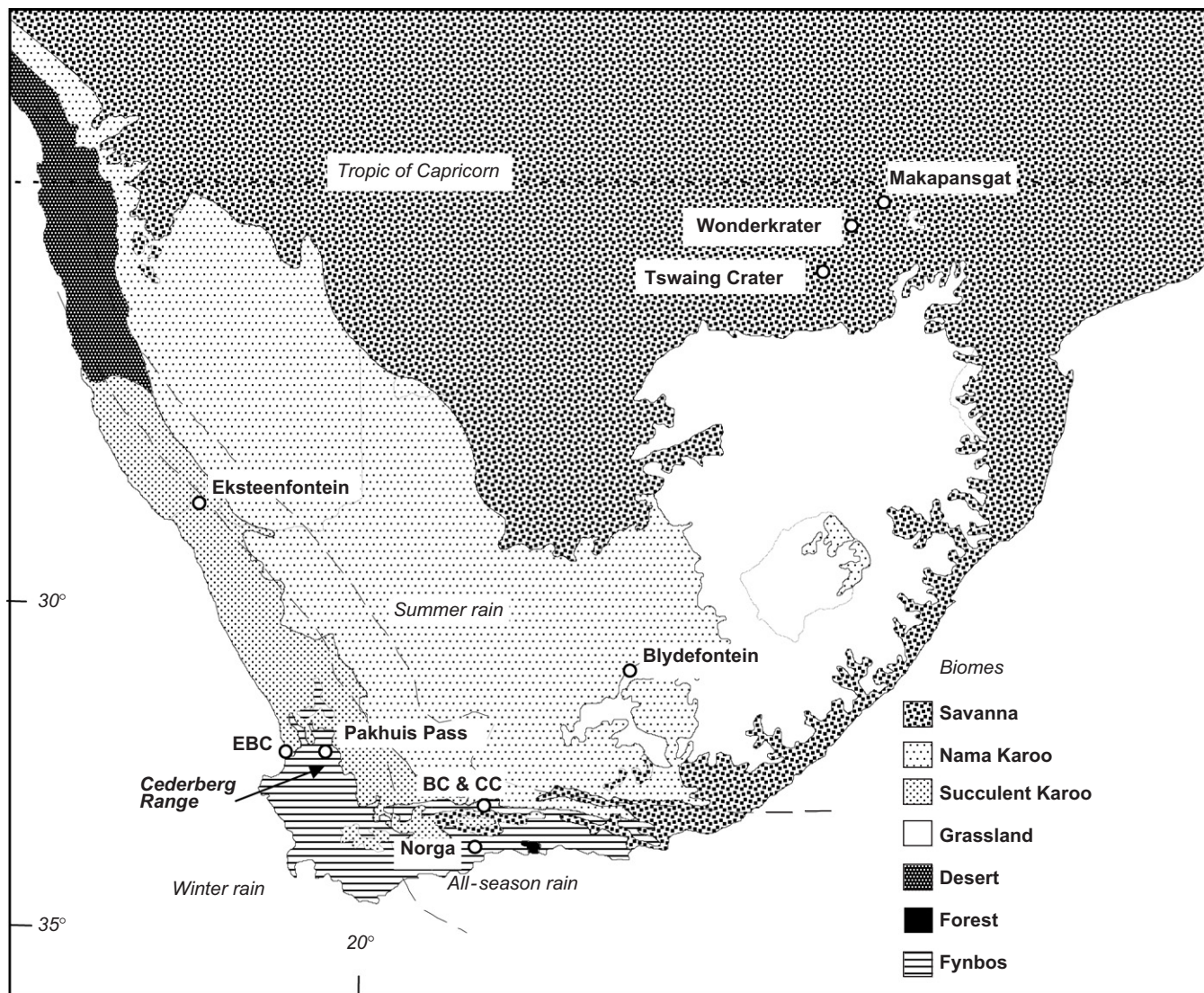


Fig. 1. Locality map showing the Pakhuis Pass site and other sequences discussed in the text. BC = Boomplaas Cave; CC = Cango Caves; ECB = Elands Bay Cave.

A series of 4 modern samples from a transect on the eastern side along the Pakhuis Pass shows a transition from succulent and karroid pollen assemblages in lower-lying altitudes near our site to assemblages rich in *Stoebe* type and with typical fynbos and *Protea* pollen at higher altitudes (Scott, 1994). A more detailed survey of pollen–vegetation relationships must be conducted in future studies in the area.

3. Materials and methods

We described the palynological methods, the radio-carbon dating of 42 samples from several dung slabs, and the generation of an age model for 50 studied spectra in Scott and Woodborne (2006). In that paper we ordinated pollen data of the sequence of fossil hyrax dung slabs by detrended correspondence analysis (DCA) but here we use

principal components analysis (PCA) (program XLSTAT-Pro). The method helps to create palaeoenvironmental sequences comparable to those from previously studied pollen and PCA data from the sub-tropical region (Holmgren et al., 2003; Scott et al., 2003). Derived factor score curves of the first three principal components based on selected pollen percentages of 27 environmentally sensitive indicator taxa in both fossil and modern samples presumably represent environmental parameters. In order to investigate regional palaeoclimatic patterns, the results are compared with stable carbon isotope concentrations in the dung as well as with relevant palaeoenvironmental sequences in South Africa, especially the Cango Caves stalagmite data (Talma and Vogel, 1992) and the Wonderkrater spring pollen record (Scott et al., 2003). The observed anomalies between records are possible indicators of regional palaeoclimatic processes.

