Multi-proxy evidence of Late-Holocene paleoenvironmental change at Princessvlei, South Africa: The effects of fire, herbivores, and humans

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Abstract

A multi-proxy approach conducted on a sediment core from a small lake in the Cape Flats (Princessvlei, South Africa), supported by five AMS dates, reveals the paleoenvironments over the last 3900 years. Despite some gaps in the records, phytoliths, diatoms, $\delta^{18}O_{diatom}$, pollen, coprophilous fungus spores, microscopic charred particles (micro-charcoal), and burnt-grass phytoliths, indicate vegetation disturbances caused by climatic changes, anthropogenic

influences, fire, and herbivore activity. Pollen spectra indicates a moist period (3600-2600 cal yr BP), which co-occurs with an increase in fires, possibly due to greater biomass fuel loads coupled with the moderate presence of large herbivores. Subsequently, a dry period (2600-1900 cal yr BP) saw a rapid increase of large herbivores probably congregating around the lake, a contention supported also by the occurrence of nutrient-rich waters. This dry period saw reduced fires and a decline of C_3 grasses in favor of C_4 grasses. The arrival of herders in the Cape after 2000 cal yr BP is not immediately apparent in the multiple records, except for minor vegetation changes and regional fires c. 1200-1400 cal yr BP. However, a more consistent presence of livestock in the immediate area of Princessvlei occurs only after c. 600 cal yr BP, when peak frequencies of coprophilous spores coincide with changes in vegetation composition and occurrence of more eutrophic waters in the lake. The introduction of exotic flora, fire suppression, and a reduction of herding activities, characterizes the period of European settlement (c. 300 BP to present).

1. Introduction

Late Quaternary vegetation change in *fynbos*, the characteristic biome of the winter-rainfall zone of southern Africa, has been studied through palynological research of numerous deposits including lakes, peat, and hyrax middens (Schalke, 1973; Meadows and Sugden, 1983; Baxter and Meadows, 1994; Scott and Woodborne; 2007, Quick et al., 2011, 2015, 2018; Valsecchi et al., 2013). Although palynological data provide evidence of climatic changes, some of the recorded vegetation dynamics appear to be associated with fire incidence (cf. Neumann et al., 2011), which is an important factor in fynbos ecology (Kruger, 1979; 1983; Cowling and Holmes, 1992; Cowling et al., 2004). However, the fire-vegetation relationship is complex due to the diverse nature of the factors involved, some extrinsic, such as climate, and others intrinsic to the vegetation type (Kruger, 1983).

Climatic changes play an important role in the fire dynamics of fynbos because moisture availability influences fuel load and temperature controls moisture and flammability (Power et al. 2008). However, various other non-climatic factors affect the fire regime, in particular the reduction of biomass by large herbivores and induced fires by humans (Kraaij and van Wilgen, 2014).

Although some high-resolution pollen records document the impact of European colonists on vegetation and fire regimes in the region (Baxter and Meadows, 1994; Neumann et al., 2011), the possible influence of prehistoric populations, particularly during the advent of pastoralism in the region, is poorly resolved. Furthermore, the possible influence of hunter-gatherer groups, which may have directly used fire for hunting (Hall, 1984; Marean et al., 2014), has not been assessed in the interpretation of paleoecological records.

Princessvlei, a small coastal lake in the Cape Flats (Fig. 1), has been the subject of two previous paleocological studies (Neumann et al., 2011; Kirsten and Meadows, 2016). Neumann et al. (2011) studied pollen, spores, and microscopic charcoal for the past 3900 years from a core taken by E. M. van Zinderen Bakker (Neumann and Scott, 2018) from a location on the northern side of the lake in 1948 (i.e. vZB core). They recorded climatic dynamics, particularly highlighting a moist period c. 3400-2600 cal yr BP and a dry period c. 2600-1900 cal yr BP, as well as the advent of non-native taxa that arrived with the first Europeans in the Cape in the late 17th century (Neumann et al., 2011). The study revealed that a minor change in vegetation occurred c. 2000 years BP, which coincides with the arrival of pastoralism in the Cape region. Nonetheless, based on the pollen record alone, it proved difficult to distinguish between anthropogenic disturbance and climatic fluctuations. Kirsten and Meadows (2016) presented a paleolimnological interpretation of Princessvlei based on the diatom record that indicates fluctuations between eutrophic and oligotrophic conditions related to hydrological and climatic changes during the past 2600 years on core labelled PV11.3 (Kirsten and Meadows 2016). Some of their observed variations correlate well with the climate changes identified by Neumann et al. (2011).

Fig. 1 about here.

To supplement the late Holocene paleoecology of the Princessvlei area, we present here the results of paleolimnological data (e.g., ecological groups of diatoms and diatom $\delta^{18}O$), pollen, phytoliths, microscopic charcoal, burnt-grass phytoliths and coprophilous fungal spores from core PV11.3 down to c. 3900 years BP. Additionally, we compare the pollen record from this

core with the higher-resolution and slightly longer record from the vZB core (Neumann et al., 2011) to explore aspects of non-climatic factors in vegetation change, such as anthropogenic disruption of the fire regime and herbivore incidence, in the context of regional climate and ecological change, and human impacts on the landscape.

Despite evidence of early agricultural impact on vegetation in lacustrine other parts of southern Africa (Scott, 1987; 2002; Carrión et al., 2000; Neumann et al. 2008, 2010; Finch et al. 2008; Cordova et al. 2017), there is no study that focuses on the environmental impacts of pre-European pastoralists in the Cape Region. Therefore, this study aims at exploring climatic conditions during the commencement of native pastoralism (dated archaeological at c. 2000 cal yr BP) and the possible changes that this cultural change brought to the area around Princessvlei.

2. Study Area

Princessvlei is located in the Cape Flats on a relatively low coastal plain (below 30 m amsl) consisting of fluvial and eolian sands forming a tombolo connecting the Cape Fold Mountains and the Cape Peninsula Mountains (Schalke. 1973; Bickerton, 1984). The geomorphology of the area consists mainly of stabilized and active sand dunes, floodplains of small rivers that descend from the adjacent mountain systems, and a series of inter-dune and coastal lakes (Schalke, 1973).

Princessvlei (known in old maps as Diep Vlei, as it was part of the Diep River) has an area of approximately 35 ha and a mean depth of 2.5 m (Harding 1992; Parsons and Harding 2002). The lake is fed primarily by groundwater from the Cape Flats aquifer, which flows in a southerly direction (Bickerton, 1984; Parsons and Harding, 2002), and secondarily by runoff from the surrounding areas during the winter rains (Harding 1992; Brown and Magoba, 2009). The Diep River, whose headwaters are in the southeastern slopes of Table Mountain, at some stage appears

to have contributed water to Princessvlei from the west via a channel, as shown in early Dutch colonial maps (Brommer and Hattingh, 2009). Princessvlei is a natural, permanent, alkaline, eutrophic, freshwater coastal lake in an interdunal depression (Harding 1992) and, despite its relative proximity and elevation with respect to the sea, the lake was not affected by marine intrusions during the late Holocene (Kirsten, 2014; Kirsten and Meadows, 2016).

In the early 20th century, the Diep River Channel was cut off from Princessvlei, thus creating a small lake, Little Princessvlei, from where the stream flows south to the Sand River, thus bypassing Princessvlei (Fig. 1). However, in the 1990s, a flood attenuation channel reconnected the Diep River to Princessvlei via Little Princessvlei (Brown and Magoba, 2009). Additionally, an artificial channel, the Southfield Canal, feeds into the lake from the northeast, and an effluent channel connects Princessvlei to Rondevlei (Fig. 1). At present, the Princessvlei is encroached on by residential and industrial neighborhoods and agricultural land, which contribute considerably to polluting its waters (Bickerton 1984; Harding, 1992; Brown and Magoba, 2009; Adelana et al., 2010).

Mean annual precipitation in the Cape Flats varies between 580 and 900 mm, while in the adjacent Table Mountain and Constantiaberg it exceeds 1000 mm per year (Cowling and Holmes 1992; Rebelo et al., 2006). Most of the precipitation occurs through the cooler season, between May and August, during which the contribution to the aquifer that feeds the lake is significant (Adelana et al., 2010). Precipitation is strongly determined by the westerly flow of cyclonic frontal systems that are most intense and frequent in the austral winter (Tyson and Preston-Whyte, 2000; Tadross et al., 2012). During the summer, the influence of the South Atlantic Anticyclone is most prominent, producing strong southeasterly winds that prevent precipitation

(Tadross et al. 2012). Temperatures vary considerably between the seasons, from an average maximum of 27°C in February to an average minimum of 7°C in July (Rebelo et al., 2006).

Because of the temperate climate with winter precipitation and the mostly sandy and poor-nutrient soils, fynbos vegetation types dominate the region (Fig. 2). Princessvlei is located at the transition between the Cape Flats sand fynbos (CFSF) and the Cape Flats dune strandveld (CFDS) (Rebelo et al., 2006). The structure and composition of these communities varies considerably despite both being located on sandy substrates (Sections S1 and S2, Supplemental Material). The sand fynbos (CFSF) consists predominantly of proteoid and restioid taxa, but with ericoid and asteroid elements in some areas (Rebelo et al., 2006). In contrast, the dune strandveld vegetation (CFDS) represents a mixture of shrubs that are associated typically with coastal dune topography along the west and southern coasts of South Africa, including a number of perennial succulent shrubs and grasses (Taylor, 1972; Rebelo et al., 2006).

Fig. 2 about here.

The response to fire and herbivory of the two dominant Cape Flats vegetation types is markedly different. The sand fynbos (CFSF) shares many fire-prone characteristics with other fynbos communities in terms of flammability (Rebelo et al. 2006; Altwegg et al., 2014; Kraaij and van Wilgen, 2014), while the dune strandveld (CFDS) has reduced flammability due to the the sparser nature of its vegetation and the widespread occurrence of succulents and (Rebelo et al. 2006). Historical data suggest that the strandveld vegetation (CFDS) attracted a large number of browsers and mixed-feeder herbivores (Skead et al., 2011) due to the abundance of edible succulent and grasses (Boshoff and Kerley 2001). The sand fynbos (CFSF) instead attacted

grazers during the early stages of post-fire regeneration when grasses and other edible plants are abundant (Altwegg et al., 2014; Kraaij and van Wilgen, 2014). Notably, these vegetation types have been heavily invaded and even replaced by alien vegetation including *Acacia saligna* and a number of invasive and non-native grasses (Taylor, 1972), and by urban development.

Two other vegetation types occur on the adjacent slopes of Table Mountain, the Peninsula Sandstone Fynbos (PSdF) and the Peninsula Granite Fynbos (PGrF) (Fig. 2), where proteoid and ericoid forms dominate. The Cape Winelands Shale Fynbos (CWShF), which occurs on the northeast slopes of Table Mountain, sustains a high diversity of proteoid and ericoid forms, and a number of geophytes (Rebelo et al. 2006). Pockets of Afrotemperate forest occur in some of the narrow gorges (known locally as *kloofs*), especially on the southeast facing slopes of Table Mountain (vegetation type SnAF, Fig. 2). The forest species in this vegetation type include *Afrocarpus latifolius* (formerly *Podocarpus latifolius*), *Ocotea bullata*, *Olinia ventosa, Cunonia capensis*, and *Rapanea melanophleus* (Rebelo et al., 2006).

Renosterveld, a shrubland community dominated by *Elytropappus rhinocerotis* (renosterbos), dominates the northern and northwestern fringes of the Cape Flats (Fig. 2) and includes in this area two vegetation types, SShR and SGrR, which develop on shale and granite respectively. Unlike most of the other fynbos types, grasses tend to be better represented in renosterveld (Rebelo et al., 2006; Kraaij and van Wilgen, 2014; Anderson et al., 2014), although this mainly depends on fire frequency and herbivore incidence (Kruger, 1979; Kraaij and van Wilgen, 2014). However, due to its relatively rich soils among the regional vegetation types, most of the renosterveld in this region has been cleared for agriculture or other forms of development.

3. Methods

3.1 Core sampling and age model

The 210.5-cm core (labeled PV11.3) was obtained from the northern shore of the lake on a narrow reed belt using a vibracorer. The core was taken at this locality because recent dredging had caused loss and disturbance of deposits in the center of the lake (Kirsten and Meadows, 2016). The core was subsampled for different proxies, including grain-size distribution, organic carbon content, pH, diatoms, pollen and spores, and phytoliths. Grain-size distribution, organic carbon and pH were processed and analyzed by Georgiou (2011) and reproduced here (Fig. 3). The descriptions of the units were originally published in Kirsten (2014) and Kirsten and Meadows (2016). The proxies presented various degrees of abundance and preservation, which resulted in differential resolution among the sets of proxy data (Fig. 3, far-right column).

Fig. 3 about here.

The core was previously dated (Kirsten and Meadows, 2016), but is presented here along with the age profile of core vZB studied by Neumann et al. (2011). The age model of the latter is updated here so that both cores are presented using new age models created by Bacon v. 2.2 (Blaauw and Christen, 2011) based on the SH13Cal curve (Hogg et al. 2013). The two resulting models are used to correlate the pollen records (See Supplemental Material, Section S3, and Supplemental Data Tables).

3.2 $\delta^{18}O$ of diatoms

Due to the exploratory nature of this aspect of the study, only ten samples were extracted from the PV11.3 core at 15-20 cm intervals and processed at the Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, Germany. Initially, the samples were chemically treated with 30 % hydrogen peroxide (H_2O_2) and 5-10 % hydrochloric acid (HCl) to remove organic matter and carbonates, respectively.

Between each chemical treatment, the solution was washed at least three times. Following this, the residue was diluted with 1000 ml of distilled water and allowed to settle overnight to remove clays. The supernatant liquid was later removed through vacuum suction and the resultant sample sieved to separate large diatoms and silt particulates (>60 μm) from mostly diatoms (10-60 μm), fine particulates and broken frustules (<10 μm), and some clay. If sufficient sample material for analysis was rendered in the larger fractions, each fraction was analyzed separately. Otherwise, upon visual inspection to validate the purity of the larger fractions, the samples 10-60 μm and >60 μm were once again combined. Finally, each sample was subjected to differential settling using sodium polytungstate at 2.3 density to separate diatom frustules from minerogenic matter. The sample was then washed three times prior to freeze-drying.

Approximately 600-800 mg of freeze-dried sample was required for each measurement; where sufficient sample material was recovered, multiple analyses were undertaken. Two laboratory standards were run between each sample to correct for instrumental drift error. For this study inductive high-temperature carbon reduction (iHTR) was utilized, which fully removes the outer hydrous layer of the diatom frustules (Lücke et al., 2005; Swann and Leng 2009). The technique involved superheating a sample of pure diatom frustules, which was placed within a glassy carbon rod, to two preset temperatures under vacuum (Swann and Leng 2009). To remove organic impurities within the frustule casing as well as the hydrous layer, the sample was heated

to 850-1050°C and evacuated before being further heated to 1550°C. At this temperature, the Si-O-Si bonds are broken and the liberated oxygen is converted to carbon monoxide. The carbon monoxide is then passed through to the gas isotope mass spectrometer (IRMS, Delta V Advantage, ThermoScientific) for oxygen isotope analysis (Lücke et al., 2005; Swann and Leng 2009). Oxygen isotope values are presented in δ notation in per mil (‰) as $\delta = \left(R_{sample}/R_{standard} - 1\right) * 1000$ with R_{sample} and $R_{standard}$ as isotope ratios ($^{18}O/^{16}O$) of sample and standard, respectively. Two standard materials (HT: 23.2 ‰, Pat81: 33.4 ‰) were used to benchmark the raw values to the VSMOW – SLAB scale (Chapligin et al., 2011). Analytical precision of standards and repeated measurements of samples was between 0.25 to 0.45 ‰.

3.3 Multi-proxy sampling and processing

To obtain pollen, spores, phytoliths and charcoal, seventy-two samples were weighed (c. 0.5-3.4 grams each) and sieved through a 140-µm grid. A *Lycopodium* tablet (batch 177745) was added to each sample. The samples were then treated in 10% HCl, heated in 5% KOH, with washing in between. The organics were then separated from the mineral fraction by means of heavy liquid floatation (sodium polytungstate, specific gravity 2.3). The residue was mounted in glycerine jelly on microscope slides. The specific methods for each proxy are described in the following sections.

3.4 Pollen and spores

Pollen grains were counted with the goal of obtaining a maximum of 300 counts and a minimum of 100. Those with less of 100 were not included in the diagrams. Pollen and spore diagrams were produced using Tiliagraph, version 2.0.41 (Grimm, 2018) and compared with

selected taxa of the higher resolution record from core vZB core (Neumann et al., 2011) in order to facilitate correlation of the respective pollen sequences. In this paper only a selection of taxa from both cores (PV11.3 and vZB) are presented. Refer to Supplementary Data Tables, for the full pollen counts for core PV11.3 and to the original (Neumann et al., 2011) for the vZB core.

3.5 Phytoliths

A minimum of 300 phytoliths was counted on each slide and classified into graminoid and non-graminoid. Graminoid includes phytolith morphotypes characteristic of Poaceae, Cyperaceae and Restionaceae (Cordova and Scott, 2010; Cordova, 2013) (see Supplemental Material, Section S4). Restionaceae include spheroids with various textures and surface appendices (Esteban et al. 2017b; Novello et al. 2018) and long morphotypes (Cordova 2013). Originally, the spheroids were described as "discoidal" (Cordova and Scott, 2012; Cordova 2013), but when rotated they turned out to be spheroids (Esteban et al., 2017b; Novello et al., 2018). Although variations of spheroids, elongates, and papillates in Restionaceae attest to the presence of Restionaceae, some of these forms may be produced by shrubs (Esteban et al. 2017a, 2017b; Novello et al., 2018).

Cyperaceae morphotypes include the typical achenes (i.e,, hats) and papillae of Piperno (2006) and a number of other morphotypes (cf. Cordova and Scott, 2010; Cordova, 2013; Cordova and Avery, 2017; Esteban et al. 2017a, 2017b; Mercader et al. 2010; Novello et al. 2018). Nonetheless, other plants including the Restionaceae (cf. above) and some Proteaceae, specifically *Leucodendron spissifolium*, produce papillae-like phytoliths (Novello et al. 2018). It is believed that because most wetland environments produce very few Cyperaceae diagnostic

phytoliths (Esteban et al. 2017b; Novello et al., 2018; the present study), a number of papillae may come from other fynbos plants.

Poaceae (grass) phytoliths include short-cells, long-cells, pointy, and bulliform grass phytoliths. Non-graminoid phytoliths include those most commonly referred to as woody plants such as globular, facetates, and woody-plant tracheids (cf. Esteban et al. 2017a, 2017b; Cordova and Avery, 2017; Novello et al., 2018). As graminoids produce more morphotypes, the non-graminoid-to-graminoid ratio is meant to represent the proportions of plants that do not belong to grass-like plants and in general, it provides an idea of closed shrub canopy versus open grassy spaces.

The short cells, or more properly grass silica short cells (GSSC), constitute phytolith morphotypes in the Poaceae, which are used as indicators of C_3 and C_4 grass subfamilies (Piperno, 2006; Rossouw, 2009). In the winter-rainfall zone of South Africa, the most dominant types are those of the C_3 grass subfamilies (Pooideae, Danthonoideae, and Ehrhartoideae), with considerably smaller proportions of C_4 grass subfamilies (Chloridodieae, Panicoideae, and Aristidoideae) (Cordova, 2013).

The classification of GSSC used here follows those of Cordova (2013), and Cordova and Avery (2017), and presented and described in Supplemental Material, Section S4. The C_3 group typically includes rondel types (5-A, 5-N, 3-C, 3-F), oblongs (4-E, 4-C, 4-K), reniforms (3-G, 8-G), trapezoid bilobates (8-A, 8-B, 8-C, 8-D, 8-E, 8-F), and round-lobe bilobates (10-Y, 10-Z). The C_4 groups include the Chloridoideae types such as the short and double saddles (9A and 9B), typical Panicoideae types such as bilobates (10-K, 10-W) and crosses (11-A), and the Aristidoideae types (10-A and 9-M). Additionally, the tall, plateau saddle (9F) is included here

as being one of the main components of *Phragmites australis*, although it is also reported in other grasses (Cordova 2013; Cordova and Avery 2014).

