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A multi-proxy analysis of late Quaternary Palaeoenvironments, Sekhokong Range, Eastern Lesotho.

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Running Head: Eastern Lesotho late Quaternary Palaeoenvironments

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Abstract

The eastern Lesotho Highlands host an array of periglacial and glacial geomorphic features. Their analysis has provided past climate interpretations predominantly for cold periods, yet no multi-proxy temporally continuous palaeoenvironmental records exist. This study presents a palaeoenvironmental reconstruction based on sedimentary characteristics, fossil pollen and diatoms from an alpine wetland located in the Sekhokong Mountain Range. The record commences in the late Pleistocene with a wet period from ~16,450-14,440 cal a BP, interrupted by dry conditions from ~16,350-15,870 cal a BP. From ~14,150-8,560 cal a BP, drier conditions are inferred, slowly transitioning to warmer, wetter conditions. Warmer, dry conditions are inferred for ~8,560-7,430 cal a BP, followed by cold, wet conditions from ~7,280-6,560 cal a BP. A dry, warmer period occurs from ~6,560-3,640 cal a BP indicated by pollen, diatom and sedimentary records, followed by cool, wet conditions from ~3,400-1,200 cal a BP. The period from ~1,110 cal a BP to present is characterised by progressive drying. Pronounced cold events are detected from the diatom record. Moisture records appear relatively specific to the topographic setting of Sekhokong near the Great Escarpment edge; thus likely driven by orographically constrained synoptic controls.

Keywords: Eastern Lesotho, palaeoenvironments, diatoms, pollen, sediments

Introduction

The Sani Top region of eastern Lesotho has been a focus of research on relict and active periglacial and glacial geomorphic features for many decades (cf. Marker & Whittington, 1971; Marker, 1994; Boelhouwers et al., 2002; Mills et al., 2009; Grab, 2010; Borg, 2012). This includes the north-facing valley-heads of the Sekhokong Range, 3.5km southwest of the Sani Top border post (Figure 1), with initial debates focussing on their slope origins (Marker & Whittington, 1971; Grab & Hall, 1996; Marker, 1994). More recently the site has been the focus of analyses on environmental features responsible for gully development (Grab & Deschamps, 2004). Most notably, the site has been investigated to develop palaeoenvironmental reconstructions based on variable sedimentary properties exposed along relatively deep wetland gullies (Marker, 1994, 1995, 1998). Further research has interpreted conspicuous debris ridges on the south-facing aspect of the Sekhokong Range as small glacial moraines (Mills et al., 2009). While these past studies have provided valuable information on contemporary geo-ecological stresses and some insights to past environments in the region, no biological proxies have yet been investigated in these records, limiting their interpretative capacity and potential for regional corroboration (Grab et al., 2005).

Detailed multi-proxy, temporally continuous palaeoenvironmental studies have been encouraged for eastern Lesotho (Mitchell, 1992; Grab et al., 2005). With precipitation exceeding evaporation, the catchment is hydrologically important, supplying regional water transfer schemes (Zunckel, 2003; Haas et al., 2010). Despite the concerns of climate change to the region, past instrumental meteorological data are sparse and of relatively poor quality (Grab & Nash, 2010). Climate modelling projections for the region, essential for adaptation, therefore rely strongly on high resolution, well corroborated palaeoclimatic reconstructions (Ziervogel & Calder, 2003; Jones et al., 2009).

Better insight to palaeoenvironmental conditions in eastern Lesotho will also contribute to late Quaternary science in the sub-continent. High altitude, relatively high latitude for mountainous regions in the Southern Hemisphere, and frequent cold-season frosts and snowfalls in eastern Lesotho, constrain the flora to only very hardy species (Carbutt & Edwards, 2006; Mokotjomela et al., 2009). Any climatic change can potentially lead to the extirpation of certain plant groups, as particularly cold temperatures restrict elevational range shifts (Parmesan & Yohe, 2003; Carbutt & Edwards, 2006; Inouye, 2008). Botanical responses to smaller climatic shifts are therefore more likely to be detected at high altitudes than in adjacent down-slope locations.

This study presents a multi-proxy palaeoenvironmental reconstruction from sediment exposed along a 5m deep gully face on the north-facing slope of the Sekhokong Range. The study utilises pollen, diatoms and sediment as palaeoenvironmental and palaeoclimatic proxies, constrained by a radiocarbon chronology.

Study Site

The Sekhokong Mountain Range is located in eastern Lesotho, south of the Sani Top border post at an altitude of 2,920 m asl and with co-ordinates 29°36.517'S, 29°15.897'E. The north-facing slope of the Sekhokong Range has at least four valley heads eroded into it, separated by basaltic ridges located just south of its highest point at Hodgson's Peaks (Marker, 1994). The valley heads are approximately 800m wide and 1200m deep, each with a tributary stream flowing into a wetland at the foot of the slope (Marker & Whittington, 1971; Marker, 1994; Grab & Deschamps, 2004). The sampling site (Figure 2) is a gully side-wall formed by one such stream (Marker, 1994: hollow C), which provided an exposed sedimentary sequence of more than 5m depth (Figure 3), with alternating colluvial and peat layers (Marker, 1994; Grab & Deschamps, 2004).

Mean seasonal temperatures for the alpine belt at Sani Top vary from 10°C for summer (December through February) to 0°C for winter (June through August; Grab, 2010). Precipitation in eastern Lesotho is strongly seasonal, with 70-80% falling between November and March, and less than 10% between May and August (Tyson et al., 1976). Summer precipitation is predominantly in the form of thundershowers and instability storms, controlled by the subtropical high pressure belt, with a smaller proportion of the summer rainfall occurring as lighter orographic drizzle, resulting from an influx of moist maritime air from the east (Sene et al., 1998; Nash & Grab, 2010). Most precipitation above ~3000m asl between May and September falls as snow, yet accounts for less than 10% of total annual precipitation, with an average of 2-8 moderate to light snowfalls per year (Nel & Sumner, 2008; Grab & Linde, 2014). Summer winds dominate from the east and northeast, bearing moisture from the Indian Ocean, while winter winds are predominantly north-westerly (Sene et al., 1998; Grab, 2010).

