# Late Quaternary research in southern Africa: progress, challenges and future trajectories

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| Journal: | *Transactions of the Royal Society of South Africa* |
| Manuscript ID | TTRS-2016-0031.R1 |
| Manuscript Type: | Reviews |
| Keywords: | Southern Africa, palaeoenvironmental research, state of the science, proxies, site selection |

# Late Quaternary research in southern Africa: progress, challenges and future trajectories

## Abstract

Southern African late Quaternary research has developed rapidly during recent decades, with an increase in the range of proxies used, the inclusion of new field sites, and increased international collaboration and skills transfer. This has enabled recent meta-studies into the synoptic drivers of palaeoenvironmental shifts across the region, and of spatial variability in climatic and environmental changes. Expanded research has also highlighted uncertainties in the understanding of southern African palaeoenvironments, and the relationships with Northern Hemisphere analogues, encouraging on-going critical debate within the discipline. Given current concerns of climate change impacts on the natural environment, the spread of invasives, increased fire frequency, and anthropogenic influences on the natural environment, palaeoenvironmental data and inferences are increasingly being utilised outside of the palaeoenvironmental discipline, providing a valuable inter-disciplinary platform for global change science in the region. Relative to the size, landscape and climatic heterogeneity and resultant biome variability across southern Africa, the network of palaeoenvironmental study sites remains sparse, and arguably insufficient to resolve key debates. This paper critically reviews these spatial gaps in palaeoenvironmental knowledge, with a particular emphasis on the shortfalls of the current network of study sites and palaeoenvironmental records in resolving debates concerning latitudinal shifts of the westerlies, conditions during the last glacial maximum and contemporaneous Northern and Southern Hemisphere climatic events. Southern African applications of palaeoenvironmental science in exploring ecological trait shifts, fire influences, and anthropogenic impacts are briefly discussed, to facilitate the future identification of key sites, proxies, debates and applications in ongoing regional Quaternary work.

## Keywords

Southern Africa, palaeoenvironmental research, state of the science, proxies, site selection.

## INTRODUCTION

Past environmental and climatic reconstructions using climate proxies isolated from sediment profiles were initiated comparatively late in southern Africa, compared to work elsewhere in the world (Scott, 1982a,b; Van Zinderen Bakker & Coetzee, 1988). Pioneering studies by Van Zinderen Bakker (1955), Martin (1959, 1968), Coetzee (1967), Schalke (1973), and Scott (1976, 1982a), were limited by uncertain chronologies, and by the considerably rich and varied flora of the region, for which no pollen collections existed (Scott, 1989; Van Zinderen Bakker & Coetzee, 1988). In recent years, studies have benefitted from access to increasingly affordable high precision dating facilities, and large pollen, phytolith and diatom collections to facilitate the identification of proxies (Kristen et al., 2007; Meadows, 2014). Despite these advances, and given the geographical and botanical diversity of the region, considerable research gaps still exist and many localities within the region remain under-represented (Kristen et al., 2007; Neumann et al., 2008). This is partly due to the scarcity of sites with uninterrupted, undisturbed sediment profiles that contain sufficient concentrations of fossil proxies to produce robust analyses, and a sparse distribution of caves with well-preserved speleothems (Martin, 1968; Livingstone, 1975; Van Zinderen Bakker & Coetzee, 1988; Kristen et al., 2007; Neumann et al., 2008). Unlike much of Europe, for which numerous palaeoecological studies have been undertaken due to the wealth of palaeoenvironmental archives, much of southern Africa is too arid to support the preservation of microfossils (including pollen and aquatic microfossil proxies such as diatoms, ostracods, and testate amoeba) (Livingstone, 1975; Scott, 1989; Chase & Meadows, 2007; Fitchett et al., 2016). Consequently, research has largely been confined to wetlands in the more humid eastern region of southern Africa, and isolated springs in the interior (Scott, 1989; Neumann et al., 2008; *Figure 1*).

This paper presents a review of southern African palaeoenvironmental reconstructions published to date, critically exploring the spatial gaps in the literature. We identify three key debates around which considerable uncertainty exist: fluctuations in the latitudinal extent of the Westerlies, the correspondence with Northern Hemisphere late Quaternary environmental and climatic events, and the climatic conditions during the Last Glacial Maximum (LGM). This uncertainty is limiting the understanding of the nature of continental southern African environmental responses to global changes in climate. These debates are critically assessed through a spatial lens, from which recommendations for future site selection are made to facilitate research attempting deliberately to resolve these uncertainties. The current array of palaeoenvironmental proxies utilised in southern African late Quaternary science is critically assessed, with recommendations for their further use to more accurately resolve the aforementioned debates. This review then details future prospects in southern African palaeoenvironmental science, including the applications of this research in climate model validation, ecosystem management, ~~and~~ understanding fire dynamics, and reconstructing anthropogenic influence on the natural environment.

## KEY DEBATES ON SOUTHERN AFRICAN LATE QUATERNARY PALAEOENVIRONMENTAL CHANGE

### Extent of the winter rainfall zone

Three climatic zones characterise the southern region of southern Africa: the winter rainfall zone (WRZ) confined to the southwestern Cape, the year-round rainfall zone (YRZ) spanning much of the southern coast of South Africa, and the summer rainfall zone which comprises the interior of South Africa, and Lesotho, Swaziland and the northern bordering countries (Engelbrecht et al., 2015; see Chase & Meadows, 2007 for a map of spatial rainfall seasonality distribution). For the southern region of southern Africa, including southern Namibia, South Africa, Swaziland and Lesotho, the most important synoptic scale changes that have likely occurred during the late Quaternary are shifts in the position and strength of the westerly belt, with resultant influences on the position of the WRZ and associated spatial changes in biomes (Barrable et al., 1998; Chase & Meadows, 2007; Stager et al., 2012; Bamford et al., 2016; Stowe & Sealy, 2016; Fitchett & Bamford, 2017). The WRZ is an important geographical region as one of few Southern Hemisphere examples of Mediterranean-type climates (Barrable et al., 1998). The region is characterised by high floristic diversity, and is the endemic habitat of the majority of the Fynbos group of species, a biome constrained by the position of the regular intrusion of mid-latitude cyclones in winter, and drier summer conditions (Barrable et al., 1998; Chase & Meadows, 2007; Quick et al., 2015, 2016). The WRZ is thus climatically and ecologically distinct from the SRZ (Stager et al., 2013), but is arguably distinct also from the YRZ, despite similarities in vegetation (Van Zinderen Bakker, 1976; Barrable et al., 1998; Carr et al., 2006; Chase & Meadows, 2007; Engelbrecht et al., 2015; Quick et al., 2015). It is argued that during glacial periods, the reduced energy budget of the planet and associated ~~increase~~ equator-ward expansions in Antarctic sea ice would have resulted in a contraction of the tropical belt, ~~northward~~ and equator-ward shifts in the Westerlies and an associated expansion of the southern African WRZ (Van Zinderen Bakker, 1976; Cockroft et al., 1987; Chase & Meadows, 2007). There is concern that should the Westerlies retreat pole-wards under contemporary climate change, a greater incidence of drought in the WRZ may occur (Christensen et al., 2007; Engelbrecht et al., 2009; Stager et al., 2012). It is difficult to obtain direct or reliable information on the seasonality of past rainfall for a particular region from climate proxies, which instead reflect broader fluctuations in total annual precipitation (Chase et al., 2015a). There is thus on-going debate concerning the nature and extent of such geographic shifts in the position of Westerlies (Chase & Meadows, 2007; Fitchett & Bamford, 2017).