4. Results and interpretation of pollen sequence

The pollen distribution over the last 23,000 years appears in Fig. 2. We attempt to interpret the principal components of the selected taxa in terms of palaeoclimate, not excluding the possibility that some of their variations may represent non-climatic factors such as disturbance. However, we assume that the most important principal components over a long sequence like the present one are likely to filter out local variations and that they represent long-term processes like climate change. Further, the pollen samples may represent a mixture of several decades, obscuring local events. In terms of the general vegetation, contrasts in the factor loadings of pollen taxa in the first three components (PC1, 2 and 3), seem to represent climatic gradients. The loadings appear in Table 1 and factor scores in Figs. 3–6. Factor scores showing simultaneous changes in several taxa in the first component (PC1) represent the biggest contrast between LGM and Holocene conditions, (Fig. 3). Scores of the first three principal components, totalling 40% of the variance, show variation that might help to describe environmental conditions that are not obvious in the pollen diagram (Fig. 2). All three PC's inherently seem to reflect different aspects of moisture availability (e.g., evaporation, seasonality or available moisture) and at certain times they show sharp variations (Fig. 3). The fynbos related taxa in PC1 (21% variance) with strong positive loadings are Proteaceae (0.72), *Stoebe* type (0.67), Scrophulariaceae type (0.62), *Lobostemon* (0.6), Malvaceae (0.53), and *Passerina* (0.53) and those with strong negative loadings are Aizoaceae type (−0.7), *Rhus* (−0.55), *Olea* (−0.6), *Dodonea* (−0.55), and *Anthospermum* type (−0.54). Although these taxa ranges overlap altitudinally, those with positive loadings may be more typical under cooler conditions than those with negative loadings judging from the Pleistocene/Holocene and altitudinal contrast in their fossil and modern distributions, respectively. The principal component score curve of modern pollen along the altitudinal gradient (Fig. 5), which also represents a temperature trend, however, is not straight, but generally seems to follow the temperature pattern. Variation in PC1 might therefore be reflecting temperature changes although it inherently also represents a moisture aspect as the high-lying forms are also associated with more moist conditions. If we assume that past temperature fluctuations are the same over relatively large areas, we must look for support for a temperature relationship in PC1 scores in other sequences. The palaeotemperature curve from the Cango Caves stalagmite (Talma and Vogel, 1992; Lee-Thorp and Talma, 2000) and the PC1 values of the Wonderkrater pollen sequence (Fig. 4) in the Limpopo Province can with more certainty be related to past temperature conditions in the summer rainfall area (Scott et al., 2003) than at the Pakhuis Pass. The values seem to support this general relationship in the Pakhuis Pass but in finer detail especially the isotope values appear to deviate (discussed below).

Table 1
Factor loadings on PC1, 2 and 3

	F1	F2	F3
<i>Podocarpus</i>	−0.129	−0.503	−0.200
Proteaceae	0.719	0.097	−0.214
<i>Rhus</i>	−0.549	−0.562	0.021
<i>Olea</i>	−0.595	0.448	−0.301
<i>Euclea</i>	−0.296	−0.571	0.245
<i>Dodonea</i>	−0.546	−0.317	0.245
Cyperaceae	−0.137	−0.001	−0.620
Restionaceae	−0.466	0.239	0.086
Poaceae	0.501	0.378	−0.282
<i>Anthospermum</i> type	−0.536	−0.513	−0.178
Campanulaceae	0.321	0.375	0.093
Malvaceae	0.529	0.045	0.219
Menispermatae	0.016	0.009	0.072
<i>Lobostemon</i>	0.596	0.156	0.152
<i>Passerina</i>	0.527	−0.051	0.185
Ericaceae	0.383	−0.383	−0.222
<i>Cliffortia</i>	0.457	−0.262	0.013
<i>Stoebe</i> type	0.674	−0.198	−0.214
Asteraceae	0.154	0.095	0.432
<i>Pentzia</i> type	0.016	−0.204	0.769
<i>Aloe</i> type	−0.440	0.610	0.019
Euphorbia	−0.335	−0.054	0.204
Aizoaceae	−0.697	0.476	−0.076
<i>Ruschia</i>	−0.250	0.314	0.398
Scroph. type	0.618	0.171	0.355
Cheno Am	0.187	0.114	−0.253
<i>Fagara</i> type	−0.356	0.449	0.201

For the establishment of a reliable basis for moisture estimation in the complex pollen sequence from the Pakhuis Pass we also consider the second and third principal components (PC2 and 3). PC2 (11% variance) has positive loadings in *Aloe* type (0.48), *Fagara* type (0.45), *Olea* (0.45), Poaceae (0.38), Campanulaceae (0.38), and *Ruschia* type (0.31) three of which represent succulent elements relating to Succulent Karoo conditions (Fig. 3), i.e., some winter-rains and warm dry summers. The taxa with negative loadings on PC2 are *Euclea* (−0.57), *Rhus* (−0.56), *Anthospermum* type (−0.51), *Podocarpus* (−0.45), and Ericaceae (−0.38). They seem to be typical of montane situations. The contrast in this factor suggest a relationship to both temperature and moisture with positive loadings indicating warm dry summers and negative loadings more even conditions. PC3 (8% variance) shows a more definite moisture relationship with Cyperaceae (−0.62), *Olea* (−0.3), Poaceae (−0.28), Ericaceae (−0.22), *Podocarpus* (−0.2), and *Stoebe* type (−0.21) versus *Pentzia* type (0.78), *Ruschia* (0.4), Asteraceae (0.43), Scrophulariaceae type (0.36) and *Dodonea* (0.21) where the former group is typical of relatively mesic fynbos or renosterbos and the latter of relatively dry karoo shrubland. Based on these dichotomies in the three components we tentatively relate PC1 with temperature variations but do not exclude the possible influence of moisture changes, PC2 with seasonality of temperature and rainfall, and PC3 with general moisture availability.

