Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

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Preface

This Master’s thesis is Jenny Sjöström’s degree project in Physical Geography and Quaternary Geology at the Department of Physical Geography and Quaternary Geology, Stockholm University. The Master’s thesis comprises 60 credits (two terms of full-time studies).

Supervisors have been Elin Norström and Jan Risberg at the Department of Physical Geography and Quaternary Geology, Stockholm University. Examiner has been Stefan Wastegård at the Department of Physical Geography and Quaternary Geology, Stockholm University.

The author is responsible for the contents of this thesis.

Stockholm, 22 March 2013

Lars-Ove Westerberg
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Abstract

Contemporary a geographical imbalance of where palaeoclimatological studies have been undertaken exists, where the majority of palaeodata is based on studies from the northern hemisphere. Multiproxy analysis was performed on a peat core from Lydenburg, north-eastern Mpumalanga, covering the last 1,600 years. Proxy focus was put on fossil grass phytoliths. A general drying trend can be noted from AD 400 to 1000, followed by more mesic conditions around AD 1200. The increasingly mesic conditions were interrupted by a significantly drier period between c. AD 1250 to 1350. This part of the Lydenburg sequence occurs in the end of a climate event termed “Medieval warm period” (MWP), suggested to have been warmer and variable but mostly wetter in southern Africa. The results are in line regarding the increased temperature and suggested variability. However, in contrast with earlier findings, significantly drier conditions seem to have prevailed at the Lydenburg fen at the end of “MWP” as interpreted by multiple proxies. Following AD 1400 increasingly mesic conditions was recorded as interpreted by several of the analysed proxies. More palaeoenvironmental studies needs to be performed in the area in order to elaborate on the driving factors of palaeoenvironmental change in the region, as well as to establish if the signals from the Lydenburg fen record local or regional changes. The results support earlier phytolith studies suggesting that small rondels should be excluded from phytolith assemblages in tropical and sub-tropical areas in Africa.
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Introduction

Global warming during the last hundred years has been 0.74°C (IPPC 2007). This temperature increase is widespread and highly uneven, with greater increase at higher latitudes than lower (IPCC 2007). This observed warming is in the IPCC report (2007) described as very likely caused by human activities, primarily related to use of fossil fuel and land-use change. Activities that cause increased greenhouse gases (primarily CO₂ and CH₄) levels in the atmosphere (IPCC 2007). The projected future climate change shows increasing warming in ranges from 1° to 6°C, depending on different greenhouse gas emission scenarios.

These changes will affect regions differently. Africa is in the report regarded as an especially vulnerable continent, partly due to low adaptive capacity and partly to the character of the projected impacts in the region (IPCC 2007). However, the knowledge base on which these assumptions rests needs to be strengthened. A great geographical imbalance of where climate observations have been performed currently exists (e.g. Scholts et al. 2003, IPCC 2007, Mann 2007, Chase et al. 2009, Holmgren et al. 2012). The majority of palaeoclimatological observations and studies have been performed in developed countries in the northern hemisphere (IPCC 2007, Mann 2007).


South Africa's vegetation is currently dominated by grass ecosystems (Mucina & Rutherford 2006). Within these grass ecosystems grasses using either a C₃ or C₄ photosynthetic pathway have a distinct geographical distribution that within current climate regime is based primarily on temperature (Ehrlinger et al. 1997). Grasses have a high turnover rate and respond quickly to environmental changes. Furthermore, different subfamilies are found in different ecological niches. The different subfamilies produce morphologically distinct phytoliths, a proxy that can be used to infer past changes in grassland composition by analysing fossil phytoliths from natural archives such as wetlands (Twiss et al. 1969; 1992, Piperno 2006).
Study aims
The thesis is performed within the frames of an existing research project within the “500 Year Initiative”, where scientists from different disciplines from both Sweden and South Africa are working together to understand a vast area of rich archaeological remains in Mpumalanga province, South Africa. In this area, termed Bokoni, traces of pre-colonial terrace agriculture have been found. Within this project there is also an interest to know what environmental changes that have occurred in the past, especially when Bokoni agriculture was active, as well as to know if maize may have been cultivated. This thesis attempts to provide insight into these knowledge gaps.

There are three aims within this study:

1. To perform a palaeoenvironmental reconstruction with emphasis on past local grassland composition. The proxy used to identify past grassland composition will be grass phytoliths. In the extent that diatoms can be found these will also be identified and used to interpret potential hydrological changes at the site. The lithology and physical composition of the master core will be used as an additional proxy. Furthermore, changes in ratios of stable isotope $^{12}$C and $^{13}$C ($\delta^{13}$C) will also be analysed throughout the core to aid interpretation of past environmental changes. All proxies will be retrieved from a peat sequence with the Bokoni area.

2. To identify if, and when, maize was cultivated nearby the sampling site through phytolith analysis.

3. Perform a survey of suitable liquid mounting mediums for enabling turning of individual phytolith grains during microscope analysis, and to document the procedure.
Site description

Geographical setting

The town Lydenburg is located in the north-eastern parts of the province Mpumalanga west of the Drakensberg Escarpment (Fig. 1). The study site is located within the summer rainfall region (SRR) of South Africa. The investigated fen (S 25°05’54.4, E 30°30’36.0), hereafter termed “Lydenburg fen”, is located in the eastern parts of Lydenburg town, within Gustav Klingbiel Nature Reserve, which hosts archaeological features as well as various species of game (Lydenburg Muesuem, Internet 2011). Within the reserve stone built terraces, cattle-kraals, and stone paved cattle lanes are found. When these terraces were constructed is still fully established, but they are believed to be constructed in the AD 1700s, probably by the ancestors of Bakoni. (Delius et al. 2012)
**Geology and hydrology**

The town Lydenburg is located in a broad and gentle valley (Hall 1913), approximately 40 km long and 10 km wide. To the west the valley is confined by a plateau, which gradually rises and merges into the steeper slopes of the Steenkampsbergen (Hall 1913) (Fig 1). To the east the valley is confined by the Drakensberg Escarpment. The valley floor consists of altered shales and intrusive rocks. The shales are part of the Transvaal Sequence, a flat blanket of sedimentary rocks, which was formed in a shallow sea between 2.7 and 2.4 billion years ago (de Wit 2007). The sedimentary shales where later eroded, a process that created the lowveld found east of the Drakensberg Escarpment. The older granites, found below the shales, constitute the bedrock of the lowveld.

The bedrock in the study area consists of the same shales as described above, intersected by gabbro (diabase) (Council for Geoscience 2001). Less than 10 km to the east of the study area gold bearing Argillite is found. Numerous active gold mines are found in this area (eg. Golden Hill, Spekboom, Nooitgedacht, Jackpot) (Council for Geoscience 2001).

The valley where Lydenburg is located is traverse by Dorpsrivier and Sterk Spruit river (Hall 1913, Google Earth 2012). The drainage basins of Waterval and Dorpsriviers cover practically the whole of the Steenkampsbergen (Hall 1913). The Dorprivier merges with Sterk Spruit and thereafter further north joins Steelpoort River. The area is part of Olifants River catchment, a sub-catchment of the Limpopo River. The Limpopo generally flows north-east and eventually enters Mozambique where it drains into the Indian Ocean (Google maps, 2012).

The drainage pattern in the Lydenburg area is generally dendritic. North of the fen a small creek runs in a south-westerly direction (Fig. 4). A second larger creek is found south of the fen. This larger creek is noted as non-perennial on a map from Council for Geoscience (2001) but according to JP Cellier (pers. Comm., 2012) both creeks are perennial. The two creeks feed into the Dorpsrivier east of Lydenburg. The bedrock underlying the creek south of the fen is constituted by gabbro (Council for Geoscience 2001), and the bedrock below and just north of the fen is constituted by a mixture of shales and gabbro (Field observations, Nov 2012). Through field observations it was established that the bedrock
immediately north-east of the fen was likely constituted by gabbro, as indicated by bedrock outcrops and by weathered gravel and large pebbles on the slopes above the fen (Fig 2). The area immediately north-west of the fen is constituted by shales, as indicated by shale bedrock outcrops and shale gravel pebbles found in the slopes (Field observations, Nov 2012).

The fen is located in a slope, with inclination both in the east-westerly direction, as well as in a north-south direction. The inclination across the fen in a north-south direction is c. 5 meters, and in from east to west the inclination is c. 11 meters (Field observations, Nov 2012). Two streams are located nearby the fen (Fig 4a), the stream immediately south of the fen is found at the base of a 3 meter drop. The fen is located at an elevation of 1,600 meters above sea level (masl) (Field observations Dec 2011, Google Earth 2012).

**Climate and vegetation**

Climate and weather of north-eastern South Africa is regulated by several large scale processes. Like the seasonal movement of Inter tropical convergence zone (ITCZ), the Congo Air Boundary (CAB), ocean-atmosphere interactions, the Southern Oscillation (ENSO), and the thermohaline circulation (Tyson & Preston-Whyte 2000). When the ITCZ migrates from the Southern hemisphere (SH) to the Northern hemisphere (NH) between January and July, precipitation decreases in SH winter (Tyson & Presont-Whyte 2000). This migration affects the rainfall pattern of the SRR of South Africa.
The climate within the Lydenburg area is governed by its location in the rain shadow of the Drakensberg Escarpment (Mucina & Rutherford 2006). The annual rainfall is between 580 to 810 mm. Rainfall is highly seasonal with the majority of precipitation occurring during the summer months during October-March. The mean annual potential evapotranspiration (1956 mm/year) exceeds the mean annual precipitation (707 mm/year). Mean annual temperature is c. 16°C. During winter months (April-September) mean temperature drops under 10°C, and during the coldest months (June-August) frost regularly occurs. Mean number of days per year with frost are approximately nine days / year.

Grassland and savanna biomes occupy two-thirds of South Africa’s landcover, and both biomes are grass dominated ecosystems (Mucina & Rutherford 2006). Lydenburg is located in the north-eastern borders of the grassland biome, just 30 km from the savanna biome. The general distinction between savanna and grassland is based on vegetation structure in combination with environmental and climatological factors (primarily amount of rainfall and minimum temperatures). Grasslands are found in areas where winters are cool and dry, while savannas are generally found in tropical and subtropical settings. In South Africa the grassland biome occurs primarily in the high central plateau, in mountainous areas of KwaZulu-Natal, and central parts of Eastern Cape. Savannas generally occur at lower elevations. Grasslands are generally dominated by C4 grasses, with little or no woody vegetation while savannas generally comprise a C4 grassy layer with C3 woody vegetation intermixed (Mucina & Rutherford 2006).

The Grassland biome is divided into different subdivisions where Lydenburg fen is located in the Lydenburg Thornveld, a mesic Highveld grassland type (Mucina & Rutherford 2006). The Lydenburg Thornveld is a transition zone between high-lying grasslands and the warmer and drier bushveld areas (Mucina & Rutherford 2006). In this vegetation unit the elevation varies from 1,160 to 1,660 m. This vegetation unit occurs at lower elevations, at the foot of mountains and on undulating plains (Mucina & Rutherford 2006).

A simplified field inventory of the current vegetation was performed by M. Schoeman in spring 2012; when the most common species were collected and forwarded to a herbarium at Buffelkloof Nature Reserve for species identification. The contemporary fen vegetation is dominated by reed; *Phragmites australis* (C3-Arundinoideae), fern; *Thelypteris confluence*, rush; *Juncus punctatus*, and sedges; *Kyllinga melanosperma* (C4-Cyperaceae).
Schoenplectus corymbosus (likely C₄). Few grasses grow in the immediate surroundings of the fen, the only grass found in a second field inventory (Nov 2012) within 10 meters of the fen was Setaria sp. (C₄ Panicoideae). Three grasses was also collected c. 50 north-east of the fen (Fig. 2); Themeda Triandra (C₄-Panicoideae), Setaria sp (C₄-Panicoideae) and Aristida junciformis (C₄-Aristideae), pictures of the grasses found in figure 3. A recently performed botantical survey in Gustav Klingbiel Reserve was used to aid identification of grasses (Research and Development FFA Operations 2012). Trees grow in the riparian zone along the creek south of the fen. The vegetation surrounding the fen is compromised by grasses, low shrubs and occasional trees. Shrubs and trees mainly use a C₃ photosynthetic pathway (Ehrlinger et al. 1997).
**Archaeological and historical context of study area**

Lydenburg fen is located in the northern parts of a region rich in archaeological remains. The area has been termed Bokoni after the ethnically diverse Bokoni speaking people who occupied the area in the past. Bokoni is located in a vast area from Ohrigstad in the north to Carolina in the south (c. 150 km long and 50 km wide) (Delius et al. 2012). Within this area densely walled settlements with circular homesteads linked by walled paths are found interspersed among agricultural terraces (Delius et al. 2012). Widgren et al. (unpublished manuscript) describe that the origin of the settlers is still not well known. The collapse and abandonment started in the early AD 1800s after intense raiding in the area by Pedi people. By 1830 the majority of open air settlements where abandoned (Widgren et al. unpublished manuscript).

Delius et al. (2012) describe that the Bokoni era, after intensive research through the “500 Year Initiative”, now is thought to be divided into four different phases. In the first phase the escarpment was lightly populated by small chiefdoms, who lived in open grassland adopted stone as building material. In the second phase open-air sites was built in the lower parts of valleys in Elands, Crocodile and Sabie valleys. During the third phase people of Bokoni retreated to settlements locations in the steeper slopes (kloofs) in the AD 1700s. In the fourth phase, during the AD 1800s, the Bokoni people were probably scattered in the landscape as a consequence of repeated conflicts (or had joined their aggressors). The abandoned terrace sites in the kloofs were repopulated by newly formed communities. In conclusion, the open valley homesteads are believed to have been used in time of peace,
and the kloof sites were refuges and fortresses used in the later part of the Bokoni era when conflicts were increasing. (Delius et al. 2012).

The Bokoni area has been suggested to have supplied the coast with surplus cattle and agricultural products. Historical sources indicate substantial regional trade with less fertile regions (Delius et al. 2012). A central question in the transdisciplinary research project to better understand the nature of the agriculture in the Bokoni area is to know what crops were cultivated. Maggs (2008) argue that maize may have been cultivated in the Bokoni area. Since maize requires higher amounts of nutrients, maize cultivation could have been one factor driving the development of terracing agriculture and possibly a driver for the use of manure. Traces of stallfed cattle and manuring have until date been rare in South African agriculture. There are records of maize being cultivated in the AD 1600s in lower Limpopo valley, c. 180 km east of Lydenburg (Ekbloom et al. 2011), but the in the Bokoni area the introduction of maize cultivation is unknown.