Late Quaternary shifts in the latitudinal position of the westerlies have been of palaeoenvironmental interest for many decades, initiated by the work of Van Zinderen Bakker (1976) and Cockroft et al. (1987). Van

Zinderen Bakker (1976) originally suggested an expansion of Mediterranean Cape flora and the associated WRZ as far north as ~24°S, encompassing Namibia and the Free State during the LGM. This was later revisited, and Van Zinderen Bakker (1983) conceded that whilst considerably stronger Westerlies occurred during the LGM, the westerly belt and associated vegetation probably did not extend as far north as originally proposed. More recently, studies within the southern Cape region have led to some consensus that the strength of the westerly belt and the resultant WRZ expanded in both northerly (Barrable et al., 1998; Chase & Meadows, 2007; Stager et al., 2012) and easterly (Carr et al., 2006; Chase & Meadows, 2007) directions, although the geographic limits of these shifts remain uncertain. Changes in the extent of the westerly belt also influence the frequency and intensity of mid-latitude cyclones which move into the interior regions of South Africa. Pollen, diatom and phytolith records from Braamhoek Wetland (*Figure 1*), located north of the WRZ in the Free State Province of South Africa, provide evidence for a greater influence of mid-latitude cyclones, associated with a northward shift of the westerly belt towards the South African interior during the terminal Pleistocene (Norstöm et al., 2009, 2014; Finné et al., 2010). This is in agreement with palaeogeomorphological evidence for eastern Lesotho, indicating an increased intensity of mid-latitude cyclones reaching the Lesotho highlands during the late Pleistocene (Mills et al., 2012). Recently, palaeoenvironmental work involving changes in synoptic patterns throughout the late Quaternary has involved exploring the role of shifts in the Inter-Tropical Convergence Zone (ITCZ) on the SRZ, based on diatom records at Lake Sibaya (*Figure 1*; Stager et al., 2013), and from the Wonderkrater (*Figure 1*) pollen record (Truc et al., 2013). The importance of easterly wave strength over northwestern South Africa and Namibia~~, and associated ocean upwelling during drought periods,~~ has also been explored for the WRZ, based on pollen, microcharcoal and stable carbon and nitrogen isotope records extracted from a hyrax midden at Swartruggens Mountains in the Cederberg of the Western Cape (Chase et al., 2015a). The results demonstrate that Holocene fluctuations in the easterly waves are associated with variability in summer rainfall (Chase et al., 2015a). Debates on changes in the strength of synoptic features are important to climate modellers, and many of the specifics remain unresolved for southern Africa, and indeed much of the Southern Hemisphere (Fletcher & Moreno, 2012). While recent efforts to resolve these issues have involved the meta analysis of 13 pollen sequences spanning the SRZ (Chevalier & Chase, 2015), the spatial distribution of records remains sparse for objective assessments attempting to determine seasonality shifts (Figure 2). Climate model developments~~s~~ would thus benefit from the continued collection of high temporal-resolution palaeo-records across transects covering the WRZ, YRZ and SRZ (Chase and Meadows 2007).

The distribution of sites for which palaeoenvironmental evidence of shifts in the latitudinal extent of the Westerlies have been derived is largely clustered in the southwestern Cape and the central eastern region of South Africa, with scattered records in northern South Africa and on the west coast of Namibia (*Figure 2*). Sites from which reanalyses of original data have been performed and provide evidence of shifts in the Westerlies are more evenly distributed across South Africa (*Figure 2*). The combination of these records provides a relatively well distributed transect of sites from the winter rainfall zone in the southwestern tip of the country, to the summer rainfall zone in the northern region. This southwest to north east transect however is currently too spatially coarse for the detection of smaller amplitude fluctuations in the extent of the Westerlies, which are likely to have occurred during the Holocene. For such a transect to be strengthened, a greater number of sites throughout the Western Cape and Free State Provinces of South Africa would be necessary so as to improve the spatial resolution of reconstructions of the Westerly belt influence throughout the late Quaternary. Moreover, as much of the initial debate concerning the extent of the Westerlies involved their transgression into Namibia (Van Zinderen Bakker, 1976,1983), a greater distribution of sites in both inland and coastal Namibia would be ideal.

## Comparing Late Quaternary Climate Shifts in the Northern and Southern Hemispheres

There is ongoing debate concerning the extent to which Northern Hemisphere climate events have contemporaneous Southern Hemisphere equivalents (Holmgren et al., 2003; Scott et al., 2012; Truc et al., 2013). Improvements in high resolution dating provide the capacity to resolve such uncertainties, but raise further discussion surrounding regional variations in the strength of inter-hemispheric similarities within southern African climatic histories (Tyson & Lindesay, 1992; Holmgren et al., 2003). Climate events which have been verified for the Northern Hemisphere, but which remain unconfirmed for southern Africa, include the African Humid Period (Burrough & Thomas, 2013) – a few-thousand year interval of particularly high moisture levels -, and short-lived cold ~~relapses~~ periods ~~-~~including the Younger Dryas (Peteet, 1995; Thackeray & Scott, 2006; Loftus et al., 2015), the '8.2 kyr' event (Smith et al., 2002; Fitchett et al., 2016), and the Little Ice Age (LIA) (Tyson et al., 2000). There is no conclusive published evidence for distinct, temporally synchronous '4.1 kyr' or '2.8 kyr' cold events (Mayewski et al., 2004; Wanner et al., 2015) in southern Africa. Unresolved questions include whether such events occurred in southern Africa, the timing of these events, with the potential for a lag effect having occurred, and the specific environmental conditions which may have been associated with them.