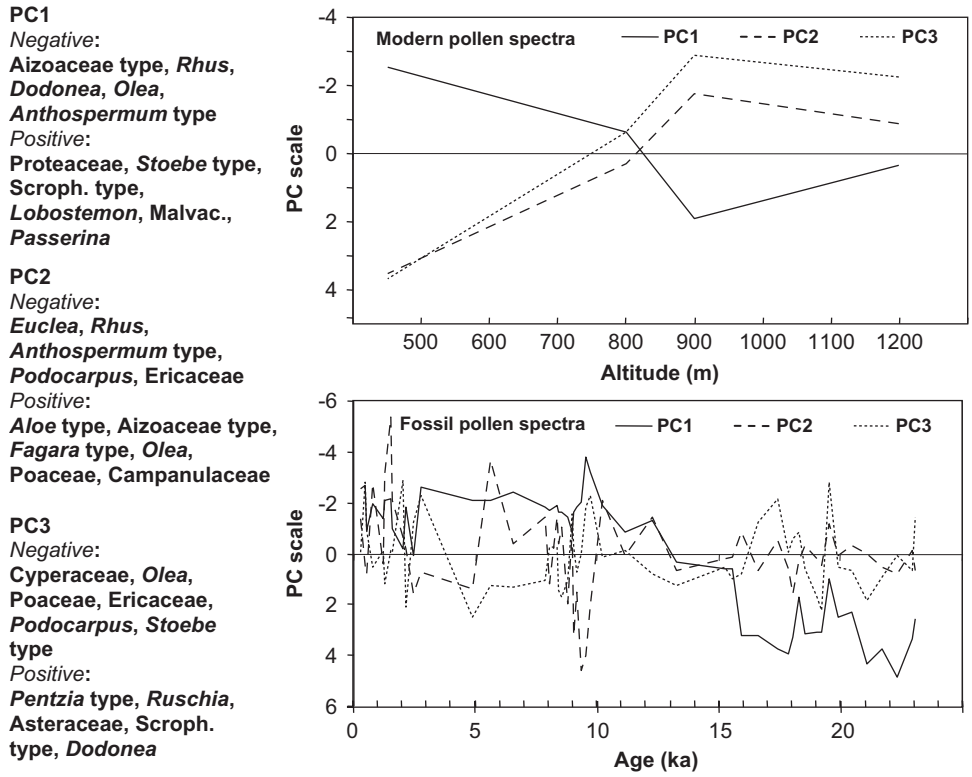


Fig. 3. Principal component (PC) scores of surface and fossil dung pollen samples from the Pakhuis Pass shelter (PC scale inverted for convenience).

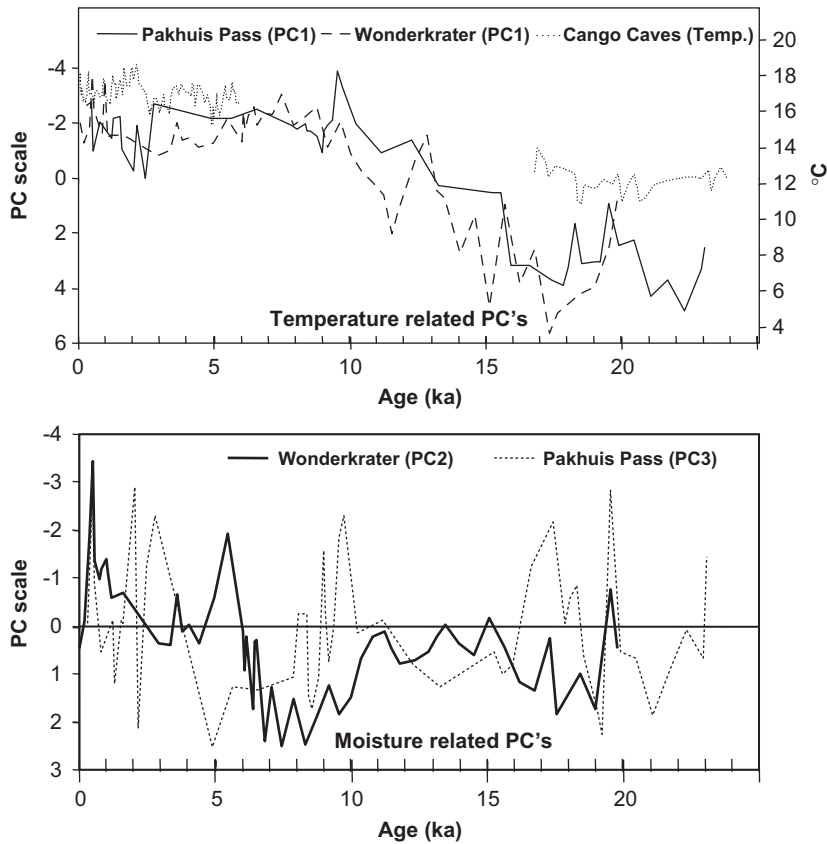


Fig. 4. Comparison of moisture and temperature related PC's from the Pakhuis Pass and Wonderkrater relative to Cango Caves (CC) temperature indications (Talma and Vogel, 1992; Lee-Thorp and Talma, 2000; Scott et al., 2003).