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a) Google Earth picture showing border of *Phragmites* stands (yellow), directions of nearby streams (blue) and location of potential terraces (black arrows). White circles indicates coring locations for fen stratigraphy. Number 1 and 2 (white boxes) indicates where grass samples were collected. Google Earth 2012. Edited by Sjöström, J. 2013
b) Example of craals (circular features) and terraces (west-easterly lines) viewed from Google Earth. This Google Earth satellite picture is from within Gustav Klingbiel reserve, c. 2.5 km west of Lydenburg fen (Google Earth 2013).

Figure 4. Satellite image of Lydenburg fen (a) and archaeological features within Gustav Klingbiel Reserve (b).
**Background and theory**

This chapter describes previous research on palaeoclimate in southern Africa, the theoretical background of C₃ and C₄ photosynthesis in grasses and theoretical background of phytoliths in palaeoenvironmental research.

**Palaeoclimatological studies in southern Africa**

Orbital variations are the main climate forcing causing Quaternary glacial and interglacials cycles (Ruddiman 2008). By changes in the Earth's tilt towards the sun, the eccentric orbit around the sun and the precession the amount of insolation at different latitudes is changed. These changes occurs in cycles of c. 100,000 years (eccentricity of the orbit), c. 41,000 (tilt of earth’s axis), and a third cycle of c. 21,000 years (precession of solstices) (Lowe and Walker 1997). These astronomical cycles were first described in the “Astronomical theory” developed over 100 years ago by Croll, later elaborated by Milankovich in the 1940's (Lowe and Walker 1997). During glacials water is accumulated in large ice-sheet and glaciers globally. During the last glacial the sea level was lowered by c. 110-125 meters (Ruddiman 2008). Changes in global vegetation cover also occurred during glacial and interglacial transitions (eg. Scott 2002, Ruddiman 2008).

Climate forcings and feedbacks on shorter time scales, such as centuries and decades, are less likely to be caused by orbital variations (Ruddiman 2008). Other climate forcings are active on these shorter time scales, such as variations of solar activity which affect insolation received at Earth’s surface, volcanic eruptions emitting CO₂ into the atmosphere and large amounts of sulphur oxide into the stratosphere, as well as human activities such as land-use changes and use of fossil fuels (Ruddiman 2008).

Important to note is that the results from different palaeo-studies in southern Africa show contrasting climate indications, making it difficult to create a coherent picture of palaeoclimate of southern Africa. The reasons causing these divergent trends are likely multiple, some being related to that the same forcing affect regions differently, different proxies are used in different studies, the proxies might be interpreted differently, and uncertainties in dating methods. This chapter reviews results from palaeoclimatological studies in Southern Africa, with emphasis north-eastern South Africa during late Holocene.
In the section below the temporal descriptions “ka” is used, meaning 1000 years before present, where present is regarded as 1950. Temporal descriptions of the last two thousand years use the Gregorian calendar years AD (Anno domini), years after 0 in the Gregorian calendar.

**Pleistocene-Holocene transition**

The last transition from glacial to interglacial occurred between 25 to 12 ka, the Pleistocene to Holocene transition. Holmgren *et al* (2003) performed a study based on speleothems collected from a cave in Makapansgat located in the Savanna biome in north eastern South Africa. The results suggest that the mean temperature difference between the Pleistocene and Holocene was c. 5.7°C. A temperature difference that in line with the results described also by Partridge (1993), which suggested that the temperature during Last Glacial Maximum (LGM) was c. 5-6°C lower than today, with widespread dryness. The Makapansgat speleothem indicated that postglacial warming was initiated around 17 ka. This warming was interrupted by a cooling, followed by a strong warming around 13.5 ka.

**Holocene**

The results from Makapansgat speleothem indicate that the climate during early Holocene was warm with evaporative conditions and few C₄ grasses (Holmgren *et al* 2003). The general climatic trend during Holocene is cooling, although temperatures and precipitation have varied throughout the period. The result of Norström *et al*. (2009), based on multi-proxy analysis of a peat sequence from Braamhoeck, also found indications of drier conditions during early Holocene. The Holocene Altithermal, a warm period that occurred somewhere between 8 to 5 ka (Tyson & Preston-Whyte 2000) is by some authors suggested to be associated with more humid conditions in the summer rainfall region (Partridge 1993) and by others with drier conditions in the region (Tyson & Preston-Whyte 2000). The result by Holmgren *et al*. (2003) suggest that cool and dry conditions prevailed between c. 6 to 2.5 ka, followed by a warming around 2.5 – 1.5 ka. Indications of widespread drying after 5 ka were also noted by Scott *et al*. (2012) and Norström *et al*. (2009). Breman (2010) found indications of drier conditions between 7 to 5 ka, followed by increased moisture after 5 ka. Several authors have found indications of wetter conditions during the last c. 2 ka until present (Norström *et al*. 2009, Breman 2010, Finné *et al*. 2010, Scott *et al*. 2012). In contrast, Holmgren *et al*. (2003) as well as Chase *et al*. (2009) found indications of drying after 2.5 ka and 3.5 ka respectively.
In late Holocene, indications of a warming in southern Africa have been found from around AD 900 to AD 1300 (Holmgren et al. 2003, Tyson & Lindesay 2000, Tyson & Preston-Whyte 2000). In NH records, mainly from Europe, a warming phase termed Medieval Warm Period (MWP) has been recorded between c. AD 950 to 1250 (Tyson & Preston-Whyte 2000, Mann 2007), the observed warming in southern Africa are by the authors related to the “MWP” (Holmgren et al. 2003, Tyson & Preston-Whyte 2000). Moisture availability was likely variable during “MWP”, but the period is generally believed to have been wetter (Holmgren et al. 2003, Tyson & Lindesay 2000). The results from additional palaeoenvironmental studies in the region however indicate divergent moisture conditions during this period. A study by Huffman (2008), based on archaeological records and isotope data, found indications of significant drying within this period. A palaeohydrological study of a lake in Mozambique also found indication of significant drying AD 1180-1700 (Holmgren et al. 2012). On the other hand, Ekblom et al. (2012) found wetter conditions in the Lower Limpopo Valley from AD 800, and drier conditions from AD 1400 to AD 1800, in line with the results by Holmgren et al. (2003). In the study by Ekblom et al. (2012) the proxies for the later period (AD 1400-1800) however showed ambiguous moisture indications, where planktonic Cyclotetlla meneghiniana actually increased, which could indicate increased water levels. Riparian vegetation however decreased which was interpreted as indications of drying (Ekblom et al. 2012).

A significant cooling in southern Africa has been indicated from c. AD 1500 to AD 1800 (Holmgren et al. 1999, Holmgren et al. 2003, Tyson & Preston-Whyte, Tyson & Lindesay 2000). Holmgren et al. (2003) found maximum Holocene cooling occurring around AD 1700. This episode is generally believed to have entailed drier conditions in southern Africa. The author relates this cooling to the Little Ice Age (LIA), a climate cooling found in NH records, mainly from records in Europe, to have occurred between c. AD 1500 to 1900 (Mann 2007). Norström et al. (2005) performed analysis on variations of δ¹³C and δ¹⁸O on Matumi trees in Tzaneen (Limpopo Province), the results indicated episodes of drying in the early 1400s, mid-1500s, 1700s and early 1900s. Wettest conditions was recorded late 1400s and in the 1600s (Norström et al. 2005).

Elinor Breman (Doctoral thesis 2010) performed palaeoecological studies in three wetlands crossing the Grassland – Savanna ecotone in northern Mpumalanga, close to Lydenburg fen. Due to the closeness of these three study sites to Lydenburg fen the results from
Breman's work is described in more detail below.

The results of Breman (2010) shows that climatic conditions during early Holocene were cool (compared to Holocene mean) and that the general climatic trend through Holocene has thereafter been warming (as inferred from increases of C₄ grasses), in contrast with the general trend of cooling during Holocene found by Holmgren et al (2003).

In Verloren Valei (c. 60 km south-east from Lydenburg), Breman (2010) concludes that the vegetation has remained an open grassland system for the past 10 ka. The author describe that changes in the composition of the grassland have however occurred within this period. The proportion of C₃ and C₄ grasses changed, as well as the proportion of short and tall C₄ grasses. In Verloren Valei the greatest water stress was found prior to 10 ka. After the start of Holocene water-stress is found to be variable in Verloren Valei. Periods of low water stress was noted around 8.6, 4.4, and from 2. ka to the present. Periods of higher water-stress was noted around 9 ka between 7 to 5 ka and 2.7 ka and, 0.4 ka (AD 1600).

In Graskop (c. 60 km north-east of Lydenburg) a mosaic of grassland and Podocarpus dominated forests existed from 6.5 until 0.6 ka, after which the forests declined and a more mesic grassland was established. A shift to wetter conditions was noted during this time. The mesic grassland persisted for 500 years after which it was replaced by plantation forestry and infrastructure. The grass in Graskop grassland have remained C₄, with C₃ input from woody taxa (Breman 2010).

Cooler conditions during “LIA” was not recorded in Bremans (2010) records. In all three study sites rapid changes are noted during the last few hundred years, related to human activities such as plantation, grazing and fire management (Breman 2010).
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

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<td>24 ka</td>
<td>Significantly cooler. Correspond in time to Heinrich events H2 and H1.</td>
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<td>1-0.5 ka</td>
<td>0.8 ka (AD 1200) brief warming, MWP.</td>
<td>0.8 to present: increased wetness at Graskop. 0.8 ka (AD 1200) dry event recorded at Versailles. Dry event recorded at Verloren Valei 0.4 ka (AD 1480).</td>
<td>0.8 to present: increased wetness at Graskop. 0.8 ka (AD 1200) dry event recorded at Versailles. Dry event recorded at Verloren Valei 0.4 ka (AD 1480).</td>
</tr>
<tr>
<td>0.5-0 ka</td>
<td>0.5-0.1 ka (AD 1500-1900) cooler and drier (LIA). Maximum Holocene cooling at AD 1700.</td>
<td>0.3 ka to present (AD 1700 to present) increased wetness at Verloren Valei.</td>
<td>0.3 ka to present (AD 1700 to present) increased wetness at Verloren Valei.</td>
</tr>
</tbody>
</table>
C₃ and C₄ photosynthesis in Poaceae

Plants can assimilate atmospheric CO₂ in three different ways: C₃, C₄ (Hatch & Slack 1970) and CAM (Ranson & Thomas 1960). Only C₃ and C₄ photosynthetic pathway will however be described further in this chapter these are the photosynthetic pathways used by grasses (Poaceae).

C₃ photosynthesis is globally the most common photosynthetic pathway (Ehlringer et al. 1997). This photosynthetic pathway is described as straightforward and involves least investment by the plant and is efficient under cool, moist conditions with normal light intensity (Vogel et al 1978).

The C₄ photosynthetic pathways represent an evolutionary advancement over C₃, utilizing a more complex photosynthetic pathway, which involves different enzymes and different anatomical leaf structure than C₃ plant leaves (Sage 2004). This anatomical leaf structure is termed Kranz anatomy (Sage 2004). C₄ grasses are therefore sometimes in literature referred to as “Kranz grasses”. The C₄ photosynthetic pathway allows the plants to be more water efficient, as the plant has the stomata open shorter time. C₄ plants are better adapted to high light intensities and high temperatures. This leads to a competitive advantage for C₄ plants over C₃ plants in low CO₂ conditions with high temperatures and high light intensities (eg. Sage 2004, Ehleringer et al. 1997).

In South Africa there is a distinct geographical distribution of C₃ and C₄ grasses related primarily to temperature (Vogel et al 1978). C₄ grasses dominate in most of the country, while C₃ grasses are dominant only in the winter rainfall region of the Western Cape, in the summits of the Drakensberg Escarpment and mountain ranges in the Eastern Cape (Vogel et al 1978). C₃ species are favoured by low temperatures during growing season and C₄ grasses are favoured by high temperatures during growing season (Vogel et al 1978). Twiss (1992) describe how studies performed in North America by Teeri and Stowe (1976) showed that winter temperatures about 10°C or lower limit growth of C₄ grasses. The author also reports that studies by Livingstone and Clayton (1980) performed in tropical Africa also found that temperature control the distribution between C₃ and C₄ grasses.
Vogel et al. (1978) produced a map over the geographical distributions of C₃ versus C₄ grasses in South Africa. This map shows that the area where Lydenburg is located C₄ grasses compromise 75-90% of the grass assemblage. The author further concludes that the C₃ grasses within this area almost exclusively come from C₃ Panicoideae, on higher altitudes more cold adapted C₃ grasses can however be found (over 2000 masl).

Under warm temperatures available soil moisture also determine what kind of C₄ grasses will flourish, where C₄-Chloridoideae grasses are common in warm and dry conditions, and C₄-Panicoideae are more abundant in warm and mesic conditions (Twiss 1992). It is common for C₃ and C₄ grass to occur together in many places (Twiss 1992). The C₃ plants can flourish early and late in the season, when the temperature is cooler and more moisture is available. When the temperature increases during the summer months the C₃ grasses give way to the C₄ grasses.