The most notable debate has focussed on the existence of a Younger Dryas cool period interrupting the warming period following the LGM, from 13,000-11,500 cal. yr BP (Abell & Plug, 2000). Analysing pollen records from a range of sites within the interior of South Africa, Scott et al. (1995) reported that should the Younger Dryas event have occurred in southern Africa, the effects are likely to have been too minimal to induce any notable vegetation changes, and has thus not been reflected in the pollen record. However, records for a Younger Dryas cold event are identified in: a) oxygen isotope and aragonite-calcite ratios from molluscs at Elands Bay, indicating colder sea temperatures (Cohen et al., 1992); b) dinoflagellate cysts from the Cunene River Mouth indicating depressed sea surface temperatures (Dupont et al., 2004); c) oxygen isotopes from giant land snails at Bushmans' Rock Shelter indicating colder air temperatures (Abell & Plug, 2000); d) stable carbon and nitrogen isotopes and pollen from hyrax middens from the Cederberg similarly indicating lower temperatures for the WRZ (Quick et al., 2011) and e) stable isotopes from organic matter and tooth enamel in archaeological material from Sehonghong in eastern Lesotho (Loftus et al., 2015). Notably, both Dupont et al. (2004) and Quick et al. (2011) remarked on distinct isotope signals for a Younger Dryas event, but ~~no~~ the pollen ~~signal~~ from the same sample in both instances reflected no anomalies, suggesting that vegetation may have remained relatively stable throughout this period. While speleothems hold the potential for higher resolution climate reconstructions, stalagmites analysed from Cold Air Cave (*Figure 1*) had a depositional hiatus covering this period, although it was argued that this might reflect drier conditions associated with the event (Holmgren et al., 2003). A re-evaluation of the Wonderkrater pollen record (Thackeray, 1994; Thackeray and Scott, 2006) found three samples close in age to the Northern Hemisphere Younger Dryas, during which a cold reversal was notable (Truc et al., 2013). Multivariate analysis on this re-analysed pollen record quantified the temperature incursion to 6 ±2°C (Truc et al., 2013). More recently, a Younger Dryas signal suggesting associated wet conditions has been identified in the Sudwala Cave (*Figure 1*) speleothem isotope record (Green et al., 2015). In contrast, a multi-proxy analysis of a sediment core from Braamhoek Wetland, ~450km southwest of the Sudwala caves, indicates a Younger Dryas cold period paired with dry conditions (Norström et al., 2014). Thus, increasing evidence supports the existence of a Younger

Dryas event in southern Africa, but the climatic conditions during this event remain uncertain. The event is likely to have been regionally varied, ~~so~~ and therefore requires better temporally and spatially resolved studies to better capture such variations (Chase et al., 2011). The spatial distribution of sites for which proxy evidence indicates a Younger Dryas cooling period is sufficiently diverse across southern Africa (*Figure 3*) to suggest that such a cooling period did occur and was regional in nature. However, the absence of evidence from sites along the warm, moist east coast of southern Africa is notable. While this may be due to a coincidental absence of samples for this time period at each of the east coast sites (*Figure 1*), it may reflect a more interesting microclimatic effect whereby global scale cooling is obscured by persistent local warming driven by the warm ~~Indian Ocean~~Agulhas current. Deliberate investigation of samples from these sites for evidence of Younger Dryas cooling would thus be of particular value.

The subsequent cold conditions associated with the 8.2kyr event (driven by a meltwater pulse in the northern Atlantic (Wanner et al., 2015)) have been detected in fewer southern African records. To date, much of the evidence for this event stems from Lesotho, with isotope records from archaeological material in western Lesotho (Smith et al., 2002) demonstrating a cool period between 8,400-8,000 cal. yr BP. Cool conditions during this period have also been reconstructed from hyrax middens in the Cederberg (Chase et al., 2015b). Due to the paucity of sites for which 8.2kyr cooling has been detected (*Figure 3*), it is not yet clear whether these records indicate a teleconnection of the cold conditions in the northern Hemisphere or an independent ~~microclimatic~~ regional cooling event. Perhaps this cool period is apparent in so few records due to the short-lived nature of the event and the relatively poor temporal resolution of many southern African palaeoclimate chronologies. Both the 8.2 kyr event and the Younger Dryas cooling are detected for Lesotho (*Figure 3*), where the higher altitude induces comparatively colder conditions than for much of southern Africa. To further understand the dynamics of this event in southern Africa, deliberate efforts to detect cool conditions during this period at a broader range of sites are imperative. Deliberate investigation for evidence of these cool events on both the warm, moist east coast and then warm, dry west coast of southern Africa would facilitate an improved understanding of the global teleconnections associated with these cooling events.

A more recently emerging debate concerns the existence of the African Humid Period in southern Africa. This event has been recorded for East Africa, occurring in the early Holocene, within the period ~14,800-5,500 cal.

yr BP (Chase et al., 2009; Burrough & Thomas, 2013). Evidence is presented from hyrax middens in Namibia, suggesting the existence of an early Holocene moist period, from which it was inferred that the African Humid Period extended at least as far south as 23° in Namibia (Chase et al., 2009). The extensive aridity in the Kalahari during this period poses contradictory evidence (Huntsman-Mapila et al., 2006; Nash et al., 2006), and whilst lake high-stands for Makgadikgadi) in central Botswana are dated to this period, arguably fed by a water supply from distant northerly sources (Burrough & Thomas, 2013). Further evidence for the African Humid Period in southern Africa has been reported from stable nitrogen isotope data from hyrax middens at Austerlitz in northwestern Namibia (Chase et al., 2010). Although not referred to specifically as the African Humid Period, and with varying time periods throughout the early Holocene, reference has been made to humid periods following the postglacial warming, with evidence from peat development throughout southern Africa (Meadows, 1988), the Caledon River charcoals (Esterhuysen & Mitchell, 1996; Esterhuysen et al., 1999), and pollen across the South African interior (Van Zinderen Bakker & Coetzee, 1988; Scott, 1993; Lewis, 2005). This evidence is of interest, as all other reports of African Humid Period conditions are from the northern region of southern Africa (*Figure 3*). Comparative humidity, and the delineation of a distinct humid period is difficult, particularly for a region separated by summer and winter rainfall conditions, and with a distinct east-west decline in precipitation (Chase & Meadows, 2007). Deliberate exploration for evidence of African Humid Period conditions in proxy records from sites across southern Africa may provide valuable information on the southerly extent of this event. In particular, reanalysis of palaeoenvironmental data from the WRZ and YRZ would confirm the southerly extent of the influence of this climatic event, while subsequent transects spanning the known north-south and east-west manifestations of this event would enable the extent of influence to be quantified.