The vegetation at the site comprises large expanses of meadow grasses, with increased sedge cover towards the more water saturated wetland regions, *Erica-Helichrysum* shrubs closer to the mountain backwalls, and a variety of small shrub species typical of the 'Drakensberg Alpine Centre' (Carbutt & Edwards, 2004) found in smaller numbers (Marker & Whittington, 1971; Grab & Deschamps, 2004). At a regional scale, there is a considerable shift in vegetation along altitudinal gradients (Carbutt & Edwards, 2004; Mucina & Rutherford, 2006). The Sekhokong site is situated above the treeline, and given its high altitude and substantially depressed temperatures, much of the vegetation comprising late Quaternary palaeoenvironmental record and the contemporary flora at the lower altitude Drakensberg palaeoenvironmental sites Braamhoek Wetland at 1,700 m asl (Norström et a., 2009, 2014) and Mahwaqa Mountain at 2,083 m asl (Neumann et al., 2014) are not present. However, it is likely that during warmer periods, some of these species were able to establish further upslope (Inouye, 2008).

Methods

Sediment was extracted horizontally from a gully side-wall following methods employed by Grab et al. (2005) at a minimum sampling frequency of 5 cm, spanning a total depth of 5.03m (Figure 2). Bulk organic material from 11 samples obtained from relatively equally spaced depths throughout the profile was radiocarbon dated using accelerator mass spectrometry (AMS) by *Beta Analytic* (Table 1). Dates were calibrated using the Southern Hemisphere SHCal13 model (Hogg et al., 2013). The Bacon model v2.2 (Blaauw & Christen, 2011) was used to interpolate dates for the remainder of the profile, selected due to the improved performance of Bayesian over linear regression models, and the inclusion of information on sample thickness. No outliers were identified by the Bacon model.

Palaeoenvironments were investigated by comparing sediment properties, pollen and diatoms throughout the profile to the contemporary environment and reference collections. At the broadest scale, sediment properties were used to determine regional moisture availability, demonstrated predominantly by relative changes in percentage organic content (Meadows, 1988), and the proportions of gravel- and sand-sized particles to silt- and clay-sized particles (Masselink et al., 2014). It must be noted that very coarse gravels could not be measured using the Malvern Mastersizer, and were therefore excluded from sediment particle size plots. Distinct variations in the skewness:kurtosis ratio were used to identify likely changes in depositional environment, for example from riverine to colluvial sediment (Masselink et al., 2014). Pollen was used to reconstruct past vegetation composition. The presence and absence of indicator species for alternating wetland and grassland conditions for the eastern Lesotho highlands region provides useful qualitative climatic information. Diatoms were used to reconstruct the aquatic conditions and algal biodiversity within the wetland.

Pollen preparation followed standard procedures outlined by Faegri et al. (1989). Once fossil pollen had been isolated and slides prepared, a minimum of 250 grains were counted per sample at a magnification of 400x using an Olympus BX51 light microscope. Identification was made with reference to the African Pollen Database. Due to morphological and environmental similarities, pollen counts from Chenopodiaceae and Amaranthaceae are summed as a single group ‘Cheno-Am’ (Scott & Nyakale, 2002). As has been conducted at the Braamhoek Wetland site, the Asteraceae:Poaceae ratio is presented as a proxy for the strength of precipitation seasonality (Coetzee, 1967; Norström et al., 2009), which is argued to represent changes in the latitudinal extent and strength of the Westerlies (Mills et al., 2012) Diatom preparation was undertaken using the procedures outlined by Battarbee et al. (2001). A minimum of 300 diatom valves were counted per sample at a magnification of 1000x using oil immersion. Diatoms were identified through consultation with both local (Schoeman, 1973; Schoeman & Archibald, 1976; Harding & Taylor, 2011; Matlala et al., 2011) and international literature (Krammer & Lange-Bertalot, 1986; Snoeijs & Balashova, 1998; Kramer, 2002). Sediment analyses involved determining the organic and carbonate content of each sample through loss-on-ignition at 550°C and 950°C respectively (Heiri et al., 2001). Sediment particle size distributions, including mean grain size, skewness and kurtosis for each sample were determined using a Malvern Mastersizer 3000.

Major gradients in the biological data were investigated using the indirect ordination technique principal components analysis (PCA) on the percentage composition of diatoms and pollen, while zonation of the multi-proxy profile was designated using the constrained incremental sum of squares (CONISS) cluster analysis technique using the Rioja and Cluster packages in R on the pollen assemblage data. For both pollen and diatom assemblages all statistics were performed on taxa with greater than 2% distribution, and square root transformed before analysis to down-weight dominant species. Redundancy analysis (RDA) was performed to determine the explanatory strength of the pollen distribution in influencing the diatom distribution for the profile (Legendre & Birks, 2012; Mackay et al., 2012). Changes in pollen are a proxy for major changes in landscape vegetation, and as these are predominantly associated with climatic or anthropogenic drivers, we use pollen here to indicate potential drivers of aquatic ecosystem change in local wetlands (Lotter & Birks, 2003; Mackay et al., 2012). All statistical analysis was undertaken using the code-based statistical platform R (Venables & Smith, 2015), and stratigraphic plots were produced using C2 (Juggins, 2007).

Results

The sediment record reflects alternating layers of dark coloured clays and peats, and orange coloured gravels (see Figures 2 and 3). The 11 AMS radiocarbon ages for the profile span the entire Holocene period, commencing during the late glacial, with a basal conventional date of 13,200 a BP (Table 1; ~15,870 cal a BP). The uppermost AMS dated sample was at a depth of 16.5 cm, with a conventional date of 1,430 a BP (Table 1; ~1,200 cal a BP). As this profile extends to the contemporary at the surface, the temporal resolution is relatively low for the surface layer of sediments. Given the topographic basinal locality of the sampling site, it is unlikely that substantial sediment has been lost through denudational processes during the Holocene. However, some past sediment loss through processes such as sheet erosion and wind deflation cannot be ruled out, but are impossible to ascertain.

The mean sediment accumulation rate, calculated by the Bacon model, is averaged for the sequence at 0.05 cm a $^{-1}$. There are notable periods of slower sedimentation in the early to mid-Holocene between 10,550 ±40 cal BP (~12,120 cal a BP) and 6,470 ±30 cal BP (~7,430 cal a BP), during which time only 40 cm of sediment had accumulated (Figure 3). Sedimentation occurs at a more constant, relatively rapid rate towards the late-Holocene, with a mean sedimentation rate of 0.03 cm a^{-1} from the surface to a depth of 107.5 cm (3,100 ±30 cal BP; ~3,190 cal a BP).