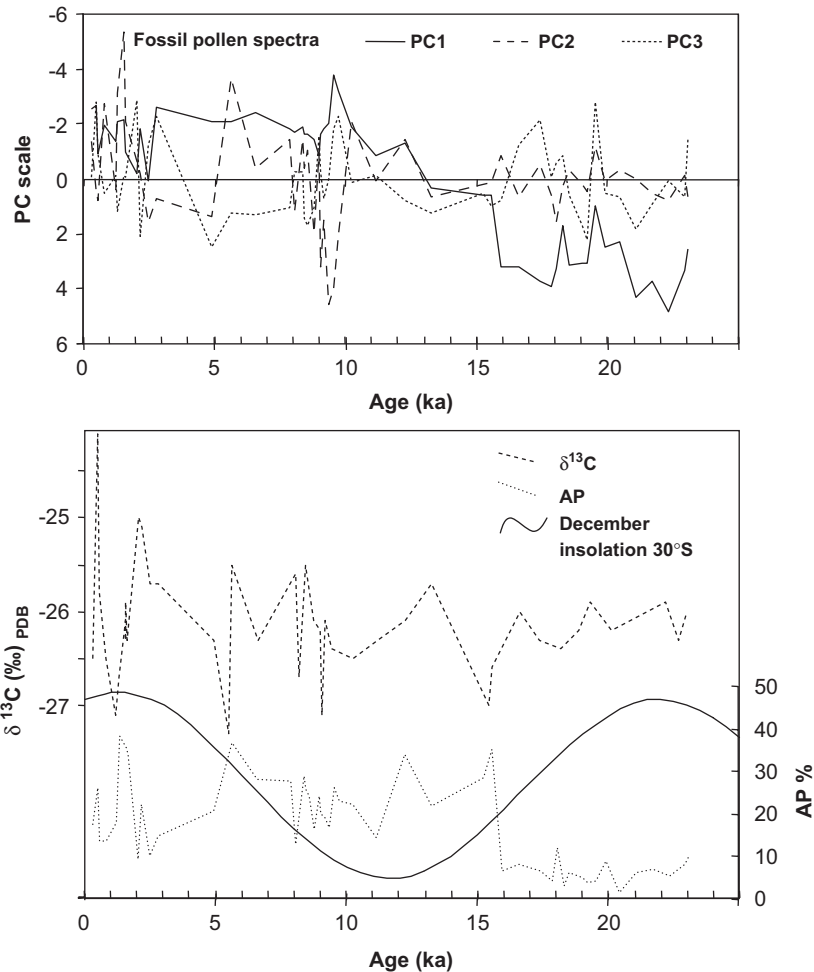


Fig. 5. Pakhuis Pass: Pollen PC's compared with $\delta^{13}\text{C}$ and AP in dung in relation to the insolation trend at 30°S (Berger and Loutre, 1991).

A further tool in tracing environmental conditions is $\delta^{13}\text{C}$ values associated with the radiocarbon dates. In view of their possible reflection of changes in hyrax diet, these results have previously been reported together with similar results from other parts of southern Africa in order to look for environmental fluctuations (Scott and Vogel, 2000; Scott, 2002). Enrichment of ^{13}C in hyraceum might indicate a greater C_4 plant component in the hyrax diet that may result from increased frequency of summer rainfall. We give an updated series here for the Pakhuis Pass (Fig. 5). A few sharp peaks in the isotope sequence in the Holocene might indicate low level events of seasonality shifting towards summer rain (Scott and Vogel, 2000), but this is within the typical range of variance for C_3 plant communities. The short durations of the enriched $\delta^{13}\text{C}$ excursions represent periods of aridity rather than changes in plant community structure driven by rain seasonality but the pollen results (discussed below) does not always support this. Both a plant community structure and a dry-land response of the C_3 plant community could co-occur with a southward displacement of the westerly belt under the Tyson model. The composition of the pollen

assemblages may elucidate which of the factors is the dominant contributor to the variability.

Based on the pollen fluctuations (Fig. 2), the principal components (Fig. 3) as well as the stable isotope curve (Fig. 5) we attempt below to reconstruct the environmental history of the Pakhuis Pass hyrax dung sequence over the last 23,000 years. Cold, relatively dry conditions with asteraceous vegetation produced *Stoebe* type pollen (including *Elytropappus*) and “fynbos” elements (Ericaceae, *Passerina* and *Cliffortia*) at ca 22–21 ka. Temporary amelioration in temperature and moisture is indicated ca 21–19 ka starting with increased Cyperaceae. A cool dry event follows ca 19 ka but moisture recovers before 17.5 ka with Poaceae pollen while temperatures remained low until ca 16 ka when postglacial warming and drier conditions brought scrub vegetation (*Dodonea*). Moderately dry conditions with vegetation that included restioids, occurred ca 13–12 ka. Warming and increasing moisture continued from 12 ka until ca 9.5 ka but the resolution of the sequence around this interval of the Pleistocene/Holocene transition is poor with only a suggestion of minor cooling at the end of the Younger Dryas ca 11 ka. Between 9.5 and 9 ka, there