Where evidence for periods of abrupt climatic variability have not yet been well constrained for the mid—to late-Holocene and Pleistocene, there exists considerable evidence for the LIA cold period (AD ~1300-1800) (cf. Talma et al., 1974; Herbert, 1987; Talma & Vogel, 1992; Tyson & Lindesay, 1992; Brook et al., 1999; Holmgren et al., 2003; Sundqvist et al., 2013; Zinke et al., 2014) in southern Africa. The majority of evidence for the LIA is based on stable isotopes from high temporal resolution speleothems (cf. Talma & Vogel, 1992; Brook et al., 1999; Holmgren et al., 1999, 2001, 2003; Repinski et al., 1999; Tyson et al., 2000; Lee-Thorp et al., 2001; Sundqvist et al., 2013). While the existence of a LIA event has been confirmed across much of the region, the associated climatic conditions remain unclear. Evidence suggests that broadly dry conditions occurred during the Little Ice Age in the SRZ (Lee-Thorpe et al., 2001; Holmgren et al., 1999; Gillson & Ekblom, 2009; Neumann et al., 2010; Ekblom et al., 2012) and wet conditions in the WRZ (Stager et al., 2012; Weldeab et al., 2013), thus supporting Tyson and Lindesay's (1992) original hypothesis. Suggestions of a 1°C negative temperature ~~departure~~ anomaly during the Little Ice Age and 3°C positive ~~departure~~ anomaly during the preceding Medieval Warm Period (Tyson et al., 2000) remain unconfirmed against evidence of more severe cooling, as this event reflects the most pronounced $\delta^{18}O$ deviation within the 25,000 yr Cold Air Cave record (Holmgren et al., 2003). An increasing number of scientific outputs detailing high resolution palaeoenvironmental reconstructions for relatively short periods spanning a few hundred to ~1,000 years (cf. Brook et al., 1999; Holmgren et al., 2009; Gillson & Ekblom, 2009; Walther & Neumann, 2011; Ekblom et al., 2012) provides considerable potential for the identification of climatic anomalies coincident with the LIA and Medieval Warm Period. Moreover, such studies facilitate an improved reconstruction of the relative temperature changes and associated precipitation dynamics associated which these events, to corroborate the modelled spatial variability (Barrable et al, 1998).

## The Last Glacial Maximum: Temperatures, Moisture and Glaciation

The pronounced Last Glacial Maximum in the Northern Hemisphere is also a major climate event in southern Africa, for which there is much palaeoenvironmental evidence (Chase & Meadows, 2007). However, debates persist on the exact timing and duration of the LGM in southern Africa, especially the timing of the coldest conditions, moisture distribution, and evidence for glaciation at high altitude locations during this period.

Studies have defined the LGM as centred around 21,000-18,000 cal. yr BP (Meadows & Linder, 1993; Meadows & Sugden, 1993; Partridge et al., 1997), or broadly in the range of 21,000-17,000 cal. yr BP (Partridge et al., 1999). The reported timing is also inconsistent between studies, including 20,000-16,000 cal. yr BP (Deacon & Lancaster, 1988) and 21,000-17,000 cal. yr BP (Partridge et al., 1993). Chase and Meadows (2007) suggest that for ease of comparison, both within southern African records, and in comparison with records from elsewhere, the 'Land, Oceans, Glaciers Programme' (EPILOG) definition be used, which conservatively places the LGM within the range of 24,000-18,000 cal. yr BP (Chase & Meadows, 2007). The timing of the coldest period during the LGM also remains unresolved, but pollen from Elim in the Free State (Scott, 1999) and speleothem isotope records from Cold Air Cave (Holmgren et al., 2003) indicate coldest conditions between ~18,000-17,000 cal. yr BP. A statistical re-analysis of 27 pollen records spanning the Namib Desert, Namaqualand, Western Cape Fynbos, east coast woodland, Karoo grassland, upland grassland, dry woodland, and sub-humid woodland ecozones in southern Africa suggests that there may have been two distinct cold periods during the LGM; at ~24,000 cal. yr BP and ~17,000 cal. yr BP (Scott et al., 2012). Given that dates for the LGM in southern Africa span such a long period, it remains uncertain whether this event is contemporaneous with the Northern Hemisphere LGM, or whether some lag period exists.

Many southern African palaeoenvironmental studies report cooler temperatures during the LGM, but are unable to quantify, or do not report, the temperature depression relative to contemporary conditions (cf. Scott, 1982a; Shi et al., 1998; Scott & Vogel, 2000; Neumann et al., 2014; Norström et al., 2014). One of the earliest studies quantifying LGM temperature depressions is based on the Wonderkrater pollen record, with results suggesting a 5-6°C departure from present for the Highveld interior (Scott, 1982a). A review and synthetic reconstruction of climatic conditions during the LGM (Partridge, 1999) similarly suggests an overall temperature decrease of 5°C throughout the LGM in southern Africa between latitudes of 24°-33°S. This collated reconstruction was based primarily on records from Talma & Vogel (1992) for a 6°C departure, Heaton et al. (1986) for a 5.2°C departure, and Stute & Talma (1997) for a 5.3°C departure. A much greater LGM temperature departure of 7-8°C is suggested based on palaeogeomorphological evidence from high altitude sites in the Western Cape Mountains (Boelhouwers & Meiklejohn, 2002). The suggestion of an even more extreme temperature depression of 10°C is based on possible glacial moraines in the Eastern Cape Drakensberg (Lewis & Illinger, 2001). More accurately resolved isotope analysis from the Cold Air Cave speleothem suggests a temperature increase of 5.7°C from the terminal Pleistocene to Holocene (Holmgren et al., 2003). A more recent statistical reanalysis of the improved pollen records for Wonderkrater (Thackeray & Scott, 2007) confirms such lower estimates, reporting a temperature depression of 6 ±2°C during the LGM. The extremely cold LGM temperatures implied from the palaeogeomorphological evidence may be due to misconceptions on moisture levels during the LGM, highlighting the importance of understanding both temperature and precipitation changes (Mills et al., 2012).

If the temperature during the LGM was to have been ~6°C cooler, wetter conditions would need to have occurred in the eastern Lesotho Highlands to have produced the glacial features observed on south-facing slopes, which is attributed to a shift in the Westerlies (Rojas et al., 2009; Mills et al., 2012). The broad understanding of moisture conditions during the LGM, however, was of drier conditions in the SRZ but wetter in the WRZ (Partridge, 1999). The dry LGM in the SRZ is supported by records spanning much of South Africa (*Figure 4*) including Mfabeni Peatlands in Kwa-Zulu-Natal (Finch & Hill, 2008; Baker et al., 2014), Tswaing Crater in the interior (Metcalfe, 1993; Partridge et al., 1993), together with numerous other inland sites including Wonderkrater, Rietvlei, Tate Vondo, Elim, Equus Cave, Boomplaas ( Scott 1989), and Braamhoek Wetland (Norström et al., 2009). Offshore pollen records obtained from the Cunene River Mouth suggest that southwestern Africa was also dry during the LGM (Shi et al., 1998). Records from the southern region of the country, originally argued to be homogenously wetter during the LGM, highlight local variations in moisture levels during this period (Barrable et al., 1998; Chase & Meadows, 2007; Stowe & Sealy, 2016). The first distinction is between the YRZ and WRZ, which were previously considered to have experienced similar climatic changes throughout much of the late Quaternary, but for which it has been found that conditions during the LGM were drier in the YRZ but wetter in the WRZ (*Figure 4*; Carr et al. 2006; Chase & Meadows, 2007; Stowe & Sealy, 2016). Further variation exists within the WRZ, with models integrating palaeoenvironmental proxy data indicating that the western coastal zone was cool and moist, whilst the southern region was colder and drier (Barrable et al. 1998; Thackeray & Fitchett, 2016). Considerable temporal variations during the LGM may have existed, as the Cederberg isotope records suggest a dry late LGM period (Chase et al. 2011). Proxy evidence for moisture conditions during the LGM from a greater number of sites spanning the transition between the WRZ and SRZ would facilitate the determination of spatial limits to the region previously characterised by wet conditions. An increased network of sites and an improved understanding of the moisture conditions during the LGM would also contribute towards the goals of better classifying the synoptic drivers of environmental changes during the late Quaternary such as shifts in the Westerlies.