Three zones in the profile were delimited using CONISS, performed on the pollen assemblage data (Figure 4). SKP3 represents the transition from the late Pleistocene to the early Holocene, extending from the bottom of the core at a mean sample depth of 502.5 cm to a depth of 302.5 cm (~~16,450 cal a BP to ~8,560 cal a BP ie. 7,890 a), comprising 12 samples. This is followed by SKP2, an extensive zone comprising 28 samples, yet representing a shorter period, spanning a depth of 287.5 cm to 16.5 cm (~7,430 cal a BP to ~1,200 cal a BP, ie. 6,230 a). SKP1 encompasses only the top two samples, extending from a depth of 9.5 cm to the surface (~1,110 cal a BP to present). These zones correspond closely with large shifts in the diatom and sediment records, and are used in the graphic representation (Figures 5-7) and discussion of each of the records.

The sediment profile comprises alternating clearly-defined layers of coarse orange coloured gravels, dark black peats and organic clays, and green-grey fine clays. Very coarse gravels were found towards the bottom of the profile (Figure 3) but the particle sizes of these were too coarse to be measured using either the Mastersizer or traditional sieving methods. Interspersed in amongst these gravels was a greater proportion, by weight, of smaller particle sizes. As these dominated the samples, their particle sizes are plotted in Figure 5. Results from LOI and particle size analyses confirm fluctuations in organic and carbonate content, and particle size throughout the profile (Figure 5). A period with high percentage organic material (>45%) is noted for depths of 457.5-387.5 cm (Figure5). AMS dates place this period between ~15,630 cal a BP and 14,150 cal a BP, within the late glacial. Within this period, organic composition of greater than 75% is observed for depths of 427.5-397.5 cm (~15,150-14,440 cal a BP). A second, smaller (>30%), peak in percentage organic content is observed for the late Holocene, for depths of 31.5-22.5 cm

(~1,320-1,260 cal a BP). The relative percentages of sand-, silt- and clay-sized particles demonstrate considerably greater fluctuation in the late Holocene, for depths of 134.5-2.5 cm (~3,400-940 cal a BP; Figure 5). Greater percentages of gravel-sized particles are observed for this period, albeit fluctuating. Notably, gravel-sized particles cease at a depth of 211.5 cm (~6,370 cal a BP). Aside from the presence of gravel for a distinct portion, the overall sequence is dominated more by low-amplitude fluctuations than by any long-term trends (Figure 5). The skewness curve largely tracks the mean particle size, indicating that samples with large mean sizes are dominated disproportionately by sand- to gravel-sized particles. The past nature of hydro-geomorphic dynamics (e.g. diffuse overland flow; concentrated/channelized flow) at the site may well have influenced some of the sedimentological characteristics described here. However, sedimentological characteristics along the lengthy extent of exposed contemporary gully sidewalls suggest predominantly uniform deposition across the site through time. Evidence for palaeo channels or palaeo gullies is conspicuously absent and we thus infer that sedimentation processes were dominated by diffuse rather than channelized flow at this site through much of the Holocene.

The pollen record (Figure 6) is dominated by Poaceae (49.2%), Cyperaceae (21.0%) and Asteraceae (19.2%), typical of southern African wetlands (Gasse & Van Campo, 1998; Norström et al., 2009, 2014; Neumann et al., 2014). Pollen grains from 24 families, or genera where identification was possible, appeared with a frequency of more than 1% at any point throughout the profile. The pollen sum is largely representative of the contemporary local environment comprising a wetland surrounded by a large expanse of meadow, vegetated by grasses, semi-aquatic species, shrubs, herbs and succulents (Figure 6). Occasional *Podocarpus* and *Olea* pollen grains were counted (<2% maximum occurrence; Figure 6). As the eastern Lesotho Highlands are situated above the tree-line, such pollen would have been windblown from adjacent lower altitude forests. PC1 accounts for 26.6% of the variance of the pollen distribution in the samples, separating at extremes *Crassula*, Aizoaceae and Asteraceae with the strongest negative scores, from Poaceae and Cyperaceae with the strongest positive scores. Similarity in species scores for Cyperaceae and Poaceae are notable for PC1, as they represent typically opposing environmental conditions of wetland and grassland respectively. Marked by the extreme isolation of the SKP1 samples, PC1 appears to be driven by differences between the long-term vegetation regime of the wetland for the early to mid-Holocene, contrasting that of the most recent 1,000 years. PC2 accounts for 22.2% of observed variance in relative pollen abundance across samples, separating Poaceae and Cyperaceae by extremes in species score, representing a division between environments dominated by grassland from those with a greater wetland expanse.

The diatom record (Figure 7) is dominated by *Synedra (Fragilaria) famelica* (26.4%), with smaller populations of *Eunotia bilunaris* (8.2%), *Hantzschia amphioxys* (7.4%) and *Pinnularia divergentissima* (6.6%). Due to the similarities in their ecological preferences (Schmidt et al., 2004; Ohlendorf et al., 2009; Wang et al., 2013), *Staurosirella (Fragilaria) pinnata* and *Fragilaria construens are* grouped together, both of which are r-strategists which can tolerate frequent environmental changes, which for Lesotho, most notably involved being tolerant of seasonal ice cover. PC1 accounts for 35.0% of observed variance in diatom species distribution across the profile, segregating at extremes *Fragilaria famelica, Pinnularia borealis, Hantzschia amphioxys* and *Achnanthes minutissima* with strongest negative scores from *Fragilaria pinnata/construens, Cymbella laevis* and *Eunotia bilunaris* with strongest positive scores PC2 accounts for 13.3% of the variance in diatom distribution, and separates planktonic and facultative planktonic *Fragilaria pinnata/construens*, *Aulacoseira ambigua and Fragilaria famelica* with negative scores, from aerophilic *Hantzschia amphioxys, Diploneis parma, Pinnularia gentilis* and *Pinnularia divergentissima* with positive scores.

Discussion

Environmental Reconstruction

This study presents the longest continuous multi-proxy palaeoenvironmental record published for eastern Lesotho to date, spanning the termination of the Last Glacial Maximum (LGM) to present. The sedimentary profile demonstrates fluctuations between peat- and clay-rich sediment and coarse gravel, previously inferred to represent moisture fluctuations (Marker, 1994). The broad sedimentation patterns are consistent with those presented by Marker (1994, 1995, 1998), however, the frequency of these fluctuations is considerably higher. Pollen and diatom records provide additional, higher resolution environmental information, enabling identification of short-lived events.