The GSSC ratios are used in this study to indicate the relative abundance of C_3 and C_4 grasses. The C_3/C_4 ratio was obtained by dividing the sum of C_3-diagnostic GSSC by the sum of all C_4-diagnostic GSSC. As C_3 grasses are abundant in the winter-rainfall zone of South Africa (Vogel et al., 1978), a mirror ratio, the C_4/C_3x100 GSSC ratio, is used to amplify the representation of C_4 grass.

It is important at this point to stress that incidence of C_4 grasses in the winter-rainfall zone of South Africa, where C_3 grasses dominate, has many complex causes, some related to moisture and some related to substrate and disturbance (Cordova, 2013). C_4 grasses, and particularly the drought-tolerant Chloridoideae, tend to be more abundant in the driest parts of the winter-rainfall zone (e.g., the succulent karoo) (Cordova and Scott, 2010; Cordova, 2013), while the Panicoideae increases towards the west along the coast with increasing summer rain (Cordova, 2013). Under these patterns of distribution, an increase in C_4 grasses may signal a climatic shift. Nevertheless, many non-climatic factors favor C_4 grasses in the winter-rainfall zone.

Modern observations also suggest that the distribution of C_4 grasses is associated with disturbance (Cordova, 2013; Cordova and Avery, 2017). For the Cape Flats, in particular, C_4 grasses are favored in the early stages of post-fire succession (Taylor, 1972). However, under conditions of fire-suppression other species are most likely to participate. Many of the presently disturbed areas in the Cape Flats characteristically have C_4 grass species such as *Pennisetum clandestinum*, a Panicoideae, and *Cynodon dactylon*, a Chloridoideae. In particular, ample distribution of the latter has been observed in the modern grounds around Princessvlei.

3.6 Paleofire proxies: charred particles and burnt-grass phytoliths

The occurrence and abundance of microscopic charred particles (i.e. microscopic charcoal) provides an indication of fire incidence around the lake. Although there are numerous ways to quantify microscopic charcoal from pollen slides, counting the total number of fragments of charcoal per unit of weight or volume of sediment may not provide a direct reflection of charcoal abundance, as fragments may result from breaking of charcoal particles through post-depositional sediment transformation and laboratory processing. Therefore, the approach taken by this study quantifies charcoal as the total area covered by charcoal particles on a microscope slide in relation to the original weight of the sample (Cordova et al. 2017). The relation between charcoal area on slide (in μm^2) and weight was calculated using *Lycopodium* markers. Thus, the results were presented as μm^2 of charcoal on a slide per gram of sediment. Customarily, charred particles in pollen studies are presented in size classes with the purpose of assessing local vs. regional fires. In this study, the sum of all sizes is calculated as well as two arbitrarily selected classes, $<50\ \mu m^2$ and $>50\ \mu m^2$. The sum of these two fractions provided the total charcoal concentration, which at the same time was used with sedimentation rates to calculate charcoal influx.

Burnt-grass phytoliths provide a suitable proxy for grassland fires (Boyd, 2002; Cordova et al., 2011) which may or may not always correlate with charcoal concentration and influx, but their presence may suggest burning of areas with grasses in the region. Burnt-grass phytoliths may occur as separate units or in the form of grass cuticles (Palmer 1976) (Supplemental Material, Section S5). The methodology for determining burnt grass phytoliths follows that used by Cordova et al. (2011), *viz*. the percent of burnt (i.e., smoke-stained) grass phytoliths to the sum of all grass phytoliths.

3.7 Coprophilous fungal spores

Ascomycete spores (or ascospores) produced by fungal growth on herbivore dung are used as a proxy for herbivore incidence (Richardson, 2001; Cordova et al., 2011), regardless of the type of herbivore (size, species, wild, or domesticated). *Sporormiella*, *Podospora*, and *Sordaria* spores are considered to be produced by coprophilous fungal spores (Graf and Chmura 2006; Richardson, 2001; van Geel et al., 2011). Their identification in this study follows the method of Gelorini et al. (2011) and van Geel et al. (2011). As suggested by several studies, not all ascomycete spores are uniquely associated with dung (Burney et al. 2003; Graf and Chmura, 2006; Richardson, 2001; van Geel et al., 2011). Their concentrations per gram of sediment were calculated using the *Lycopodium* spores. Other ascospore types, i.e., those not considered coprophilous fungal spores, are presented in the diagram as a separate group.

4. Results

4.1 Core chronology

The Bacon age model for the PV11.3 (Kirsten and Meadows, 2016) indicates a basal age for the core of c. 3903 cal yr BP (Fig. 4). Two phases with different sedimentation rates are recognized, *viz.* the section below 152 cm (c. 1644 cal yr BP) with an accumulation rate of 1 cm in c. 40 years, and an upper section that accumulated at a faster rate (1 cm in c. 10 years). This accumulation pattern differs from the vZB core (Neumann et al., 2011), possibly because the older core was not extracted very close to the PV11.3 location (although it was also on the north side of the lake). Showing less pronounced variations in sedimentation rates than the PV11.3 core, the vZB core averages 1 cm in c. 14 years between 322 and 108 cm. The top of the vZB

core sequence comprised a 73 cm floating mat that is presumed to have accumulated at a rate of approximately 0.25 cm/year based on the first records of alien neophyte taxa brought in by European settlers (Neumann et al., 2011).

Fig. 4 about here.

4.2 Sediment characteristics

PV11.3 consists of 210 cm of lacustrine sediment and approximately 17 cm of disturbed surface sediment (Fig. 3). Although changes through the profile are gradual, it is possible to distinguish several units based on color, grain size distribution, and organic content, which here are used as criteria for identifying sedimentary units (Fig. 3).

Unit 1 extends from the base of the core to 150 cm (c.1590 cal yr BP) and consists of black (2.5Y 2.5/1) sediment with relatively high proportions of medium and coarse sand, and smaller proportions of fine sand and silt. The proportions of coarse sands decline towards the top of the unit. Calculated sedimentation rates indicate that the deposition of this unit was relatively slow and uniform with the organic content varying from 100% in the bottom sample to 10% at the top of the unit.

Unit 2 extends between 150 and 130 cm (c.1700-1300 cal yr BP) and consists of light grey (2.5Y 6/2) fine sand and silt sediments with lower organic content than Unit 1. This unit coincides with a conspicuous increase in sedimentation rates from c. 0.2 to 2.0 mm/year. The predominance of sand and silt suggest either an increase in eolian deposition or shifts in stream energy input. Organic content in this unit is less than 5%.

Unit 3 extends between 130 and 65 cm (c. 1300-1040 cal yr BP) and consists of light yellowish brown (2.5Y 6/3) fine sand with small proportions of medium sand; the organic content is very low (usually less than 4%). High sedimentation rates (1.9 to 2.1 mm/year) and grain size characteristics suggest substantial inputs of eolian sand.

Unit 4 extends between 65 and 22 cm (c. 1040-560 cal yr BP) and consists of an alternating sequence of light grey (2.5Y 7/2) and black (2.5Y 2.5/1) fine sand, with inputs of medium sand and silt. Organic content is low, but variable, forming conspicuous darker layers interbedded lighter sandy layers. Sedimentation rates are lower than the unit below and inconsistent, suggesting changes in sediment inputs over time.

Unit 5 extends between 22 and 16 cm (c. 550-480 cal yr BP) and consists of a greyish brown (2.5Y 5/2) deposit dominated by fine sand with medium and coarse sand, and silt. Organic matter content remains low, but increases considerably towards the top boundary as sedimentation rates fall from c. 1.25 to 0.4 cm/year.

Unit 6 extends between 13 and 0 cm (c. 480 cal yr BP to near present) and consists of a light-brownish grey (2.5Y 6/2) sediment exhibiting higher sedimentation rates (from c. 0.4 to 0.8 cm/year). Unit 7 encompasses the top 17 cm (marked as 0 to -17) (Fig. 3) and consists of greyish brown (2.5Y 5/2) sediment with bioturbation, most likely corresponding to the soil formed on the lake shoreline where the core was taken (Kirsten and Meadows, 2016).

4.3 Diatoms and $\delta^{18}O$

Previous characterization of diatom habitat (Kirsten 2014; Kirsten and Meadows 2016) and the newly obtained $\delta^{18}O_{diatom}$ data from the PV11.3 are combined here in a single graph (Fig. 5).

In this section, only the $\delta^{18}O_{diatom}$ data are described. Diatom habitats indicators are mentioned in more detail in relation to all other proxies in the discussion section.

Fig. 5 about here

The $\delta^{18}O_{diatom}$ values remain within a narrow range from 36.0 ‰ to a maximum of 39.00‰ along the length of the core. Initially, enriched values of 38.4 ‰ at 2450 cal yr BP, declined to values ranging 36.3 - 36.6 ‰ between 1750 to 1300 cal yr BP. A diatom community with smaller sized frustules is evident between sample depths 100 cm and 73 cm, which rendered insufficient material for analysis in the 10-60 μm fraction, leading to a 300-year gap from 1300-900 cal yr BP in the isotope record. A further enrichment in $\delta^{18}O_{diatom}$ occurs from 900 cal yr BP before values peak at 500 cal yr BP. The modern water sample shows some isotopic enrichment (pers. Communication, Chris Harris).

4.4 Phytoliths

There is a relatively rich phytolith record for PV11.3, except between 195 cm and 172 cm (approximately 3500-2500 cal yr BP), where only one sample produced phytoliths, and between 62 cm and 82 cm (approximately 1100-950 cal yr BP) (Fig. 6). Concentrations per gram of sediment vary considerably throughout the profile with three prominent peaks. A first peak occurs at the base of the sequence (c.3900-3800 cal yr BP), a second in the only phytolith-bearing sample in an otherwise poor-preservation zone (c. 3100 cal yr BP), and a third around 500 cal yr BP. Moderate phytolith concentrations with various smaller peaks occur between 2100 and 1900 cal yr BP. Poaceae and Restionaceae phytolith morphotypes dominate throughout

the record, with the exception of the top 25 cm (c. 600 cal yr BP to present), where non-graminoid phytolith morphotypes become relatively abundant (Figs. 6).

Fig. 6. About here

The percentages of the different types of Poaceae phytoliths (short-cell, long-cell, pointy, and bulliform) show little variation throughout the sequence, except in the basal sample (c. 3800-3900 cal yr BP), where bulliforms dominate over other grass phytolith morphotype groups (Fig. 7). Anywhere else in the record, the short cells (i.e., GSSC) dominate in percent, followed by the long cells and the pointy morphotypes (i.e., trichomes).

Fig. 7 about here.

The most abundant morphotype associated with the C_3 grasses in this record is the common rondel (5-N). However, large proportions of oblongs (4-E, 4-C, and 4-K) and reniforms (3-G and 8-G) tend to be abundant in some samples (Fig. 8). Within the C_4-grass diagnostic GSSC morphotypes, the saddles are the most common (9-A). This morphotype, which is associated with the Chloridoideae grasses, increases considerably after c. 250 cal yr BP (Fig. 8). Typical panicoid-bilobates (10-K and 10-W) and crosses (11-A) are less abundant, but appear more frequently between c. 2200 and 400 cal yr BP. In general, the GSSC record and its ratios show a dominance of C_3 grasses (Fig. 8), which is typical of the winter-rainfall zone (Cordova, 2013). However, an important incidence of C_4 GSSC diagnostic types is evident in the ratios after c.

600 cal yr BP. Notably, this increase in C_4 GSSC corresponds mainly to the Chloridoideaed-type saddle (9-A).

Figure 8 about here

Cyperaceae phytoliths are rare in the record (Fig. 6), despite the relatively high frequencies of Cyperacaeae pollen, due most likely to the poor preservation of Cyperaceae-diagnostic morphotypes. Restionaceae phytoliths are more abundant in the record given the location in the fynbos area, and the good preservation and distinctiveness of their morphotypes (Cordova 2013; Esteban et al. 2017a). The Poaceae-Restionaceae ratio varies throughout the record, albeit with no marked changes, except near the base of the profile where grasses are clearly dominant over the restios (Fig. 6).

Among the non-graminoid phytolith groups, the globular types (decorated and undecorated), typically associated with trees (Piperno, 2006; Mercader et al., 2010; Esteban et al., 2017a, 2017b; Novello et al., 2018), have very poor representation in the samples of this core (Fig. 7). Conversely, the rounded blocky and irregular types, both typical in shrubs are common, particularly after c. 600 cal yr BP. The “undifferentiated dicots”, some of which have no association to a particular group of plants, appear in low frequencies, only increasing considerably after ca. 600 cal yr BP, at the time when non-graminoid phytoliths become noticeably prominent in the record (Fig. 6).

4.5 Pollen and spores

Differences in pollen frequencies among certain taxa in both cores exist (Fig. 9), probably because of differences in local pollen input at the two core localities. Although the exact location of vZB core is not known (Neumann et al. 2011), it is probable that it was closer to the feeding stream of the Diep River, as suggested on a small map in van Zinderen Bakker's notes. On the other hand, the location of the PV11.3 core is on the northern edge and definitely away from the feeding stream.

Fig. 9 about here.

The pollen record from PV11.3 (Fig. 9a), while having less resolution than the vZB core, reveals trends in the development of the most important plant taxa, that can be correlated with the re-calibrated, higher resolution record from the vZB core (Neumann et al., 2011) (Fig. 9b). However, the pollen records in the PV11.3 core is useful from a palynological point of view because it covers the period between 970 and 350 cal yr BP, which is absent from vZB due to a hiatus.

Despite the differences, some taxa bear noticeable correlation between the two cores. In particular, the distribution of *Morella* shows a clear parallel between the cores, mainly in its conspicuous peak between 3400 and 3300 cal yr BP (Fig. 9). Also, in some parts of the core Cyperaceae and Restionaceae present similar trends. Additionally, both cores coincide with the arrival of neophytes beginning c. 300 yr cal. BP. These include taxa such as *Pinus* and *Quercus*, and the increase in Myrtaceae, purportedly associated with the introduction of *Eucalyptus* trees (see Discussion).

By far the most abundant taxa in the core are Anthospermae (*Anthospermum* and *Carpacoce*), Ericaceae, and Restionaceae, followed by Asteraceae and Proteaceae, all of which are prominent components in fynbos vegetation. Restionaceae pollen frequencies exhibit little variation through the profile, except between 2350 and 1250 cal yr BP in the PV11.3 core (Fig. 9a) and between 2200 and 1800 cal yr BP in the vZB core (Fig. 9b). Restionaceae pollen frequencies are generally higher than Poaceae pollen frequencies in both cores. In core PV11.3, two Poaceae fractions of >22μm and <22μm, parallel each other, with the smaller fraction having more prominent peaks. Considerable increases in both fractions only occur after c. 600 cal yr BP. In the vZB core, Poaceae pollen increases considerably, but only after c. 250 cal yr BP.

Among the aquatic and subaquatic taxa, Cyperaceae and Haloragidaceae, display considerable variability along the sequence. Cyperaceae increases to reach maximum frequencies between c. 700 and 400 cal yr BP in core PV11.3. Haloragidaceae frequencies are reasonably consistent until c. 2500 cal yr BP, and subsequently become lower before reaching their highest values c. 200 cal yr BP. With the exception of this peak, however, the Haloragidaceae frequencies are not consistent between the two cores.

4.6 Fire and herbivore incidence proxies

Charcoal incidence in terms of concentration per gram of sediment show considerable parallel with charcoal influx (Fig. 10), except for a peak in the latter c. 1500 cal yr BP, which occurs earlier than the peak of charcoal concentration c. 1400 cal yr BP. The record of charcoal suggests for the most part regional fires, as particles smaller than 50μm^2 are considerably abundant, except for the period 3400-2600 cal yr BP when high incidence of both size classes (i.e,, smaller and larger than 50μm^2) suggest burning seems to be both local and regional.

Fire incidence becomes prominent between 3800 and 2600 cal yr BP, then undergoing a steady decline between c. 2600 and 1700 yr BP. After that, significant peaks occur at c. 2400 and 600 cal. yr BP. Burnt-grass phytoliths, though missing in the record before 2600 cal yr BP, do not parallel charcoal burning, as peaks happen at different times. This is understandable as the latter indicates only the burning of grasses, which are elements relatively rare in the fynbos. The only coincidence in the two records occur c. 1400-1200 cal yr BP.

The records of coprophilous fungal spores and other ascospores, along with records of micro-charcoal are the most complete of the sequence, as they are preserved in most of the samples in the core (Fig. 3). The concentration curves of coprophilous fungal spores (*Sporormiella*, *Podospora*, and *Sordaria*) co-vary throughout the profile, but not with the curve of other ascospores (Fig. 10). By far the highest concentrations of coprophilous fungal spores occurs between c. 3600 and 2200 cal yr BP, with a significant peak at c. 2600 cal yr BP and between 600 and 2000 cal yr BP with a prominent peak at c. 440 cal yr BP.

Fig. 10 about here

5. Discussion

5.1 Environmental changes at Princessvlei during the past 3900 years

Each set of proxies studied here reflects different aspects of the environment and each set presents different resolution, coverage, and gaps. For this reason, it is difficult to correlate events across the proxies. Thus, to discuss the general aspects of environmental change at Princessvlei, aspects synthesis diagram is necessary (Fig. 11). Additionally, such a diagram facilitates the correlation of local changes with changes in the broader region.

The combined pollen data from the two cores from Princessvlei reflect moist conditions between 3800 and 2600 cal yr BP. Neumann et al. (2011) interpreted this moist period by the increase of *Euclea*, Ericaceae, and Anthospermae, which is evident in core PV11.3 as well (Fig. 9). This moist phase has been identified in various other coastal lakes of the Western Cape (Meadows and Baxter, 1999; Martin, 1968; Carr et al., 2006, 2015; Wündsch et al., 2016, 2018; Kirsten et al., 2018, Quick et al., 2018).

During most of this moist period, charcoal concentrations indicate high incidence of fires (Fig. 10), due likely to increased biomass produced by the favorably wet conditions. Charred particle sizes suggest that both local and regional fires were common. Notably, however, towards the end of this wet phase, c. 2800-2600 cal yr BP, charcoal concentration slowly declines as coprophilous fungal spores increase. This change could be interpreted as large number of herbivores formerly favored by moist conditions congregating around the lake as moist conditions begin to dwindle.

Unfortunately, for the beginning of the moist period, the phytolith is scarce and the diatom record absent, a problem that might be caused by unfavorable conditions in the sediments of this zone for the preservation of biogenic silica, as some phytoliths from these levels show signs of excessive dissolution. Although pH at this depth fluctuates between 5.6 and 6.5, similar acid levels appear in other parts of the record, where diatoms are preserved. However, it is possible that other unknown post-depositional changes may be involved in the dissolution of silica.

Subsequently, pollen spectra in core vZB suggest a drying phase c. 2600 and 1900 cal yr BP (Neumann et al., 2011), as Ericaceae, Proteaceae and *Morella* decline, a pattern n in core PV11.3 (Fig. 9). During this time, the GSSC data and ratios show a decline in C_3 grasses in favor of the more drought resistant C_4 grasses (Fig. 8), supporting the drying conditions. During this same

time, charcoal incidence decreases considerably followed by a decline in coprophilous spores, suggesting both the decrease in vegetal biomass and the less frequent incidence of herbivores in the immediate area.

This dry phase detected in the proxies of Princessvlei coincide with the driest phase registered between 2250 and 2000 yr BP in the hydrological variations in the southwest river catchments within the winter rainfall zone interpreted as the result of a poleward migration of the Southern Hemisphere Westerlies (Granger et al., 2018).