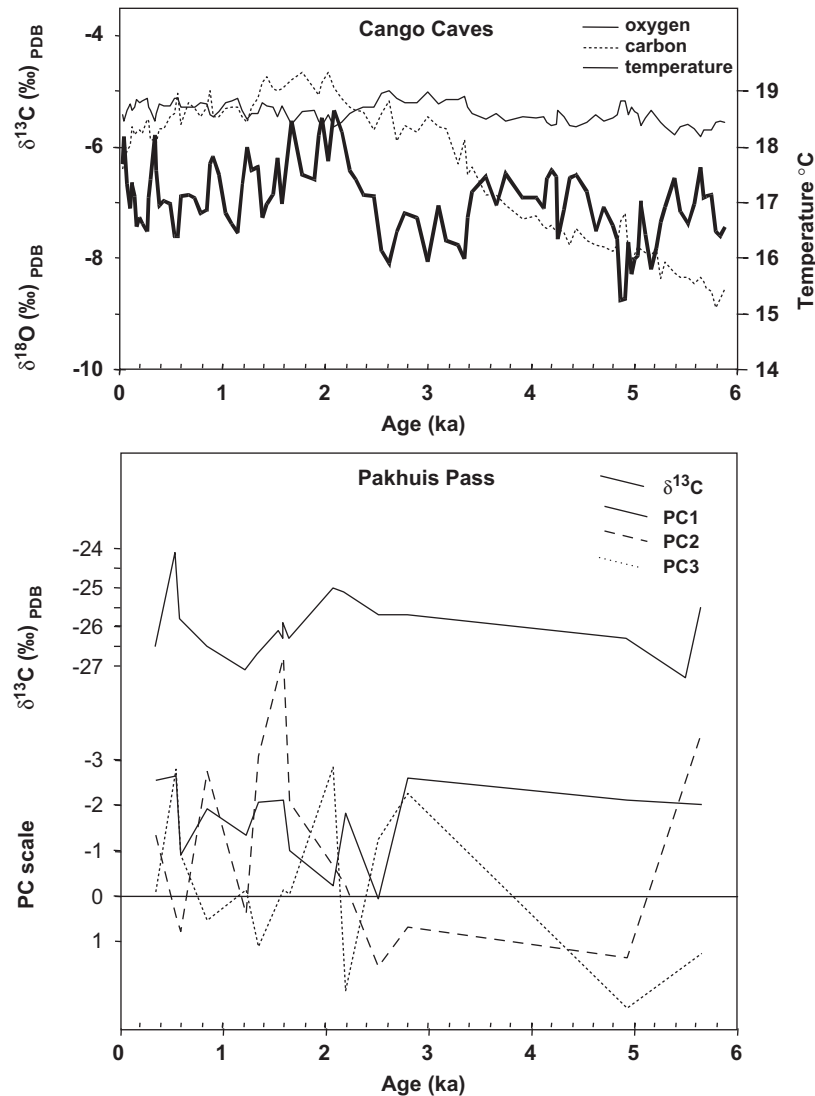


Fig. 6. Pollen PC's and $\delta^{13}\text{C}$ (‰) in Pakhuis Pass hyrax dung compared with Cango Caves (CC) data for the Late Holocene; note inverted PC scale (Talma and Vogel, 1992; Lee-Thorp and Talma, 2000).

is a marked shift to succulent and scrub vegetation. Marked fluctuations in vegetation occurred between ca 9 and 8 ka starting with *Olea* and Cyperaceae, which indicate a moist event and slightly cooler conditions, changing to more Asteraceae-rich shrubland ca 8.5 ka. There is a brief increase in moisture but prominent Asteraceae including *Pentzia* type pollen persisted during the early–Mid Holocene with lower succulent presence ca 5.6 ka, possibly suggesting a weak shift to shrubby karroid vegetation and summer-rain seasonality. Unfortunately, resolution during this phase of the pollen sequence is poor but the prominent Asteraceae persisted until ca 5 ka when restioid pollen peaks again. A marked change occurs between 5.6 and 4.9 ka by a sharp shift in the stable isotope curve, which together with changing PC2 values (Figs. 3, 5, and 6) indicates more C_3 plants and possibly a decline in influence of any summer-rains. This move towards succulent vegetation seems to accompany weak cooling ca 5 ka as indicated by a slight decline in the PC1 curve. The

resolution for the next phase is poor with a gap between 4.9 and 2.8 ka but dry karroid conditions were over by 2.8 ka when Cyperaceae became prominent. However, strong variations in Late Holocene vegetation composition are suggested from then onward with moist phases ca 2.8, 2 ka and during the last 500 years, while prominent Asteraceae (including *Pentzia*-type pollen) and lower arboreal pollen (AP) persisted and fynbos elements (*Passerina* and Ericaceae) increased slightly in numbers until ca 1 ka. The strong variations that seem to occur within the last two millennia include a dry period before ca 0.8 ka. A prominent decline in stable carbon isotope values occurs at ca 2–1.2 ka (Fig. 5) with a subsequent sharp reversal by ca 0.5 ka. The decline at 1.2 ka conforms to dry conditions in view of PC 2 and 3 values. A general decline of scrub especially *Dodonea* is indicated in most recent times (Scott, 1994) and this may be due to a local sampling bias in the modern sample as *Dodonea* is still important in the area today.

5. The Pakhuis Pass sequence compared with other records

If our interpretation of the Pakhuis Pass pollen data reflects climatic conditions it is worthwhile to compare the results with other proxy evidence sequences from the area to look for regional similarities. The study of pollen in the nearby Pakhuis sedimentary basin is in progress (B. Smith, M. Meadows, pers. commun.). An apparent moist phase with peat or lake sediments in the early Holocene (Cornell, 2001; P.J. Holmes, M.E. Meadows, pers. commun.) may eventually help to test our moisture interpretations of pollen in the Pakhuis Pass hyrax dung. Otherwise the nearest detailed pollen record from the area is the Cederberg peat core studied by Meadows and Sugden (1991, 1993) from the higher-lying parts of the mountain range ca 35 km to the south. Considering the known worldwide pattern of changing climates during the Late Pleistocene and Holocene, the pollen composition in this sequence apparently shows little sensitivity to these processes. They recorded a virtually constant vegetation pattern throughout the sequence, except for gradual declining numbers of *Widdringtonia* pollen (Clanwilliam cedar). Although the Pakhuis Pass sequence covers a longer time, its pollen contents show marked fluctuations but especially during the terminal Pleistocene. According to available dating, the bottom section of Meadows and Sugden's (1991, 1993) sequence should be coeval to the main transitional phase from glacial to interglacial conditions as recorded in the Pakhuis Pass, but no correlation is seen. Cowling et al. (1999) suggest that the stability may be due to the more constant rainfall on the higher peaks, which is in contrast with the warmer dry climate of the Pakhuis Pass Shelter, which is in a rain shadow. Prominent secondary fluctuations in the younger section of the Pakhuis Pass sequence also find no equivalents in the Cederberg peat record. The gradual decline in *Widdringtonia* pollen (Meadows and Sugden, 1991, 1993) in this record cannot be confirmed by the Pakhuis Pass sequence because it is situated too far east to capture enough pollen from the Clanwilliam cedar.