The CONISS output for Sekhokong indicates few statistically significant zones relative to the long time period covered, and considerable variation in pollen. Redundancy analysis (RDA) on the Sekhokong records reflects the low, yet statistically significant, explanatory strength of pollen in determining the diatom composition (13.3%), indicating that the diatom communities are more likely to be influenced by local habitat than broader regional vegetation. At a more local scale, however, Cyperaceae pollen closely tracks the percentage organic content of sediments, representing marsh conditions. The Asteraceae:Poaceae pollen ratio is very low throughout the profile (<0.5), indicating a wet, probably summer rainfall regime throughout much of the past ~16,450 cal a (Figure 6). As Poaceae and Cyperaceae dominate the contemporary landscape which is limited by relatively cold temperatures at the high altitude of the site, the periodic dominance of a wider range of taxa including *Crassula,* Aizoaceae and Asteraceae, and the coincident increase in absolute taxa for these periods, is interpreted as representing warmer periods during which upslope migration of species can occur, thus increasing the total taxon count (Inouye, 2008). The diatom profile demonstrates a shift from an environment with a large proportion of r-strategist ice tolerant *Fragilaria pinnata/construens* group in SKP3 to an environment dominated by snow tolerant, benthic *Fragilaria famelica* in SKP1 (Figure 7). PC1 for the diatom record separates the undisturbed conditions which comprise the majority of the profile, from a period of heightened pollution and wetland disturbance during SKP1. PC2 indicates moisture fluctuations throughout the profile. Interpretations of the diatom results largely relate to their habitat, with notable segregations in the profile of periods dominated by aerophilic species relative to those dominated by planktonic and benthic species. The relative abundance of *Fragilaria* species is of interest due to their tolerance of seasonal ice and snow, through their abiity to respond quickly to environmental change (Schoeman, 1973; Ohlendorf et al., 2000; Karst-Riddoch et al., 2005; Wang et al., 2013). For periods during which the profile is dominated in great quantities by this group, conditions are interpreted as being particularly cold, prohibiting the survival of less ice/snow tolerant diatoms. As the group have a facultative planktonic and benthic habitat (Sonneman et al., 1999), the alternate vegetation stressors of dry conditions are unlikely.

SKP3: ~16,450-8,560 cal a BP

SKP3 commences with the highest relative abundances of Cyperaceae pollen and planktonic diatom species *Aulacoseira ambigua* for the profile, indicative of rather wet conditions, allowing planktonic diatoms and wetland plants to thrive (Gasse & Van Campo, 1998; Sitoe et al., 2015). A peak in *Fragilaria* species (>40% of the diatom sum) occurs concurrently. Fragilarioids are r-strategists which tolerate disturbance well, and they are particularly common in high alpine lakes impacted by snow and ice cover (Schmidt et al., 2004; Ohlendorf et al., 2009; Wang et al., 2013) It may well be that their dominance at this time is indicative of cold, harsh environments associated with globally cooler temperatures, and more prolonged ice cover (Figure 7). The pollen profile is also characterised by large proportions of Poaceae during this period, which combined with the presence of the facultative planktonic *Fragilaria pinnata/ construens* and Cyperaceae pollen (Figures 6, 7), is indicative of a large wetland expanse, with at least ponds of shallow water to support this diatom community and Cyperaceae, but surrounded by meadow grasses. This is followed immediately by a short-lived, but very dry period from ~16,350-15,870 cal a BP, inferred from a decrease in the proportion of Cyperaceae pollen, a decline in the relative abundance of planktonic diatoms and increase in aerophilic species *Diploneis parma, Eunotia praerupta, Hantzschia amphioxys* and *Pinnularia divergentissima* (Gasse & Van Campo, 1998), and a lower percentage organic content of sediments (Figures 5-7).

A return to wet conditions occurs from ~15,630-14,440 cal a BP, with a marked dominance of Cyperaceae pollen, a peak in organic content, and a re-emergence of planktonic *Aulacoseira* and facultative planktonic *Fragilaria pinnata/construens* (Figures 5-7). The diatom record during this period is dominated by epiphytic species, particularly *Eunotia bilunaris* and *Cymbella laevis* (Schoeman, 1973; Gasse & Van Campo, 1998), indicating a large presence of macrophytes in the wetland (Figure 7). The percentage carbonate content is particularly low throughout the period, which may be due to reduced levels of photosynthesis due to the predominance of peat (Figure 5). Together, these proxies suggest the re-establishment of a more extensive wetland, but with shallow water restricted to small ponds suitable for the establishment of macrophytes, and herbs along the drier wetland edge. This cool, moist period is consistent with results obtained from the eastern Drakensberg foothills (Neumann et al., 2014) indicating a progressive shift from the arid conditions during the LGM.

By ~14,150 cal a BP, the relative abundance of Cyperaceae pollen had decreased to 15%, coinciding with a decrease in Asteraceae pollen and a peak in Poaceae pollen (Figure 6). At the same time a peak in aerophilic diatoms, particularly *Diploneis parma* and *Eunotia praerupta* is noted, and an increase in the percentage composition of sand-sized particles and carbonates, but with a decrease in organic matter (Figures 5, 7. This indicates a drying of the site, reducing the spatial extent of the wetland. The percentage organic composition decreases more slowly, suggesting a change from wetland to grassland species which maintained the organic input in the sediment (Figure 5). If the Asteraceae:Poaceae pollen ratio accurately reflects the strength of seasonality (Norström et al., 2009), which for the eastern Lesotho highlands would be driven by shifts in the Westerlies (Mills et al., 2012), then the low ratio for this period (Figure 6) would indicate warmer conditions associated with weakened Westerlies, which in turn would further increase the rate of peat production. Thereafter, the relative abundance of Cyperaceae and Asteraceae pollen progressively increases, paired with a more pronounced decrease in Poaceae pollen which persists throughout the remainder of the profile (Figure 6). This is concurrent with a low relative abundance of planktonic and facultative planktonic diatoms, but large proportions of epiphytic species (Figure 7). Such proxy evidence suggests that the region was slowly warming throughout this period, with surface water supporting macrophytes, indicating the persistence of wetland conditions Maximum temperatures are inferred from a reduction in *Fragilariods* and an increase in pollen taxon diversity to have been experienced between ~8,560-7,280 cal a BP, consistent with the Holocene Altithermal in southern Africa (Neumann et al., 2014).