This dry phase is not clear in the $\delta^{18}O_{diatom}$ record, as the only value shows a moderate enrichment (38.4 ‰) at 2450 cal yr BP, which would be more suggestive of wet conditions due to the incidence of westerlies (Harris et al. 2010). Nonetheless, between 2600 and 2400 cal yr BP, the diatom record show species indicative of turbidity (Kirsten and Meadows, 2016), which is consistent with the substantial presence of herbivorous fauna at c. 2400 cal yr BP, suggesting that large animals around the lake may have contributed to the turbid waters (Fig. 11). This initial high turbidity phase, however, grades into less turbid and more oligotrophic conditions between 2400 and 2200 cal yr BP as planktonic and nutrient-rich diatoms decline (Fig. 5). This shows a parallel decline with coprophilous fungal spores suggesting less favorable conditions for large herbivores around the lake (Fig. 11).

The pollen records after 1900 to c. 900 cal yr BP show variations, but not indicative of particularly moist or dry conditions. During this time, phytoliths show little change in the composition of the different groups (Figs. 6 and 7). The GSSC record, however, shows a recovery of the C_3 grasses between c.1700 and 1500 cal yr BP, but a decline in favor of the C_4 grasses occurs again between c. 1400 and 1200 cal yr BP.

Signs of vegetation disturbance during this period (c. 1400-1200 cal yr BP) are evident in several of the records. In particular, Restionaceae in the two pollen records display a short drop c. 1400 cal yr BP (Fig. 9). According to Neumann et al. (2011), this could be a sign of disturbance, which in the record coincide with an increase in regional burning (Fig. 11). However, a modest incidence of predominantly smaller than 50μm^2 charcoal particles suggest that burning was not local. Furthermore, the sudden increase in burnt-grass phytoliths suggest that perhaps sizable areas of grass were burned, which is likely to have occurred in the broader region, perhaps in the renosterveld, and not in the grass-poor fynbos vegetation around the lake. Interestingly, although charcoal incidence decreases at c. 1200 cal yr BP, the incidence of burnt-grass phytoliths continues for a few more centuries (Fig. 11).

Diatom species present during c. 2000-1750 cal yr BP favor high nutrient availability, most likely sourced from surface run-off (Kirsten and Meadows 2016) (Fig. 5). Depleted $\delta^{18}O_{diatom}$ values from 1750 to 1300 cal yr BP are accompanied by a transitional phase in the diatom community as it shifts to a predominantly nutrient-poor, dilute environment, which favors benthic taxa (Fig. 5). This coincides with little changes in vegetation and the paucity of local herbivore disturbance (Fig. 11).

During the period c. 900-600 cal yr BP, pollen records disagree with each other in the proportions of certain taxa. For example, Restionaceae decrease first and increase and then decrease again in the PV3.11 core, but increase steadily in the vZB core (Fig. 9). Interestingly, the Restionaceae phytolith record does not support either scenario. During this period, the diatom species show mostly benthic species and those tolerant of low nutrients at the time when the $\delta^{18}O_{diatom}$ record show still depleted values (Fig. 5)

Between 600 and 400, however, changes are conspicuous in all records. The pollen record in the core PV11.3 (but not in vZB) has major shifts in almost all taxa, notably the increase of Cyperaceae and Poaceae (<22 μm), the decrease of Ericaceae, the abrupt decline of Restionaceae, (Fig 9a). The phytolith record shows the rapid increase in non-graminoids (Fig. 9), particularly the rounded blocky and irregular types, which dominate until the present. The GSSC record shows a noticeable shift to the C_4 grasses. Likewise, the $\delta^{18}O_{diatom}$ shows an abrupt increase in tandem with rapid increase in planktonic and epiphytic species typical of nutrient-rich environments (Fig. 5). The concentration of charcoal and coprophilous fungal spores increase dramatically during this period. Burnt-grass phytoliths, however, show an increase, but somehow out of phase with the increase in charcoal, notably spanning the period c. 800-550 cal yr BP (Fig. 10).

Among trends apparent in both pollen records after c. 400 cal yr BP are the increases in Anthospermeae and Poaceae, and a decline in Restionaceae. The eventual appearance of *Pinus* and *Quercus* c. 300 cal yr BP point to the European introduction of exotic flora (Fig. 9). Although there are African Myrtaceae (*Metrosideros*), distinction to the level of genus is not possible. Therefore, the significant increase in Myrtaceae pollen in recent centuries is presumed to reflect the introduction of *Eucalyptus* spp. In terms of phytoliths, the trends are similar to the previous period, with more non-graminoids than graminoids, and with relatively high incidence of rounded blocky and irregular phytoliths typical of shrubs (Fig. 7). Charcoal and burnt-grass phytolith decline, but become prominent in the topmost sample, suggesting perhaps fire suppression with a recent peak in fire incidence. Coprophile fungal spores practically disappear during this late period, suggesting a decline of herding around the lake. Changes in the diatoms are difficult to discern because the topmost 200 years are missing in the record. However, at the

beginning of the period the trend towards more planktonic and nutrient-rich species seems to be the result of pollution.

5.2 Pre-European pastoralism and the records of Princessvlei

Because human impact on the environment is a complex phenomenon, multi-proxy data are the best way to corroborate changes caused by human activities. Therefore, this study attempts to analyze the multi-proxy record of Princessvlei against the archaeological record of early pastoral societies in the Cape.

Neumann et al. (2011) attributed an increase in micro-charcoal starting at c. 1900 cal yr BP to the possible presence of pastoralists around the lake and noted the coincident changes in the vegetation. They also allude to the temporary reduction of *Morella* and the concomitant increase of Anthospermeae, Cyperaceae and Ericaceae at c. 1800 cal yr BP (Fig. 9) as possibly caused by pastoral disturbance. The timing of such vegetation changes coincides with the earliest radiocarbon ages associated with domestic sheep remains in Later Stone Age sites within the winter-rainfall zone of South Africa, ranging between c. 2100 and 1800 cal yr BP (cf. Bousman 1998; Sadr 1998; Smith 2008).

Although a relatively high increase in burnt-grass phytoliths occurs between 2000 and 1400 cal yr BP (Fig. 10), other proxies in core PV11.3 do not indicate human-led fire disturbance, grazing, and evident vegetation change coinciding with these early dates. Minor, albeit abrupt increases in micro-charcoal concentration and influx, and burnt-grass phytoliths occur c. 1400-1200 cal yr BP. During this period, however, the PV11.3 pollen record (Fig. 9b) registers sudden changes in Restionaceae, Anthospermae and Asteraceae, which may be associated with some

disturbance by fire. However, the paucity of coprophilous fungal spores in the lake sediments at during that time suggests that herding did not occur around the lake or in its catchment area.

It is only around and after c. 600-500 cal yr BP that all the proxy records in PV11.3 suggest changes associated with strong herding presence near Princessvlei and a more consistent occurrence of fire and vegetation change in the broader region. Microcharcoal concentration, influx, and burnt-grass phytolith frequencies become prominent between 600 and 400 cal yr BP, while a prominent peak in coprophilous fungal spores centers between 600 and 500 cal yr BP. The pollen record in the vZB and PV11.3 cores register increases in Poaceae and Asteraceae also at around 600-500 cal yr BP (Fig. 9), suggestive of widespread vegetation change in the Cape Flats and adjacent areas. This change coincides with major increases in planktonic, nutrient-rich diatom species, which would point to eutrophication (Fig. 5). At the same time, the record indicates an increase in micro-charcoal, burnt grass phytoliths, and coprophilous fungal spores (Fig. 10), which collectively are most likely the best evidence of pastoral activities around the lake and in the broader region.

If pastoralism existed in the Cape between 2000 and 1800 cal yr BP, as the archaeological record shows, it would have been limited restricted to optimal areas near springs and richer soils (i.e., Renosterveld and floodplain vegetation). Early evidence for domestication of grazing animals is associated with the Vredenburg Peninsula on the west coast and Boomplaas Cave on the south coast (Smith, 2006). Both regions (off the map of Fig. 2) have easier access to larger perennial rivers, springs, and richer soils (Smith, 1992; Smith, 2006), and both are within or in close proximity to the renosterveld vegetation, which has been deemed as one the most appealing vegetation types to domesticated livestock (Deacon 1983; Smith 1992, 2006). Such habitats are not characteristic of the areas immediately around Princessvlei and the Cape Flats altogether.

There is an interesting pattern in grass phytoliths in the records that may suggest the effects of pastoral activities, particularly after 600 BP. The evident shift from C_3 to C_4 grasses after c. 600-500 cal yr BP (Fig. 8) seems not to be associated with climatic shifts that would favor C_4 grasses. Records from Verlorenvlei show an increase in moisture around 500 cal yr BP (Stager et al., 2012), which would have favored the C_3 grasses, but not the C_4. Furthermore, C_4 grasses, as seen today in the Cape Flats and other areas of the Cape, are prone to occupy disturbed areas (Taylor 1972; Cordova 2013).

If an increase in C_4 grasses resulted from changes in veld management, it is important to consider that livestock was introduced to the winter-rainfall zone of the Cape region from the summer-rainfall areas of Africa, where C_4 grasses predominate. Interestingly, the $\delta^{13}C$ values on human remains from pastoral sites in the broader winter-rainfall region of South Africa suggests a shift to C_4 plants after c. 1000 cal yr BP, a change that coincides with the introduction to cattle in the Cape Region (Sealy, 2010). Before then, the mixed-browser fat-tail sheep provided most of the diet. Cattle, which were putatively acquired from pastoral groups in the east (summer rainfall region) was probably more prone to consuming C_4 grasses (Sealy, 2010). However, this regional shift occurred at least 400 years earlier than the shift to C_4 grasses in the GSSC record at Princessvlei. Therefore, solving the relation between introduction of livestock and change in veld composition requires further, more detailed studies associated with settlements and faunal remains.

6. Conclusions

Despite data gaps in the core sequence, the use of a wide range of different proxies facilitates a robust reconstruction of the environmental changes that occurred around Princessvlei during the

past 3900 years. The pollen and phytolith records complement each other, while the diatoms are helpful in distinguishing the changing influence of climate and hydrology on the local environmental processes. Additionally, the co-occurrence of phytoliths and diatoms, both biogenic silica, reveals information about processes of dissolution in parts of the core.

The combination of proxies indicate that the relatively moist period (3800-2600 cal yr BP) is accompanied by an escalation in fires, due possibly to biomass fuel increase. The subsequent dry period (2600-1900 cal yr BP), evidenced by pollen data, begins with a decline in fires. At the beginning of this dry period, an increase in coprophilous fungal spores, suggests congregation of fauna around the water body, which is evident in water turbidity by planktonic and nutrient-rich diatoms. During this time, intermittent, but noticeable increase in C_4 grasses c. 2400-1600 supports the occurrence of dry conditions. The diatom and $\delta^{18}O_{diatom}$ record suggests that dry conditions may have lasted until about 900 cal yr BP, during which rain-bearing cyclones shifted southwards. Regional records suggest that moist conditions returned c. 500 cal yr. However, this moist phase is not clear in the Princessvlei record due to noise introduced by human disturbance, b

Although archaeological evidence suggests that pastoralism was present in the Cape as early as c. 2000 cal yr BP, the multi-proxy record from the PV11.3 core does not show clear evidence of herding in Princessvlei or its immediate area until much later. Incidence of charcoal and burnt grass-phytoliths between c. 1400 and 1200 cal yr BP suggest perhaps regional burning which may be associated with herding activities. However, strong evidence of local water and vegetation disturbance suggestive of herding in the immediate area of Princessvlei appears in the records only after c. 600 yr BP, when concentrations of coprophilous fungal spore peak, diatoms indicate eutrophication of the lake, and pollen indicates marked vegetation changes. At this

time, grass-phytolith record shows a shift from C_3 to C_4 grasses, which seem not have been steered by climatic shifts but by human disturbance through livestock and veld management.

Pollen of neophyte plant species in the pollen records at c. 300 yr cal yr BP signal the European colonial introduction of alien species which, coupled with a decline in micro-charcoal concentration and burnt-grass phytoliths, appears to have been accompanied by a regional decline in fire frequency. In the most recent sediments (c. 250 yr BP), the C_4 grasses increase considerably, this time due to disturbance and introduction of alien grasses.

Multiple proxies from cores in small lakes in the Cape can provide a broader set of environmental factors, which present possibilities of correlating ecological interactions. As the case of Princessvlei show, it is possible to apply this multi-proxy approach to small, interdunal and coastal lakes in the Western Cape to complement the picture of late-Holocene climatic change and the transformations of fauna and humans.

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Supplemental Material

Supplemental Data Tables

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Supplementary Material: Additional Information and Tables

Figure captions

Figure 1. Area immediately surrounding Princessvlei (PV on map). Acronyms: LPV, Little Princesvlei; PV, Princessvlei; RV, Rondevlei; ZdV, Zandvlei; ZkV; Zeekoevlei; CFWTW, Cape Flats Water Treatment Works.

Figure 2. Vegetation types in the broader Cape and Cape Flats region.

Figure 3. The PV11.3 core, sediment texture, carbon percent, and samples tested for each proxy. Solid boxes on the far right indicate samples that produced enough material for analysis.

Figure 4. Age model using Bacon v. 2.2 for the P11.3 core, and recalibrated curve for the vZB core on dates previously published pollen record (Neumann et al., 2011). See original Bacon graph models in Supplementary Material, Section S3, and data in Table S2.

Figure 5. Summed percentage diatom data categorized by habitat preference, salinity, and nutrient tolerances. Freshwater, fresh-brackish and brackish-fresh water species are grouped under dilute. The $\delta^{18}O_{diatom}$ profile and modern water sample (SMOW) for core PV11.3.

Figure 6. Phytolith concentration and frequencies of major phytolith groups and ratios.

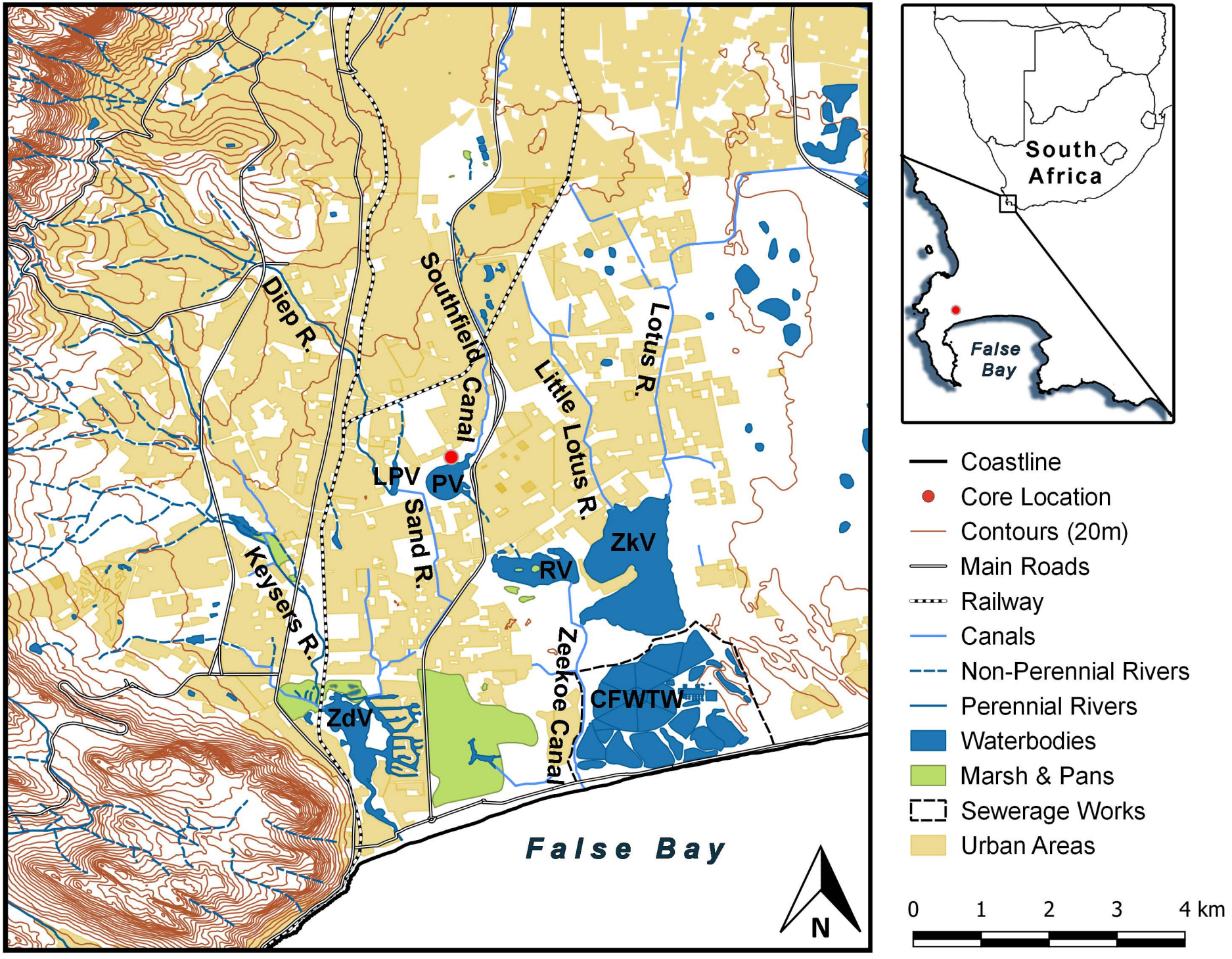
Figure 7. Percentages of Poaceae phytolith morphotypes and common non-graminoid morphotypes.