Given the considerable temperature depression of at least 5°C during the LGM in southern Africa, questions of possible alpine glaciation have been the subject of much debate (cf. Sparrow, 1967; Harper, 1969, Marker & Whittington, 1971; Marker, 1991; Grab, 1996a,b, 1999, 2000, 2002a,b; Grab & Hall, 1996; Boelhouwers &

Meiklejohn, 2002; Sumner, 2004; Mills et al., 2009a). Glacial moraines been positively identified on the basis of diagnostic micro- and macro-sedimentological characteristics in eastern Lesotho; their age determinations confirm origination during the LGM (Mills et al., 2009a,b, 2012). Such glaciation was, however, spatially constrained to a few isolated high altitude south-facing sites (Mills et al., 2009a,b, 2012). More widespread glaciation in eastern Lesotho and elsewhere in southern Africa during the LGM was most unlikely (Boelhouwers & Meiklejohn, 2002; Mills et al, 2009b). An improved constraint of the temperatures during the LGM has facilitated more accurate reconstruction of moisture conditions during this period, which suggest a northward shift in the Westerlies and an associated increase in moisture (Mills et al., 2012

A study from off-shore Namibia reports increases in wind flux during the LGM (Shi et al., 1998), but little further information on the climate dynamics for this period exists. Future work to improve reconstructions for the LGM includes refining the chronology of the LGM event, and better constraining the associated climatic fluctuations during the period (Chase & Meadows, 2007; Chase et al., 2011). Research to quantify the climatic conditions during the LGM relative to the contemporary state, and to understand the regional variations in LGM climates and their drivers, also warrants attention (Barrable et al., 1998).

## FUTURE PROSPECTS OF QUATERNARY SCIENCE IN SOUTHERN AFRICA: THE IMPORTANCE OF APPLICATION

Southern African regional palaeoenvironmental reconstructions remain relatively limited in quantity, and are spatially clustered in the more moist areas and those with alternative archive such as hyrax middens and speleothems. Consequently, large regions of the subcontinent are currently omitted, owing to numerous factors including the comparatively late inception of the discipline in the region, difficulties in obtaining suitable archives in arid regions, and limitations in skills and expertise (Neumann et al., 2008; Meadows, 2014). The uneven distribution of study sites, and the resultant omission of key bioregions (Neumann & Bamford, 2015), requires a deliberate strategic approach in planning forthcoming palaeoenvironmental research. Increasingly, it has been suggested that the delineation of transects across southern Africa spanning these biogeographical regions would be a valuable approach to rapidly obtain sufficient data to clarify many of these debates (Chase & Meadows, 2007). This requires the identification of key bioregions, the establishment of existing palaeoenvironmental reconstructions within these transects, and the determination of the most promising study sites in the excluded regions (Meadows, 2015; Neumann & Bamford, 2015). These sites are arguably those for which evidence to resolve key debates presently is absent, but where an improved spatial or temporal resolution could facilitate a direct comparison of environmental or climatic conditions for the time period in question, as have been outlined for each of the key debates.

Adapted from Scott et al. (2012, p. 101), limitations in southern African palaeoenvironmental research can be summarised as: 1) a scarcity of appropriate sites with well preserved, representative proxies; 2) the use of poor dating techniques, and/or low temporal resolution; 3) sub-regional ecological differences, many of which are unaccounted for in the palaeoenvironmental literature; 4) varied levels of, and often inadequate, taxonomic resolution in fossil identification; 5) non-uniform methods of presentation of palaeoenvironmental evidence; and 6) non-uniform methods for the interpretation of proxy-based results. The future of late Quaternary research in southern Africa necessarily needs to address these challenges in a holistic manner (Scott et al., 2012; Meadows, 2014). There has, however, been a shift in academic focus since the inception of palaeoenvironmental work in the 1960s, with climate change ~~interpretations~~ reconstructions increasingly ~~taking greatest importance~~dominating the discipline, replacing earlier debates regarding proxy preparation methods, the publication of fossil flora, and descriptive works on the environmental landscapes (Meadows, 2007). Much of the immediate future of palaeoenvironmental work thus arguably involves the application of an understanding of palaeoenvironments to contemporary management, including ~~global climate modelling,~~ ecological monitoring through determining critical thresholds, a grasp on the role of fire, and the attribution of human influence to environmental changes (Willis et al., 2005; Meadows, 2012; Seddon et al., 2014; Gillson, 2015). The potential to address these challenges and to improve the capacity for the application of palaeoenvironmental research is improved through the adoption of multi-proxy approaches, and this relies on the successful analysis of a range of proxies (Meadows, 2012; Fitchett et al., 2016).

## Southern African Palaeoenvironmental Proxies

Despite the rapid development of palaeoenvironmental science in southern Africa over recent decades, pollen remains the most commonly used proxy for late Quaternary palaeoenvironmental reconstructions in the region (*Figure 5*; Chase & Meadows, 2007; Scott et al., 2012). Increasing use of isotopes, geochemistry and diatoms is apparent during recent decades (*Figure 5*). In particular, since the early 1990s, there has been a predominant use of speleothems as a palaeoenvironmental archive, from which high resolution isotope analysis is possible, supported by temporally well constrained chronologies (cf. Holmgren et al., 1995, 1999, 2001, 2003; Brook et al., 1999; Repinski et al., 1999; Finch et al., 2001; Lee-Thorp et al., 2001; Sundqvist et al., 2013; Green et al., 2015). Isotopes are also increasingly used from a range of archives including sediment cores, hyrax middens, and shells and bones at archaeological sites (Cohen et al., 1992; Cohen & Tyson, 1995; Johnson et al., 1997; Abell & Plug, 2000; Chase et al., 2012; Weldeab et al., 2013; Meadows, 2014). The increasing diversity of palaeoenvironmental proxies being used across published work and at particular field sites, highlights the benefits that the region has been afforded by enhanced funding allocation and international collaboration (Chase & Meadows, 2007; Meadows, 2007; Fitchett et al., 2016). This enables a wider range of palaeoenvironmental variables, tipping points, and stressors to be analysed, and facilitates multi-proxy work (Meadows, 2014). The few studies which have utilised foraminifera (Strachan et al., 2014, 2015, 2016), phytoliths (Rossouw et al., 2009; Burrough et al., 2012; Backwell et al., 2014), dinoflagellate cysts (Dupont et al., 2004) and biomarkers (Norström et al., 2014; Carr et al., 2015), would suggest that there is a greater wealth of suitable palaeoenvironmental proxies available in southern Africa than has typically been applied to Quaternary science in the region. Important to the improved use of multiple proxies is a robust understanding of the limitations of the proxy and its archive (Meadows, 2014). Recent analysis of the variability of the distribution of pollen within offshore marine sediments from the west coast of South Africa highlight the importance in understanding the provenance of the proxy material sampled (Zhao et al., 2016)