Another sequence to compare with the Pakhuis Pass pollen is a charcoal record from Elands Bay Cave (EBC), ca 80 km to the west (Fig. 1), (Cartwright and Parkington, 1997; Cowling et al., 1999; Parkington et al., 2000). Gaps occur in both records and time resolution varies but there are some overlapping sections. The EBC charcoal record (Table 2) contains afromontane and riverine thicket before 23 ka, mesic thickets and fynbos during the LGM and xeric communities during the Holocene. The main change of the increase of *Dodonea* ca 16 ka in the pollen finds vague support in Elands Bay Cave while other prominent forms like smaller shrubs of the *Stoebe/Elytropappus* group are not present in the charcoal record. However, the charcoal variations are not directly comparable to the pollen due to different local environments, to assemblage biases by anthropogenic wood selection and to pollen trapping

Table 2

Environmental conditions at Elands Bay Cave (EBC) (see text) and the Pakhuis Pass Shelter during the Late Pleistocene and Holocene

Age kyr BP (and ka)	EBC charcoal sequence	Pakhuis Pass sequence
4–0	Xeric shrub	Generally dry but with some fluctuations
4.4–4.2 (4.9–4.7)	More mesic	—
7.9–4.4 (8.5–4.9)	—	Relatively dry
10.7–7.9 (12.6–8.5)	More mesic	Relatively moist but with some variations
(14.5–12.6)	—	Becoming drier
13.6–12.45 (16.2–14.5)	Good soil moisture	Warming, slight improvement in moisture
(19–16)	—	Moist, cold
17.8 (21)	Good soil moisture?	Slightly drier, slight temperature increase
(23)	—	Cold
21–20.5	Temperate Afromontane forest	—
(25–24)	—	—
>40	Afromontane plus riverine woodland	—

biases. The inferred climatic variations in the two sites appear in overlapping sections in Table 2. It is interesting to note that the intervals of non-occupation in the charcoal concentrations occur at periods when our interpretation of the hyrax dung sequence indicate either extremely dry or cold conditions, possibly implying that harsh environments prevented human occupation at EBC. Although pollen from Elands Bay Cave studied by Baxter (Parkington et al., 2000) supports conditions inferred by the charcoal at the site, meaningful comparison to the Pakhuis Pass record is difficult because of differences in local conditions and continuity in the records. For the same reason and because of a lack detailed dating in a Late Holocene pollen sequence from Verloren Vlei near Elands Bay (Meadows et al., 1996), we do not attempt correlate it with the Pakhuis Pass sequence.

From areas more distant to the Pakhuis Pass, to the north and to the east, we consider other palaeoclimatic records (Fig. 1). They are the spring pollen sequences from Eksteenfontein (Scott et al., 1995), hyrax dung from the Brandberg (Dâures Massif) in Namibia (Scott et al., 2004), the charcoal sequence from Boompas Cave (BC) (Scholtz, 1986; Deacon and Lancaster, 1988), and the speleothem isotope record from the Cango Caves (CC) (Talma and Vogel, 1992) (Figs. 4 and 6). These sites lie between the winter-rain and all-season rainfall regions (Fig. 1). In addition, to the north-east in the summer-rain region the Blydefontein hyrax dung and spring and cave pollen

sequences (Scott et al., 2005) are considered and even further away to the north, also the Wonderkrater spring pollen and the Makapansgat Valley sequences (Scott, 1982; Holmgren et al., 2003; Scott et al., 2003) (Fig. 1). First, the Eksteenfontein sequence covers the Pleistocene/Holocene transition and is radiocarbon dated between ca 8450 yr BP and some time before 12,000 yr BP. The bottom age of the sequence is uncertain but based on extrapolation of the three upper radiocarbon dates, we expect an age of between 14.5 and 15 ka. Although typical fynbos pollen is scarce, the pollen sequence parallels the Pakhuis Pass transition of a *Stoebe/Elytropappus* type to succulent Aizoaceae type assemblage. The absence of other fynbos suggests no marked northward intensification of Cape winter rain during the period covered (Scott et al., 1995). The presence of *Stoebe/Elytropappus* type and the absence of other fynbos during the LGM, is also recorded in hyrax dung from the Dâures Massif in Namibia (Scott et al., 2004).

The BC charcoal sequence (Scholtz, 1986; Deacon and Lancaster, 1988) is not detailed enough to allow a close comparison with the Pakhuis Pass. However, its most prominent transition involve the same taxa in the main transition in the Pakhuis Pass pollen sequence at approximately the same time (ca 16 ka), i.e., from Asteraceous shrub (including *Elytropappus*) to *Dodonea* and *Olea* woodland.

Further, we consider the 35 ka CC palaeotemperature record, which shows a gap between 16.7 and from 5.9 ka BP (Talma and Vogel, 1992; Lee-Thorp and Talma, 2000). In general, the long-term pattern of this sequence corresponds with the PC1 curve from Pakhuis Pass (Fig. 4). Differences in available resolution hamper short-term correlation between the sections but smaller, secondary fluctuations seem to show opposite tendencies (Fig. 6). In the Late Holocene section, the Pakhuis Pass PC2 curve, as indicator of dry warm summer conditions, generally corresponds better with the CC temperature curve than our PC1 curve (Figs. 4 and 6). One cause of differences between the temperature indications at Pakhuis Pass and CC will be a date offset caused by the water residence time between vegetation change and isotope deposition in the cave speleothem, but this time is thought to be short (Talma and Vogel, 1992) and negligible at the resolution we are dealing with. Short-term anomalies in environmental indications should best be resolved in future higher-resolution sampling, analysis and rigorous dating of pollen records.