SKP2: ~7,430-1,200 cal a BP

SKP2 commences with a change in the pollen, diatom and sediment record (Figures 5-7). The gradual increase in Asteraceae and Cyperaceae pollen noted during the terminal period of SKP3 is reversed with a decrease in these taxa, while Poaceae pollen increases (Figure 6). This is paired with major increases in *Fragilaria famelica* and aerophilic diatom species (Figure 7), suggesting regional drying and a dominance of snow in mean annual precipitation to support the *Fragilaria group*. The pollen and diatom composition suggests a sudden, extreme drying of the wetland, potentially during a period of comparatively colder temperatures than those immediately preceding it, which possibly reflects cooling following the maximum temperatures of the Holocene Altithermal (Neumann et al., 2014). This is followed by an increase in Cyperaceae pollen and decrease in Poaceae until ~6,720 cal a BP (Figure 6), indicating progressively wet conditions. This terminates with a peak in *Fragilaria* diatoms (Figure 7), inferred as a second pulse of particularly cold conditions unsuitable to many other species. Consistent proportions of drought tolerant *Crassula*, Aizoaceae, Cheno-Am, Apiaceae and *Anthospermum* and the largest sum of aerophilic diatoms follows, persisting until ~3,640 cal a BP. The multi-proxy evidence indicates that this was likely the driest period represented by this palaeoenvironmental sequence. Poaceae predominates the pollen sum during this period, suggesting regional grassland conditions, while the relative increase in the total observed taxa is interpreted to be driven by an increase in temperatures facilitating an up-slope plant succession in an environment otherwise too cold to support considerable plant diversity (Inouye, 2008; Figure 6).

The second half of SKP2, from ~3,400-1,200 cal a BP, is marked by continuous fluctuations in the relative abundance of Poaceae, Cyperaceae and Asteraceae pollen, and in the ratios of benthic and aerophilic diatoms (Figures 6, 7). Very pronounced and frequent changes in sediment particle size distributions mark clearly defined sedimentary lenses observed *in situ*. This period is characterised by the emergence and maintenance of the ice tolerant, facultative planktonic *Fragilaria* species, suggesting persistently cooler conditions throughout SKP2 (Figure 7). The pollen and sediment record, and changes in the ratios of aerophilic to planktonic diatom species, indicate fluctuations in moisture throughout SKP2, resulting in large variations in wetland size. Wet phases, with greater wetland size and surface water depth, are indicated by peaks in Cyperaceae pollen and supported by increases in the proportional representation of benthic diatoms from ~3,260-3,190 cal a BP, and at ~3,050 cal a BP. Dry phases with smaller wetland extent and drier wetland surface are indicated by pollen of drought resistant succulents, shrubs and grasses, supported by increases in aerophilic diatoms at ~3,260 cal a BP, ~2,690 cal a BP and ~1,380 cal a BP (Figure 5). A prolonged wet event is indicated from ~2,690-1,470 cal a BP, inferred from a high percentage composition of organic material in the sediment record, and supported by a peak in benthic diatoms *Fragilaria famelica* and *Eunotia bilunaris* which would require a habitat comprising standing water*,* and greater proportions of Cyperaceae pollen, and which may include more regular snowfalls (Figures 5-7), (Gasse & Van Campo, 2001; Vilbaste, 2001). This is followed by the highest relative abundance of Poaceae pollen in the sequence, coinciding with a peak in aerophilic diatoms, indicating a particularly dry period (Figures 6, 7).

SKP1: ~1,110 cal a BP - Present

SKP1 comprises only two samples, representing the period from ~1,110 cal a BP to present, limiting the detail of climatic or environmental inferences. The two samples, however, indicate contrasting climatic and environmental conditions. An increase in organic content, silt-sized particles, and the Asteraceae:Poaceae pollen ratio occurs (Figures 5,6), suggesting wet, yet seasonally less distinct rainfall, likely a response to a strengthening of the Westerlies. The diatom record reflects a peak in snow-tolerant diatoms *Fragilaria famelica* (Wang et al., 2013) and of aerophilic species (Figure 6), supporting the inference of cold but relatively dry conditions. SKP1 terminates with a decrease in Cyperaceae pollen and continued increases in *Crassula* and *Pentzia*, which with increased aerophilic diatoms, suggests drying to present conditions (Figures 6, 7). Abundant *Crassula* pollen may be indicative of human and animal disturbance during recent centuries (Norström et al., 2009). A higher resolution record is required to determine the validity of these inferences of contrasting climatic conditions over the past ~1000 years.

Regional Comparison

The Sekhokong palaeoenvironmental reconstruction contributes to refining the Holocene environmental and climatic record for southern Africa. The commencement of the Sekhokong record coincides with the phase of deglaciation following the LGM. Pollen records from Mahwaqa Mountain in the eastern Drakensberg foothills (Neumann et al., 2014), and multiproxy analyses of charcoal, pollen and diatoms from Braamhoek Wetland in the northern Drakensberg foothills (Finné et al., 2009; Norström et al., 2014), indicate a shift towards wetter conditions during this cool post-glacial phase, with maximum precipitation inferred from speleothem records from Makapansgat to have been attained by 13,000 cal a BP (Holmgren et al., 2003). This period is further been confirmed to have been characterised by greater moisture availability in meta-analyses for southern Africa (Chevalier & Chase, 2016). This is consistent with wet conditions inferred for the start of the Sekhokong record based on diatom, pollen and sediment results. This is notable as the speleothem record suggests a progressive increase in moisture following the LGM, extending into the early Holocene (Holmgren et al., 2003). These wet conditions by 13,000 cal a BP may indicate a northerly shift of the Inter-tropical Convergence Zone (Truc et al., 2013; Singarayer & Burrough, 2015).