**Application in Climate Modelling**

A valuable application of southern African palaeoenvironmental data is to validate climate models. The first southern African climate model to include both surface and upper air dynamics for the contemporary climate was compared with, albeit sparse, palaeoclimatic reconstructions for the region (Cockroft et al., 1987). From the correlation between model simulations and palaeoclimatic evidence, support was provided for the conceptual palaeoclimatic model proposed by Tyson (1986). At a smaller geographical scale, and with a greater volume of palaeoclimatic work for comparison, Barrable et al. (1998) evaluated the palaeoclimatic evidence for the southern African WRZ against climate model simulations, and confirmed a difference in moisture conditions within the WRZ during the LGM. It was argued that such correlations between models and proxy data have the potential to improve both methods, as proxy data can validate the climate model output and provide further data to improve the reliability of projections, whilst the model data can improve explanations of the synoptic drivers of palaeoclimatic changes, and indicate locations for which palaeoclimatic studies would be of particular value to establish past regional climate patterns (Barrable et al., 1998). Despite the value of such work, and the use of palaeoclimatic data to validate the IPCC climate models (Meadows, 2012, 2014), detailed work in southern Africa is yet to happen. Deliberate efforts to integrate the existing palaeoenvironmental reconstructions into climate models would both strengthen the predictive capacity of the models, and would facilitate the identification for key sites for palaeoenvironmental science required to address modelling shortfalls.

### Applications in Conservation Management Decisions

A further important application of palaeoenvironmental work is to improve our understanding of ecosystem functions by exploring the dynamics of their changes over variable and long time-periods, although the adoption of palaeoenvironmental evidence by ecologists has arguably been overdue (Willis et al., 2005; Meadows, 2012; Seddon et al., 2014; Fitchett et al., 2017). The value of understanding the long-term history of ecological systems is most apparent with regard to the management of grasslands, as decisions inherently require the nature of grassland development to be understood, because anthropogenic development through deforestation would have significantly different implications to the existence of grasslands in the region prior to permanent human occupation (Meadows & Linder, 1993; Scott, 2002; Gillson, 2015). Management decisions which relied on the assumption that grasslands were anthropogenically initiated, have been critiqued by palaeoenvironmental evidence from pollen, phytoliths and stable isotopes of southern African grasslands (Scott, 2002), presence of Afromontane grasslands prior to permanent human occupation in southern Africa (Meadows & Linder, 1993), and a progressive shift from $C_4$ dominated grasslands and open savannah to $C_3$ thicket, forest and densely wooded savannah in KwaZulu-Natal (Gillson, 2015). Studies of the ecological histories in other biomes include an analysis of the palaeoenvironmental history of the Cape Floristic Kingdom (Meadows & Sugden, 1993), ~~and of~~the *Podocarpus* forest history in Maputuland (Finch & Hill, 2008), and the classification of *Chrysocoma ciliata* as an invasive in the Lesotho Highlands (Fitchett et al., 2017). It can further be argued that studies which do not intend to provide purely historical information from palaeoenvironmental proxies, would be of great value to ecologists for determining historical vegetation communities, and drivers causing their spatial shifts (Willis et al. 2005; Meadows, 2012; Fitchett et al., 2017).

Of increasing interest within the grassland history of southern Africa is the role of fire, and the relationships between fire intensity and vegetation composition (Duffin, 2008; Ekblom & Gillson, 2010). An empirical relationship between charcoal deposits in surface sediment samples from Kruger National Park (*Figure 1*) and the proximity of fires, area of fires and fire intensity, has been developed (Duffin et al., 2008). This has enabled the comparison of palaeoenvironmental records, which indicate higher fire intensity related to higher percentages of herbaceous cover and lower percentages of woody plant growth (Duffin, 2008). Further work in the Kruger National Park has challenged the assumption that fire suppresses tree seedling growth and hence encourages grasslands. During grassland-dominated periods, the high frequency of fire appears to shift the system to a savannah environment by increasing woody recruitment, while during savanna-dominated periods fire limits woody recruitment and retains the environment in a savanna state (Ekblom & Gillson, 2010). A longer-spanning record covering the mid- to late-Holocene for Graskop and Versailles in Mpumalanga Province, South Africa (*Figure 1*), indicates that fire was rare during the grassland dominated period prior to 4,000 cal. yr BP, but that fire incidence increases from 600 cal. yr BP following a decrease in *Podocarpus* pollen, and spiked in the last 70 years due to human influence (Breman et al., 2011). At the scale of interglacial-glacial cycles, a study of charcoal from a core off the coast of Namibia found six periods of heightened fire incidence over the past 170,000 cal. yr, which coincided with precessional forcing of north-south shifts in the ITCZ and notably occurred during periods with wetter and cooler climates, assumed to be due to changes in rainfall seasonality (Daniau et al., 2012). A more complete understanding of the dynamics between vegetation and fire throughout periods of vegetation change enables improved ecosystem fire management, and these developments in palaeoecological fire studies provide an example illustrating the value of palaeoenvironmental work to ecologists (Ekblom & Gillson, 2010).