**Phytoliths in paleoenvironmental research**

Phytoliths are microscopic silica particles formed by plants (e.g. Twiss et al. 1969, Madella et al. 2005, Piperno 2006). They are produced through plant uptake of ground water containing soluble silica (Piperno 2006). The soluble silica is transported upward in the plant and some is deposited in and between the cells of the plant as solid silicon dioxide (silica). Patterns of silicon accumulation and placement of the silica deposits are similar within plant species and closely related taxa. The phytoliths are deposited into sediments and soils after the plant dies and decays. As phytoliths are inorganic they are generally resilient and well-preserved in various natural archives. Phytolith analysis is particularly useful in the context of grass ecosystems since grass (Poacea) produce a great amount of phytoliths (up to 10%) by weight, and since grass sub-families, and sometimes species, can be identified through identification and quantification of different phytolith shapes (Piperno 2006). An increasing number of studies have identified the potential for phytoliths to be used to reconstruct palaeovegetation in the last decades (Piperno 2006), especially in arid and semi-arid tropical and sub-tropical regions where other proxies such as pollen and diatoms are generally less well preserved (e.g. Scott 2002, Barboni et al. 2007, Finné et al. 2010, Burrough et al. 2012). Palaeoenvironmental studies using fossil pollen is furthermore limited by that grasses cannot be distinguished below family level, fossil phytolith analysis is allows distinction between different grass subfamilies (eg. Rossouw 2009). In South
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

Africa, phytolith studies has been used to study palaeovegetational shifts between C\textsubscript{3} and C\textsubscript{4} grass vegetation and/or subfamilies (e.g. Scott 2002, Rossouw 2009, Finné \textit{et al.} 2010, Breman 2010). Grass silica short cell (GSSC) phytoliths are located in both the costal zone and intercostal zones of the leaf epidermis and make up only a small portion of the total siliceous residue. These cells provide the most taxonomically useful grass phytoliths since different subfamilies produce different morphological shapes of phytoliths, hereafter called morpho-types (e.g. Twiss \textit{et al.} 1969; 1992, Piperno 2006, Rossouw 2009). Grasses have a high turnover rate and respond relatively quickly to environmental changes, a factor contributing to making grass phytoliths useful in palaeoenvironmental reconstruction contexts (eg. Twiss 1969 \textit{et al.}; 1992, Rossouw 2009). Some shapes produced by grasses, generally termed elongates or long-cells, cannot be used to identify sub-families as they frequently occur in all Poaceae subfamilies.

Important to note is that within a specific subfamily many phytolith morpho-types are produced a property called termed multiplicity (Rovner 1971). Individual phytolith shapes may also occur in many grass taxa, a characteristic is denoted redundancy (Rovner 1971). Different shapes are however more frequently produced in some families than others, which enable analysis of dominating subfamily through quantifying and assessing dominating phytolith shape occurrences in a fossil assemblage (Twiss \textit{et al.} 1969). A few morpho-type are however unique to a certain subfamiliiy or species, these morpho-types are described as “diagnostic”, ie no multiplicity or redundancy occurs with other subfamilies (Piperno 2006).

To use previous studies as reference material for morphological classification can sometimes be difficult as different standards to describe phytolith morphotypes are used by different authors. A standard for naming and describing phytoliths was therefore developed by the ICPN (International Code for Phytolith Nomenclature 1.0) (Madella \textit{et al} 2005). This standard protocol is used, as far as possible, within this thesis.
GSSC phytolith morphology.

All GSSC phytoliths are three dimensional, a relief and/or height is present (Mullholland & Rapp 1992). The phytoliths usually have one broader face which is denoted the base (Fig. 5). The face opposite to the base is denoted top, and elongated faces alongside the base and top are called sides. The shorter end sides of the elongated faces are called ends. A phytolith can be found oriented in any direction when mounted in a laboratory slide, but often it is found with the base up (however not always). The morphology of the baseview is therefore commonly used to describe different features such as the typical saddle or bilobate shape. If phytoliths are located in side- or end-view, in a permanent medium, the risk of misidentification is high and it is common for phytoliths found in this position to be discarded, or counted as an unknown morphological type (Twiss et al. 1969, Alexandre et al. 1997). This could pose problems with representatively and some authors therefore recommend mounting in liquid medium (eg Rossouw 2009, Piperno 2006). Mounting in liquid medium enables turning of the phytoliths and potentially allows better identification, and at some instances allows species identification (Piperno 2006). A detailed methodological description of how to use liquid mediums seems however to be lacking. An attempt to compare liquid mounting mediums, as well as to document this procedure, has been applied within this thesis (see method chapter).

![Diagram of phytolith and naming of sides](image_url)

Figure 5. Schematic sketch of a phytolith and naming of the different sides

Diatoms in palaeoenvironmental research

Diatoms are single cell algae that create a siliceous cell wall consisting of two shells (frustules) (Lowe & Walker 1997). Their size varies from 2 micrometers up to 2 mm. The frustule is resistant to decomposition and diatoms are therefore found in various natural archives such as soils, sediments and peat as microfossils. One of the frustules is slightly bigger (epitheca) than the other (hypoteca). The frustules are either centric or oval and are perforated by openings – so called apertures. How these apertures are organised, as well as the shape of the frustule, are analysed in order to identify species. Diatoms can be benthic
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

(dwelling at lowest level of body of water), epiphytic (attached to plants), epilithic (attached to bedrock) or planktonic (drifting in pelagic zone). They are found in both fresh- and brackish/saline water. All diatoms species share one limiting factor – they require light. The distribution of the species varies with a number of factors like pH, salinity, oxygen level in the water, nutrition and water temperature. Ecological preferences of fossil diatom assemblages can be used to interpret the palaeoenvironment at the time of deposition.

Chrysophycean algae is primarily freshwater algae (Duff et al. 1995), and may indicate presence of water in a sample. The siliceous resting cysts of chrysophyceae stomatocysts are possible to count along with diatoms in palaeoenvironmental studies.

**Stable isotopes in peat and sediments**

**Carbon**

There are two stable isotopes of carbon $^{12}$C and $^{13}$C. Different plants have different ability to take up the heavy isotope $^{13}$C in relation to the lighter $^{12}$C, leading to different isotopic ratios ($\delta^{13}$C) within their tissues. In this way, it is possible to distinguish if for example C$_3$ or C$_4$ plants have dominated the past vegetation in natural archives, through measuring values of $\delta^{13}$C in peat, soils and sediments (e.g. Norström 2008). In general, C$_3$ plants have ratios from c. -20 to – 35‰ and C$_4$ species have $\delta^{13}$C values between c. -9‰ to -14‰ (Rundel et al. 1989). In the context of South Africa studies have shown that C$_3$ grasses display $\delta^{13}$C values more depleted than -20‰ and C$_4$ grasses show values less depleted than -16‰ (Vogel et al. 1978).

**% Carbon**

The carbon content gives information about the organic content in a sample, calculated in relation to the minergogenic component. This can give information about varying organic content in a sequence.
Grass Silica Short Cell (GSSC) phytolith classification system

Twiss et al. (1969) developed a classification system, based on phytolith morphology, where certain phytolith morphology can be related to grass subfamilies (Table 2). This classification system has been used, and refined, in palaeoenvironmental studies with the aim to reconstruct palaeovegetation in grass ecosystems. Later studies generally support this classification system (eg Barboni and Bremond 2009, Rossouw 2009), although some modifications can be made to the original system. In the following section an introduction to the grass subfamilies that can be identified by analysing fossil GSSC phytoliths is described, results from recent research is also integrated.

Grass subfamilies and related phytoliths

Within the Poaceae family twelve subfamilies are recognised (GPWG 2001), of which eight occur in South Africa (Rossouw 2009). Five of these grass families use exclusively C3 photosynthetic pathway (Bambusoideae, Pooideae, Danthonioideae, Arundinoideae and Ehrhartoideae). Three subfamilies contain genera and/or species using both a C3 and C4 pathway (Aristidoideae and Panicoideae), or alternatively exclusively C4 pathway (Chloridoideae). Of these grass families three produce phytoliths that can be related to specific subfamilies; C3-Pooidea, C4-Chloridoideae and C3/C4-Panicoideae.

Since these three grass subfamilies occur in different ecological niches their relative distribution in a fossil assemblage can yield interesting information about past shifts in grassland composition. Below follows an introduction to the five most common subfamilies in tropical and subtropical settings, as well as the type of phytoliths they produce.

C3-Pooidea

The Pooidea dominate the grass flora in the temperate zones of the northern and southern hemispheres, but can also occur in cooler seasons in the tropics and in high altitudes (Twiss 1992). In general, Pooidea are absent in lowlands between the Tropics of Cancer and Capricorn. Twiss et al. (1969, 1992) suggested that phytoliths of the Pooidea subfamily are represented by circular, oval, oblong and rectangular phytoliths. Circular and oval phytoliths are those which are currently named rondels (Madella et al. 2005). Later
research found that the size of the rondel is of importance when relating this morpho-type to Pooideae subfamily (Barboni and Bremond (2009). Trapeziform sinuate (Barboni and Bremond 2009) are only reported in Pooideae. This morpho-type was originally termed oblong, elliptical and/or rectangular by Twiss et al (1969). Pooidea also include the cereal grains barley, rye, oat and wheat (Twiss 1992).

**C₄-Chloridoideae**

The Chloridoideae subfamily occur frequently in arid regions of Africa, Australia, and India where precipitation occur in the summer (or where no distinct rainy season occur) (Twiss 1992). They are abundant in savannas or open grasslands. Chloridoideae uses a C₄ photosynthetic pathway and tolerate high temperatures and aridity better than other grasses. Several studies have found that the phytoliths of Chloridoideae produces mainly saddle shapes (eg. Twiss et al 1969, Twiss 1992, Mullholland & Rapp 1992). However, Barboni and Bremond (2009) found that one saddle shape more than others indicate occurrence of the Chloridoideae subfamily; saddles with long convex edges. The authors also conclude that saddle shapes are still a good indicator of presence of C₄ grass since 78% of species that produce saddles type phytoliths use C₄ photosynthetic pathway.

**C₃/C₄-Panicoideae.**

Panicoideae subfamily uses mainly C₄ photosynthetic pathway, and these grasses are favoured warm and moist habitats. This subfamily consists of two supertribes; Andropogonodae which uses the C₄ photosynthetic pathway and Panicoidea where genera that uses both C₃ and C₄ photosynthetic pathway are found (Twiss 1992). Species of Andropogoneae are concentrated in the tropics and subtropics, and seems to be favoured by warm temperatures and high summer moisture. The tribe Paniceae has a wider geographical distribution and a more varied photosynthetic pathways than Andropogoneae. The Panicoideae subfamily contain maize, sorghum and sugarcane. Twiss (1992) describe that bilobates (previously called dumbells) and crosses are characteristic of the panicoid grasses. It is further noted that these morphotypes also occur in Bambusoideae and Chloridoideae grasses, but in low numbers.
C₃-Bambusoideae

The subfamily Bambusoideae uses a C₃ photosynthetic pathway and are concentrated in the tropic and subtropics in central and southern Africa, India, Asia, Central and South America (Twiss 1992). The author describe that phytoliths from this subfamily cannot be distinguished from other sub-family phytoliths as some species produce only saddles, others only crosses and bilobates and some both saddles and bilobates (Twiss et al. 1969). Piperno (2006) suggest that tall or plateaued, are phytoliths from the Bambusoidea grasses, as well as a bilobate with wide, short shaft and convex lobes.

C₃/C₄-Arundinoideae

Arundinoideae lacks, according to Twiss (1992), specialized and reliable diagnostic characteristics. Three tribes are included: Arundineae (which includes Stipae and Aristdieae), Danthonieae and Crotaderieae (Twiss 1992). The author describe that most grasses are C₃, but a few genera are C₄. The genera and tribes are widely distributed over several continents. Arundioideae grasses produce saddles, bilobates and rondels (Piperno and Pearsall 1998). Several authors have noted that Aruninodeae grasses can affect fossil assemblages (Piperno and Pearsall 1998, Bremond et al. 2008, Breman 2010). *Phragmites australis* is for example known to cause an overestimation of Chloridoideae grasses in fossil assemblages as this species produce saddles. The saddle produced by *P. australis* is however potentially possibly to distinguish in an assemblage as it is plateaued (Ollendorf et al. 1998). This morpho-types has in this study been counted separately in order to remove these phytoliths from the assemblage.
**Original Twiss scheme and adapted scheme**

The basic morphological classes, as originally described by Twiss *et al* (1969), are found in table 2. Originally the different morphological shapes were given other names than used here. Throughout this thesis an attempt to follow the characterisation and name standard described by ICPN Working Group has been applied (Madella *et al* 2005).

Table 2, basic simplified classification of GSSC phytoliths based on morphology

<table>
<thead>
<tr>
<th>Class</th>
<th>Phytolith morphology</th>
<th>Morphological description</th>
<th>Related sub-family</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panicoid class</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bilobates</td>
<td>Bilobate, polylobates and crosses</td>
<td>Panicoideae C3/C4</td>
<td></td>
</tr>
<tr>
<td>(previously denoted dumbbells)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Festucoid class</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chloridoid class</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Twiss *et al* (1969) and Mullholland and Rapp (1992).

These three categories represent grass families that thrive in different environments where C3/C4 Panicoideae grasses flourish in warm and mesic environments, C3-Pooideae grasses grow in cooler temperatures than C4 grasses (humidity can vary) and C4-Chloridoideae grasses are found in warm and arid environments (Twiss *et al* 1969).

In this thesis this original system (Table 2) has been used as a baseline and later studies, mainly but not exclusively, performed in tropical and Southern Africa, have been used as a complement to refine the morphological (Table 3). Some authors have related morphological shapes to different ecological settings (*eg* Barboni & Bremond 2009, Rossouw 2009), these results has also been taken into account. For example Barboni and Bremond (2009) conclude that rondels < 15 µm occur in several grass sub-families (not only Pooideae), but that rondels > 15 µm are only reported in C3-Pooideae. However, the results by Rossouw (2009) found all rondels (regardless of size) related Pooideae subfamily. Barboni and Bremond (2009) further conclude that Trapeziform sinuate are diagnostic to Pooideae.
Barboni and Bremond (2009) suggest that Bilobates with long shank occur most frequently in xerophytic (arid adapted) species and Bilobate with short shank are most frequently reported in mesophytic (moisture requiring) species. Lu and Liu (2003) also reported this relationship between shank length and ecology. Rossouw (2009) on the other hand found that bilobate’s with long shank is an indicator of mesic conditions.

Several authors have confirmed the relationship between C₄-Chloridoideae and saddles, (eg Barboni and Bremond 2009, Rossouw 2009). The study by Barboni and Bremond (2009) also confirmed the relationship established by Twiss et al. (1969) that the subfamily Panicoideae most frequently produce bilobates, polylobates and crosses, even though the authors note that some species within the family do not follow this general trend. Also, the subfamily Chloridoideae are found to produce mainly saddles (short and symmetrical).

Piperno (2006) describe how the morphology of bilobates differ between different subfamilies, this information was also taken into account here. As well as the results by Rossouw (2009) indicating that a certain Saddle type (variant 2) is related to subfamily Aristoideae. Based on the findings discussed above additional sub-division of phytolith morpho-types have been added (Table 3) and applied within this thesis. Additional sub-division/categories were also added to the actual counting sheet (Appendix C), in case new relationships between different morphological shapes and taxonomic and/or ecological were to be found in the future.
### Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

Table 3. Categories and subdivisions used when performing phytolith analysis. Subfamily or ecology described when known. The dark gray rows represent the original morpho-types and related subfamilies (Twiss et al. 1969). The white rows represent added morpho-types and related families and/or ecology (Ollendorf et al. 1988, Lu and Liu 2003, Piperno 2006, Barboni and Bremond 2009, Rossouw 2009).