The deglaciation period globally is interrupted by two cold events globally which coincide with this record: Heinrich event H1 from 18,000-15,000 cal a BP (Álvarez Solás et al., 2011) and the Younger Dryas from 13,000-11,500 cal a BP, both driven by meltwater pulses in the Northern Atlantic (Mayewski et al., 1996). The period of rapidly fluctuating environmental conditions detected in the Sekhokong record by an increase in *Fragilaria* species, is concurrent with and a decrease in the relative number of pollen taxa. It is possible, therefore, that these changes dated to ~15630 cal a BP are indicative of particularly cold conditions resulting in increased seasonal ice cover and a decline in vegetation diversity. By contrast, sample SK24 which has an interpolated date of ~12,120 cal a BP, reflects evidence for warm conditions coincident with the Younger Dryas, but at too poor a sampling resolution for a definitive interpreation. Isotope records from the archaeological sites in western Lesotho similarly reflect contradictory evidence for a Lesotho manifestation of Younger Dryas conditions (Smith et al., 2002; Roberts et al., 2013), although arguably this may be attributed to cold dry conditions discouraging settlement during this period, and consequently not accumulating archaeological material at the excavated sites. More recent analysis of stable isotopes from organic material and tooth enamel at Sehonghong in the eastern Lesotho Highlands, by contrast, provides supporting evidence for cold conditions associated with this event (Loftus et al., 2015). Further evidence in support of a Younger Dryas event in southern Africa includes oxygen isotopes from mollusc shells at Elands Bay (Cohen et al., 1992), archaeological isotope evidence from Bushman's Rock Shelter (Abell & Plug, 2000), a re-analysis of pollen data from Wonderkrater (Thackeray & Scott, 2006), and isotope records from hyrax middens in the Cederberg (Quick et al., 2011; Chase et al., 2015). Southern Hemisphere manifestations of global cooling events associated with instabilities in the Arctic ice sheets clearly requires further investigation.

The overall warming period associated with deglaciation continues until optimal conditions at the Holocene Altithermal (Wanner et al., 2015). The timing of this event is unclear, with discrepancies for much of southern Africa, but it broadly spans the period 7,500-6,500 cal a BP (Holmgren et al., 2003; Truc et al., 2013; Neumann et al., 2014; Wanner et al., 2015). Maximum temperatures at Sekhokong are inferred to have been attained by 7,280 cal a BP. There is no clear warm signal coinciding with the Holocene Altithermal for the lower-altitude (1700m asl), more northerly Braamhoek Wetland (Norström et al., 2009, 2014; Finné et al., 2010). However, pollen records from a similarly low altitude eastern Drakensberg site, Mahwaqa Mountain, indicate a clearly defined Holocene Altithermal maximum at 6,500 cal a BP (Neumann et al., 2014). By this time, cooler conditions are indicated for Sekhokong by a reduction in pollen taxon diversity, and supported by a re-emergence of *Fragilariods*.

Climate and environmental change over the past 2,000 years is of interest given rapid climate fluctuations and increased anthropogenic influence on the environment (Mayewski et al., 2004; Wanner et al., 2008, 2014). The LIA, a short-lived cold event from AD 1300-1800 (Wanner et al., 2008, 2015), has been of regional interest (Tyson et al., 2000). A peak in *Fragilaria* species coupled with a decrease in pollen taxa diversity tentatively suggests a cold period some time during the past ~1,110 years at Sekhokong. Debate regarding precipitation during the LIA in southern Africa continues, with current understanding that dry conditions prevailed in the summer rainfall zone (cf. Ekblom et al., 2008; Gillson & Ekblom, 2009; Neumann et al., 2010; Chevalier & Chase, 2016) and wet conditions in the winter rainfall zone (Stager et al., 2012; Weldeab et al., 2013). For Sekhokong, proxy evidence for the past ~1000 years suggests dry conditions, in support of this hypothesis. However, due to the low temporal frequency of samples, any rapid fluctuations in moisture would not have been detected. Evidence for increased anthropogenic influence on the local and regional environment, similar to that inferred from the pollen and diatom records at Sekhokong for this period, have been reported from a range of locations since AD ~1,800 (cf. Baxter & Meadows, 1999; Neumann et al., 2008, 2011, 2014; Norström et al., 2009).

Comparisons with the pollen-based palaeoenvironmental reconstruction for Mahwaqa Mountain in the eastern Drakensberg foothills (Neumann et al., 2014) are notable due to the proximity of the sites. Of particular interest are delays in the onset of dry periods at Sekhokong relative to Mahwaqa. The driest period in the profile from Mahwaqa Mountain is inferred to occur from 4,600-3,500 cal a BP (Neumann et al., 2014). For Sekhokong, the period of driest conditions occurs earlier, at ~6,560-3,640 cal a BP. This may reflect the influence of the escarpment in blocking moisture, as the Mahwaqa Mountain site is situated at a lower altitude to the east of the Great Escarpment, and would thus more easily receive moisture from the Indian Ocean than the eastern Lesotho highlands located in the rain shadow, particularly during periods of strengthened or more frequent coastal lows (Scott et al., 2012; Neumann et al., 2014). This hypothesis requires further investigation, and provides strong impetus for the analysis of synoptic climate drivers throughout the late Quaternary using spatial transects (Chase & Meadows, 2007).

Conclusion

This study presents the longest temporally continuous multi-proxy palaeoenvironmental reconstruction for eastern Lesotho. The high altitude setting is host to a niche environment of cold-resilient plant and diatom species, the analysis of which facilitates the detection of subtle fluctuations in local and regional climate. Results indicate cycles of dry and wet conditions throughout the late-Quaternary, and discrete, particularly cold events. Climatic and environmental variability is substantially more enhanced during the last ~5,450 years, with evidence for anthropogenic influence during the last ~1100 years.

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Table 1: AMS radiocarbon dates acquired for the Sekhokong profile.

Table 1: Raw AMS radiocarbon dates acquired from Beta Analytic for the Sekhokong profile.

Beta Analytic Laboratory ID	Sample Number	^{14}C Age (yr BP)	1σ Uncertainty (yr)	2σ calibrated age range (BP)	Mean depth (cm)	Sample Thickness (cm)	d13C
Beta-405431	SK3	1,440	±30	1,345-1,275	16.5	5	-24.5
Beta-405432	SK7	1,380	±30	1,300-1,185	45.5	5	-25.1
Beta-405433	SK11	2,680	±30	2,780-2740	75.5	5	-24.0
Beta-405434	SK14	3,100	±30	3,360-3,175	107.5	5	-25.3
Beta-393710	SK21	3,130	±30	3,375-3,215	134.5	3	-25.3
Beta-405436	SK25	5,450	±30	6,258-6,180	202.5	5	-26.5
Beta-405437	SK30	6,420	±30	7,415-7,225	267.5	5	-24.8
Beta-405438	SK31	6,470	±30	7,425-7,272	287.5	5	-26.8
Beta-405439	SK34	10,550	±30	12,555-12,420	327.5	5	-28.9
Beta-405440	SK38	12,660	±40	15,135-14,860	412.5	5	-28.5
Beta-393710	SK41	13,180	±40	15,880-15,675	472.5	5	-26.0