## Determining Anthropogenic Influence

The third application of palaeoenvironmental work to contemporary management is in determining the influence of prolonged anthropogenic settlement on the natural environment (Baxter & Meadows, 1999; Seddon et al., 2014). This has been facilitated through improvements in sampling resolution and dating accuracy to capture high resolution environmental changes over the past few centuries (Baxter & Meadows, 1999; Neumann et al., 2008; Reinwarth et al., 2013; Neumann et al., 2014). This is particularly important in regions with a high level of human occupation, as progressively the anthropogenic effect on vegetation changes has exceeded those of climate shifts (Neumann et al., 2011; Seddon et al., 2014), which has an influence on the success of management decisions (Gillson, 2015). The relative anthropogenic and climatic influences on shifts from afromontane forest to grassland in the Western Cape, was inferred on the basis of species richness from fossil pollen in the Winterberg escarpment region near Cape Town, which demonstrated that climatic shifts remained the most dominant drivers even during the late Holocene (Meadows & Linder, 1993). By contrast, considerable human influence is noted in regions which experienced sudden shifts to agricultural land-use (Meadows et al., 1996; Neumann et al., 2008). Pollen records demonstrated a sudden, marked appearance of cereals at Verlorenvlei (Meadows et al., 1996; Baxter & Meadows, 1999), the adjacent Klaarfontein Springs (*Figure 1*; Meadows & Baxter, 2001), Lake Sibaya (*Figure 1*; Neumann et al., 2008), and in present-day Kruger National Park (Gillson & Ekblom, 2009), all dating to the 19th and 20th centuries. Further evidence of anthropogenic impacts includes the increased occurrence of algae, which are synchronous with the introduction of cereal pollen at Lake Sibaya (Neumann et al., 2008); the appearance of pine pollen during the 19th century in the core from Mahwaqa Mountain (*Figure 1*), indicating the introduction of alien plants to the region;(Neumann et al., 2014), and an increase in sediment and nutrient deposition in Eilandvlei (*Figure 1*) from the 19th century onwards, a possible consequence of agriculture and associated soil erosion (Reinwarth et al., 2013). By quantifying anthropogenic influence on the environment and the relative effect of climatic shifts over long time periods, more informed management decisions can then be made (Gillson, 2015).

## CONCLUSION

Late Quaternary palaeoenvironmental science, and the reconstruction of late Quaternary climates and environments, has rapidly advanced over the past half century in southern Africa. This has provided a baseline understanding of the rate and cyclicity of past climate changes, and a broad understanding of palaeoclimatic and palaeoenvironmental boundaries across the region. However, this research has arguably unearthed more questions than have been answered. The complex contemporary climate dynamics and biome divisions in southern Africa extend back through the Holocene and Pleistocene, resulting in an intricate relationship between climate, space and time. Debates that remain unresolved include the spatial extent of the WRZ and the role of the westerlies throughout the late Quaternary, the comparability of Northern and Southern Hemisphere palaeoclimatic events, and the climatic conditions of the LGM. To continue to resolve these debates, high resolution palaeoclimatic and palaeoenvironmental reconstructions are required from a larger range of sites covering existing geographical gaps, and a concerted effort to integrate the findings of palaeoclimatic reconstructions into regional and global climate models.. A key limitation has been the difficulties in obtaining archives from the more arid regions of southern Africa, yet recent work on hyrax middens is rapidly addressing this concern. With climatic influences from the ITCZ and the Westerlies, and with forcings from the regional oceans, ~~moisture sources off the cold Atlantic and warm Indian Oceans,~~ southern Africa provides a biogeographically rich backdrop to explore environmental shifts related to both small- and large-amplitude climatic shifts.

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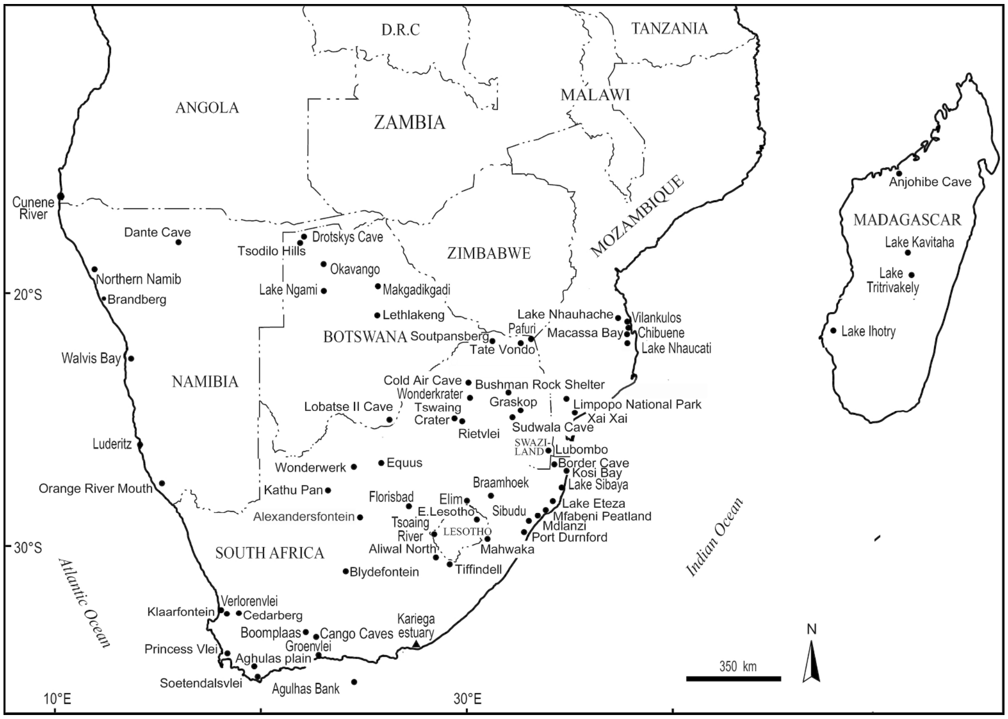

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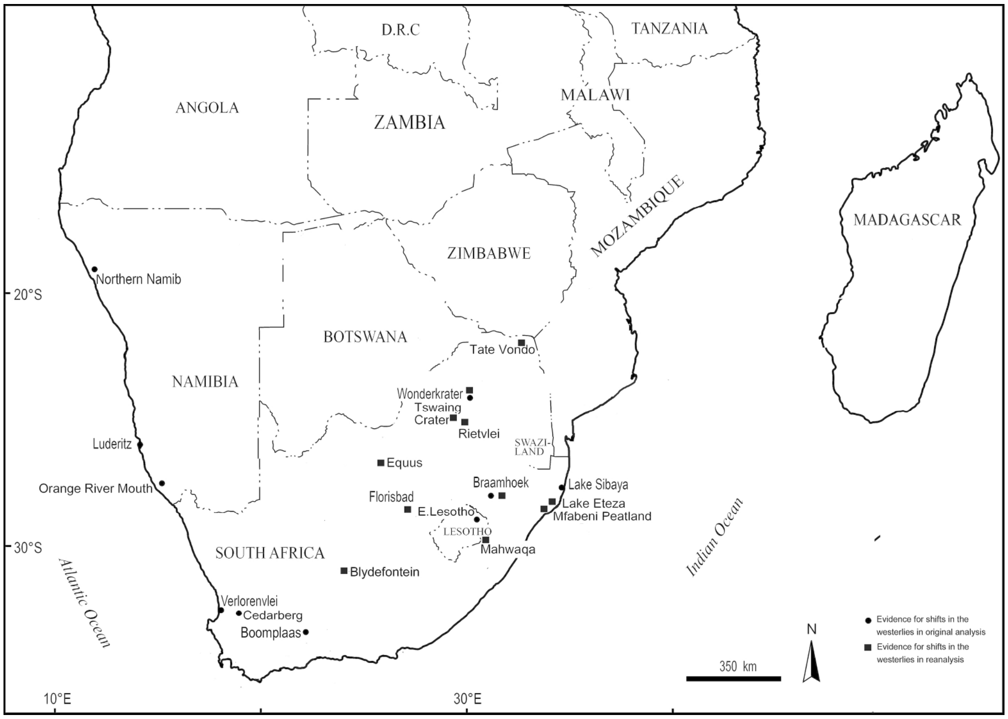