<table>
<thead>
<tr>
<th>Class (morphology)</th>
<th>Added subdivision</th>
<th>Remark</th>
<th>Related sub-family, genus or species</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Papillae</strong></td>
<td></td>
<td></td>
<td>Cyperaceae (e.g. Twiss et al. 1969; 1992, Alexandre et al. 1997, Piperno 2006)</td>
</tr>
<tr>
<td><strong>Panicoideae</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bilobate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bilobate, long shank</td>
<td>Xerophytic species (Barboni and Bremond 2009)</td>
<td>Bilobate, long shank</td>
<td>Panicoideae Twiss (1969)</td>
</tr>
<tr>
<td>Bilobate long (slender) shank</td>
<td>Xerophytic species (Rossouw 2009)</td>
<td>Bilobate long (slender) shank</td>
<td>Aristidoideae (C4, C3) and Arundinoidae (C3)</td>
</tr>
<tr>
<td>Bilobate long (wide) shank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bilobate short (narrow shank)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bilobate stipsa</td>
<td>Polylobate</td>
<td>Panicoideae (Barboni and Bremond 2009)</td>
<td></td>
</tr>
<tr>
<td>Polylobate</td>
<td>Panicoideae (Barboni and Bremond 2009)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cross</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross, sloping trapezoid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross, blocky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross var 1 &lt; 16 um</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross var 1 &gt; 16 um</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross var 1 &gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

31
| Festucoid | | |  |  |  |
|---|---|---|  |  |  |
| 20 um | | |  |  |  |
| Rondels and oblongs | | |  |  |  |
| Rondel < 15 um, short | | | Occur in several sub-families (Barboni and Bremond 2009) |  |  |
| Rondel < 15 um, tall | | | Occur in several sub-families (Barboni and Bremond 2009) |  |  |
| Rondel < 15 um, tall and wide | | | Potentially *P. australis* (Piperno 2006) |  |  |
| Rondel > 15 um, short | | | Pooideae C3 (Barboni and Bremond 2009) |  |  |
| Rondel > 15 um, tall | | | Pooideae C3 (Barboni and Bremond 2009) |  |  |
| Rondel, wavy- or ruffle-top | | | Zea Maize (Bozarth 1993) |  |  |
| Trapeziform sinuate or smooth | | | Pooideae C3 (Twiss 1969; 1992, Barboni and Bremond 2009) |  |  |
| Chloridoideae | | |  |  |  |
| Saddle | Bodies with saddle like bases and/or tops. Concave edges. | Chloridoideae, C4. (Twiss 1969) |  |  |  |
| Saddle, short. Convex edges | | | Produced in abundance in Chloridoideae, but also reported in Arundinoideae and Bambusoideae (Barboni and Bremond 2009) |  |  |
| Saddle, long convex edges | | | Chloridoideae (Barboni and Bremond 2009) |  |  |
| Saddle, plateau trapezoid | | | Arundinoid, *P. australis*. (Ollendorf 1988) |  |  |
| Saddle, symmetrical | | | Chloridoideae (Barboni and Bremond 2009) |  |  |
| Saddle var 2 | | | Aristidoideae (Rossouw 2009) |  |  |

Long-cells, flat elongated shapes, which are not specific to any subfamily have also been quantified within this thesis. Long-cells are however presented separately from those that can be used to identify subfamilies. Variations in ratios of long-cells versus GSSC phytoliths can yield valuable information as they are suggested to be a potential indicator of preservation throughout an assemblage. Long-cells are much less silicified than GSSC phytoliths and therefore more vulnerable to chemical or physical degradation (Madella & Lancelotti 2012).
Palaeoclimatic indices from a phytolith assemblage

Ic index

Twiss (1992) describe that the different ratios of phytoliths belonging to Pooideae, Chloridoideae or Panicoideae subfamilies can be used to make palaeoclimatic indices based on ratios of C₃ and C₄ grasses. Since the distribution of C₃ and C₄ grasses is mainly driven by temperature, this index, termed the Ic index, can be used as a climatic temperature index. The author suggest that so called Pooid phytoliths (ie phytoliths that in the new ICPN standard are denoted rondels, and trapeziform sinuate, smooth, rectangular or square) can be compared with the sum of Pooid, Chloridoid (Saddles) and Panicoid (Bilobates, Crosses and Polylobate) phytoliths. The index is calculated as follows:

\[
Ic \% = \frac{\text{Pooid}}{(\text{Pooid} + \text{Chloridoideae} + \text{Panicoid})}
\]

High values from this ratio calculation suggest a cool climate and low values suggest a warm and humid to arid climate. Barboni et al. (2007) results, based on studies of recent soil samples in intertropical Africa, found that values over 60 percent from the Ic index indicated C₃ dominated grasslands and that values below 40 percent indicate C₄ dominated grasslands. In the Ic index calculated here the transition zone between C₃ and C₄ grasses has therefore been put between 40 and 60 %. Studies performed in different grass dominated environments world-wide has shown that C₄ grasses are favoured when the daytime growing-season temperature exceeds somewhere between 20-28°C (Ehleringer et al. 1997). A study by Vogel et al. (1978) showed that in a South-Africa context C₄ grasses are favoured when the day-time growing season temperature exceeds 25°C. C₄ grasses was also found to be limited by day-time growing season temperatures below 10°C (Vogel et al. 1978).
Diester-Haass et al. (1973 in Twiss 1992) developed a palaeoclimatic index, the Iph index, that can be used as a proxy for moisture in the environment. This index calculates the ratio of the different C4 subfamilies Chloridoideae and Panicoideae. In this index the proportion of Saddles phytoliths versus Bilobates, Crosses and Polylobates is compared. A high index (close to 100) suggest arid conditions, whereas a low index suggest a humid climate. (Diester-Haass in Twiss 1992) The index seems to be valid both in tropical West Africa (Diester-Haass et al. 1973 in Twiss 1992), as well as in East African grassland environments (Barboni and Bremond 2009). The index is calculated as follows:

\[
\text{Iph \%} = \frac{\text{Saddles}}{\text{Saddles} + \text{Bilobates} + \text{Crosses} + \text{Polylobates}}
\]

The transition values, i.e. the values indicating transitions from xerophytic grasses to mesophytic grasses are varying by different authors. Fredlund and Tiezen (1994) put the transition zone between the Iph values 40 and 60, where Iph values lower than 45 % indicate mesic grasslands and over 60 % indicate xeric grasslands. A study by Alexendre et al. (1997) however put this boundary between 30 and 40 %. In the absence of Iph cut-off studies in a South Africa context, values between 30 to 50 % are regarded as a tentative transition zone between mesic and xeric conditions in this study.
Method

This study employed a multi-proxy approach, i.e., multiple proxies were analysed and compared in order to interpret palaeoenvironmental changes. A multi-proxy approach enables evaluation of the inferred indications from several proxies, a potential to evaluate and compare if the proxies indicate the same or divergent development (Walker 2005). The biogenic proxies (proxies from plants and/or organisms) analysed within this master thesis were phytoliths and, to some extent, diatoms. Minerogenic proxies (proxies of mineral origin) were studied through a modified Troels-Smith analysis, lithological description and by analysing % carbon. Based on material from the same master core as used here carbon isotope analysis was also performed in South Africa by J. Smith, Cape Town University. This chapter describes the field techniques and methods applied within this study.

Field techniques

Fieldwork was performed in the beginning of rain season in mid-December 2011. A hand operated Russian corer was used to perform transect coring as well as collection of a master core. The corer had a chamber length of 50 cm and diameter of 5 cm. Two extension rods was available, allowing us to a maximum of 4.5 meters depth. In an attempt to establish the lithostratigraphy of the fen 19 locations were cored (Fig. 6).

Figure 6. Schematic picture of the extension of Phragmites stands of the Lydenburg fen, coring sites and location and direction of nearby streams. The three circles outside the fen represents sites where water samples were collected. One surface sample was also collected as coring site number 19. Squares with number represent sites where grasses was collected during second field visit.

The aim with the transect coring was to investigate the stratigraphy of the fen, and to locate
the most representative site to collect cores for further analysis. All cores where investigated in field in terms of lithostratigraphy, this allowed a visual cross-section of the fen to be established on site. Core site 1-8 was cored until the believed bottom of the basin was reached. Core sites number 9 – 19 was cored to a maximum depth of 150 cm. Based on information from the transect coring, site number 5 was recognised as the most suitable site for collection of a master core. Two alternating bore holes were used to retrieve the core, with a 25 cm vertical overlap (Fig. 7). One additional core was collected from a third bore hole, without overlap. Five additional boreholes were used to collect cores which were sub-sampled in field with the purpose to collect extra material that could be used to extract macrofossils for radiocarbon dating.

Figure 7. Picture of sampling site for master core and extra cores

The material collected was removed from the corer and wrapped in plastic film and put in half-cylindric plastic tubes (Fig 8). The purpose of this procedure is to avoid contamination, prevent water loss and maintain anaerobic conditions. Each part of the core was labelled with site name, date, sample depth (at both bottom and top). The cores were put in cold
storage at 3°C on arrival at Stockholm University, seven days after fieldwork was performed.

![Wrapping of cores. From the left: J. Risberg, S. Lundqvist and M. Schoeman.](image1.png)  
![Cores wrapped in plastics and put in half-cylindric tubes.](image2.png)  
Figure 8. Picture of wrapping procedures. *Photo: J. Sjöström* (December 2011)

The two overlapping cores constituting the master core, was subsampled in the lab. The two cores were put side by side and correlated through a distinct gravel layer found at 155 cm. The core was subsampled every centimetre starting from the bottom (300 cm) upwards and put in plastic containers (Fig. 9). Between 0-25 cm and 275 – 300 cm material was only collected from one core.

![Sub-sampling in the lab. The sequence cut in 1 cm pieces and put in plastic containers.](image3.png)  
![From the top and bottom 25 cm of the sequence, only material from one core was collected.](image4.png)  
Figure 9. Pictures of subsampling procedure in laboratory. *Photo: Sjöström 2012*
Preparation of laboratory test slides

Previous palaeoenvironmental studies in the area (e.g. Norström et al. 2009, Finné et al. 2010, Breman 2010, Walther and Neumann 2011) has shown that the occurrences of siliceous microfossils (diatoms) and pollen can be scarce in peat sequences in South Africa. In order to make an informed decision regarding proxy focus five test slides for pollen and siliceous microfossils respectively were initially prepared. The two sets of slides were prepared using standard laboratory methods: Battarbee (1986) for extraction of siliceous microfossils, Berglund (1986) for extraction of pollen.

Sample material for siliceous microfossils slide preparation was collected at the following depths: 285, 177, 155, 120 and 66 cm.

Sample material for pollen slides were collected at the following depths: 283,5, 176,5, 154,5, 120,5 and 79,5 cm. For pollen preparation Lycopodium tablets were added (batch no 483216, 18 583 spores/tablet).

Extraction of siliceous microfossils

After the test slides had been analysed it was decided to focus on siliceous microfossils, with emphasis on phytoliths and (where possible) diatoms (see result chapter). Extraction of siliceous microfossils followed the standard laboratory method described by Battarbee (1986) for extraction of diatoms. This is, however, contemporary not the standard procedure for phytolith extraction, but many of the extraction steps are similar and aims for the same outcome, *i.e.* removal of carbonates, organics, and mineral grains of smaller and coarser fractions than silt. Diatoms and phytoliths are found in the silt fraction and both proxies are therefore extracted through this method. The main difference between the method for extracting diatoms (Battarbee 1986) and the contemporary phytolith extraction (*e.g.* Rovner 1971, Piperno 2006) method is that the latter involves the use of heavy liquids, which are used to separate mineral particles in the silt fraction from biogenic silica through floatation. This procedure has been well studied and determined to remove only mineral grains in the silt fraction (Piperno 2006), other authors have however found that not only mineral grains are removed but also some diatoms (Battarbee 1986). Since the aim within this study is to analyse both phytolith and diatoms, and since standard method for diatom extraction does not seem to risk removing diatoms or phytoliths, to use the method described by Battarbee (1986) seemed reasonable. A potential negative outcome of using
this method in this context is that mineral grains in the silt fraction remains in the material mounted on laboratory slides, making the concentration of phytoliths and diatoms somewhat diluted (Battarbee 1986). The presence of large amounts of mineral grains might potentially also make identification of primarily phytoliths more difficult.

Initially c. 10-20 grams of material was collected from the master core, every 10\textsuperscript{th} cm starting from 5 cm until 295 cm. The material was put in beakers and the presence of carbonates was tested by adding hydrochloric acid (HCL). Where a reaction was noted more HCL was added until a reaction no longer occurred. With the purpose to remove organics hydrogen peroxide (17\%) was thereafter added, and the beakers was thereafter kept in room temperature for approximately 8 hours. The beakers were then gently heated on a water-bath until approximately 100\degree C was reached, and then left to boil at least two hours or until the organics were removed. In order to remove clays a process of gravity sedimentation was thereafter initiated. The material was put in suspension, distilled water added and material left for settling for two hours after which decanting was performed. This process was repeated until the liquid 1 cm above the bottom became clear. Distilled water containing 5\% ammonia was thereafter added, with the purpose to dissolve clay agglomerates, after which the decanting process continued until the liquid was once again clear. Some samples also contained coarser grains, these where removed by setting the material in suspension, letting the coarser grains settle (after 5 seconds) and thereafter pouring the liquid with suspended material into a new beaker.

When the decanting process was finalized, approximately one centimetre of distilled water and material in the silt fraction was left. This was poured into laboratory tubes and left for sedimentation for 2 hours after which a last decanting was again performed.

Phytoliths have a refractive index of c. 1.42 and are recommended to be mounted in medias with a refractive index of 1.51 to 1.54 (Piperno 2006, p 93). First a set of slides was prepared where the material was mounted in Naphrax ©, a permanent medium often used in diatom analysis. Since identification of some plants or subfamilies may require rotation of phytoliths (e.g. Piperno 2006) an attempt to find and evaluate a suitable liquid mounting media was therefore performed. This process is described in more Liquid mounting mediums chapter.
Identification and ecology interpretation of diatoms was made using Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Gasse (1986), and Schoeman and Archibald (1979).