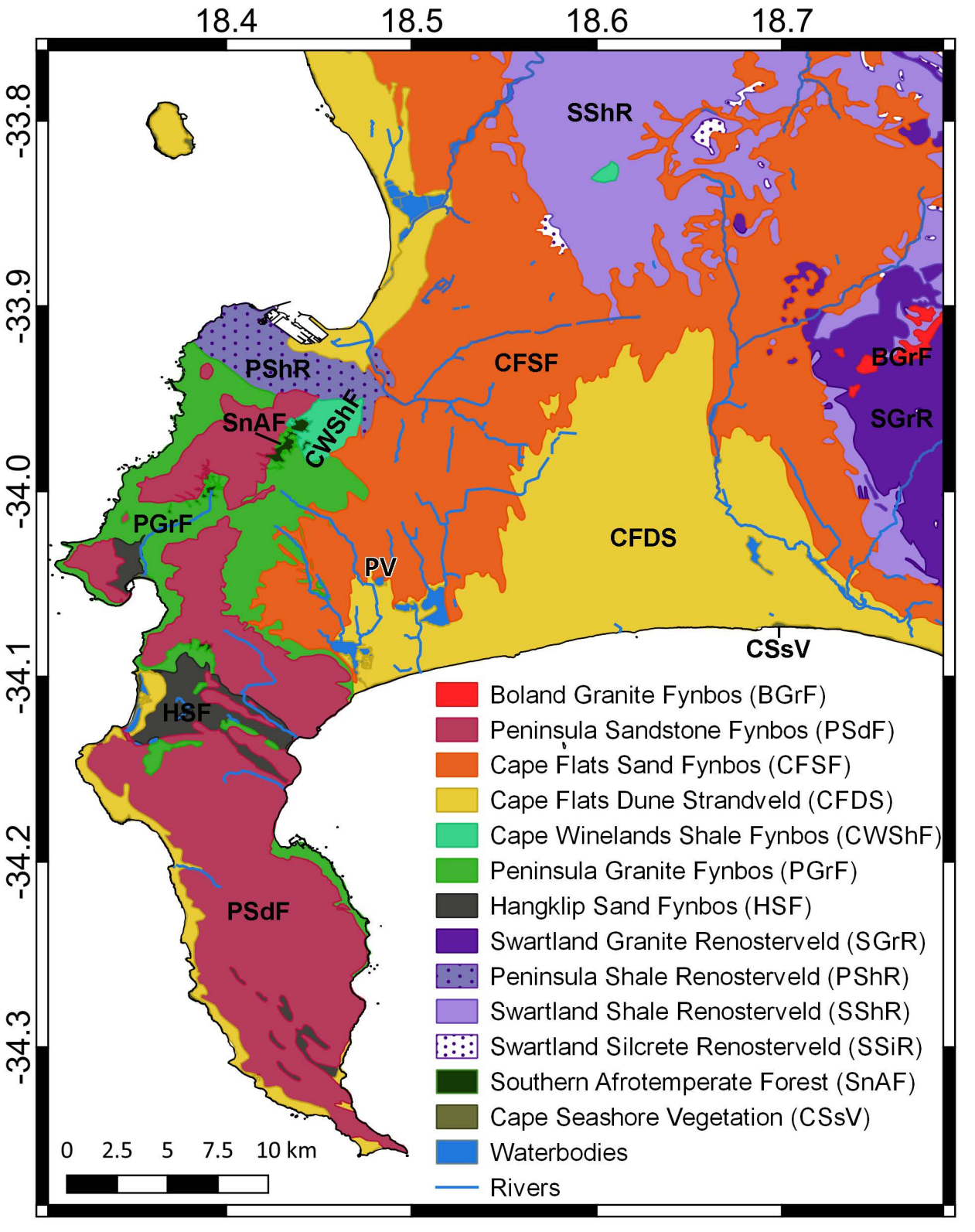
Figure 8. Grass silica short cells (GSSC) frequencies and ratios

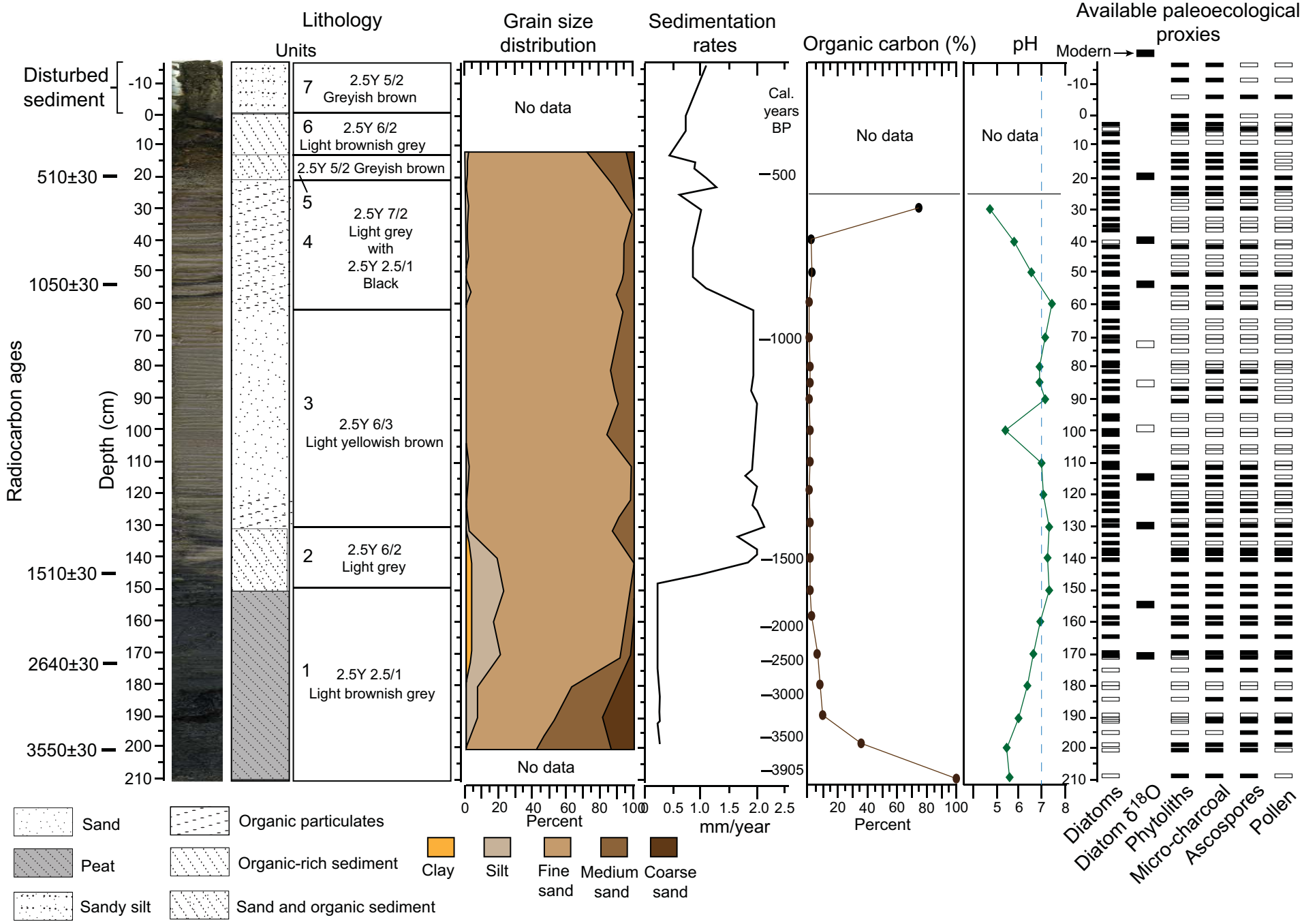
Figure 9. Pollen records from (a) the PV11.3 core (this study) and (b) and the vZB core (Neumann et al., 2011).

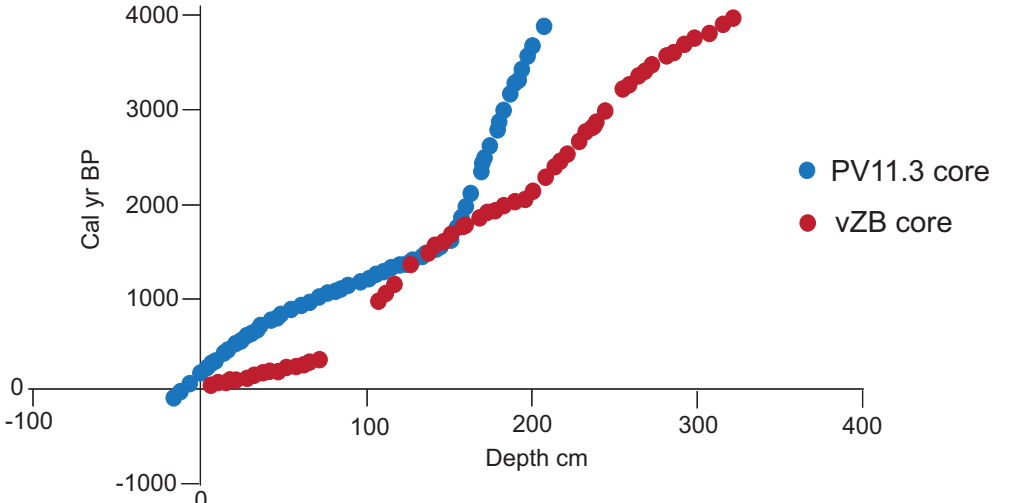
Figure 10. Coprophilous spores, other ascospores, microscopic charcoal, and burnt-grass phytoliths.

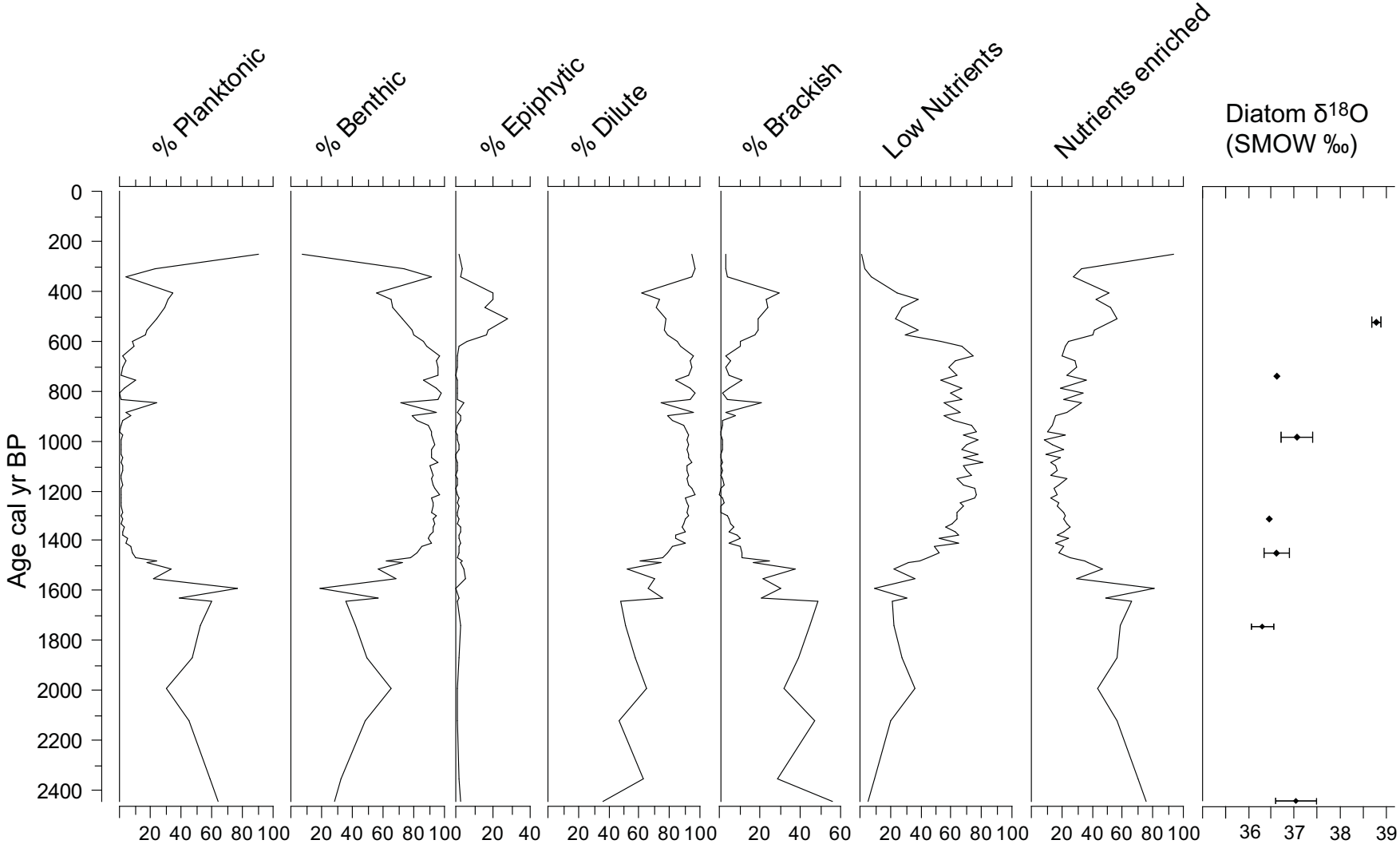
Figure 11. Synthesis of multi-proxy data from the cores obtained at Princessvlei in the context of environmental changes in the broader Cape Region.

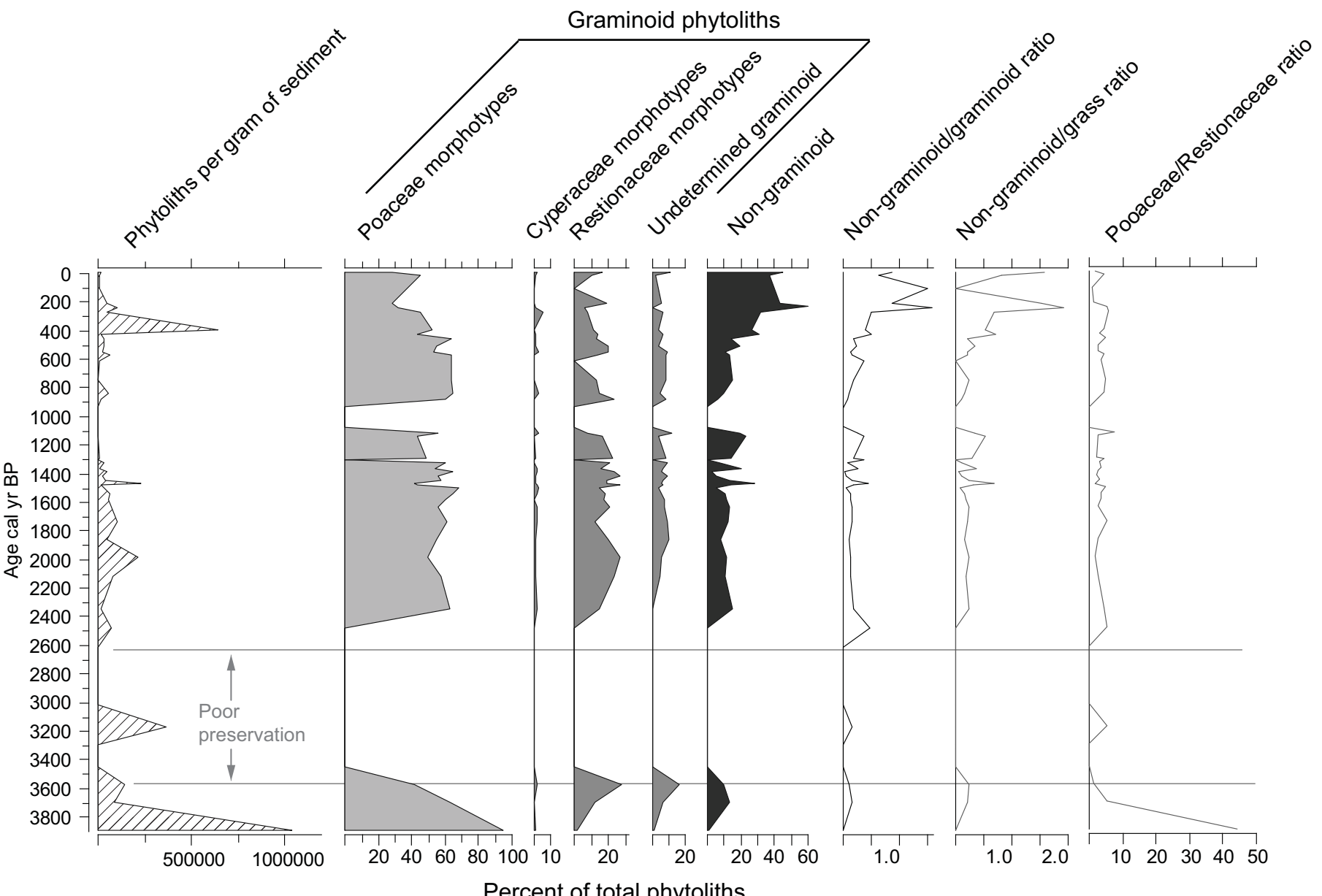

Diep R.
Southfield Canal
Little Lotus R.
Lotus R.
LPV
PV
Sand R.
Keysers R.
RV
ZkV
Zeekoe Canal
CFWTW
ZdV
False Bay
N
South Africa
False Bay
Coastline
Core Location
Contours (20m)
Main Roads
Railway
Canals
Non-Perennial Rivers
Perennial Rivers
Waterbodies
Marsh & Pans
Sewerage Works
Urban Areas
0 1 2 3 4 km

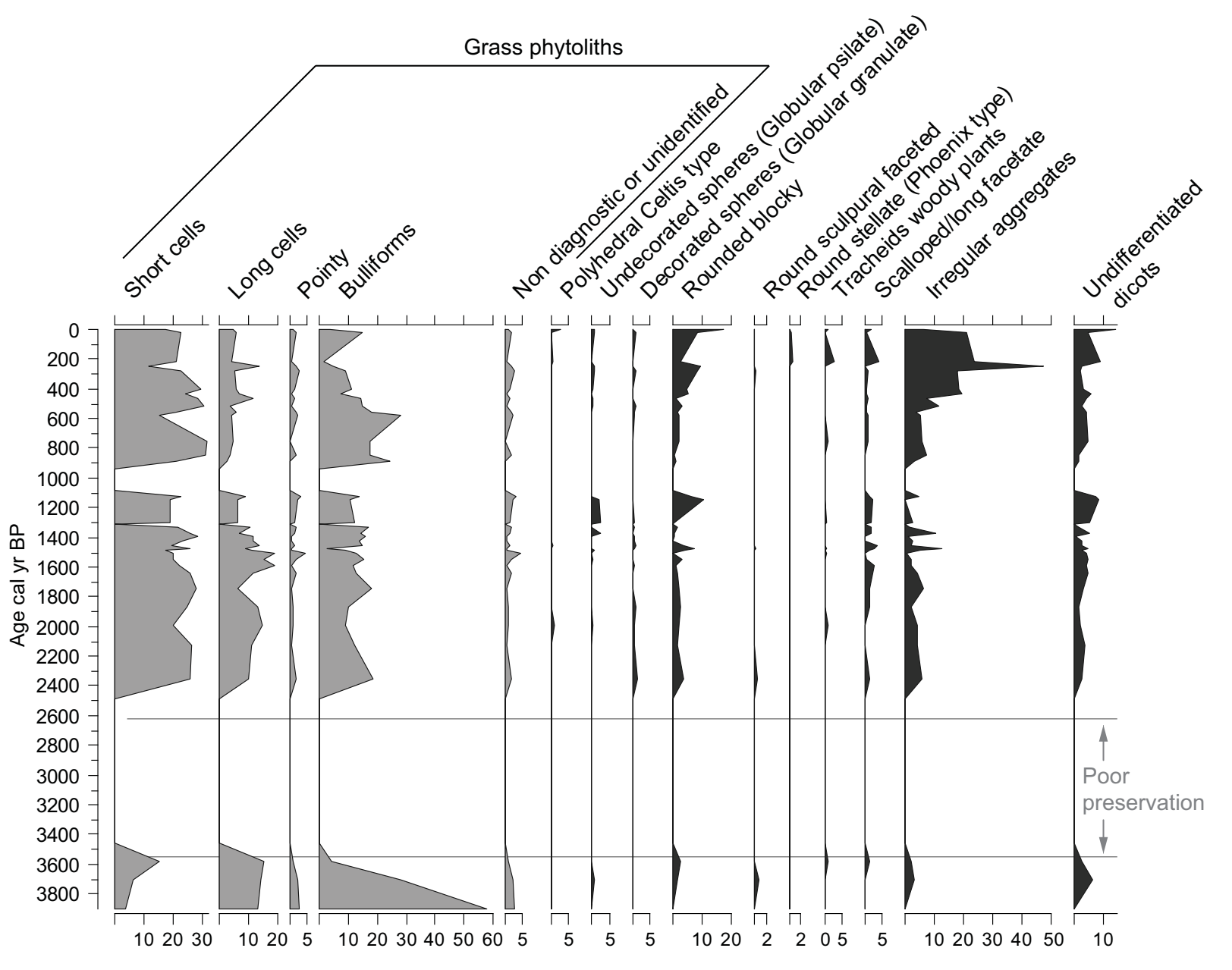

18.4
18.5
18.6
18.7
-33.8
-33.9
-34.0
-34.1
-34.2
-34.3
SShR
PShR
CFSF
BGrF
SGrR
SnAF
CWShF
PGrF
CFDS
PV
CSsV
HSF
PSdF
0 2.5 5 7.5 10 km
Boland Granite Fynbos (BGrF)
Peninsula Sandstone Fynbos (PSdF)
Cape Flats Sand Fynbos (CFSF)
Cape Flats Dune Strandveld (CFDS)
Cape Winelands Shale Fynbos (CWShF)
Peninsula Granite Fynbos (PGrF)
Hangklip Sand Fynbos (HSF)
Swartland Granite Renosterveld (SGrR)
Peninsula Shale Renosterveld (PShR)
Swartland Shale Renosterveld (SShR)
Swartland Silcrete Renosterveld (SSiR)
Southern Afrotemperate Forest (SnAF)
Cape Seashore Vegetation (CSsV)
Waterbodies
Rivers