The low hyraceum $\delta^{13}\text{C}$ variation in the Pakhuis Pass sequence implies that the position of the summer/winter rainfall boundary did not show significant southward movement at during the last 23 ka. The Pakhuis Pass and CC stable carbon isotope records show few similarities (Fig. 5) (Scott and Vogel, 2000). In the Late Holocene, the isotope peak at around two thousand years ago at both sites. Limited grass pollen improvement shortly before 2 ka (Fig. 2) may be following a widely recognized pattern elsewhere in South Africa which suggests optimal summer

rain in a transect between CC and Makapansgat Valley stalagmite data (Talma and Vogel, 1992; Scott and Vogel, 2000; Scott and Nyakale, 2002; Holmgren et al., 2003; Scott and Lee-Thorp, 2004; Scott et al., 2005).

A Late Holocene pollen record from the humid southern Cape at Norga (Fig. 1) is comparable with the climatic development in the Pakhuis Pass over the last 3000 years (Scholtz, 1986) but the very different local environments at these two sites are difficult to compare in terms of climatic developments. Nevertheless, like the Pakhuis Pass (Fig. 3 and 5), it has clear indications for lower arboreal pollen values (AP) or more open vegetation ca 2500 yr BP, possibly forming part of a regional pattern that was already established by 3 ka (Scott and Lee-Thorp, 2004).

Table 3 shows comparison of the Pakhuis Pass pollen sequence with the Blydefontein pollen sections (Scott et al., 2005) from the summer-rain karoo-region. Moist conditions started to develop at Blydefontein ca 4.6 ka, but unfortunately the Pakhuis Pass record shows a gap between 4.9 and 2.8 ka. The Blydefontein record has one between 4 and >2 ka. The wetter conditions that are evident at ca 2.8 ka at Pakhuis Pass may be as result of some summer moisture and possibly reflect the maximum southward movement of the summer rain zone at ca 2 ka as suggested at the Cango Caves (Talma and Vogel, 1992).

Table 3
Environmental interpretation of Blydefontein (Karoo) pollen results (Scott et al., 2005) compared with that of the Pakhuis Pass

Age kyr BP (and ka)	Blydefontein climate	Blydefontein vegetation	Pakhuis Pass climate
Ca 0.3–20th century	Gradual drying	Increasing asteraceae	—
1–0.4	Sub-humid	Grassy	Becoming wetter
Ca 1.3–1.1	One (or two?) dry events	Brief spread of asteraceae	Dry
2–1.3 (2–1.3)	Sub-humid, brief dry event	Grass/ asteraceae alternate	Becoming wetter
(2.5–2.2)	Sub-humid?		Dry event
Ca ?–2.2 (2.6–2.1)	Sub-humid	Grassy	Cool, relatively moist
Ca 4–3 (4.4–3.1)	Cool, varying moisture conditions	Poor pollen preservation: Fynbos in shelter varying grass cover	—
Ca 4 (4.4)	Moderately dry	Shrubby	—
Ca 4.6–4 (5.3–4.4)	Sub-humid with some drier variations	Grassy with some shrubs	Dry (slight cooling?)
< 5–4.75 (< 5.7–5.45)	Dry	Shrubby with grasses	Relatively dry warm
Ca 5.1–5.4 (5.8–6.2)	Sub-humid with dry variation	Grassy with shrubs	—
> 5.4–11.85 (6.2–13.4)	Dry indications but record incomplete	Small shrubs	Relatively warm, moist becoming drier

In order to place the suggested palaeoenvironmental sequence from the Pakhuis Pass in a broader sub-continental pattern of environmental change it should be compared further with long records like the Wonderkrater spring pollen sequence from the Limpopo Province in the north of South Africa (Fig. 1). Apart from an apparently similar Pleistocene/Holocene temperature trend of both sites, opposite millennial scale moisture fluctuations occur (Fig. 4). These differences might relate to time lags and/or other effects of varying degrees of frontal penetration or retreat between the winter rainfall and summer rainfall areas. Based on these two sequences, we attempt to view the vegetation development over South Africa in terms of atmospheric circulation changes proposed.

6. The Pakhuis Pass sequence and climatic forcing

When considering the LGM phase of the Pakhuis Pass it is noted that the spiky moisture curve (PC 3) does not follow the smooth December insolation curve for 30°S (Berger and Loutre, 1991) (Fig. 5) suggesting that summer insolation did not cause a persistent increase of moisture as far south as the Pakhuis Pass (33°S) during this phase. However, in view of the strength of the predicted precessional forcing it is likely that the available rain did include a significant portion of summer rain. This forcing possibly explain moisture availability ca 20 ka. It coincides with an apparent temporary temperature increase and we should consider the possibility that higher temperatures have played a role in briefly reversing the glacial pattern of low moisture at this time. Although persistence of fynbos vegetation and the constant depletion of stable carbon isotope in the hyrax dung seem to suggest winter rain conditions from the westerly system, a scenario of fynbos and predominantly C₃ growth under increased summer rain is feasible. This suggestion may seem unusual but if growing temperatures are low enough typical southern African C₄ vegetation will not develop, even under summer rain conditions (Scott, 2002). Under present conditions fynbos occurs in the mountains of the Eastern Cape in the all season rainfall zone (Fig. 1) with a fair amount of summer rain and this could be an analogue for fynbos in the western Cape at 20 ka.

The next peak in moisture availability ca 16 ka occurs when precessional forcing has already declined considerably. We have no convincing evidence to relate this to summer precipitation. However, an apparent increase in this type of rainfall occurred in the Makapansgat Valley at this time (Holmgren et al., 2003) while at Wonderkrater the pollen sequence suggests a moderate increase (Scott et al., 2003). The distance of northward westerly penetration according to Tyson's (1999) model during the LGM is difficult to estimate but whatever the kind of rainfall reached Wonderkrater and the Makapansgat Valley, low evaporation due to reduced temperatures must have contributed to high moisture availability in both the Cape and subtropical area.