**Count size**

In order to create a representative fossil GSSC phytolith assemblage a sufficient number of total phytoliths per analysed level needs to be counted. The total sums, or base sum, of different studies reviewed within this thesis differed between 100-300 (Table 4). A sum that sometimes included both GSSC phytoliths and long cells (Alexandre *et al.* 1997, Lu & Liu 2003, Thorn 2004, Novell *et al* 2012), and sometimes only GSSC phytoliths (Breman 2010, Finné *et al*. 2010).

<table>
<thead>
<tr>
<th>Author</th>
<th>Total base sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alexandre <em>et al.</em> (1997)</td>
<td>200 GSSC and long cells</td>
</tr>
<tr>
<td>Thorn 2004</td>
<td>300 GSSC and long cells</td>
</tr>
<tr>
<td>Novello <em>et al.</em> (2012)</td>
<td>200 GSSC and long cells</td>
</tr>
<tr>
<td>Finné <em>et al.</em> (2010)</td>
<td>300 GSSC</td>
</tr>
<tr>
<td>Breman (2010)</td>
<td>200 GSSC</td>
</tr>
<tr>
<td>Lu &amp; Liu (2003)</td>
<td>350 GSSC and long cells</td>
</tr>
</tbody>
</table>

The goal within this thesis was initially to count 300 GSSC phytoliths, this goal was however amended at this obviously was too time consuming. Counting of phytoliths took particularly long time in slides where the concentration of phytoliths was low. The counting process was also quite slow due to the many subdivisions into different phytolith morphotypes, and potentially also because counting was performed in a liquid medium (often each phytolith was turned before counted). The minimum total sum of GSSC phytoliths was therefore instead changed to 100 GSSC phytoliths per depth level, including long cells the base sum ended up between c. 200-500. Breman (2010) produced an accumulation curve (Fig. 10) which showed that majority of morpho-types appeared from 0-150, a great proportion of morphotypes however appeared already between 0-100. To be able to also identify subfamilies that may occur in very small numbers, a greater number of phytoliths are however recommended to be counted (Breman 2010)
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

Figure 10, accumulation curve for diagnostic morpho-types. Breman (2010)

**AMS Radiocarbon dating**
Plants and animals are constantly taking up radiocarbon ($^{14}$C) during their lifecycle, $^{14}$C is thereby embedded into the plant or organism (Walker 2005). When the organisms die the $^{14}$C decays into nitrogen through emitting beta particles. Radiocarbon dates can be measured on biogenic materials like for example wood, peat, leak sediments, charcoal, shells and coral. Measurement of radiocarbon can be done through either counting the beta particles emitted or alternatively through accelerator mass spectrometry (AMS) which counts the relative number of $^{14}$C particles. Since the half-life of $^{14}$C is known the relation of unstable $^{14}$C and stable $^{12}$C and $^{13}$C can be used to infer the time when the plant/organism lived. There are however also some inherent uncertainties to this dating methods, related to contamination (of older or younger carbon), the reservoir effect, variation of $^{14}$C in the atmosphere, and isotopic fractioning (Walker 2005).

In total five radiocarbon dates were submitted to Ångström Laboratory in Uppsala for AMS radiocarbon dating. Four of the dates are based on macrofossils collected from the master core, see specification in Table 2. One date (150-155 cm) was based on macrofossils picked out from the extra cores that was sub-sampled in field (Fig. 7).
Terrestrial macrofossils are preferred for radiocarbon dating compared to dating bulk samples as some common errors associated with bulk dating can be avoided. When dating bulk samples the risk of dating too young material increases (i.e., down-penetrating roots). If the bulk sediment is deposited in standing water bulk samples are further also potentially affected by the reservoir effect which affects aquatic plants and animals (Ohlsson 1986).

For all five radiocarbon dates the same procedure to collect macrofossils was used. The material was initially sieved in a sieve with 0.125 mm mesh, and thereafter stored in tap water with KOH. The material was thereafter put in petri dishes, and a Leica stereoscope of X 10 - 100 was used to locate and collect macrofossils.

In the sub-sample material from c. 150-155 cm depth beetle wings were used for dating (Table 5). Insect wings are preferential to use for dating as flying beetles have a C\textsuperscript{14} content in balance with the atmosphere. The species was however not identified. Large insect parts were prioritized as this decreased the likelihood of down transportation in the core through roots or by bioturbation. Seeds from terrestrial plants were collected from 72-74, 111-112, 232-234 cm depth. Terrestrial plants take up carbon through photosynthesis and thus have carbon content in balance with the atmosphere. From 284-285 cm depth charcoal was used for dating. Woody elements, like charcoal, are also terrestrial in origin and are therefore suitable for radiocarbon dating.
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

Table 5, Macrofossils used for AMS radiocarbon dating.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Material used for dating</th>
<th>Weight*</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>74-75 cm (master core)</td>
<td>Seeds. Polygonaceae, Cyperaceae, Carex</td>
<td>35 mg</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td></td>
<td>Beetle wings. Unknown species.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>111-112 cm (master core)</td>
<td>Seeds. Polygonaceae, Cyperaceae, Solanaceae</td>
<td>36 mg</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>150-155 cm (sub-sample)</td>
<td>Beetle wings. Unknown species.</td>
<td>37 mg</td>
<td><img src="image3.png" alt="Picture" /></td>
</tr>
<tr>
<td>232-234 cm (master core)</td>
<td>Seeds. Polygonaceae, Solanaceae, Caryophyllaceae, Apiace</td>
<td>52 mg</td>
<td><img src="image4.png" alt="Picture" /></td>
</tr>
<tr>
<td>284-285 (master core)</td>
<td>Charcoal</td>
<td>50 mg</td>
<td><img src="image5.png" alt="Picture" /></td>
</tr>
</tbody>
</table>

* Sample weight refers to weight of wet sample. Photo: J. Sjöström (2012)
**Test of liquid mounting mediums**

In this chapter testing of three different mounting medias are described; glycerine, immersion oil and Entella. The aim is to find a liquid medium that is viscous enough to allow turning of phytoliths while not being too fluid for analysis in X 1000 magnification. If the mounting media is too fluid the phytoliths/diatoms might be dispersed when tapping or pressing the laboratory slide, potentially risking counting of the same phytolith or diatom multiple times.

**Glycerine**

1. A solution with water and glycerine is added to the laboratory tube containing the extracted siliceous microfossils.

2. Extracted siliceous microfossils, water, and glycerine is mixed through stirring with a glass stick and by using a rotor mixing device, for complete mixing of the sample.

3. The mixture is added to laboratory slides with a glass stick. 2-3 drops usually enough to cover laboratory slide. Cover glass added.

4. Laboratory slides are left to dry 6-8 hours before they are sealed with nail polish.

**Immersion oil**

1. A drop of siliceous microfossils and water added to a laboratory slide.

2. A drop of immersion oil added to the same laboratory slide and cover glass added.

**Entella**

1. The extracted material in the silt fraction dried in laboratory tubes. To speed up the drying process the tubes can be put in an oven in 50-70° C for a couple of hours (time is dependent on how much water there is in the tubes to start with).

2. To avoid damaging of primarily the diatoms Entella was added directly into the glass tube and left (sealed) for few hours. This process allows the dry material to become moist, which decreases the amount of stirring required mix the material with Entella. The amount of Entella should be no more than 4-5 times of the amount of material (adding to much Entella causes the phytoliths/diatoms to be too few on the lab slide).
3. Material and Entella mixed by stirring with a glass stick and using a rotor mixing device. A small amount of the mix retrieved by a pipette and added to a laboratory test slide. Cover glass added and gently pressed down. 2-3 drops is usually enough for the solution to cover the entire surface of cover glass.

4. Laboratory slide left for 36-48 hours to dry before being sealed with nail polish.

**Troels-Smith**

A modified Troels-Smith analysis (Troels-Smith 1955, Aaby & Berglund 1986) of the master core was performed. The purpose was to evaluate proportion of organic and minerogenic material, to evaluate if there was also organic material present in gravel layers, and lastly also to determine the grain size of larger (≥ sand) mineral particles.

J. Troels-Smith developed this descriptive classification in 1955 (Aaby & Berglund 1986). The classification system is based on the assumption that deposits are mixtures of various elements. The objective with the classification system is to provide a simple way to characterize the dominating elements in unconsolidated deposits. Aaby and Berglund (1986) describes that one of the advantages with this system is that it allows a deposit to be characterized without considering its’ genesis (origin). The terminology of the system uses Latin names. The first term describes the genus (if known) and the second term describes the species. When characterizing the accumulation three factors are important: physical properties, humicity and the component parts (nature and proportion of the elements). The deposit elements are divided into five main groups: Turfa, Detrius, Limus, Argilla and Grana. A special element has also been included, Substantia humosa (Sh) as it may sometimes be difficult to determine genus of a homogenous, disintegrated, organic black substance.

As the aim with the Troels-Smith classification in this study was primarily to describe proportion of the different elements a simplified classification was performed. For the organic elements only two terms where mainly used; Sh (Substantia humosa) for all highly disintegrated organic elements and Th (*Turfa herbacea*) for the less disintegrated organic herbaceous plants remains (roots, intertwined rootlets, rhizomes, stems, leaves etc). Occurrences of woody herbaceous plant remains are indicated by presence of Turfa lignosa (Tl). Here the balance between Sh and Th describes the level of humicity. The minerogenic particles are classified into; As+Ag (clay and silt), Gs (sand) Gg min (gravel), and Gg maj
(pebbles). Physical properties (such as color, stratification, elasticity and dryness) was not described.

Starting from 31 cm, about 0.5 g of material was taken every 10 cm throughout the core, until 291 cm and put in petri dishes with tap water. The material was analysed in a stereoscope of X 160 alternatively, when needed, X 400 magnification.

**Stable isotope analysis**

Sub-samples of 50-100 mg was extracted from the master core, freeze dried and sent to Jeanette Smith at Cape Town University. The ratio of stable isotopes of carbon, $\delta^{13}C$, and % carbon was measured by mass spectrometry.

By measuring $\delta^{13}C$ from bulk samples every 10 cm of the Lydenburg core an additional proxy will give indications of past C$_4$ and C$_3$ vegetation. Using bulk samples entails that it is the $\delta^{13}C$ of the total organic matter that is measured. The % carbon refers to the amount of carbon of the total measured mass in each sample.
Results

*Transect, lithological description, and Troels-Smith classification*

**Transect of Lydenburg fen**

Boreholes 1-8 was made in a north-south direction (Fig. 11) and boreholes 9-19 from north-east towards south-west (Fig. 12). Borehole number five was identified as the most representative site, and both transects crossed this point. Detailed results from the stratigraphy coring, for each core, is found in Appendix A (Lithostratigraphical description).

The underlying lithostratigraphy as well as the topography of the basin was revealed through the transect coring. The fen is located in a slope, causing inclination both in a north-south direction and north-east to south-west direction. This inclination is also visualized in the figures below. This represents a simplification of the lithology, a more detailed description results from the transect coring is found in of the lithology of the master core is found in the lithology section,

The transect coring shows that the Lydenburg fen occupies a depression with steep slopes. In core number 5 gravel layers were noted. Towards the south the fen is most likely dammed by bedrock, after which a steep drop of approximately 3 meters is found towards the stream running south of the fen.
The transect coring from north-east towards the outlet (Fig 12) shows a more undulating topography compared to cores 1-8. A steep depression can be noted from core site number 9 towards number 15. Core site number 12 and 11 displayed organic accumulations below the minerogenic parts. This was interpreted as signs of potential re-deposits, potentially caused by slides of fen material. Gravel layers were noted in cores 5, 9 and 10. Core number 15 and 16 showed that this part of the basin is shallower. The fen also appeared to be drier here; low shrubs were also found nearby these coring locations.
Figure 12. Results from transect coring, cores 9-19. The grey part of the core represents the part of the lithology where organic accumulations dominate and the black lowermost parts where minerogenic sediments dominate.

Lithology of master core

The lithological investigations showed a marked difference of the lowermost part (300 – 155 cm depth) where minerogenics dominate and generally decrease upwards and the uppermost (155 to 0 cm) which is dominated by organics. Two distinct gravel layers occurred in the core, one between 199 and 190 cm and another between 159 and 155 cm. The organics are also more decomposed in the lowermost 300-155 cm compared to uppermost parts of core (Fig 17).

From 300 to 264 cm depth a unit constituted by peaty sand clayey silt is found. This unit is followed by peaty gravely/pebbly clayey silt. Clayey silty peat overlays this unit between 240-199 cm. Followed by a minerogenic layer between 199 and 190 cm; peaty gravely sandy silt. From 190 to 159 cm gravelly sandy peat is found, superimposed by a gravel unit from 159 to 155 cm. Between 155 cm and towards the top the core is dominated by sandy peat.
**Troels-Smith classification and % carbon**

The results from the Troels-Smith classification are shown to the right of the lithology column (Fig. 13).

The results from the classification show a dominance of minerogenics in the lowermost parts of the core (300-155 cm), in line with the results of the lithological description. The increase of organics and decrease of decomposition following the gravel layer (159-155 cm) is also supported by the Troels-Smith classification. The three gravel layers are also shown, as occurrences of Gg min and Gg maj (gravel and pebbles).

In the unit of between 240 and 199 cm a sharp increase of organics occurs where Turfa herbaceae is found. This increase in organics in the lowermost parts was not detected in the lithological investigation.

In figure 17 the lithology, Troels-Smith classification and % C results are put together. The % C results generally support the findings from the lithology and Troëls Smith classification which depicts a generally increasing trend of organics upwards in the core. The sharp increase of organics noticed in the lowermost parts of the core through the Troëls Smith classification is also supported by the % C results as the carbon content also increases at the same depth. An input of minerogenic particles throughout the core is also supported by the % C results as the carbon percentage never exceeds 45%.
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy.

Figure 13. Lithology, Troels-Smith classification, and % carbon of the Lydenburg master core. Substantia humosa (Sh) represents highly decomposed organics, Turfa lignosa (Tl) represents woody herbaceous plant remains and Turfá herbaceae (Th) represents visible herbaceous plant remains. The Detritus granosus (Dg) represents insect parts, Limus ferruginous (Lf) occurrences iron precipitates The remaining four columns represents the minerogenic component; As+Ag (clay and silt), Gs (sand) Gg min (gravel), and Gg maj (pebbles).
AMS Radiocarbon dating
The results from Ångström Laboratory in Uppsala are displayed in Table 6. Calibration is based on southern hemisphere calibration curve, ShCal04, (McCormac et al. 2004) and was done online through OxCal v4.2.