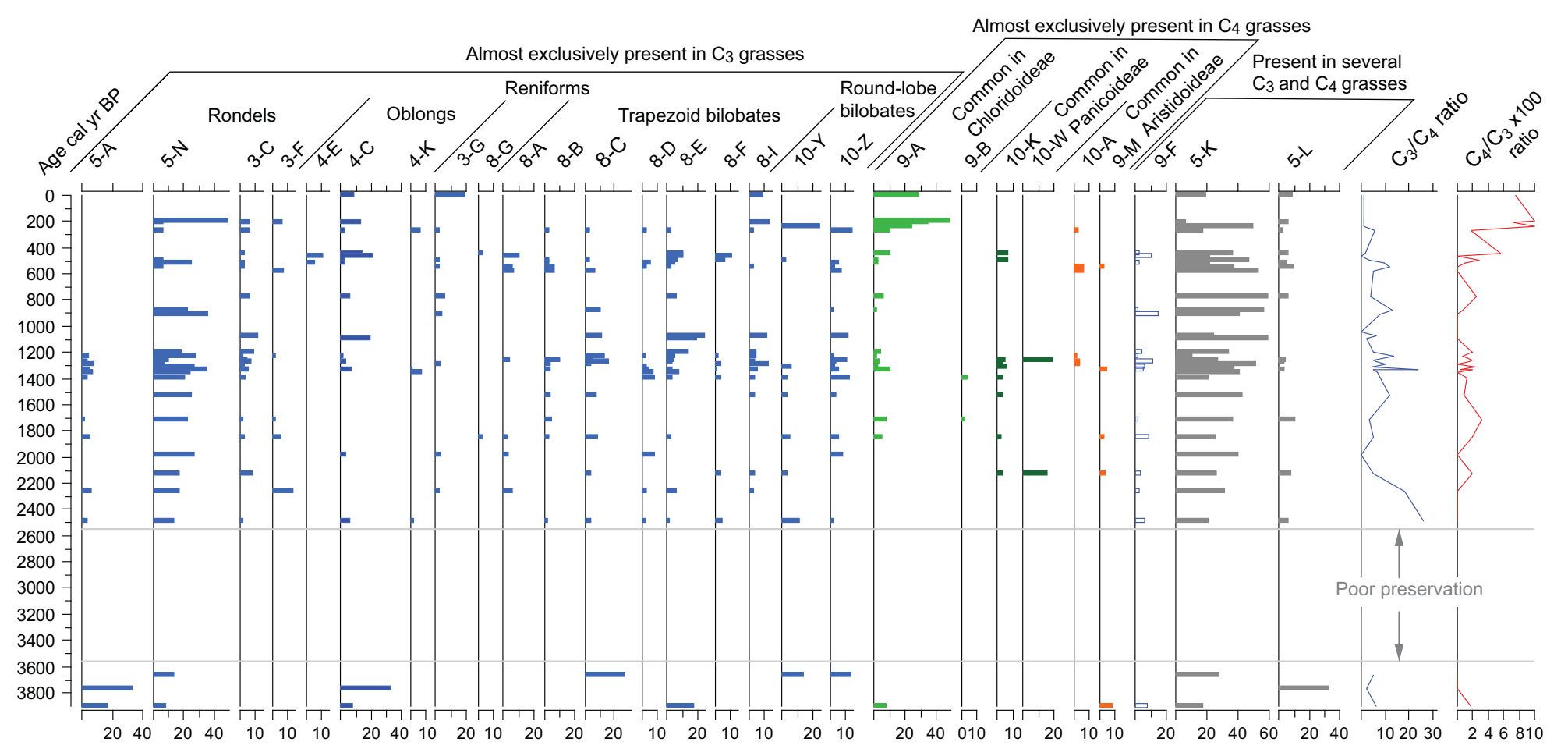

Lithology
Units
Grain size distribution
Sedimentation rates
Organic carbon (%)
pH
Available paleoecological proxies
Modern
Disturbed sediment
Radiocarbon ages
Depth (cm)
510±30
1050±30
1510±30
2640±30
3550±30
7 2.5Y 5/2 Greyish brown
6 2.5Y 6/2 Light brownish grey
2.5Y 5/2 Greyish brown
5
4 2.5Y 7/2 Light grey with 2.5Y 2.5/1 Black
3 2.5Y 6/3 Light yellowish brown
2 2.5Y 6/2 Light grey
1 2.5Y 2.5/1 Light brownish grey
No data
No data
Cal. years BP
No data
No data
Percent
mm/year
Percent
Diatoms
Diatom δ18O
Phytoliths
Micro-charcoal
Ascospores
Pollen
Sand
Peat
Sandy silt
Organic particulates
Organic-rich sediment
Sand and organic sediment
Clay
Silt
Fine sand
Medium sand
Coarse sand

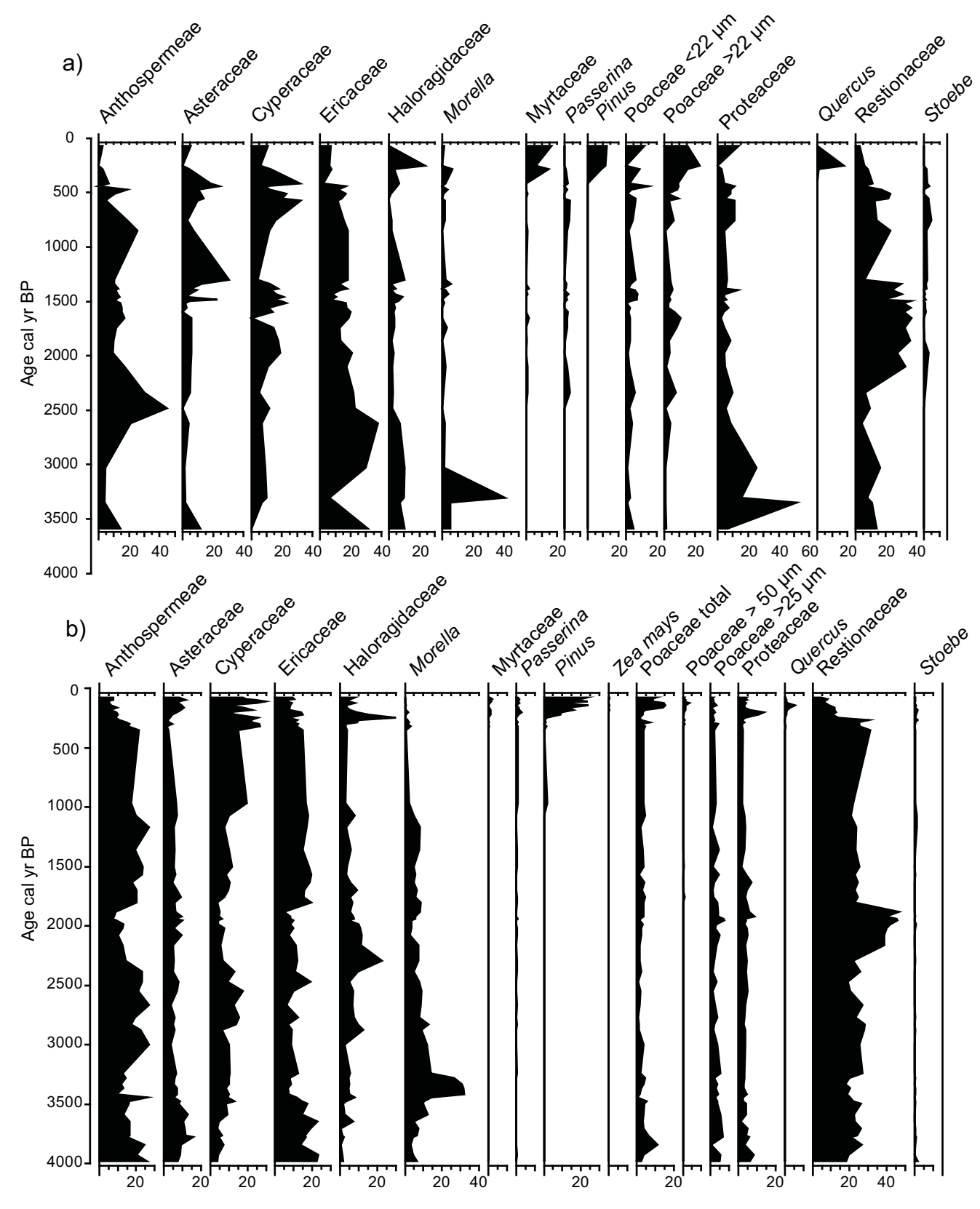

4000
3000
2000
1000
0
-1000
Cal yr BP
-100
0
100
200
300
400
Depth cm
PV11.3 core
vZB core

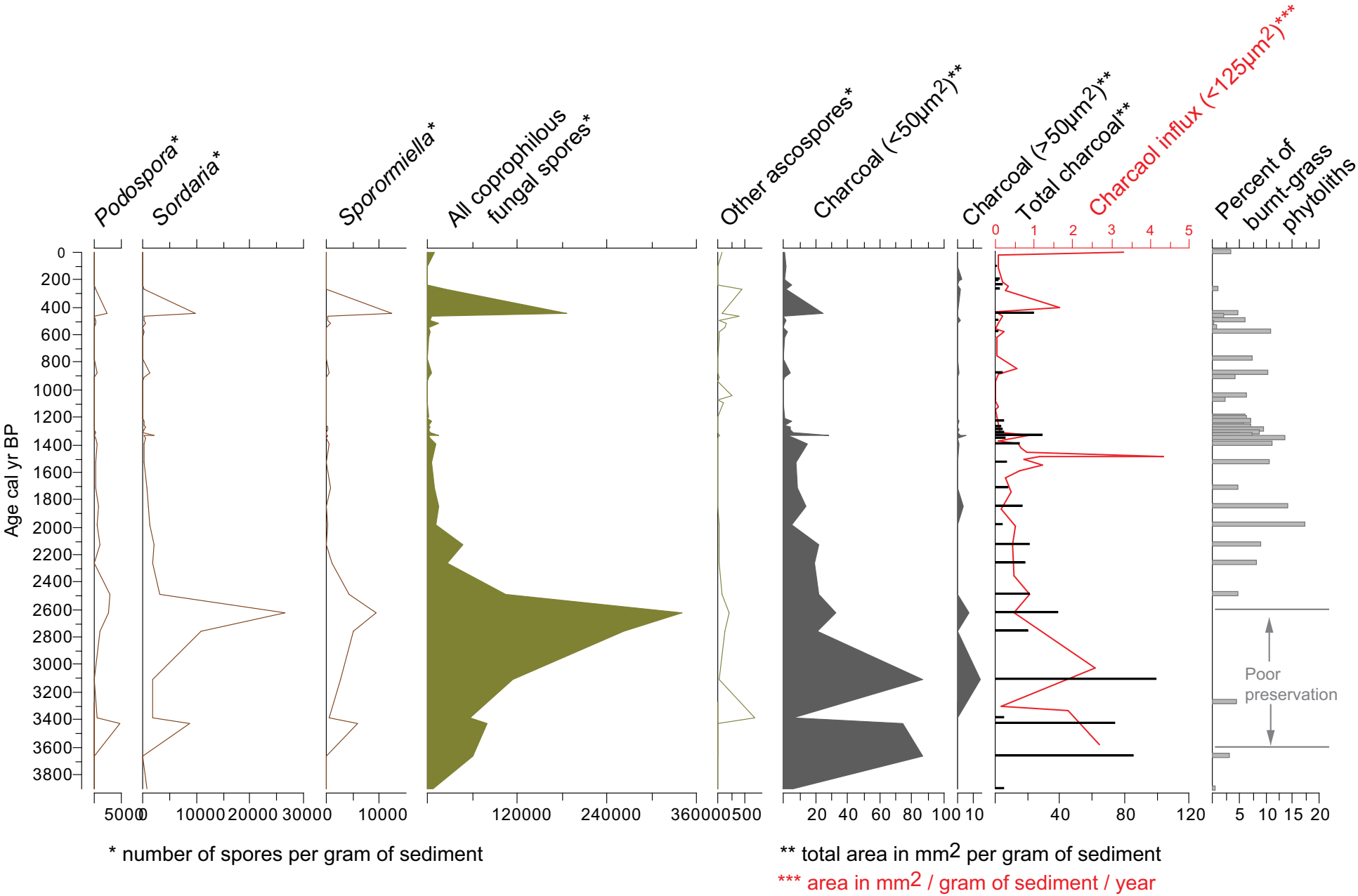

% Planktonic
% Benthic
% Epiphytic
% Dilute
% Brackish
Low Nutrients
Nutrients enriched
Diatom δ18O (SMOW ‰)
Age cal yr BP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
20 40 60 80 100
20 40 60 80 100
20 40
20 40 60 80 100
20 40 60
20 40 60 80 100
20 40 60 80 100
36 37 38 39

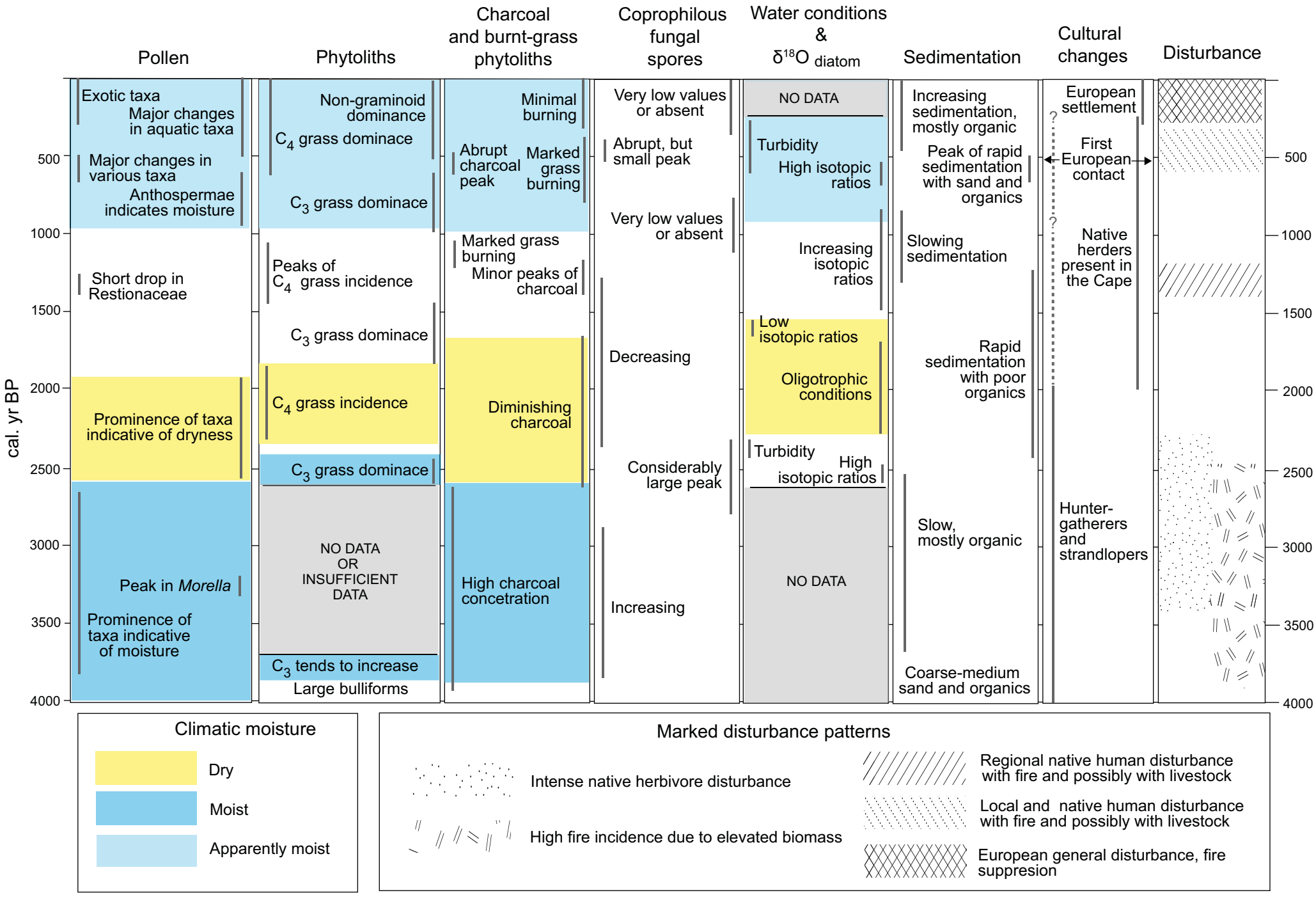

Graminoid phytoliths
Phytoliths per gram of sediment
Poaceae morphotypes
Cyperaceae morphotypes
Restionaceae morphotypes
Undetermined graminoid
Non-graminoid
Non-graminoid/graminoid ratio
Non-graminoid/grass ratio
Pooaceae/Restionaceae ratio
Age cal yr BP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
Poor preservation
500000
1000000
20 40 60 80 100
10
20
20
20 40 60
1.0
1.0 2.0
10 20 30 40 50
Percent of total phytoliths


Grass phytoliths
Short cells
Long cells
Pointy
Bulliforms
Non diagnostic or unidentified
Polyhedral Celtis type
Undecorated spheres (Globular psilate)
Decorated spheres (Globular granulate)
Rounded blocky
Round sculpural faceted
Round stellate (Phoenix type)
Tracheids woody plants
Scalloped/long facetate
Irregular aggregates
Undifferentiated dicots
Age cal yr BP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
Poor preservation
10 20 30
10 20
5
10 20 30 40 50 60
5
5
5
5
10 20
2
2
0 5
5
10 20 30 40 50
10


Age cal yr BP
Almost exclusively present in C3 grasses
Almost exclusively present in C4 grasses
Rondels
Oblongs
Reniforms
Trapezoid bilobates
Round-lobe bilobates
Common in Chloridoideae
Common in Panicoideae
Common in Aristidoideae
Present in several C3 and C4 grasses
5-A
5-N
3-C
3-F
4-E
4-C
4-K
3-G
8-G
8-A
8-B
8-C
8-D
8-E
8-F
8-I
10-Y
10-Z
9-A
9-B
10-K
10-W
10-A
9-M
9-F
5-K
5-L
C3/C4 ratio
C4/C3 x100 ratio
Poor preservation


a)
Anthospermeae
Asteraceae
Cyperaceae
Ericaceae
Haloragidaceae
Morella
Myrtaceae
Passerina
Pinus
Poaceae <22 µm
Poaceae >22 µm
Proteaceae
Quercus
Restionaceae
Stoebe
Age cal yr BP
0
500
1000
1500
2000
2500
3000
3500
4000
20
40
60
b)
Anthospermeae
Asteraceae
Cyperaceae
Ericaceae
Haloragidaceae
Morella
Myrtaceae
Passerina
Pinus
Zea mays
Poaceae total
Poaceae > 50 µm
Poaceae >25 µm
Proteaceae
Quercus
Restionaceae
Stoebe
Age cal yr BP
0
500
1000
1500
2000
2500
3000
3500
4000
20
40


Podospora*
Sordaria*
Sporormiella*
All coprophilous fungal spores*
Other ascospores*
Charcoal (<50µm²)**
Charcoal (>50µm²)**
Total charcoal**
Charcaol influx (<125µm²)***
Percent of burnt-grass phytoliths
Age cal yr BP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
5000
0
10000
20000
30000
10000
120000
240000
360000
0
500
20
40
60
80
100
10
0
1
2
3
4
5
40
80
120
5
10
15
20
Poor preservation
* number of spores per gram of sediment
** total area in mm² per gram of sediment
*** area in mm² / gram of sediment / year


Pollen
Phytoliths
Charcoal and burnt-grass phytoliths
Coprophilous fungal spores
Water conditions & δ18O diatom
Sedimentation
Cultural changes
Disturbance
cal. yr BP
500
1000
1500
2000
2500
3000
3500
4000
Exotic taxa
Major changes in aquatic taxa
Major changes in various taxa
Anthospermae indicates moisture
Short drop in Restionaceae
Prominence of taxa indicative of dryness
Peak in Morella
Prominence of taxa indicative of moisture
Non-graminoid dominance
C4 grass dominace
C3 grass dominace
Peaks of C4 grass incidence
C3 grass dominace
C4 grass incidence
C3 grass dominace
NO DATA OR INSUFFICIENT DATA
C3 tends to increase
Large bulliforms
Minimal burning
Abrupt charcoal peak
Marked grass burning
Marked grass burning
Minor peaks of charcoal
Diminishing charcoal
High charcoal concetration
Very low values or absent
Abrupt, but small peak
Very low values or absent
Decreasing
Considerably large peak
Increasing
NO DATA
Turbidity
High isotopic ratios
Increasing isotopic ratios
Low isotopic ratios
Oligotrophic conditions
Turbidity
High isotopic ratios
NO DATA
Increasing sedimentation, mostly organic
Peak of rapid sedimentation with sand and organics
Slowing sedimentation
Rapid sedimentation with poor organics
Slow, mostly organic
Coarse-medium sand and organics
European settlement
First European contact
Native herders present in the Cape
Hunter-gatherers and strandlopers
Climatic moisture
Dry
Moist
Apparently moist
Marked disturbance patterns
Intense native herbivore disturbance
High fire incidence due to elevated biomass
Regional native human disturbance with fire and possibly with livestock
Local and native human disturbance with fire and possibly with livestock
European general disturbance, fire suppresion

Multi-proxy evidence of Late-Holocene paleoenvironmental change at Princess Vlei, South Africa: The effects of fire, herbivores, and humans

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Supplemental material

Contents

S1 Dominant families and common species in the Cape Flats Sand Fynbos (CFSF) vegetation type (after Rebelo et al. 2006).