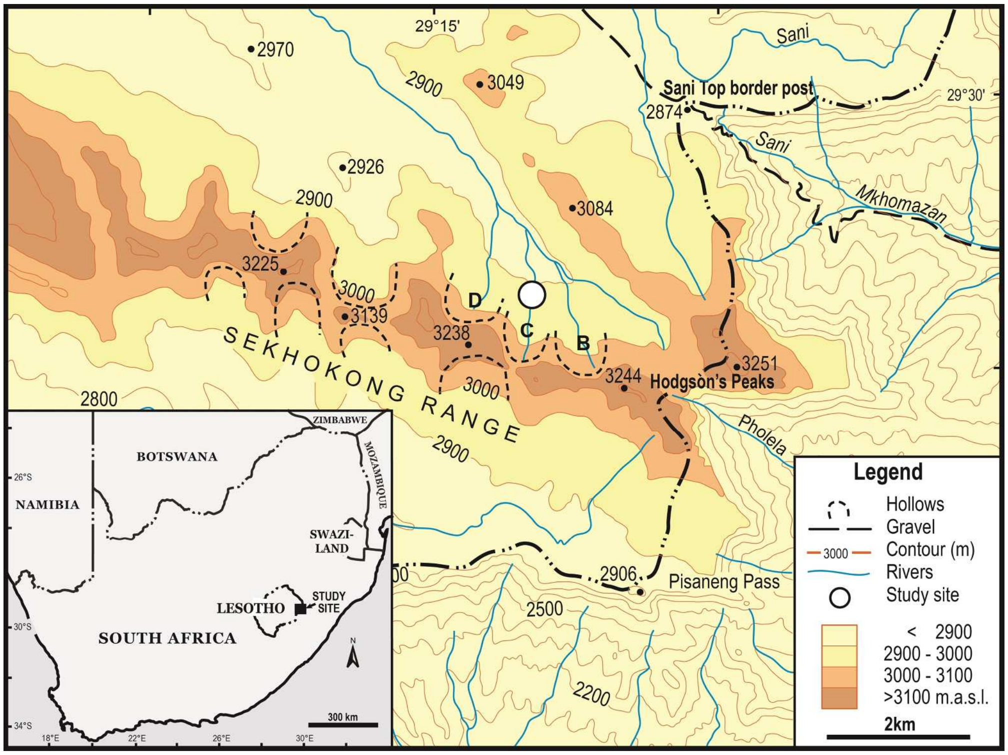

Figure 1: Location of the Sekhokong study site in the regional and local context.

109x82mm (600 x 600 DPI)

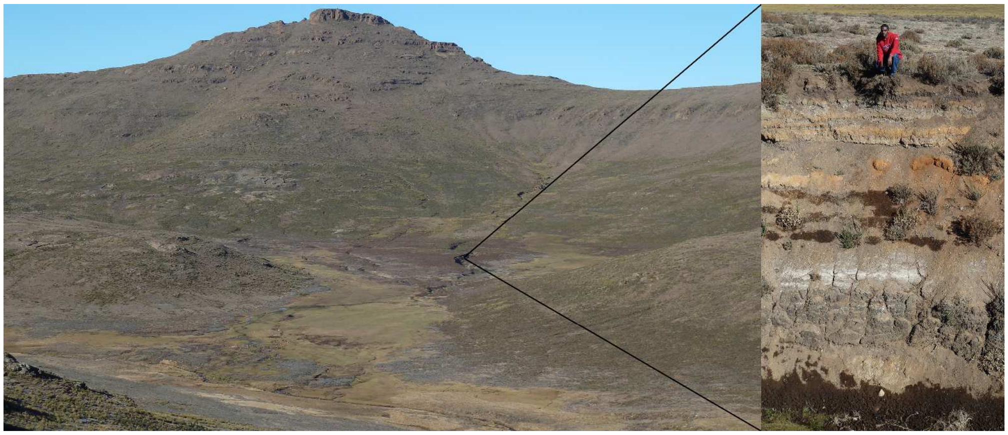

Figure 2: Exposed gully profile sampled at Sekhokong.

805x343mm (180 x 180 DPI)