Table 6. Results from radiocarbon dating. From the left: laboratory Id, sample depth specification of material used for dating, the radiocarbon years (BP=years before present, where present is regarded as year 1950), the calibrated age, and the highest probability point.

<table>
<thead>
<tr>
<th>Lab-id</th>
<th>Depth (cm)</th>
<th>Material used for dating</th>
<th>¹⁴C BP Age</th>
<th>Cal Age</th>
<th>Highest probability point Cal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ua-44205</td>
<td>72-74</td>
<td>Seeds, Cyperaceae, Carex 149 ± 30</td>
<td>AD 1660-1890 (78.4%)</td>
<td>AD 1711 or 1856*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beetle wings. Unknown species.</td>
<td>AD 1900-1950 (17.0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ua-44863</td>
<td>111-113</td>
<td>Seeds, Polygonaceae, Cyperaceae, Solanaceae</td>
<td>AD 1429-1506 (83.8%)</td>
<td>AD 1456</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>455 ± 32</td>
<td>AD 1587-1618 (11.6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ua-43320</td>
<td>150-155</td>
<td>Beetle wings. Unknown species.</td>
<td>AD 1270-1400 (95.4%)</td>
<td>AD 1346</td>
<td></td>
</tr>
<tr>
<td>Ua-44864</td>
<td>232-234</td>
<td>Seeds, Polygonaceae, Solanaceae, Caryophyllaceae, Apiaceae</td>
<td>AD 1049-1080 (7.8%)</td>
<td>AD 1196</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>903 ± 31</td>
<td>AD 1144-1234 (84.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>655 ± 36</td>
<td>AD 1245-1264 (3.2%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ua-44102</td>
<td>284-285</td>
<td>Charcoal</td>
<td>AD 1678 ± 30</td>
<td>AD 426</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AD250-300 13.2% prob</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>AD320-430 82.2% prob</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This date include a broad interval with similar probability values. The second highest probability point, at AD 1711, was chosen for the age-depth model, see motivation below.

When calibrating the ¹⁴C dates the probable calibrated ages are displayed by age intervals (as the Cal Age range in table 6). The probable calibrated ages are also displayed graphically in a diagram (see Radiocarbon appendix). From the probable calibrated ranges a single probable calibrated date was located. There are different methods to find the single most probable date, for example using by Bayesian statistical models, calculating the weighted mean of the probability ranges, or through locating the highest probability point. The highest probability point was the chosen method used to locate the most likely calendar age. The probability data for each ¹⁴C date was downloaded from OxCal and the highest probability was identified by sorting the data ascending after highest probability value in MS Excel. In each radiocarbon date, there is usually a distribution of calibrated ages with similar probability so this procedure entails simplifying the ranges to one date for each radiocarbon date. The single calibrated dates described hereafter represents a simplification of probable date ranges, the forthcoming calendar ages should therefore be regarded as a tentative ages.
The age-depth model in figure 14 shows the calibrated radiocarbon dates plotted against the depth. The grey lines shows the 94.5% probability range, and the dotted line the age depth model based on linear regression between the highest probability points. The distribution of the ages throughout the Lydenburg sequence shows consistently younger ages upwards. The uppermost date (72-74 cm, AD 1701-1856) is the most imprecise date and thus the most problematic date to find a single probability point for. This radiocarbon date occurs in a period that is difficult to calibrate due to the industrial effect (Walker 2005). After AD 1700 calibration is generally difficult, partly related to human activities such as industrialization. In order to aid a pinpoint of this date a line was there for drawn from the highest probability point of the date below (111-113 cm, AD 1450) to the present (0 cm depth, represents year 2012). This line indicates a situation where accumulation/sedimentation is continuous in this section of the core, which is an assumption based on the visual homogeneity in the stratigraphy. This procedure indicates that the most likely calibrated date should be located within the first range of the probability distribution graph (AD 1660-1890, Appendix A). The highest probability from this probability range occurs at AD 1711, which was chosen as most likely calibrated date.
Figure 14. Age depth model of the Lydenburg sequence. Grey lines shows the 94.5% probability range. Dotted line the linear regression applied between the highest probability points. From AD 1456 a line (dotted grey) was drawn to the present to aid identification of suitable highest probability date for the radiocarbon date at 72-74 cm.

From this age depth model likely ages in between the highest probability point for each radiocarbon dates was calculated using linear regression. These dates were used to create an age-depth scale bar, which assists when relating a certain depth to a calibrated age within the paleoenvironmental graphs (see discussion chapter).

The mean accumulation rate throughout the core is c. 1.9 mm / year. The value has varied throughout the sequence, with higher accumulation rates further up in the core and a significant increase in the middle of the sequence (Fig. 15). Starting from the lowermost parts the accumulation rate was c. 0.65 mm / year between 285 to 232 cm. From 232 to 155 cm the accumulation rate increased significantly to c. 5 mm / year. Between 155 and 113 it was c. 4 mm / year. From 113 cm to the top of the sequence the accumulation rate was c. 2 mm/year.
Figure 15. Accumulation rate per year (mm/year) based on the five radiocarbon dates performed on the Lydenburg sequence. The varying accumulation visualised throughout the core (depth). Significant increase in the middle of the sequence, and higher accumulation rates in uppermost parts compared to lowermost parts. Due to low number of radiocarbon dates and simplification of date ranges into highest probability points the accumulation rate should be regarded tentatively.
Liquid mounting mediums

In this chapter the general benefits of using liquid mounting mediums, compared to using a solid medium, is initially described. Results from the three tested liquid mediums are thereafter described.

Solid versus liquid media

Being able to turn individual phytoliths was beneficial for improving identification accuracy. Below follows some examples, including pictures, of phytolith types that are more easily distinguished from each other when using liquid medium compared to a permanent medium:

- Papillae and tall rondels. The tall rondel looks like a papillae type phytolith when viewed from end (Fig. 16).

![Example picture of a tall rondel viewed from end, looking like a Papillae type phytolith.](image)

![The same rondel turned to side-view. The top is not conical as a Papillae should be, rather it has a widening top.](image)

Figure 16. Example picture of a rondel appearing like a papillae phytolith. Pictures: J. Sjöström 2012

- Crosses, saddles and bilobates. Viewed from side or end these can sometimes not be identified and/or distinguished from each other. By, turning them to polar alternatively to base-view enables identification (Fig. 17)

![A bilobate type phytolith viewed from the end.](image)

![The same phytolith turned to base-view.](image)
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

Cross type phytolith, oriented in sideview. The same cross type phytolith oriented in polar-view.

Bilobate type phytolith in sideview. The same bilobate type phytolith turned to polar-view.

Figure 17. Example pictures of crosses and bilobates viewed in different orientations. Photo: J. Sjöström 2012

In addition to the examples above it was also apparent that rondels and saddles can be confused with each other, as well as that mineral grains can look like phytoliths. Identifying the “Saddle Var 2” (Rossouw 2009) type of phytoliths, which are very similar to rondel phytoliths, also requires the phytolith to be oriented both in baseview and sideview. By turning the grains faulty identification was avoided on many occasions during microscope analysis.

Glycerine and Immersion oil
Using glycerine or Immersion oil water allows rotating of phytoliths and analysing in in X 400 magnification. However, when using X 1000 magnification these mediums are too liquid and the phytoliths/diatoms are dispersed when cover glass is tapped/pressed.

Entella
The use of Entella as mounting media allows the siliceous microfossils in the laboratory slide to be liquid enough for turning individual grains by tapping the slide or simply by focusing in and out. The mounting media is thick enough to allow analysis in X 1000 without dispersing the phytoliths or diatoms. Entella seems to be beneficial for phytolith analysis, but the refractive index of Entella is not beneficial for identification of diatoms.
Result from test slides and water samples

The siliceous microfossils test slides prepared from the master core showed low occurrences of diatoms but generally high occurrence of phytoliths.

The pollen test slides showed low concentration of pollen. The pollen found are however well preserved indicating that they have not been destroyed. *Cyperacea*, and *Poacea* are the most commonly found pollen in the test slide. Spores are also found. At 79,5 cm a larger Poaceae pollen was found, with a diameter of approximately 55 µm. (Potentially Zea?) From the lowermost depth, 283,5 cm, no pollen is found.

Water samples

Water samples from within the fen showed a pH value between c. 6-7. The water samples from the small water pool above the fen showed a great occurrence of diatoms. Species such as: *Pinnularia subcapitata*, *Navicula halophile* and *Mastogloia elliptica* var. *Dansei* were most commonly occurring. The following species was also recorded: *Cymbella* sp., *Nitaschia* sp., *Diploneis* sp., *Epitemia argus alpetris*, *Pinnularia borealis*.

From the water sample collected at coring site number 19 fewer diatoms were recovered compared to the small water pool and the southern creek. Occurances of the following species were recorded: *Amphora normanni*, *Pinnularia subcapitata*, *Rhopalodia gibberula*, *Cymbella naiviculiformis*, *Mastogloia elliptica* var *Dansei*, *Diploneis* sp., and *Pinnularia* sp.

The water sample from the big creek showed great occurrence of diatoms. The most commonly occurring was: *Navicula halophila*, *Stauroneis Smithii*, *Nitzschia* sp., and *Surirella* sp. Occurances of *Pinnularia* sp., and *Diploneis* sp., was also recorded.

The water sample from the small creek, north-west of the fen, showed low occurrences of diatoms. *Gomphonema* sp., and *Fragilaria* sp., where the only recorded occurrances.
**Phytolith assemblage**

Two assemblage percentage diagrams are presented and described here. The first shows the total phytolith assemblage per morpho-type (Fig 18a, b). The second diagram displays data grouped according to related subfamilies, the so-called Twiss scheme (Fig. 19). Following the phytolith assemblage diagram, the climatic indices Ic and Iph are presented.

Figure 18 shows the phytolith assemblage with the different phytolith morphotypes categories displayed from the left to the right. The most dominant morphotype throughout the core is “saddle short, convex edges”. This morphotype has the highest percentage in the central parts of the core (c. 140-190 cm). “Saddles long, convex” are also relatively common, as are “bilobates with wide shank and convex lobes”. “Rondel < 15, short” is also commonly occurring, ranging from 10-20 percent throughout the core. Trapeziform sinuate and smooth occur throughout the core, but generally in low numbers (c. 5-10 percent respectively). Crosses and bilobates with long shanks are generally rare throughout the core.

No confirmed maize phytoliths were found throughout the sequence (absence of wavy-top rondels, ruffle-top rondels and crosses > 16 µm).
Figure 18a. Diagram displaying the different morpho-types of GSSC, from bilobate to polylobate (diagram divided into two figures).
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy.

Figure 18 b. Diagram displaying the different morpho-types of GSSC phytoliths, Cyperaceae and Long-cells.
The attempt to categorise different bilobates, based on their morphology, to a variety of categories proved difficult. This attempt, which could have enabled identification of grass species, as suggested by Piperno (2006) most likely requires more experience of phytolith analysis as well as access to reference material for the different grasses. Insufficient measurable information on how to categorise the bilobates, like precise length, width, and length/width relationships further hampered this attempt. A decision was therefore made to use the original found relationship where all bilobates are related to sub-family Panicoideae (Twiss 1969 et al.; 1992). The type of bilobate that occurred mostly throughout the assemblage (Bilobate short, wide shank, convex ends) was by Piperno (2006) suggested to be related to Bambusoideae. However, no other indications of Bambusoideae presence were found, like a certain type of plateaued saddle, commonly occurring in this sub-family. This type of bilobate was therefore related to Panicoideae subfamily.
Figure 19 is a percentage diagram that shows the different morpho-types grouped according to subfamily according to an amended Twiss scheme. The subfamilies are shown in percentage occurrence compared with all GSSC phytoliths.

- Bilobates, Crosses and Polylobates are related to C$_3$/C$_4$-Panicoideae
- Saddles are related to C$_4$-Chloridoideae (except for plateau saddles)
- Rondels > 15 um and Trapeziforms are related to C$_3$-Pooideae.

According to the study by Vogel et al. (1978) about 75-90% of the grasses in Lydenburg area are to be C$_4$. The percentage C$_3$-Pooideae in the phytolith assemblage is more in line with the general vegetation description if small rondels are not related to C$_3$-Pooideae. If the original Twiss scheme is applied between 30-50% of the grasses in in the assemblage would have been interpreted as related to C$_3$-Pooideae throughout the Lydenburg sequence. Furthermore, this would not be in line with the grass composition growing there today. To exclude small rondels, as suggested by Barboni and Bremond (2009) therefore seems relevant also in this study. Breman (2012, pers. Comment) also suggest removal of small rondels from the assemblage in tropical and sub-tropical settings. Small rondels are put in an own category, and occupy approximately 10-20 % of the total assemblage throughout the core.

In addition, Cyperaceae phytoliths are displayed in percentage of total GSSC and Cyperaceae phytoliths. Some additional Poaceae subfamilies are also displayed; C$_3$-Bambusoideae, C$_3$-Arundineae (P. australis), and C$_3$/C$_4$ Aristoideae subfamily. The morpho-type called Bilobate stipa is not known to be related to any specific subfamily in South Africa and is therefore shown separately (occur in very few numbers throughout the core). Long-cells are displayed in percentage of all phytoliths (GSSC, Cyperaceae and Long-cells). Arundineae (P. australis) have been put in a own category mainly to avoid skewing of data and should not be regarded as a as a certain species identification as some uncertainties exist to how accurate identification of “plataeue saddles” was, why this type will be removed from further diagrams and data. C$_3$-Bambusoideae, and Bilobate stipa are for the same reasons also removed from further data and diagrams.
The assemblage was divided into three zones, based on visual inference. The zones were identified primarily based on where the most prominent changes in the phytolith assemblage occur, but also in comparison with the $\delta^{13}$C data. The diagram is described from the lowermost depth and upwards through the sequence.