A. Dominant families

Shrubs (tall and short): Ericaceae, Asteraceae, and Proteaceae

Herbaceous forbs: Asteraceae, Aizoaceae, and Scrophulariaceae

Graminoids: Restionaceae

B. Common species

Shrubs (tall and short):

Woody: *Diastella proteoides, Diosma hirsute, Erica lasciva, E. muscosa, Phylica cephalantha, Senecio halimifolius, Serruria glomerata,* and *Stoebe plumosa.*

Succulents: *Crassula flava.*

Other common shrubs: *Anthospermum aethiopicum, Cliffortia eriocephalina, Erica capitata, Leucadendron floridum, Leucospermum hypophilocarpodendron.Metalasia densa, E. ferrea, Morella cordifolia, M. quercifolia, Protea scolimocephala, Staavia radiate.*

Herbaceous forbs:

Succulents: *Carpobrotus acinaciformis.*

Climbers: *Dipogon lignosus.*

Geophytes: *Watsonia meriana.*

Other common forbs: *Berkheya rigida, Conyza pinnatifida, Helicrysum tinctum, Indigofera procumbens,* and *Knowltonia vesicatoria.*

Graminoids:

Restios: *Elegia tectorum, Restio quinquefolious, Thamnocortus erectus, Willdenowia incurvata, Elegia juncea, Hypodiscus aristatus, Ischyrolepis capensis, I. paludosa, Restio bifurcus, R. quadratus*, and *Willdenowia incurvata*.

Grasses: C_3: *Chaetobromus involucratus Ehrharta villosa* var. *villosa, E. calycinia, Hordeum capensis, and Pentaschistis airoides.* C_4: *Cynodon dactylon* and *Sporobolus virginicus.*

Sedges and rushes: *Ficinia lateralis* and *Juncus capensis.*

S2 Dominant families and common species in the Cape Flat Dune Strandveld (CFDS) (After Rebelo et al. 2006).

A. Dominant families

Shrubs (tall and short): No dominant family

Herbaceous forbs: Asteraceae, Aizoaceae, and Crassulaceae

Graminoids: Poaceae

B. Common species

Shrubs (tall and short):

Woody: *Euclea racemosa, Metalasia muricata, Rhus glauca, Chrysantemoides monilifera, Cullumia squarrosa, Cassine peragua subsp. barbara, Pterocelastrus tricuspidatus, Salvia africana-lutea.*

Succulents: *Cotyledon orbiculata var. Spuria, Euphorbia mauritanica, Tetragonia fruticosa; Ruschia macowanii.*

Other common shrubs: *Eriocephalus africanus* var. *africanus, Morella cordifolia, Myrine Africana, Phylica ericoides, Passerina paleaecae, P. rigida, Rhus crenata, R. glauca, R. laevigata, and Thesidium fragile, Olea exasperata,*

Herbaceous forbs:

Succulents: *Carpobrotus acinaciformis, C. edulis, Conicosia pugioniformis subsp. Pugioniformis, Senecio littoreus.*

Climbers: *Babiana tubulosa* var. *tubiflora, Chasmanthe ethiopica, Trachyandra ciliata.*

Geophytes: *Babiana tubulosa* var. *tubiflora, Chasmanthe ethiopica, Trachyandra ciliata.*

Other common forbs: *Helicrysium crispum* (d), *Cineraria geifolia, Galium tomentosum, Knowltonia capensis, Helicrysium litorale, Lyperia tristis, Nemesia versicolor.*

Graminoids:

Grasses: C_3: *Ehrharta villosa* var. *villosa*, *Chaetobromus involucratus*

Restios: *Ischyrolepis eleocharis*, *Thamnochortus erectus*

Sedges: *Ficinia lateralis*

S3 Age models

Age models for the PV11.3 and vzB cores were created by Bacon v. 2.2 (Blaauw and Christn, 2011) using R version R 3.2.4 revised. Original RCYBP dates and generated calibrated dates in Tables S1 and S2 in the Excel sheet (Supplementary Data Tables) and generated curves for each core (PV11.3 and vZB) are shown in Figure S1.

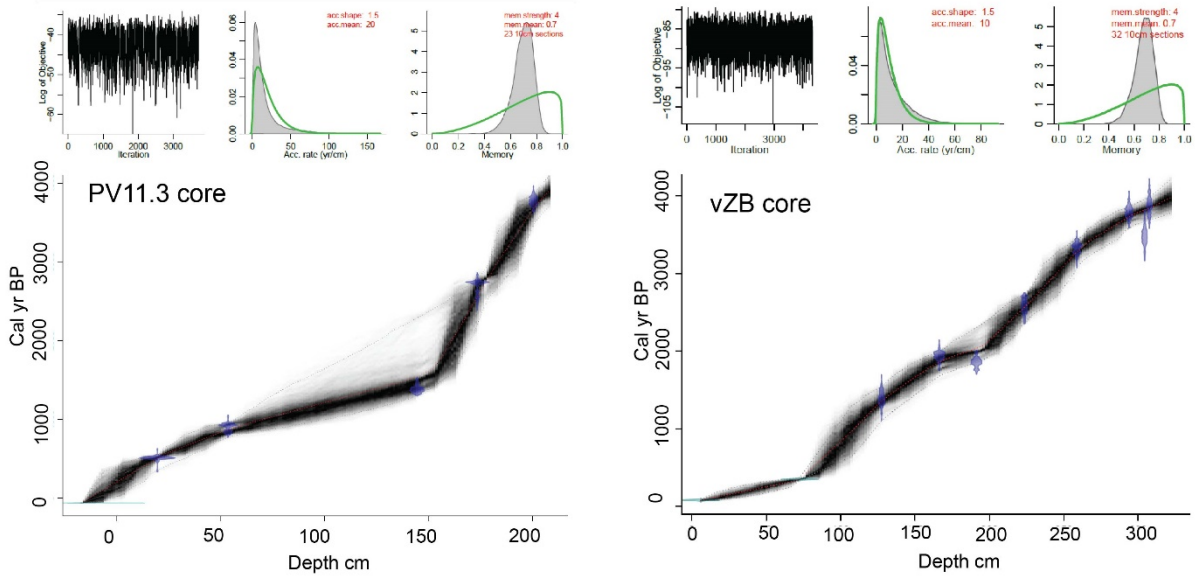

Fig. S1 Generated age models for PV13.1(left) and vZB (right). Original RCYBP and calibrated dates are in Tables S1 and S2 in the attached Excel Sheet (Supplementary Data Tables)..

S4 Criteria for graminoid phytolith identification.

Graminoid phytoltihs here include those produced by Poaceae, Restionaceae, and Cyperacaeae. Some of the typical morphotypes for each are included in Fig. S2.

The classification of GSSC used in this study (Fig. S3) follows closely the one previously published by Cordova and Scott (2010) and Cordova (2013), slightly modified and updated for the present study (Table S1). This classification has its basis on the nomenclature proposed by Madella et al. (2005) and uses terms from Piperno (2006) and a number of other studies (Fredlund and Tieszen, 1994; Alexandre et al. 1997; Barboni and Bremond, 2009; Neumann et al., 2009; Rossouw, 2010).

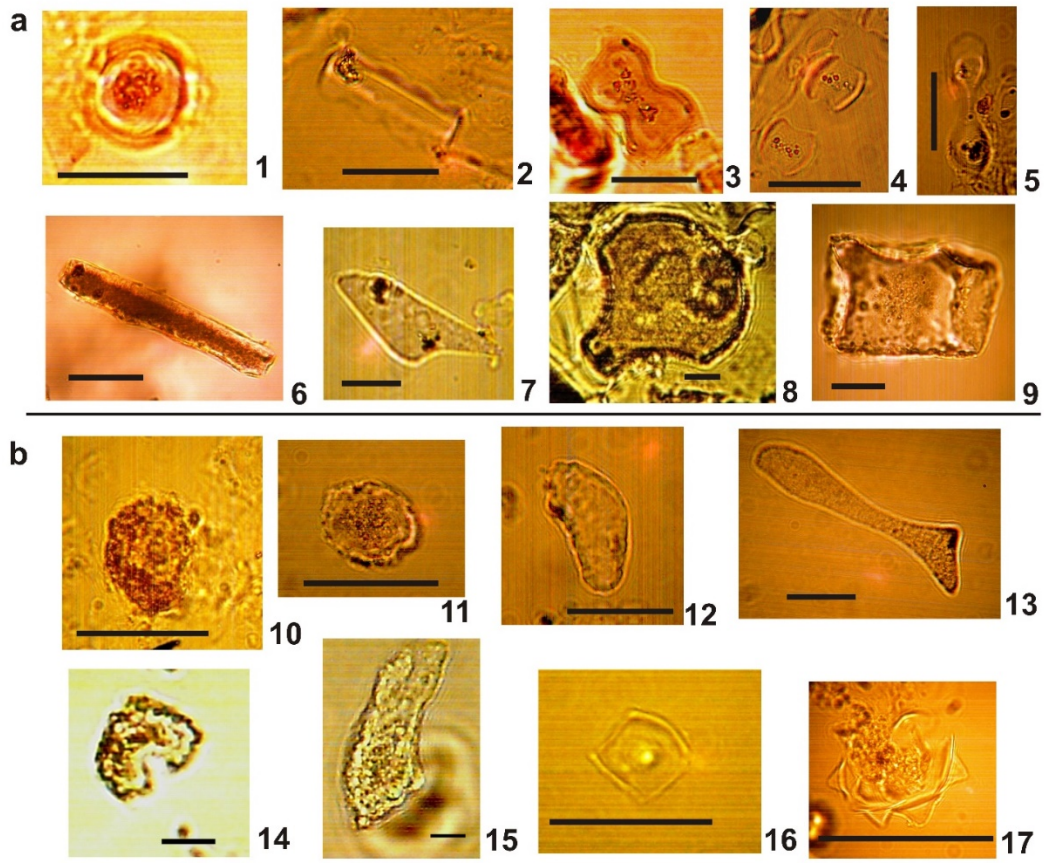

Fig. S2 Selected graminoid phytolith morphotypes. All bars are 20µm long. (a) Poaceae phytoliths Short cells: 1, rondel; 2, trapeziform sinuate; 3, panicoid bilobate; 4, short saddle; 5, aristidoid, long and narrow shank bilobate. Other: 6, elongate; 7, trichome; 8, cuneiform bulliform cell; and 9, parallepipedal bulliform cell. (b) Other graminoids, Restionaceae, 10 and 11; disks; 12, boomerang; 13; paddle 13 and 15 deteriorated disk and paddle from dental calculus (SME-2). Cyperaceae: 16, papilla; and 17.hat-shaped cell.

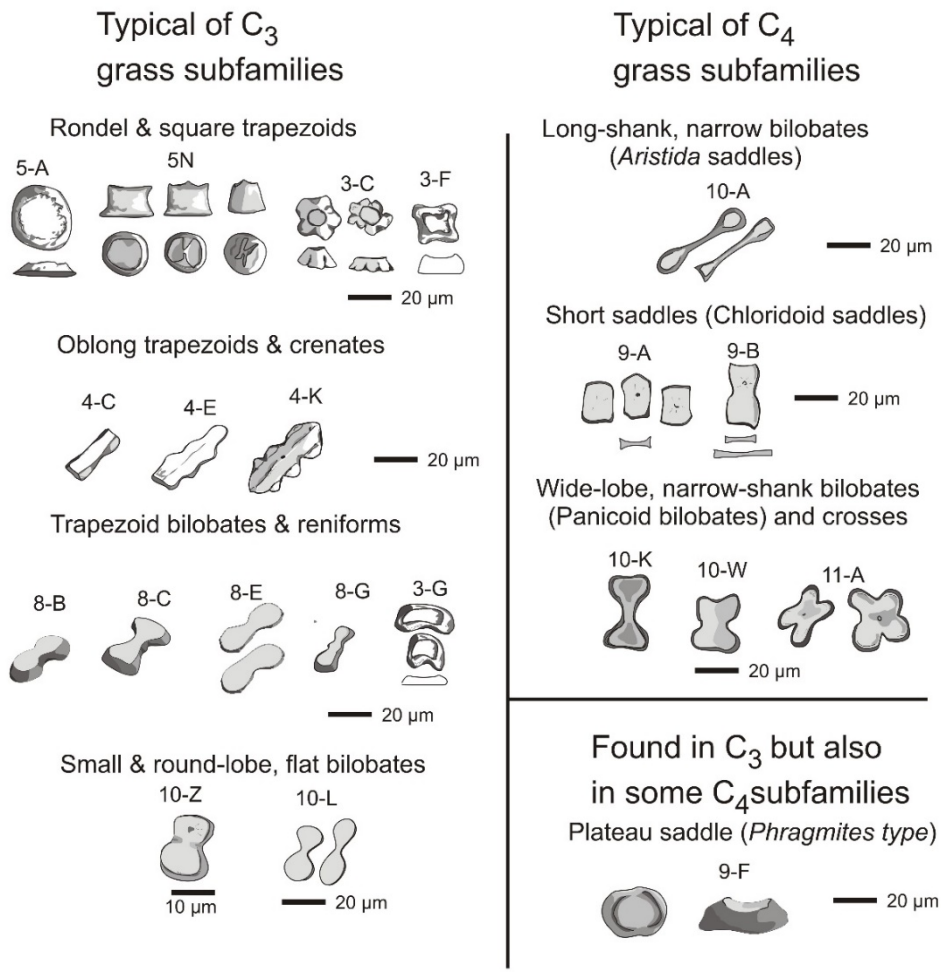

Fig. 3. Grass subfamilies and their corresponding diagnostic grass silica short cells (GSSC). Bars are 20µm long, unless otherwise indicated.

Table S3. GSSC used in this study. Definitions and references to other studies.

Morphotype groups	Code	Reference to other names (source at the bottom)	Poaceae taxonomic group
Rondels and trapezoids	5-A, 5-N, 3-C, 3-F	Conical (1) (Q) Rondels (2) (G) Trapeziform rondels (3)(I) Pyramidal (1) (Q)	Pooidea, Danthonioideae and Ehrhartoideae

Oblong trapezoid and crenates	4-C, 4-E, 4-K	Long crenates (1) (E) Trapeziform polylobates & trapeziform sinuates (2)(E) Oblongs (3) (I)	Pooideae and Danthonioideae
Trapezoid bilobates and reniforms	8-B, 8-C, 8-E 3-G; 8-E (including reniform variant)	*Stipa*-type (1) Bilobate Variant 2 (3) (I) Trapeziform bilobates (4) Reniforms (3)(I)	Danthonioideae, Pooideae and Ehrhartoideae
Small, round bilobates	10 L 10Z	Bilobates Variant 3 (3) (1) Bilobates Variant 2 (3) (I) Other bilobates (1)(I)	Ehrhartoideae, Danthonioideae & Pooideae
Long, narrow bilobates	10A	Bilobates variant-1 (3)(E)	*Aristida* (Aristidoideae)
Chloridoid saddles	9A 9B	Short saddles (5)(E) Saddles Variant 1 (3)(E) A variant of chloridoid saddles (6)(E)	Chloridoideae
Panicoid bilobates and crosses	10K, 10W 11A	Panicoid bilobates (1) BilobatesVariant-2 (3)(I) Quadra-lobates (2)(E) Crosses (3)(E)	Panicoideae

Phragmites-type saddle	9F	Plateau saddles [5](E)	Typical of *Phragmites* (Arundinoideae), but found in some Danthonioideae and some *Stipagrostis* (Aristidoideae)

Designation sources: (1) Fredlund and Tieszen (1994); (2) Madella et al. (2005); (3) Rossouw (2010); (4) Cordova (2011); (5) Lu and Liu (2003); (7) Piperno (2006, p. 31).

Degree of equivalence with designation source: (E) exact equivalent; (I) included as a sub-type in this variant or class; (G) general morphotype designation; (Q), quasi-equivalent morphotype

S5 Burnt-grass phytoliths types and mode of transportation

When grass leave blades burn, they become fragmented and the fine ash rises up with the heated air and may be carried over considerable distances by wind (Palmer, 1976). Phytoliths can travel as separate particles (Fig. S4a-c) and staining of these would indicate burning (Fig. S4b-d). However, burnt phytoliths may be transported still attached to charred parts of the leaf and husk (Figs. S4d-f). The latter are more properly referred to as grass cuticles (Palmer, 1976; Wooller et al., 2000).