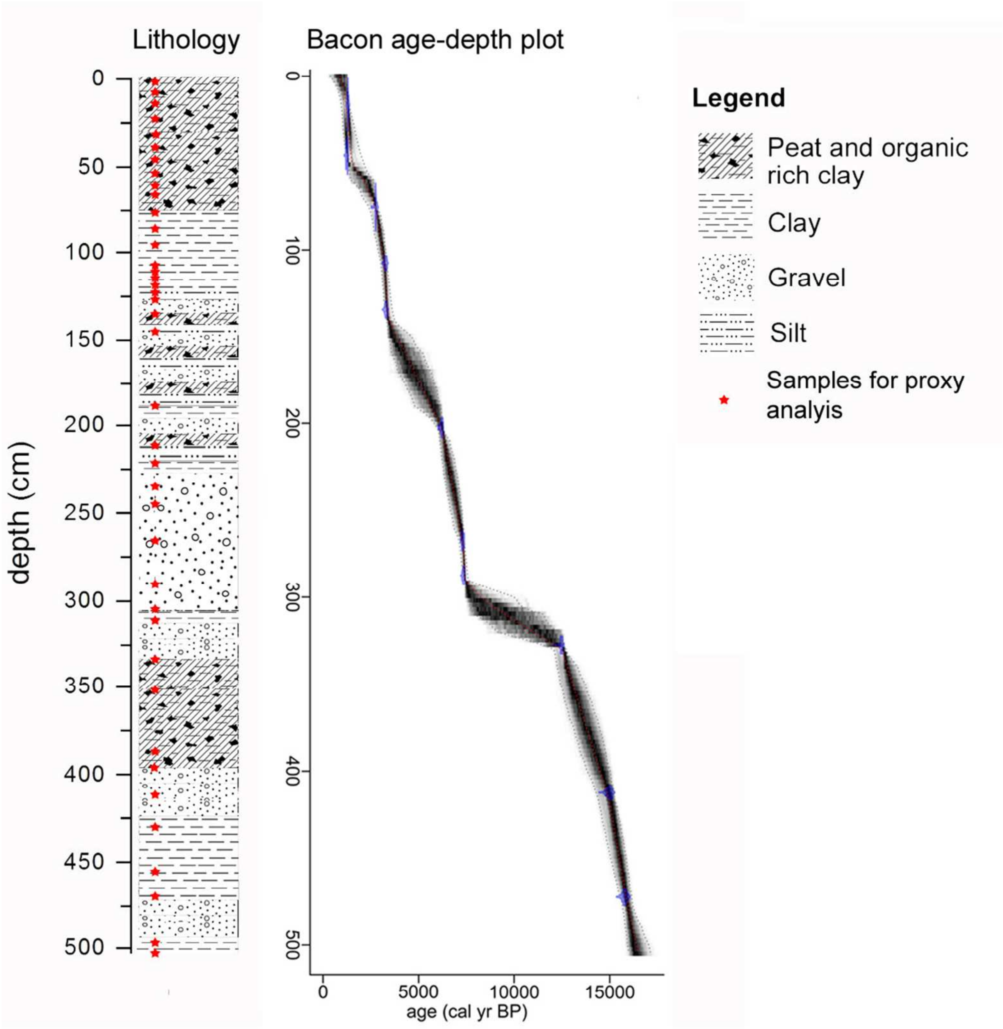

Figure 3: Stratigraphic log of the Sekhokong gully section, with the Bacon age-depth model.

143x159mm (220 x 220 DPI)

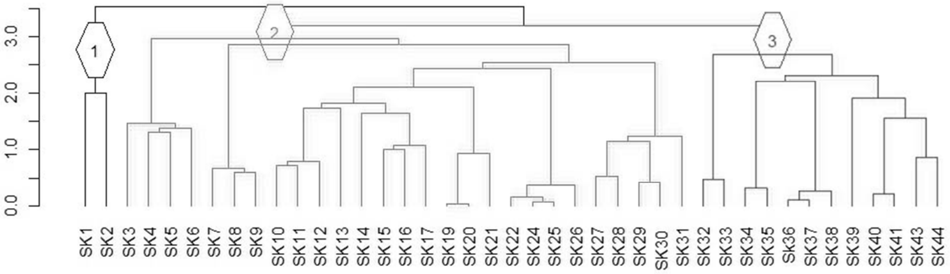

Figure 4: CONISS output separating the Sekhokong pollen profile into zones.

352x107mm (72 x 72 DPI)

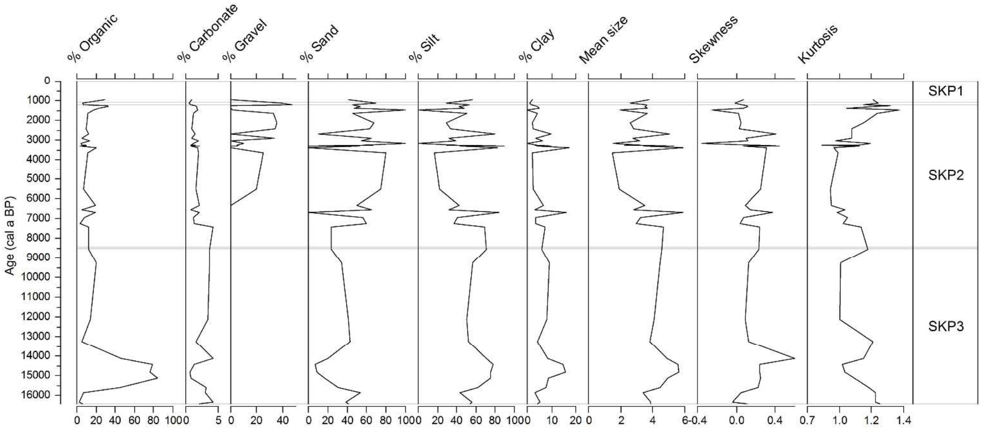

Figure 5: Stratigraphic diagram reflecting changes in sediment properties at Sekhokong.

1725x752mm (72 x 72 DPI)

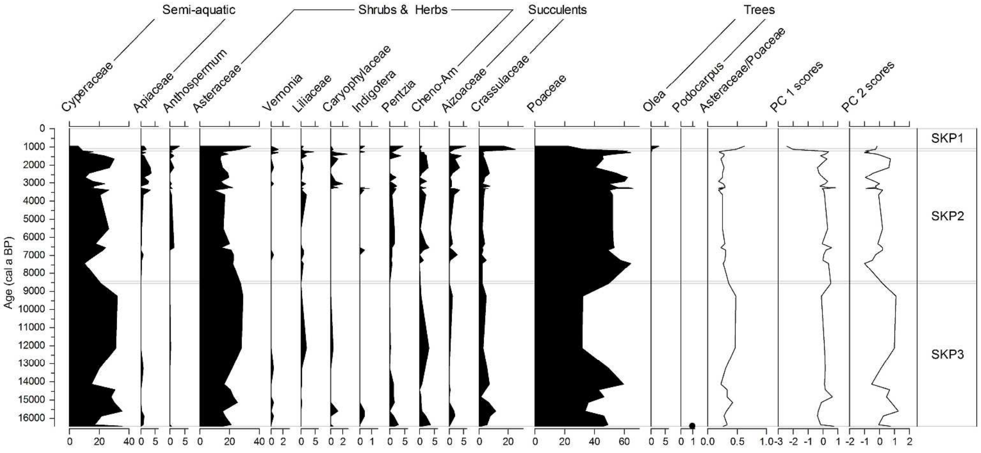

Figure 6: Pollen percentage diagram for the Sekhokong profile.

1872x861mm (72 x 72 DPI)

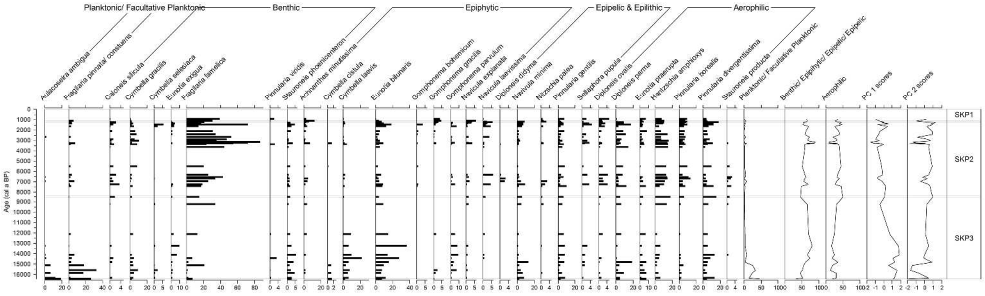

Figure 7: Diatom percentage diagram for the Sekhokong profile.

3261x971mm (72 x 72 DPI)