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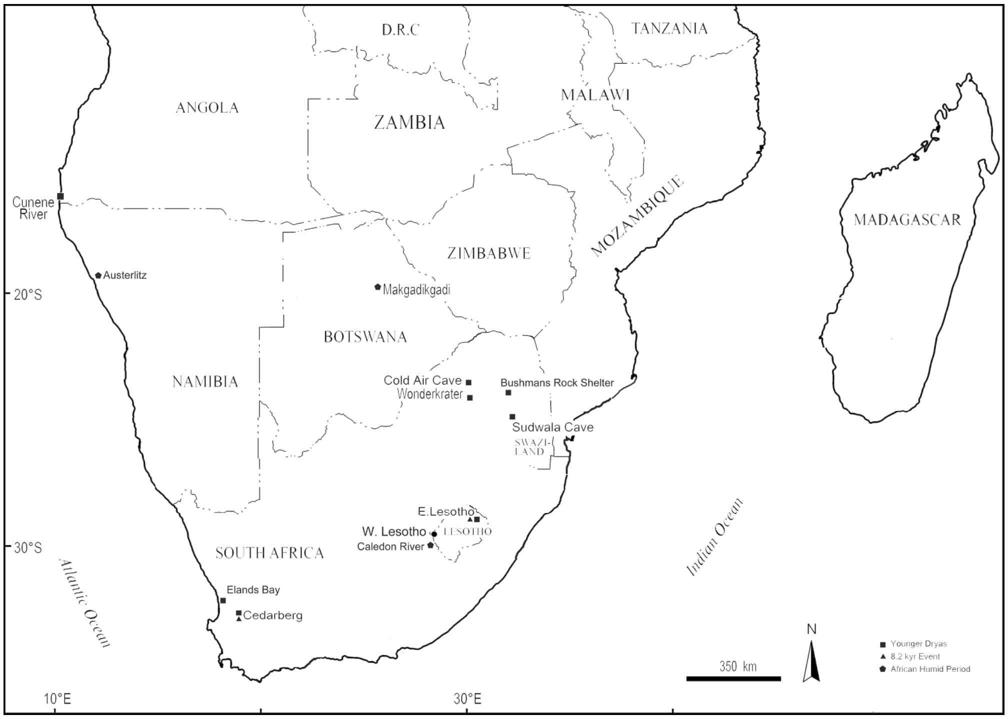

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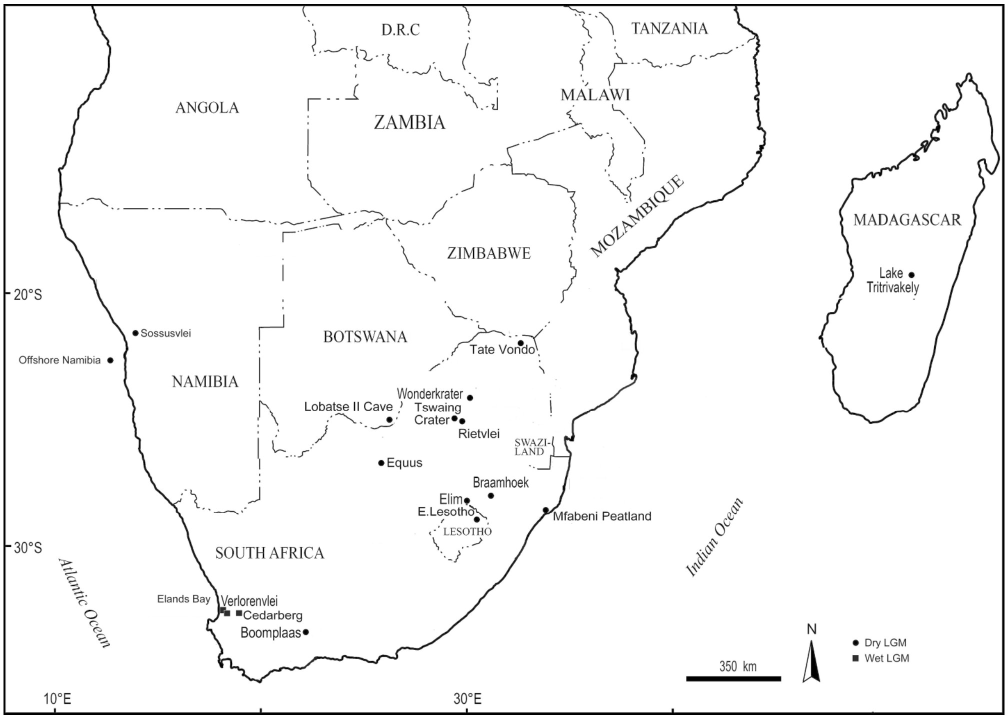

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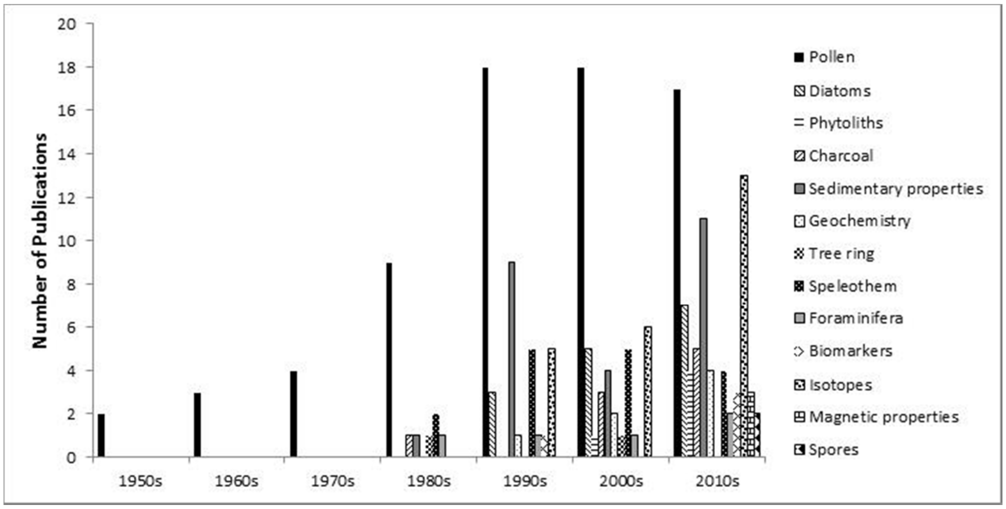

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