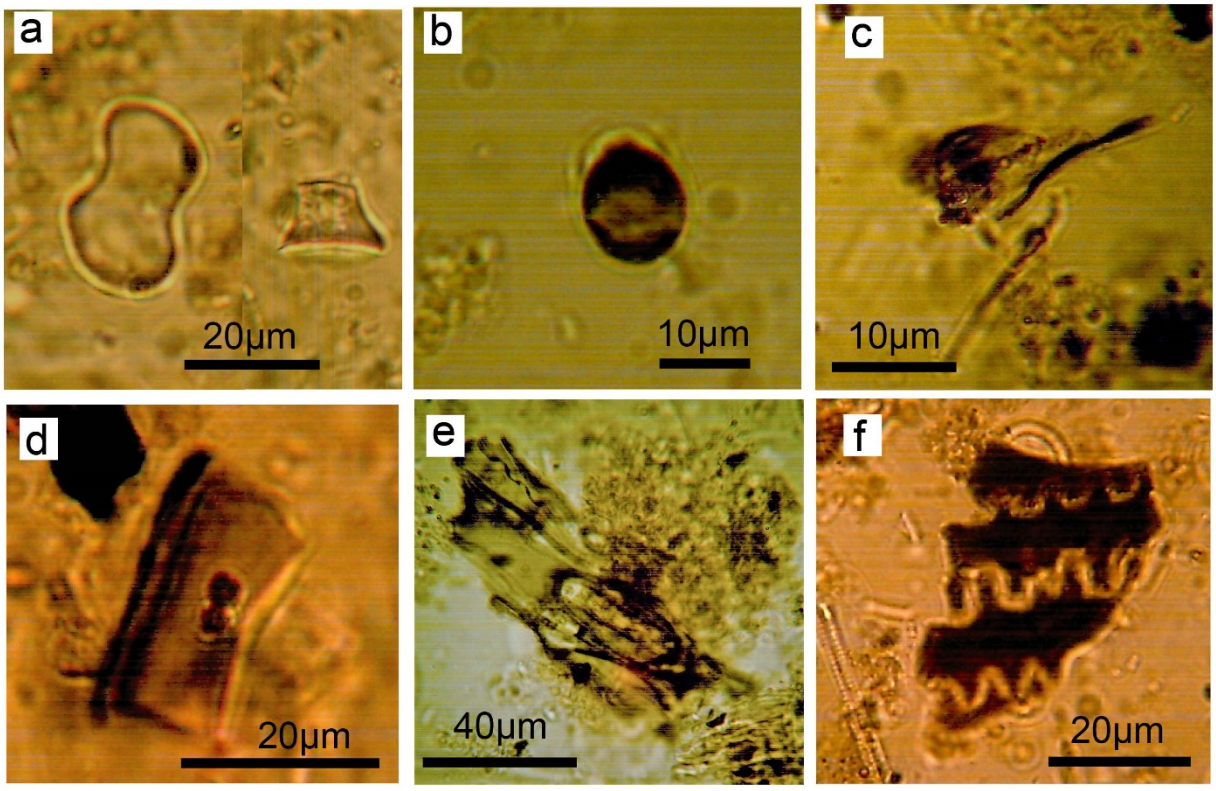

Figure S4. Burnt grass phytoliths: a) unburnt grass short cells: 8-B trapezoid bilobate and 5-N rondel (side view) from sample at 52 cm (c. 850 cal years BP); (b) burnt 5-N rondel (top view) from sample at 122 cm; (c) partially burnt lobe from a 10-A bilobate; (d) short cell still attached to charred particle from sample, also from sample at 52 cm; and (e) articulated leaf phytoltihs including silicified stomata and (f) burnt husk phytolith, both from sample at112 cm (c. 1300 cal years BP),

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Tables:

The effects of fire, herbivores, and humans

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Table S2 Chronology PV3.11 core

labID	age	error	depth	cc
modern su	-61	1	-17	0
PV2011-3E	510	30	19.5	3
PV2011-3F	1050	30	53.5	3
PV2011-3D	1540	30	144.5	3
PV2011-3C	2640	30	173.5	3
PV2011-3A	3550	30	200.5	3

Bacon-generated age model

depth	min	max	median	wmean
-17	-64	-58.1	-61	-61
-12	-54	136.9	9.2	18.7
-6	-30.8	341.3	95.6	113.7
0.5	24.4	404.5	211.4	213.8
3	39.7	457.6	252	251.5
5	92.4	465.4	282.8	282.5
7	130.5	475.3	315.7	313.4
9	160.6	487.8	350.5	344.3
13	206.5	530.3	421	405.9
15	269.7	535.5	447.9	436.1
17	320.7	541.4	475.4	466.4
20	357	560.2	518.2	511.7
23	395.3	646.8	558.4	557.1
25	422	663.9	580.2	577.7
27.5	454.8	700.7	605.1	603.4
29.5	475.1	739.8	623.8	624
33	505.4	816	654.8	660.1
35	539.2	826.8	677.5	681.6
37	568.3	842	701.6	703.3
40	592.2	869.7	737	735.7
42	607.9	898.4	760.1	757.6
45	654.5	919.9	787.4	787.9
47	690.2	927.2	804.8	807.9
49.5	729.6	938.9	825.8	833
51	748.2	948.8	838.2	848.1
55	784.8	981	869.8	884.1
57	798.8	1005	885.8	899.8
59.5	813.8	1049.6	909	919.6
62	821.5	1096.2	930.7	939.1
65	836	1135.3	952.3	961.7
67	845.5	1166	966.1	976.6
69.5	854.4	1215.6	982.8	995.3
72	860.5	1263.8	998.7	1013.2
75	876.8	1307.3	1017.6	1034.7
78	889.3	1353	1037.8	1056.6
79.5	894.2	1373.8	1048.1	1067.6
82	904.3	1413.9	1063.3	1085.4
84	914.1	1445.4	1076.4	1099.7

87	932	1480	1096	1121
89	941.4	1501.6	1109.5	1135.2
91	950	1527.8	1122.8	1149.2
95	971.3	1579.4	1148.8	1178
97	984.3	1603	1162.2	1192.5
100	998.4	1642.9	1182.1	1214.3
102	1006.8	1675.3	1194	1228.6
105	1024.7	1709.6	1212.5	1250
107	1035.8	1737.7	1223.9	1264
110	1050	1775.1	1241.9	1284.7
112	1058	1804.8	1253.9	1298.5
114	1072	1832.4	1266.2	1312.4
117	1095.2	1871.2	1285.1	1333.9
119	1108	1901.2	1297.3	1347.8
121	1119.2	1938.1	1311.1	1362
123	1127.6	1965.4	1323.9	1376.1
125	1146.9	1989.8	1335.9	1391.2
127.5	1164.2	2029.6	1352.2	1410.2
129.5	1177.1	2060.2	1365.9	1425.3
133	1197.9	2135.6	1388.7	1451.7
135	1217	2153.6	1401	1466.5
137	1236.2	2183.5	1413.8	1481.4
138	1243.5	2195	1419.9	1489.3
141	1264.7	2236.9	1440.9	1512.1
145	1317.9	2297.2	1478.2	1552.8
148	1365.4	2335.1	1515.9	1592.6
151	1389.3	2383.9	1552.1	1631.2
152	1396.2	2398.9	1563.7	1644
155	1464.7	2445.4	1672.2	1740.8
158	1523.3	2491	1823.5	1867.2
161	1569.5	2546.5	1965.3	1993.6
164	1677.2	2634.4	2098.8	2123.9
169	1982.8	2697.4	2347.8	2353.7
171	2061.6	2738.3	2456.4	2444.5
172	2095	2764.1	2506.8	2489.6
175	2320.5	2829.7	2643.5	2624.4
179	2561	2980.3	2830.6	2805.7
181	2607.1	3176.1	2898.4	2897.7
184	2688.6	3414.8	3010.1	3026.7
188	2829.3	3518.1	3183.9	3183.9
191	2895.2	3642.5	3308.8	3301.3
192	2911.9	3698	3349.7	3340.5
195	3085.9	3779.8	3465	3459.5
198	3318.6	3817.6	3582.7	3581.2
201	3503	3872.3	3705.1	3703.5
208	3711.2	4090.2	3899.4	3903.3

Table S3 Chronology vZB core

labID	age	error	depth	cc
top mat	80	5	6	0
bott mat	350	5	72.5	0
Pta-7747	1530	30	127.5	3
AA87105	2027	37	166.3	3
AA87106	1956	37	191.3	3
AA87107	2539	38	223.5	3
AA87108	3168	39	258.8	3
AA87109	3565	39	293.8	3
AA87110	3290	30	304.3	3
Pta-7749	3620	70	307.5	3

Bacon-generated age model

depth	min	max	median	wmean
6	61.9	93.7	79.1	78.9
8.25	68.4	106.7	87.1	87.6
11.25	73	135	96.3	99
14	75.3	162.3	104.6	109.4
17.5	81.7	187	117.4	122.9
22.5	90.8	210.7	138.7	142.7
27.5	101.9	242.4	157.6	162.1
32.5	114.1	259.6	178.8	181.2
37.5	127.7	280.6	198.4	200.7
42.5	145.5	293.8	222.5	222.3
47.5	164.2	315.7	243.7	243.3
52.5	188.1	324.7	265.4	263.3
57.5	208.7	337.7	285.6	282.7
62.5	231.5	345.2	305.2	301.5
66.5	250	356.2	321.9	317.4
72.5	333.2	368.1	349.5	350
107.5	644.5	1297.6	969.1	967.9
112.5	756.4	1356.7	1076.6	1069.3
117.5	864.2	1435.9	1178	1168.9
127.5	1103	1542.9	1355	1355.4
137.5	1262.4	1718.2	1497.3	1501.3
142.5	1330.8	1769.3	1567.6	1566.6
147.5	1398.6	1840.4	1631.3	1631.3
152.5	1476.4	1879	1699.8	1696
157.5	1544.9	1933.1	1762.8	1759
161.12	1613	1952.9	1809.6	1803.5
168.75	1706.2	2023	1889.9	1883.1
173.75	1739.4	2095.2	1920.2	1919.6
176.25	1756.8	2140.3	1934.5	1937.7
178.75	1777.1	2162.2	1945.9	1953
183.75	1807.1	2217.6	1969	1984.7
188.75	1842.1	2271.7	1991.8	2018.6
196.25	1891	2366.6	2034	2074.5
201.12	1951.8	2429.3	2139.3	2159.4

208.75	2058.2	2561.5	2284.4	2294.5
213.75	2130.5	2627	2389.1	2387.3
218.25	2232.5	2688.1	2470.7	2469.4
222.5	2350.8	2717.5	2545	2545.4
228.75	2466.1	2829.8	2666.7	2665.6
233.75	2530.7	3020.9	2768.1	2769.9
236.75	2567.2	3135.1	2823.3	2831.7
238.75	2611.2	3156.8	2866.1	2872.9
245	2701.4	3269.4	3003.5	3000.5
256.75	2996.5	3423.5	3249.3	3242.5
258.75	3069.3	3438	3280.8	3278
261.75	3145.9	3471.4	3328.5	3331.7
263.75	3179	3506.7	3366.9	3367.6
266.75	3221.3	3583.8	3416.5	3417
268.75	3248.8	3602.2	3441.6	3440.6
271.75	3282.5	3639.8	3478.2	3475.8
273.75	3301.6	3674.2	3500.6	3499.1
281.25	3394.4	3757	3588.4	3586.3
286.25	3441.8	3810.2	3649.7	3644.5
291.25	3551.2	3836.7	3706	3703.4
296.25	3613.6	3890	3765.1	3761.6
298.75	3633.4	3903.7	3783.2	3779.2
307.5	3688.8	3989.3	3846.8	3843.7
316.5	3745	4124	3923.6	3926.8
321.75	3781.8	4211.8	3974.6	3980.5

Table S3 GSSC used in this study. Definitions and references to other studies.*

*See main supplement document (Supplementary Material)

Table S4 PV11.3 Sedimentation rates

Depth	Cal yr BP	mm/year
-17	200	1.1
0.5	206	0.73529
3	240	0.7352941
5	267	0.7407407
13	445	0.4494382
15	468	0.8695652
17	491	0.8695652
20	519	1.0714286
23	543	1.25
25	576	0.6060606
29.5	622	0.9782609
42	770	0.8445946
51	873	0.8737864
55	909	1.1111111
62	945	1.9444444
82	1048	1.9417476
87	1074	1.9230769
91	1094	2
112	1202	1.9444444
114	1213	1.8181818
117	1228	2
123	1259	1.9354839
125	1269	2
129.5	1290	2.1428571
133	1311	1.6666667
137	1331	2
138	1336	2
141	1352	1.875
145	1393	0.9756098
148	1530	0.2189781
152	1712	0.2197802
155	1849	0.2189781
158	1986	0.2189781
161	2123	0.2189781
164	2260	0.2189781
169	2488	0.2192982
172	2627	0.2158273
175	2755	0.234375
184	3112	0.2521008
188	3270	0.2531646
191	3389	0.2521008
192	3429	0.25
198	3667	0.2521008

Table S5 | PV11.3

Cal yr BP	% Plankton	% Benthic	% Epiphytic	% Dilute	% Brackish	Low Nutrie	Nutrients E	delta18O
0	0	0	0	0	0	0	0	
251.5	90.8	7	1.4	95	3.2	0.6	93.6	
313.4	23	74.2	3.4	97.2	2.8	3.6	33.4	
344.3	4.6	91.4	2.8	94.8	4.2	7.4	27.2	
405.9	35	56	20	62.2	29.2	24.4	51.4	
436.1	31.8	65.2	20.4	73.6	22.8	38.8	42.8	
466.4	29.6	66.4	15.4	71.8	24.2	27.2	52.4	
511.7	24.6	72.6	28.2	77.6	19.4	23.4	56.4	38.76
557.1	17.4	78.6	17.6	76.8	19.4	38.4	41	
577.7	16.8	79.6	16.6	79.2	17.8	29.8	40.2	
603.4	8.2	86.8	6.4	84.6	10.4	53.4	24	
624	9.2	88.2	1.4	87.4	10.4	66.8	22.2	
660.1	2.2	96.4	1.2	96	2.8	74	20.6	
681.6	4	94.6	1.2	93.4	5.2	62.8	28.2	
703.3	2.6	95.4	0.8	95	3	59	30.2	
735.7	1.2	95.8	0.4	92.4	4.6	63.6	23	36.66
757.6	10.4	85.8	1.2	84.2	11.4	53	35.8	
787.9	3.4	95.2	1.2	93.4	5	67.2	19.2	
807.9	0.4	97.6	0.8	96.8	1.2	59.4	33.8	
833	0.8	96	0.6	93.4	3.6	66.8	21.4	
848.1	24	71.6	4.2	74.6	20.4	55	33.2	
884.1	3.8	95.2	1.2	95.4	3.4	66.2	23.2	36.59
899.8	7	79.4	2.2	78.2	8.2	55.8	16.2	
919.6	1.6	81.6	2.6	81.8	1.4	61.6	15.2	
939.1	1.4	89.2	0.8	89	1.8	73.2	14.2	
961.7	0.4	91.6	0.4	91.4	0.6	77	10.8	
976.6	1.8	91.6	0.6	92.4	1	67.6	22.2	
995.3	0.6	92.8	1.2	92	1.6	77.4	8.4	
1013.2	0.6	93.2	1.8	92.6	1.2	70.2	14	
1034.7	1.4	92	1.6	91.8	1.8	67.2	21	
1056.6	1.2	91.6	0.2	92.6	0.4	77.6	9.6	
1067.6	2	92	0.2	93	1	67.8	18.8	
1085.4	0.6	95.6	1	95	1.2	81	12.4	
1099.7	1.8	91	0.8	91.8	1	68.2	16.2	
1121	2.2	91.2	0.6	92	1.4	69.8	16.8	
1135.2	0.6	92.2	0.4	92.2	1	73.8	12.6	
1149.2	1.4	91.4	0.8	91.2	1.4	64.2	23.4	
1178	2.4	92.8	0.8	93	2	67.8	18.6	
1192.5	1.4	93.8	0.4	94.4	1	75	15	
1214.3	0.6	96.4	1	96.8	0.2	76.2	16.8	
1228.6	1	91.4	1.6	90.8	1.8	75.6	12.8	
1250	1.4	92.4	0.8	91.6	2.2	66.2	18.6	
1264	1.2	92.2	1.4	92.8	1	68	16.6	
1284.7	1.6	91.2	0.8	91.8	1	63.4	21.4	
1298.5	1.2	94.6	1	92.2	3.6	63.6	22	
1312.4	1.8	92.8	2	90.2	4.6	64	21.6	36.46
1333.9	1.4	93.6	1	89.6	5.4	61	23.8	
1347.8	3	92.4	2.6	88.2	7.4	56.6	26	
1362	1.6	93	2.6	90.2	4.6	62.4	21	
1376.1	2.2	90.8	1.6	84.4	8.6	64.4	16.8	
1391.2	5	89.4	1.8	83.8	10.2	52	24	
1410.2	3.8	91.4	2.4	90.6	4.8	65.4	16	
1425.3	7.4	85.4	1.8	82.2	10.2	49.4	21.4	

1451.7	8.2	81.8	2	78.2	11.2	51.6	18.6	
1466.5	10.4	77.8	0.8	76	11.4	44.8	25.4	36.66
1481.4	23.8	62.2	3.4	61	25	39	35	
1489.3	18.4	73	2.2	74.8	16.4	32.2	37.4	
1512.1	33.6	56.4	4	52	37.6	22.4	47	
1552.8	22.4	68.6	5	69.8	21.4	35.8	29.6	
1592.6	77	19.2	0.2	65.6	30.6	9.4	81.2	
1631.2	39.2	57	1.8	75.6	20.6	30.8	48.6	
1644	60.2	35.8	0.8	47.6	48.4	21.2	65.6	
1740.8	52.8	42.6	2.2	51	45	22.4	58.8	36.28
1867.2	47	49.2	1.6	57	38.8	27.2	56	
1993.6	30.8	65.2	1.2	64.6	31.8	36.4	43.6	
2123.9	44.8	48.4	1.2	46.4	47.2	20.4	56.8	
2353.7	59.4	32.2	2	62.8	28.4	9.6	70.6	
2444.5	64.2	28.2	2.4	36.6	55.8	5.6	75.6	38.46

Table S6 PV11.3 Phytolith summary counts Yellow highlights, no data

		GRAMINOIDS						
		Poaceae						**Cyperacae**
Depth	Caly yr BP	Short cells	Long cells	Pointy	Bulliforms	ıostic or unt	grass phyt	Hats
-17	-61	55	14	5	37		4	
-12	18.7	19	5	1	4	2		
-6	113.7							
0.5	213.8	31	6	1	2	2		
3	251.5	12	14	2	5			
5	282.5	72	17	8	28	19	2	2
13	405.9	77	15	3	29	14	7	
15	436.1	46	13	1	14	9	2	
17	466.4	70	28	3	36	20	10	
20	511.7	96	12	2	46	15	1	1
23	557.1	69	20	6	60	22	2	
25	577.7	30	8	4	55	27	14	
29.5	624							
42	757.6	32	5		18	10	5	
51	848.1	68	8	4	38	21	15	2
55	884.1	38	5		44	22	5	
62	939.1							
82	1085.4						2	
87	1121	15	6	2	9	5	1	
91	1149.2	9	3	1	5	3		
112	1298.5	31	10	2	20	16	5	
114	1312.4						3	
117	1333.9	66	32	5	53	30	14	
123	1376.1	55	15	3	31	11	7	
125	1391.2	47	19	1	26	12	8	
129.5	1425.3	38	19	1	23	11	9	
133	1451.7	60	43	4	47	22	16	
137	1481.4	81	28	2	9	11	7	1
138	1489.3	26	17	1	14	7	5	
141	1512.1	32	30	7	20	18	15	
145	1552.8	42	32	4	33	27	16	1
148	1592.6	40	34	1	21	12	12	
152	1644	63	29	4	31	10	7	
155	1740.8	83	18	2	54	25	26	
158	1867.2	36	19	1	15	8	14	
161	1993.6	39	29	2	18	8	9	
164	2123.9	43	18	1	20	12	8	2
169	2353.7	96	37	7	68	25	12	2
172	2489.6							
175	2624.4							
184	3026.7							
188	3183.9						1	
191	3301.3							
192	3340.5							
195	3459.5							
198	3581.2	22	22	1	6	8	2	

201	3703.5	8	18	3	35	15		
208	3903.3	43	149	28	646	192	8	1

		Restionaceae			Unidentified graminoids	NON-GRAMINO
Papilae	Other	onaceae Rołockey stick		Other		Polyhedral Celtis
3		22	3		4	
2		8	10		6	3
		21	6	1	4	1
1		5	1			
10	4	21	4		12	
	1	23	6	1	6	
1		17	10		8	
1	1	27	4		11	
1	1	50	11		9	
	8	58	8		26	
		25	2		13	
		7	6		7	
3	1	27	5		8	
		27	14	1	13	
2		4	1		6	
		7	1		1	
2		29	7		10	
		50	13		25	
1	2	23	11		10	
3		30	8		9	
1		29	15		13	
1	1	46	13	1	16	1
3		53	8		11	
	3	35	5		7	
	4	20	3		5	
	3	28	10		10	
		25	6		11	
2	2	46	4	1	16	
6		28	7		23	
	1	23	6		12	
	1	38	15		9	2
		33	5		6	
	4	47	8			
2	1	32	5	3	20	