**Zone 1**

At the lowermost depth (285 cm, c. AD 400), Pooideae presence is about c. 17% (if all rondels are related to Pooideae would have occupied c. 35% of the assemblage). Panicoideae dominates, accounting for almost 30% of the total assemblage. Chloridoideae phytoliths constitutes c. 25% of the assemblage. In the first zone Panicoideae generally decrease and Chloridoideae is variable. Pooidea initially increases, and thereafter decreases after 240 cm (c. CalAD 1000) and upwards in this zone. Long-cells as a percentage of GSSC short-cell phytoliths are variable throughout the zone. Cyperaceae phytoliths generally occur in low numbers in zone 1, a general trend of increasing occurrences can be noted upwards in the sequence.
**Zone 2**

Pooideae continues to decrease and Chloridoideae increase until it dominates the assemblage. Panicoideae initially increase, only to decrease around 180 cm (c. AD 1250). Chloridoideae dominance peak around 150 centimetre (c. AD 1350) and thereafter sharply decrease. The general increase upwards of Cyperaceae is broken in zone 2, and Cyperaceae presence decreases. Percentage of long-cells also decreases in zone 2.

**Zone 3**

Pooideae initially increases. Panicoideae generally increase throughout this zone. At 125 cm (c. AD 1450) Pooideae decreases and Panicoideae increases. Chloridoideae is variable with a slight decreasing trend in the middle of the zone and displaying an increasing trend towards the top. Pooideae is variable but occurs in larger relative proportion in the lowermost parts compared to the uppermost parts. From 35 cm (c. AD 1900) and upwards Panicoideae dominate and also shows the greatest proportion compared to Chloridoideae and Pooideae throughout the assemblage so far. Between 25 and 5 cm depth Panicoideae decrease. Cyperaceae phytoliths occur all through zone 3, but in low numbers until c. 35 cm (c. AD 1900) after which Cyperaceae increases significantly upwards. Long-cells increases sharply initially in zone 1, and the percentage of long-cells are generally significantly higher in zone 1 than in zone 3 and 2.

Aristideae only occurred in very few numbers throughout the sequence. No indications of this sub-family was found in zone 1, and in total Aristideae phytoliths (saddle var 2 type of phytoliths) where only identified in three analysed levels. In these levels, less than 5 “saddle var 2” type of phytoliths was recorded.
**Ic and Iph indices**

Due low base sums, three analysed levels were removed before figure 20 was constructed (45, 60 and 85 cm). This data was removed to prevent the data from these levels to skew the interpretation.

From the uppermost samples analysed (from 5 cm depth) the values from the Ic index shows 33 if all rondels are included, and 19 if these are removed. The Iph value is 53. This indicates a warm and mesic to seasonally arid climate, in line with the contemporary climate of the area.

![Figure 20. Iph and Ic index. Iph index generally shows indications of increasingly mesic conditions upwards. Drier conditions indicated in zone 2. The Ic index shows generally small variations.](image)

In zone 1 the Iph value is variable, but a general trend towards drier conditions can be depicted. A sharp excursion towards drier conditions are found at 245 cm. The Ic values are variable but within a limited span of the index, an trend towards cooler conditions are depicted after 245 cm, only to decrease (warmer conditions) towards the end of zone 2.

In zone 2 the general trend of the Iph value indicate drier conditions. Several of the analysed levels depict this trend. The Ic index continue to show quite small variations, but with indicating a more stable and possibly warmer trend than lower levels.
In zone 3 the Iph values show a trend towards wetter conditions upwards in the sequence. At 75 cm Iph index indicates drier conditions occurring. The Ic index shows a trend towards cooler conditions at this time. The trend of the Ic index, even though with very small variations, is of increased warming upwards in zone 1.

The general trend throughout the sequence, from the Iph index, is of lower more mesic values. The Ic index generally shows quite small variations, but shows the coolest conditions occurring around 245 cm (AD 1000) and a slight warming trend in zone 1.
Ratios of stable isotopes of carbon, $\delta^{13}C$

Figure 21. Variations in $\delta^{13}C$ values throughout the Lydenburg sequence indicates a mixed C$_3$ and C$_4$ input into the in zone 1, a shift to C$_4$ input in zone 2 and increasingly depleted values in zone 3 (increased C$_3$ input).

$\delta^{13}C$

The general trend of the $\delta^{13}C$ values are of increasingly depleted values upwards in the sequence. In zone 1 a mix of C$_3$ and C$_4$ input can be noted and the variations are generally small. In zone 2 a significant increase in the $\delta^{13}C$ values can be noted, a clear dominance of C$_4$ input can be noted around 200 cm. In zone 3 the $\delta^{13}C$ varies, but shows a trend towards increasingly depleted values. At 45 cm an excursion towards less depleted values can be noted only to show increasingly depleted values towards the top.
Diatoms and chrysophyceae stomatocysts

Figure 22 show the number of diatoms and chrysophyceae stomatocysts found at each depth analysed. The numbers are generally low (< 35), limiting the possibilities to construct a percentage diagram. A trend of generally increasing number of diatoms and chrysophyceae stomatocysts can be noted throughout the core upwards. An exception can be noted in the middle of zone 2, c.140-220 cm, where a decrease of diatoms and chrysophyceae stomatacysts occurs. Following zone 2 the general increase upwards continues again. All diatoms found are benthic, and have been subdivided into halophilous, freshwater and aerophilous taxa.

Zone 1 display low amounts of both diatoms and chrysophyceae stomatocysts. In the upper part several halophilous taxa, *Mastogloia elliptica v. dansei*, *M. elliptica* and *Navicula halophila*, were noted. In zone 2, diatoms and chrysophyceae stomatocysts decrease and none are found between c. 180 to 160 cm depth. In the lower part of zone 3, there are several observations of aerophilous taxa, i.e. *Hantzschia amphioxys*, *Pinnularia v. rectangularis* and *P. divergens*. In the middle part of zone 3, halophilous taxa re-occur, now including *Epithemia turgida v. granulata* but excluding *Navicula halophila*. Chrysophyceae stomatocysts show a peak contemporary with the increase in halophilous taxa.
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Figure 22, number of diatoms and chrysophycean stomatacysts per analysed level. The diatoms are grouped according to if they are Halophilous, Freshwater or Aerophilous taxa. Zonation based on visual inspection (primarily based on changes in the phytolith assemblage).
Discussion

The aims within this thesis were to 1) perform a palaeoenvironmental grassland reconstruction 2) identify if maize was cultivated nearby the fen and 3) to perform a survey of liquid mounting medias. Here, the results (see summary illustration, Fig. 23) are discussed, interpreted and compared with previous palaeoenvironmental studies performed in the area of north-eastern South Africa. Some of the most common errors of each method are also discussed. Lastly, potential future studies are also described.

Lithology and basin

Lydenburg fen has accumulated since ca 1600 cal yrs BP, despite the complexity of the location, involving steep inclination and a deep creek bordering the fen to the south. Its presence is most likely dependent on local geomorphology and the characteristics of the underlying bedrock. Towards the southern edge, bedrock probably impedes drainage as it seems highly unlikely that a soil could hold the weight of the entire fen without collapsing. The drainage to the south-west (current outlet) is a bit more unclear, it could either be an affect by built-up soil/sediments and/or bedrock causing the impeded drainage. The inclination of the basin is steep, both in east-west, and north-south directions. It is possible that the current fen was once a small stream, that continously got infilled with minerogenics and possibly also plant material from the surrounding slopes. Eventually, this enabled organic accumulations to develop. Another possible explanation of the origin of the fen is gully erosion, a landform created by running waters, in tropical and sub-tropical settings (Thomas 1994). Gullying occurs during substantial waterflows where soils on hillsides are removed leaving behind a small valley or large ditch (Thomas 1994), similar to the basin of the Lydenburg fen. The factors contributing to the fens existence cannot be fully established here. Attempts to compare the lithological composition with the indications of the other proxies are still made in the following sections, but the main interpretations about environmental changes in and around the Lydenburg fen are derived from the indications of the other proxies.

The input of minerogenic particles throughout the core indicates that Lydenburg sequence has both an autochtonous component (deposits from within the fen, e.g. organic matter) and an allochtonous component (material transported from the surrounding into the fen, e.g. mainly minerogenic components). This entails that parts of the phytolith assemblage is also
likely to have been transported into the fen from the surrounding slopes. The autochtonous (organic) component increases upwards in the sequence.

**Palaeoenvironmental grassland reconstruction**

Here, the results from the various investigated proxies are compared and presented. The zones are presented in calendar ages.

**c. AD 400 to 1230, zone 1, 300 – 215 cm**

Within this time period Panicoideae and Chloridoideae dominate. Panicoideae displays a decreasing trend upwards in this zone, which is interpreted as a slightly drying trend towards from AD 400 to 1000. The Iph index, depicting the relative distribution between the the dry adapted Chloridoideae and mesic adapted Panicoideae, also indicates a drying trend, the sharpest excursion in the Iph index throughout the sequence is found around AD 1000. The $\delta^{13}C$ shows less depleted values, supporting increased input of C$_4$ vegetation at this time. It should however be noted that this particular excursion of the Iph index is based on one analysed sample. The other proxies furthermore also seem to indicate a potential drying around AD 1000. The carbon content does not show any major variations around AD 1000, but show generally low values from AD 400 to 1000. The accumulation rate in the lowermost parts of the sequence is lower than further up (Fig 15). In the context of wetlands in southern Africa, increased minerogenic content in combination with slow accumulation rates, are often interpreted as indications of drying as decreased wetness cause oxidation of organic accumulations leaving behind increased minerogenic content (e.g. Ekblom et al. 2012). The low organic content in the bottom Lydenburg sequence is therefore tentatively interpreted as another indicator of drier conditions. No diatoms and chrysophyceae stomatocysts are recorded in the lowermost and middle part of zone 1, which is another indication of drier conditions. The Ic index indicates the coolest conditions throughout the sequence between AD 1000 and AD 1200.

Immediately after AD 1200, diatoms and chrysophythes are recorded, indicating wetter conditions. The type of diatoms found, halophilous taxa, support wetter conditions as the taxa prefer slightly saline conditions, indicating that evaporation of standing water occurred at this time. The increased wetness is not noticed in the GSSC phytolith assemblage as the mesic adapted Panicoideae (Twiss et al. 1969) grasses do not increase. The Cyperaceae however increase, also supporting more mesic conditions prevailing around AD 1200. In
the same time period the carbon content as well as occurrences of *Turfa herbacea* indicates a period where organic accumulation occurred, i.e. wet and anaerobic conditions prevailed. The Ic index indicates a warming trend during this period.

Pooideae grasses are found in greater relative numbers in zone 1 than further up in the sequence indicating that the climate potentially was slightly cooler climate between AD 400 and 1200 than later.

c. AD 1230 to 1370, zone 2, 215-145 cm

Initially in zone 2, starting from c. AD 1230 the Panicoideae grasses increased simultaneously with the Chloridoidea grasses. The Panicoideae grasses decrease shortly after c AD 1250 and give way for the dry adapted Chloridoidea (e.g. Twiss 1969, Barboni & Bremond 2009). Chloridoidea dominate the assemblage from c. AD 1250 to 1350. This is interpreted as indicating a significantly drier period compared to earlier and later time periods (zone 1 and 3). The $\delta^{13}$C data supports the interpretation of dominating C$_4$ vegetation in this zone, in fact the greatest C$_4$ input throughout the sequence, based on the $\delta^{13}$C data, is noted between AD 1250 and AD 1350. The decrease of Cyperaceae, which are moist requiring sedges, also supports this interpretation. Cyperaceae type phytoliths (Papillae) are by some authors suggested to dissolve more easily than GSSC phytoliths (e.g. Alexandre *et al.* 1997). The generally increasing trend of Cyperacea from the lowermost parts towards the uppermost parts of the sequence might therefore either suggest increase wetness upwards in the assemblage, alternatively increased dissolution of Papillae type phytoliths downwards in the core. However, the general trend of increasing Cyperaceae phytoliths upwards is broken after AD 1250, suggesting that not only dissolution drives the representation of these phytoliths. The decline after AD 1200 is tentatively interpreted as an indication of lower moisture availability. The declining representation of diatoms and chrysophytes also indicates drier conditions, as both these are water-living organisms.

The initial increase of Panicoideae grasses in early zone 2 could potentially be interpreted as an effect from increased temperatures which might have led to increased precipitation and more mesic conditions (as interpreted by increase of Panicoideae grasses, *Turfa herbacea*, and carbon content), until a temperature threshold was reached after which drier conditions prevailed (dominance of C$_4$-Chloridoidea, decrease of diatoms, chrysophyceae stomatocysts and carbon content).
The two distinct gravel layers within zone 2 are likely the result of material transported from the surrounding hills into the fen by fluvial processes during summer rains. However, to identify the driving factors behind these gravel layers is complex, as increased transport of gravel could be an effect of climate, local environmental change, and/or human activities. Occurrences of increased grain sizes and poor grain size sorting, may indicate increased erosion, as an affect of a more open landscape, in a southern African context (Walther & Neumann 2011). If the climate was drier at Lydenburg fen, as indicated by the dominance of Chloridoideae subfamily, this would have affected vegetation and possibly exposed the soil on the slopes surrounding the fen. In the case of Lydenburg fen, this could have entailed sand, gravel and pebbles to more easily be transported from the surrounding hills into the fen with the intense summer precipitation. On the other hand, human activities, like construction of terraces or grazing by live stock could also expose soils and increase likelihood of erosion and transport of minerogenic material into the basin. According to archaeological records, the terraces in the area were however more likely constructed well after the last gravel layer was deposited. Based on the radiocarbon dates, the last gravel layer was deposited before AD 1400. The terraces in the slopes (kloofs) are currently believed to have been constructed in the 1600s-1700s (Schoeman 2012, pers. comm.). It should however be noted that not all terraces have been sufficiently dated yet, human activities can thus not be completely ruled out. A third possible interpretation of the gravel layers are that they actually indicate increased and intensified precipitation which allowed increased transport and sedimentation of early and late in zone 2. Since several of the other proxies indicate drying, and no or very few diatoms are found in this zone increased wetness seems unlikely. Given current knowledge the most likely cause of the gravel layers is therefore here tentatively interpreted to be related to drying of the local climate.

The percentage of long-cells decreased significantly in zone 2, indicating increased chemical and/or physical attack of siliceous microfossils occurring in zone 2 (Madella & Lancelotti 2012).

c. AD 1370 to present, zone 3, 145 – 0 cm
The general trend in this zone, as inferred from several of the analysed proxies, is increased wetness after c. AD 1370. The moist and warm-adapted Panicoideae (e.g. Twiss et al.
1969) increases, along with diatoms and chrysophyceae stomatocysts, Cyperaceae and Turfa herbaceae. The lithology supports wet anaeorobic conditions prevailing and increasing upwards, as indicated by increases in carbon content and Turfa herbaceae. The type of diatom taxa recovered in zone 3 indicate increased wetness upwards, as initially aerophilous diatoms are found, indicating initially mesic but erosive conditions compared to further upwards where occurrences of halophilous diatoms indicate presence of standing water.