The Pakhuis Pass PC1 curve shows correspondence with the so-called Antarctic Cold Reversal (ACR) in ice records (Blunier et al., 1997; Bianchi and Gersonde, 2004) and seems to find support in the Wonderkrater sequence (Fig. 4) (Scott et al., 2003; Holmgren et al., 2003). The decline in summer insolation together with rising temperatures seems to correspond with increased AP (Fig. 5), especially *Dodonea*. The pollen data shows a weak deviation, which may be associated with the end of the Younger Dryas phase possibly lagging slightly behind it. Unfortunately, the cover of this phase is poor in our record.

The Pakhuis Pass experienced a brief phase of favourable moisture conditions during the early Holocene ca 10 ka when Wonderkrater to the north experienced dryness and when temperatures continued to rise (Fig. 5). It is likely that this moisture increase related to an increase in the ratio of winter- to summer-rain considering the absence of precessional forcing and the sharp deviation of the PC2 curve, which indicates succulent vegetation or dry summers (Fig. 5). The stable carbon isotope ratios under ameliorated temperatures also suggest winter-rains. Interestingly, the end of this moist event at Pakhuis Pass, which coincides with sharp deviations in PC 2 and 3 ca 9 ka, is coeval with marked events in the subtropical area. They are a decline in local Cyperaceae growth at Wonderkrater and the recovery of depleted stable carbon isotopes in stalagmite T8 in Cold Air Cave, Makapansgat Valley (Holmgren et al., 2003; Scott et al., 2003). Although relatively dry, both subtropical sites possibly experienced a favourable winter moisture ca 9 ka at the same time as in the Pakhuis Pass. After this date at ca 8.5 ka, relatively more dry-adapted C₄ grass developed at both the subtropical sites. The period of dryness that follows at Pakhuis Pass ca 8.5–5 ka, overlaps in time with the continued dry early Holocene phase in the subtropics but it might have lagged ca 1–2 ka behind that at Wonderkrater (Fig. 4). In view of the pattern in the Blydefontein pollen sequences, a lag is possible but the degree is difficult to estimate due to the lack of resolution in this part of the Pakhuis Pass sequence (Scott, 1993; Scott et al., 2005). We need more records from both regions to prove this. The dry early to middle Holocene phase at Pakhuis Pass invokes the early phase of southward movement of the ITCZ system, which forced its peripheral dry air zones (currently forming the Karoo region), southward from the tropical areas. The replacement of succulent Aizoaceae type pollen with Asteraceae types ca 5 ka onwards and the occurrence of slightly more grass typical of the Nama Karoo environment seem to parallel the Blydefontein sequence. The low AP content at Pakhuis Pass between 5 and 2 ka (Fig. 5) corresponds with a succulent increase and is possibly accompanied by cooler conditions. The continued southward movement of the ITCZ that apparently brought moisture as far as the Little Karoo at CC (Talma and Vogel, 1992; Scott, 1993) probably also influenced the Pakhuis Pass region. A slight increase in grass pollen and an isotope increase in the hyrax dung ca 2 ka suggest this (Figs. 2, 5 and 6). There is by no

means any indication of a gradual summer rain progression at Pakhuis Pass in the late Holocene as is suggested at CC (Lee-Thorp and Talma, 2000). Although the trend of PC2 may suggest less dry summer conditions ca 2 ka, does not seem to indicate a gradual seasonality change (Fig. 6). The enriched stable carbon isotope ratios in the hyrax dung sequence around 2 and 0.5 ka and depleted values centred on 1 ka, can according to the pollen results, be interpreted as a change from wet summer-rain conditions to relatively dry conditions. This is in contrast with the original speculations for moist conditions for the depleted levels and is in support of a regional interpretation that is suggested as far north as ca 800 km in the Namib (Lee-Thorp and Talma, 2000; Scott and Vogel, 2000).

7. Conclusion

The hyrax dung pollen from the Pakhuis Pass shows that this material is a good source of palaeo-environmental data that can be effective in determining complex patterns of change. In general, we interpret the results in terms of the conceptual palaeoclimatic circulation models of Tyson (1999) but they raise questions about the sharp fluctuations within the LGM. It is clear that the climate of the poorly known LGM period in the region is more complex than previously suggested in the usual generalizations. Sharp variations of similar scale to those found in the LGM also characterize the climatic evolution throughout the Holocene. We assume that regular marked centennial or even decadal variability occurred in the Cape region similar to that recorded at the Makapansgat Valley (Holmgren et al., 2003). Our current hyrax dung sampling resolution only gives an incomplete indication of this.

There are indications for the north/south movement of the ITCZ system during the Holocene from different sites in the interior (Scott, 1993; Scott and Nyakale, 2002) and the Pakhuis Pass data seem to support this. A question is, however, how far to the south summer-rains driven by precession during the LGM could have influenced the climate.

Our pollen record does not cover short-term variations such as the Little Ice Age in any detail at this stage. However, hyrax dung from the Namib Desert (Scott, 1996; Gil Romera et al., 2006) has shown that adequate resolution to cover short time spans is potentially available from this source if more sections are studied. An important gap is the hiatus around 2.8 to 5 ka which includes a time period that is poorly covered by most other pollen records in southern Africa (Scott and Lee-Thorp, 2004). The only detailed proxy data from this period come from the speleothem records (Talma and Vogel, 1992; Holmgren et al., 2003). In certain respects, the speleothem data correspond with, and in others deviate from, the emerging pollen and isotope data from the Pakhuis Pass (Fig. 6) and promise to present interesting future challenges in interpretations of environmental conditions in the Cape region. We must reveal local sub-continental processes and

understand climatic evolution in a closer grid proxy records like those discussed above, in order to establish patterns of synchronicity and lags between the summer- and winter-rain zones. This will place southern Africa more effectively in models of the southern Hemisphere and the global system. We therefore anticipate filling gaps by analyses of more hyrax dung material in the Cederberg or wider southern African regions.

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