		12	3		6			
2	9	18	6		10			

OID								OTHI
spheres (Gl	neres (Glob	unded bloc	sculpural f	ellate (Phoe	eids woody	ped/long fa	ular aggreg	erentiated
2	2	20		1		1	52	12
1		19			1	2	7	16
		4		1	4	6	35	13
1		10					49	3
2	3	27	1			3	57	6
1		12				1	49	8
		10				1	37	11
1		3				2	18	11
1	3	10				2	36	8
	1	6				1	13	14
	1	4				2	10	8
		2			1	1	6	5
		1					16	4
		2					6	3
		4				1	3	5
1		5				1		4
4	1	1			1	3	4	9
	1	5				6	5	5
5		1				4	22	11
	1	1					2	1
	1						4	4
	3	11				12	6	8
	1	23	1		2	8	40	15
1		6				2	8	4
					1		1	7
1		7				1	4	10
	1	2				5	4	8
		4				6	10	12
		6				4	18	9
	1	4				2	3	2
1	1	4			2		8	4
	1	3					7	6
	5	14	2			5	21	9
		4			1	2	3	4

1		2	1			4	8
			1		1	2	2

ER UNASSIGNED			
dicots	Lycopodiur	Lycopodiur	Weight in grams
12	208	18584	2.3
3	61	18584	1.7
9	67	18584	0.8
1	62	18584	0.3
20	231	18584	0.5
18	4	18584	1.9
14	107	18584	1.7
11	90	18584	1.5
9	104	18584	1.9
19	137	18584	2
6	31	18584	1.9
	55	18584	1.7
2	535	18584	2.5
11	25	18584	3.1
6	121	18584	1.5
	113	18584	4.4
	240	18584	3.3
3	287	18584	2
7	282	18584	4
12	128	18584	4.1
	248	18584	1.7
13	88	18584	1.9
8	151	18584	3.4
4	31	18584	2
5	69	18584	2
14	53	18584	3
18	51	37168	1
15	417	37168	1
10	47	18584	2.1
	30	18584	2
10	30	18584	2.1
7	33	18584	1.9
13	27	18584	1.9
12	37	18584	1.6
14	10	18584	1.7
6	29	18584	1.3
20	33	18584	12
	14	18584	1
	3	18584	0.7
7	13	18584	1.4

9	15	18584	1.7
8	8	18584	2.5

Table S7 PV11.3 GSSC counts

		Found mostly in C3 grasses										
		Rondel and square trapezoids				Oblong			Reniform		Trapeziform	
Depth	Caly yr BP	5-A	5-N	3-C	3-F	4-C	4-E	4-K	3-G	8-G	8-A	
-17	-61			1								
-12	18.7						1			2		
0.5	113.7			1	1	1	2					
3	213.8											
5	251.5			2	2		1		2	1		
13	282.5				1		4				1	
15	405.9						2	1				1
17	436.1			2			1			1		
20	466.4			8	1		1	2				
23	511.7			2	1					1		2
25	557.1					1						1
42	577.7				1		1			1		
51	848.1			8								
55	884.1			7						1		
82	1085.4											
87	1121				1							
91	1149.2						1					
112	1298.5			4	2							
117	1333.9		2	10	1	1	1					
123	1376.1			2	1							1
125	1391.2		1	2	2		1					
129.5	1425.3		2	1						1		
133	1451.7			8	1							
137	1481.4		3	6	3		4		1			
138	1489.3			6	1							
141	1512.1		1	3					1			
145	1552.8		1	5	1							
148	1592.6			6								
152	1644		1	8	1	1						
155	1740.8		2		1	2					1	1
158	1867.2			6			1			1		1
161	1993.6			4	2							
164	2123.9		2	5		4				1		2
169	2353.7		2	6	1		3		1			
198	3581.2			1								
201	3703.5		1				1					
208	3903.3		2	1			1					

n bilobates						Round-lobe bilobates	
8-B	8-C	8-D	8-E	8-F	8-I	10-Y	10-Z
					1		
					2		
						1	
	1	1	1	1	1		4
				3			
				1	1		
	1	1		2	2	1	
	1		2	2			2
	2		1	1	1		1
	1	1					1
				1			
		4					1
		1		2	1		1
				1			
				3	1		
		5	1	2	1	2	1
	2	1		1			2
		4		1	1		1
	1	1			1	3	
			1			2	1
	2			2	1		2
			1			1	1
			1	1			
			2	1	1	1	1	3
	1	2				1	1	1
	2							
	1	3		1			2	2
			2					2
		1			1	1	1	
			1	2		1		
	1	2	1	1	2		5	1
		2					1	1
				2				

Found mostly in C4 grasses+AE26AE2X2X2:AD32									Found in pa
Short saddles		Panicoid bilobate and crosses				Round sad	Long-shank bilobates		
9-A	9-B	10-K	10-L	10-W	11-A	9-M	10-A		5-L
	1								
	3								1
	5								1
	1								
	3							1	1
	3		2						2
	1		2						
	1			1					2
						1	2		3
							1		
	1								1
	1								
	1			1					
	1			1			1		
			1		1				1
	1		1				1		1
							1		
	1		2						
	1								2
	2					1			
		1	1						
			1						
	3	1							4
	2		1			1			
			1		1	1			2
									3
									1
	1					1			

articular groups C3 or C4

9-F	5-K
	2
	1
	2
	5
1	10
1	2
	13
1	7
	11
	7
	9
1	20
3	8
	2
	3
1	7
1	4
	5
3	4
	12
2	11
3	18
	4
	5
	5
	10
1	13
3	8
	9
1	6
1	9
3	9
	2
1	2

Table S8 PV11.3 pollen and spore counts Yellow highlights, no data

Depth	Age	Hi Pollen Pinus	Salix	Quercus	Celtis	Cassuarina	Acacia	Ambrosia-t
-17	0	9	3		1	1	2	
-12	18.7							
-6	113.7							
0.5	213.8							
3	251.5	2		3				
5	282.5	10		1		2		1
13	405.9							
15	436.1							
17	466.4							
20	511.7							
23	557.1							
25	577.7							
29.5	624							
42	757.6							
51	848.1							
55	884.1							
62	939.1							
82	1085.4							
87	1121							
91	1149.2							
112	1298.5							
114	1312.4							
117	1333.9							
123	1376.1							
125	1391.2							
129.5	1425.3							
133	1451.7							
137	1482.4							
138	1489.3							
141	1512.1							
145	1552.8							
148	1592.6							
152	1644							
155	1740.8							
158	1867.2							
161	1993.6							
164	2123.9							
169	2353.7							
172	2489.6							
175	2624.4							
184	3026.7							
191	3301.3							
192	3340.5							
198	3581.2							
208	3903.3							

Polygonum	Plantago	Podocarpus	Olea	Celastracea	Myrsine	Buddleja	Morella	Passerina
						2	1	
		1				2		
		1	2			2	7	1
			1			2	1	1
					3			
			1			4	2	1
	1				3	4	1	
						2	1	2
		1				2	1	2
					3	1		2
			1			1	1	
						1	5	1
					3	2		1
							1	
	1	1			1	1	5	3
			1		2	1	2	1
			1		1			1
	1					4	1	1
					1	4	2	
					1			
			1					3
		1			1	3		2
	1		1		1	3	4	2
					1	1		1
				1		1	2	
				1		1	4	3
		1	1		2	3	1	4
						4	1	
							1	
					1		42	
			1		3		5	
							4	

Rhus/Anac	Clutia	Euclea	Carpobrotu	Anthosperr	Crassula-ty	Liliaceae	Stoebe-typ	Artemisia
		1		1		2		1
		2						
1		1		1		2	2	
		3		2	1		1	
			1				2	1
		1	1	9		1		1
	1			10	2			1
			1	4	2		2	3
			1				2	1
		1	1	11			3	
1	1	3	3	25			2	1
				4		1	1	
				8	2		1	
		2	1	11	1		2	
1		1		6				
	1	1		16			1	1
	1	2	4	12	7			2
				8	3		1	
1		1	1	20	9			
			2	29	6		2	
		1		23	3		1	2
		1		24	6	1	2	1
			1	22	2			1
		4		16	1			2
		2	2	18	2	1	1	1
		2	3	11	6		5	
		1		31	4		4	1
		2		36	2		1	
	1	3		52	2			
1		1		14	1			
		1		4		1		1
1		2		4	1			
1		3	1	4	8			
		2		9	4			

Aizoaceae	Amarantha	Myrtaceae	Cliffortia	Carpacoce	Psoralea	Restionace	Blaeria-typ	Ericaceae
	2	12	4	1		2	2	5
		1				1		1
1	3	16		2		9	1	8
				1		5	1	1
	1		1			3		9
	3		1	2		10	1	7
1	2	1		4		30	2	22
	1		3		1	14		9
			1	3		8		7
	1		2	1		9		10
1	1	1	2	3		25		20
				1		3		9
			1	1		27	1	11
1	1	2	1	4		29	1	20
	3		2			13		7
	5	1				39		10
2	8			5		31		13
	3		1			12		5
2	2		4	1		68	1	20
	1		6			64	2	34
	2		2	1		57	2	27
2	1		6			51	2	32
	1	2	2	2		52	3	26
	2		4		1	45	1	18
2	3	1	12	3		76	1	28
1	1		5	4		43		33
	3	1	5	1		62	2	33
4		1	1			8	2	26
				5		12		29
3				1		3		27
	1		1			14	3	26
						8	6	6
1			1			11	4	10
2	3		4	2		11		24

Proteaceae	Staavia typ	Bruniaceae	Phyllica	Penaea	Asteraceae	Brassicacea	Rumex	Poaceae	<2
10		2	1		4			9	
			1			2			
3		1			5	3		10	
2		1	1		8		1	1	
6	1	3			13			8	
5			1		6			2	
11		5			16			1	
3		2			9			4	
7		4			6			4	
7		4			2			3	
5		4			8			2	
3		3			15			3	
5	1	1			11			3	
6		3	6		6			2	
7	1	3	1		5			3	
6		2	3	1	6			10	
5		3	4	1	4			9	
4		1	3		16			5	
6	1	3	3		9			6	
9	1	5	1		4			1	
11		2			4			4	
6	1	1		1				3	
3	2	3			8			4	
6	2	5			8			4	
18	3	10			12			6	
7	1	8	2		9			2	
9		6	1		10			4	
12		10	1		6			7	
7		2	1					3	
6		2	3		3			3	
22		3			1			1	
16	1	3	1		2			3	
52		8	1		2			1	
5	2	1		1	9			4	

Poaceae >2	Typha	Drosera	Cyperaceae	Potamoget	Juncaceae	Haloragida	Hydrochari	Alisma
11	23		8		5			
4	13		1	2	6	4		
17	26		14	3	11	4	1	
4	7		14	2	1	3		
5	3		5		5	3		
5	3		7	2	1	2		
3	6		30	4	5	2		
6	6	1	13		8			
2	1		20	2	1			
4	3		10		6	1		
1	3		13	4	1	2		
2	2	2	2	2		5		1
4	4		11	1	3	1		
6	2	1	20		4	5		1
3	3		7		2	1		
5	6	3	21	1	13	5		
4	9		26	2	6	11		
3	6		10	4	2	5		
7	8	1	36	5	1	12		
6	2	1	47		2	6	1	
4	4	1	18		1	6		
11	7		22	1	1	5		
15	5	32		1	2	5		
11	7	1	20	3	4	5		1
7	6		37		1	4		
6	8		30	1	2	5	1	
3	4		21		2	4		
9	6		6		4	3		
1			15			3		
3			5	1	4	5		1
1	2		8			9		
1	2		10		2	10		
1	1	1	7			7		
1	3	16			1	8		

Nymphaea	Persicaria	Aponogeto	Trapa	Apiaceae	Boraginace	Dipasacace	Euphorbiac	Gentianace
	1		1				1	
		7					1	
2		3					1	
1					1		2	
							1	2
		1		1				
		3						
2			2					
1		1		1				
3		3	2					
		2		1				
			2					
1	2	2	2					
	1		2					
4		2						
			2					
1						1		
2			2	1				
4	1	1						1
2			2					
		2	1					
2		1	2					
				1				
			1					
	1	3		1				
	2	5		1				1
1								
				2				

Geraniacea	Hermannia	Ranunculac	Ruschia	Rutaceae	Tarchonant	Urticaceae	Viscum	Unknown
								2
								1
								2
								1
								4
								1
								5
								2
								2
						1		
								2
								1
						1		3
						2		5
						2		3
						1		1
								1
	1			2	2	1		1
	1			1	2	1	1	2
			1	1	1	2		3
	1			1				6
					1			3
						1		2
						1		3
				3		1		2
					2	3		4
1								8
					1	1		
								5
					1	1		1
						1		
					2	2		2
					1			5

			Spores and other palynomorphs				
Undetermi	**Total sum**		Inapertural	Monolete s	Other undet spores	Podospora	Sordaria
	127		5	3	1		1
	0						
	0						
	0						
8	**58**						
2	**184**		19	4	2	1	1
11	**83**				3	1	4
2	**83**		2		4		2
12	**95**		6	1	3	1	1
	175		14		3	3	6
8	**105**		15	1	3		1
6	**83**		4		5		1
	0						
6	**96**		4	1	3	1	2
13	**156**		9	1	3	2	5
	0					1	2
	0						
	0						
	0						
	0						
2	**65**		4		2	1	3
	0						
9	**125**		8		4	1	2
6	**160**		4		6	3	5
9	**86**		6		1		2
9	**187**		9	2	3		1
5	**186**		4		4	2	1
5	**107**		2		4		3
7	**251**		3		4		3
4	**253**		6	2	3	1	3
7	**198**		12	1	8	2	1
9	**216**		19		8	1	1
17	**226**		3		10	1	3
12	**201**		6		6	2	3
10	**279**		12	12		2	4
18	**225**		2	1	5	1	2
17	**248**		6	3	1		4
10	**183**		9		5	6	7
	138		3			2	20
1	**107**				2	1	11
7	**111**		3		2		2
	123		4		4	4	14
8	**148**		4		3	5	9
6	**130**		1	1	8		
							1

Sporormiel	Other ascospores	Mycorhizae hyphae	Pediastrum	Botryococcus	Spike spore Lycopodiur
	224	3	40	5	208
			3		47
			63		61
			15		67
			17		62
	157	1	25	1	231
5	76	2		3	4
2	55			1	107
1	29				90
9	153				104
	36	1			137
	10			1	31
	5				55
	15			1	535
2	25			7	25
	17				120
	1				113
	6				240
	4				287
	6				282
	34				128
					248
	48			2	88
	28			2	151
1	15				31
1	21				69
1	32			1	53
	22			1	51
2	14			1	417
	21				47
2	37				30
	19				30
3	29				33
	40				27
1	38				37
	43			1	10
2	54			1	29
9	224	3		6	33
7	257		1		14
5	264	1		2	11
3	124			3	20
5	436			2	563
6	82			12	12
	60			1	13
	9				8

es

Lycopodium added spores
18584
18584
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37168
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18584
37168
18584
18584
18584

Table S9 PV11.3 Charcoal concentration

Age	Charcoal <ˢ	Charcoal >ˢ	Total charc	CHAR <50u	CHAR >50u	CHAR < 125 um2
0	1.252673	2.383483	3.636156	1.138793	2.166803	3.305596
18.7	0.963385	0	0.963385	0.060845	0	0.060845
113.7	1.356456	0	1.356456	0.088082	0	0.088082
213.8	2.078565	0.866791	2.945356	0.137836	0.05748	0.195315
251.5	5.190531	0	5.190531	0.334873	0	0.334873
282.5	2.098142	1.689455	3.787596	0.136022	0.109527	0.245549
405.9	25.10063	0	25.10063	1.662293	0	1.662293
436.1	0.158357	0	0.158357	0.010453	0	0.010453
466.4	1.366268	1.404124	2.770393	0.090481	0.092988	0.18347
511.7	0.853491	0	0.853491	0.056398	0	0.056398
557.1	0.16278	0	0.16278	0.015804	0	0.015804
577.7	2.271728	0	2.271728	0.220794	0	0.220794
624	0.447209	0	0.447209	0.041842	0	0.041842
757.6	0.244545	0.112546	0.357091	0.024319	0.011192	0.035512
848.1	4.328274	0.599484	4.927757	0.480919	0.066609	0.547529
884.1	0.683994	0	0.683994	0.087054	0	0.087054
939.1	0.047656	0	0.047656	0.006515	0	0.006515
1085.4	0.002933	0	0.002933	0.000412	0	0.000412
1121	0.275199	0.323763	0.598962	0.039035	0.045924	0.084959
1149.2	0.004531	0	0.004531	0.000637	0	0.000637
1298.5	0.769317	0	0.769317	0.110693	0	0.110693
1312.4	0.886002	0.220398	1.1064	0.123628	0.030753	0.154381
1333.9	5.524072	0.611316	6.135388	0.785413	0.086917	0.87233
1376.1	0.539349	0	0.539349	0.071437	0	0.071437
1391.2	4.548584	0	4.548584	0.600253	0	0.600253
1425.3	4.1612	0.808	4.9692	0.551674	0.107121	0.658795
1451.7	6.332798	0	6.332798	0.82512	0	0.82512
1482.4	27.98532	1.821961	29.80728	4.055843	0.264052	4.319895
1489.3	3.066137	5.659875	8.726012	0.403439	0.74472	1.14816
1512.1	7.456195	0	7.456195	0.732796	0	0.732796
1552.8	15.40923	0.774333	16.18357	1.1615	0.058367	1.219867
1592.6	8.141562	0	8.141562	0.633585	0	0.633585
1644	8.714029	0	8.714029	0.270063	0	0.270063
1740.8	14.4995	3.260351	17.75986	0.344134	0.077382	0.421516
1867.2	5.72902	0	5.72902	0.135974	0	0.135974
1993.6	22.21881	0	22.21881	0.511561	0	0.511561
2123.9	19.74242	0	19.74242	0.429557	0	0.429557
2353.7	21.98168	0	21.98168	0.485247	0	0.485247
2489.6	32.38926	7.168114	39.55737	0.720829	0.159528	0.880357
2624.4	20.80017	0	20.80017	0.465328	0	0.465328
3026.7	86.50852	14.4026	100.9111	2.205243	0.367146	2.572388
3301.3	6.261785	0	6.261785	0.159739	0	0.159739
3340.5	74.74253	0	74.74253	1.863129	0	1.863129
3581.2	86.58919	0	86.58919	2.68827	0	2.68827
3903.3	5.94688	0	5.94688			

Table S10 PV11.3 Charcoal concentration

Age	<50um are	>50um are	CHAR < 125 um2/mm/year
0	1.138793	2.166803	3.305596
18.7	0.060845	0	0.060845
113.7	0.088082	0	0.088082
213.8	0.137836	0.05748	0.195315
251.5	0.334873	0	0.334873
282.5	0.136022	0.109527	0.245549
405.9	1.662293	0	1.662293
436.1	0.010453	0	0.010453
466.4	0.090481	0.092988	0.18347
511.7	0.056398	0	0.056398
557.1	0.015804	0	0.015804
577.7	0.220794	0	0.220794
624	0.041842	0	0.041842
757.6	0.024319	0.011192	0.035512
848.1	0.480919	0.066609	0.547529
884.1	0.087054	0	0.087054
939.1	0.006515	0	0.006515
1085.4	0.000412	0	0.000412
1121	0.039035	0.045924	0.084959
1149.2	0.000637	0	0.000637
1298.5	0.110693	0	0.110693
1312.4	0.123628	0.030753	0.154381
1333.9	0.785413	0.086917	0.87233
1376.1	0.071437	0	0.071437
1391.2	0.600253	0	0.600253
1425.3	0.551674	0.107121	0.658795
1451.7	0.82512	0	0.82512
1482.4	4.055843	0.264052	4.319895
1489.3	0.403439	0.74472	1.14816
1512.1	0.732796	0	0.732796
1552.8	1.1615	0.058367	1.219867
1592.6	0.633585	0	0.633585
1644	0.270063	0	0.270063
1740.8	0.344134	0.077382	0.421516
1867.2	0.135974	0	0.135974
1993.6	0.511561	0	0.511561
2123.9	0.429557	0	0.429557
2353.7	0.485247	0	0.485247
2489.6	0.720829	0.159528	0.880357
2624.4	0.465328	0	0.465328
3026.7	2.205243	0.367146	2.572388
3301.3	0.159739	0	0.159739
3340.5	1.863129	0	1.863129
3581.2	2.68827	0	2.68827
3903.3			