Pooideae displays a general decreasing trend in zone 3 and Chloridoideae is variable. The decrease of Pooideae is not very large, but could tentatively be interpreted as a slight warming of the climate. The δ13C data suggest an increased input of C3 plants into the organic accumulation after AD 1370 until the present. The phytolith data does not suggest an increase in C3 grasses (Pooideae). The divergent trends in these proxies can be related to the fact that the δ13C data is based on bulk samples of the entire organic matter, not just from grasses as the phytolith assemblage. The increased C3 input is thus derived also from other plant communities. Contemporary shrubs grow around (and even in) the fen, which also adds material to the organic matrix of the peat. Trees grow along the north-eastern borders of the fen and along both streams. The leaves from these trees are likely to also end up in the fen. If the δ13C values would be interpreted as a grass signal alone, the indications towards the uppermost parts of the sequence could be interpreted as a cooling of the climate (due to increase in C3 grasses). Since the phytoliths assemblage does not support this and given the strong relationship between grass distribution and to temperature this seems unlikely. Taking into account the input from trees and shrubs, the lower δ13C-values might instead indicate an increase in forest and shrub vegetation around (and within) the fen. The Ic index shows generally quite small variations (between values 10-30 on a scale of 0 to 100) but indicates, a slight warming of the climate after AD 1370.
Figure 23. Summary diagram displayed with phytoliths grouped according to the amended Twiss scheme, the climatic indices (Iph and Ic), $\delta^{13}$C and % Carbon results shown in the same view to enable comparisons between the different proxies.
**Results related to previous studies**

Several previous studies show a general trend towards increasingly mesic conditions in north-eastern South Africa during the last c. 2000 years (Scott *et al.* 2008, Norström *et al.* 2009, Breman 2010, Finné *et al.* 2010, Scott *et al.* 2012). The results from this study show the same indications during c. 1600 years that the Lydenburg sequence cover. Except from the general trend of increasingly warm and mesic conditions during late Holocene, linking changes in precipitation and/or temperature based on studies from different locations (and proxies) in northern South Africa is complicated by that different climatic indications are derived from different palaeo studies. Some of the inherent uncertainties in different dating methods can also cause difficulties in aligning records (Blaauw 2012). Furthermore changes in grassland composition can occur as an effect of different driving forces, such as changes in nutrient cycles, fire regimes, grazing pressure, precipitation and temperature (Breman 2010, Breman *et al.* 2012). Some of the recorded changes in different geographic locations may furthermore only have local significance. These circumstances should be kept in mind when the results from Lydenburg fen are compared with previous studies.

Holmgren *et al.* (2003) describe that a warm and variable but mostly wetter period was recorded in the Makapansgat speleothem data, between c. AD 800 – 1400. This is the same time period as the greatest variability occurs in the Lydenburg sequence; input of gravel layers, the dry event from c. AD 1250 to 1350, and where great changes in % carbon occur. The results from Lydenburg fen therefore seem to be in line with the results by Holmgren *et al.* (2003) suggesting “MWP” as a warm and variable period. However, the results from this study indicates that end of “MWP” in Lydenburg was mostly dry, in contrast with Holmgren *et al.* (2003) and Tyson and Lindesay (2000) indicating “MWP” as mostly wetter. Other studies however also indicate drier conditions within this time interval (Huffmann 2008, Breman 2010, Holmgren *et al.* 2012).

Holmgren *et al.* (1999, 2003) found indications for the “LIA” to have occurred at AD 1300-1800, with maximum cooling occurring at AD 1700. The climate during “LIA” is described by the authors to have been cool and dry. The chronology for Lydenburg fen, based on the radiocarbon dates, is uncertain in the uppermost parts of the core where changes related to the “LIA” could potentially be recorded. The general trend after AD 1400 is, however, of increasingly mesic conditions. After c. AD 1500 there is a slight decrease in this general
and Panicoideae grasses decrease and Chloridoideae increase; possibly implying a decrease in the generally increasingly wet trend at this site. The cool adapted Pooideae grasses furthermore occur in relatively greater numbers between AD 1400-1700 than before and after this event. Which possibly implies a slightly cooler climate between AD 1400 and 1700 than later in the sequence. It should be pointed out that these indications are quite weak, even with slight decrease of Panicoideae grasses the Lydenburg fen is still more mesic between after AD 1400 than before. The other proxies also indicate increasingly mesic conditions upwards, with a slight drying trend towards the top. Neither Breman (2010) found clear indications of cooling nor drying around AD 1700 in the three wetlands investigated.

To summarize; a general trend of increasingly wet conditions have been recorded in the region during the last 2000 years (Scott et al. 2008, Norström et al. 2009, Breman 2010, Finné et al. 2010, Scott et al. 2012), this seems to be reflected also in the Lydenburg fen. The end of “MWP” is reflected as a particularly dry and possibly warm period in Lydenburg fen. The observed warming during “MWP” is in line with the results by Holmgren et al. (2003), the indicated dry period from AD 1250-1350 is however not in line with the increase wetness noticed in the Makapansgat records. The “LIA” cannot be clearly depicted in the Lydenburg proxies of Lydenburg fen, a slight decrease in a general trend of increased wetness can be noted, but the end of “MWP” seems to have been a significantly drier period in the Lydenburg fen sequence compared to the “LIA”. This might either be related to that the temperature drop did not affect precipitation in the Lydenburg area, or that the event was not captured due to a to low resolution of analysed samples.

It should be noted that both in the papers by Holmgren et al. (1999, 2003) the underlying assumption when interpreting the δ¹³C values is that more enriched values of indicates periods of increased C₄, which is taken as indications of warmer and wetter conditions. In this thesis it has through phytolith analysis been possibly to identify which grass species the C₄ input of the organic matrix comes from (ie, the more mesic C₄-Panicoideae grass or, the dry adapted C₄-Chloridoideae grass). In the Lydenburg sequence the C₄ input from AD 1250 to AD 1350 is known to come from mainly C₄-Chloridoideae and this zone is thus interpreted as indicating a drier period. This is further supported by the other investigated proxies, such as the lithology, diatoms, chrysophyceae stomatocysts and % carbon.
Maize cultivation
During analysis no maize phytoliths were located, maize cultivation near the Lydenburg fen can therefore not be confirmed on basis of this study. Some suggestions of future studies are outlined in the forthcoming “Future studies” section.

Test of liquid mounting mediums
The survey of the three different mounting mediums showed that some general benefits in regards to identification accuracy are achieved by using a liquid medium. False identification was avoided at several occasions. Entella proved to be viscous enough for allowing turning of phytoliths and analysis to be performed at X 1000 magnification. Entella does however not seem like a suitable mounting media for diatoms, most likely related to the refractive index of the medium, causing fine features of the diatoms (raphes, striations) to become less clearly visible.

Uncertainties and potential errors
Taphonomy refers to processes affecting a plant or organism after it dies until its discovery in sediment, soil or other natural archives (e.g. Neuendorf et al. 2005). Bias can be introduced into an assemblage if post-depositional processes have occured. Re-working of peat or lake sediments is an example of such a processes. Re-working can occur either by bioturbation or for example by a weather event, such as a storm (Walker 2005). These processes potentially affect both the fossil proxy assemblage as well as the accuracy of the radiocarbon ages. Large mammals (zebras, giraffes, warthogs, baboons etc) are today found in the Gustav Klingbiel reserve, animals that potentially can cause re-working if passing through the fen. The fen does however not seem like a natural passage for animals as passing it leads to a steep drop into the creek south of the fen. Animal paths were not noted in any of the two field visits. Human activities can also cause re-working, and since human presence is documented in the area biases through human activities cannot be excluded. The radiocarbon dates from Lydenburg fen however suggested continuous deposition, no indication of major re-working was recorded.

Bias can also be introduced into an assemblage if chemical dissolution of siliceous microfossils has occurred. Silica is recycled in wetlands and soils through plant deposition and up-take of silica (Struyf & Conley 2009). The solubility of biogenic silica is greater than of minerogenic silica (Struyf & Conley 2009), i.e. biogenic silica is more rapidly recycled than minerogenic silica. In a study of tidal marshes in Belgium P. australis was
found to significantly increase silica recycling (Struyf *et al.* 2007). *P. australis* contemporary dominate the vegetation of Lydenburg fen. Potential impacts on the assemblage from chemical dissolution can therefore not be ignored. Some studies however indicate that GSSC phytoliths seem to be less prone for dissolution than both long-cells (Madella & Lancelotti 2012) and diatoms (Miller *et al.* 1990). A laboratory test by Miller *et al.* (1990) showed that phytoliths are more than five times more resistant to dissolution than diatoms. Both long-cells and diatoms has a greater specific surface compared to GSSC phytoliths, which potentially make them more prone for dissolution.

If some phytolith morpho-types are more prone for dissolution than others this could introduce a bias into the phytolith assemblage. Some studies aiming to investigate how different morpho-types of GSSC phytoliths are affected by dissolution have been undertaken. The results showed that the dissolution of different morpho-types was equal (Madella & Lancelotti 2012) suggesting that even if dissolution has occurred this process should not affect have affected relative distribution of GSSC phytoliths significantly. With the above in mind, GSSC phytoliths could potentially be regarded less affected by dissolution than long-cells and diatoms. It cannot however be excluded that the general increase of diatoms and chrysophyceae stomatocysts throughout the assemblage could be an effect of chemical dissolution downwards in the sequence and not from increased wetness upwards. There are still, however, several other indications of increased wetness based on other proxies of the Lydenburg sequence. The effects of chemical dissolution are difficult to fully evaluate within this thesis, more studies of these processes and how they affect different siliceous microfossil and interpretation of siliceous microfossils are obviously required.

Other potential sources of error can occur from downwards movement of phytoliths in a sediment or peat sequence with water, erosion or abrasion of phytolith grains during transport or mistakes during field- or laboratory work (Madella & Lancelotti 2012). The same processes also affect the accuracy of the radiocarbon dates. Some of the most common errors of radiocarbon dating have already been mentioned in the method chapter. However, the results by Wohlfarth *et al.* (1989) are also worth mentioning, which showed that that fungal growth during storage can cause to young ages to be derived. It is therefore recommended that material should be sent in for dating as soon as possible. In the case of the Lydenburg sequence three dates was sent in within 2 months, and two (ua-44863, 111-
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

113 cm and ua-44864, 232-234 cm) was sent in after 8 months of storage. The macrofossils from these samples where however picked out carefully. Seeds that showed indications of potential fungal growth were not sent in for dating. The Ångström Laboratory also chemically treated the samples to avoid potential errors.

The total sum of counted GSSC phytoliths in this study was c. 100 per analysed level, which might be a bit low. Presence of more uncommon subfamilies could have been under- or overrepresented (or even missed). The relative proportion of the different grass families might change slightly if the total sum is increased. However, some authors suggest that between 100 to 200 GSSC phytoliths (Piperno 1988) should sufficient. The accumulation curve of different morph-types by Breman (2010) also sugges that a majority of morphotypes should have been counted within the current base sum. It is recognised here that counting more phytoliths for each analysed level would increase the quality of the study.

Strömberg (2009) suggest that 200 – 250 GSSC phytoliths (index specific phytoliths) needs to be counted in order for the Iph and Ic indexes to produce statistically reliable estimates. Since the number of GSSC phytoliths are much lower in this study (100), and index specific numbers even lower, the results from these indices should be reviewed with caution. Bremond et al. (2005) found another factor that potentially can be distorted the Iph index; when Arundinoideae grasses are present in large numbers. The Arundinoideae grasses produce phytoliths characteristic of Panicoideae (e.g. Aristida, Stipa) and Chloridoideae (e.g. P. australis) (Bremond et al 2005). Barboni et al (1999) also found a potential to overestimate aridity when P. australis is common. As previously mentioned, P. australis contemporary dominate the immediate fen vegetation. P. australis does however produce a certain kind of saddle “Plataeu saddle”, this type has been counted separately and excluded from the data. The “Plataeu saddle” was furthermore found in quite few numbers (<7) throughout the sequence.

Bremond et al (2008) found that Ic index does not always depict relationship between C₃ and C₄ grasses correctly in an East Africa environment. These errors are related to that not all grasses within the Panicoideae sub-family use the C₄ photosynthetic pathway. The authors describe that in tropical mountain areas grasses growing in the shade can use a C₃ photosynthetic pathway even though they belong too sub-family Panicoideae (which is compromise 78% C₄ grasses). Panicoideae grasses growing in more open areas such as
grasslands, shrublands and open forests reportedly generally use a C\textsubscript{4} photosynthetic pathway. The vegetation of Lydenburg fen contemporary is quite open, and Paniocoideae C\textsubscript{3} grasses should therefore not pose a problem.

**Conclusions**

The palaeoenvironmental grassland reconstruction shows a general trend towards more mesic conditions from AD 400 until the present. Within this period variability has occurred, a significantly drier period was recorded between AD 1250 and 1350. The indications of generally increasing moisture availability during the last millennium is supported by several other studies from the region (Scott et al. 2008, Norström et al. 2009, Breman 2010, Scott et al. 2012).

A general drying trend can be noted from AD 400 to 1000, followed by more mesic conditions around AD 1200. The increasingly mesic conditions throughout the sequence were interrupted by a significantly drier period between c. AD 1250 to 1350. This part of the Lydenburg sequence occurs in the end of a climate event termed “Medieval warm period” (MWP), suggested to have been warmer and variable but mostly wetter in southern Africa (Holmgren et al. 2003). The results are in line regarding the increased temperature and suggested variability. However, in contrast with earlier findings, significantly drier conditions seem to have prevailed at the Lydenburg fen at the end of “MWP” as interpreted by multiple proxies. Within this time period two distinct gravel layers are found in the Lydenburg sequence. The gravel layers are possibly related to the increased drying of the environment, causing exposed soils, which in turn caused more material (gravel and pebbles) to be transported down the slopes and into the fen by water during summer rains. However, human activities nearby the fen could also have promoted increased erosion and transport of gravels into the Lydenburg fen.

After c. AD 1400 increasingly mesic conditions can be noted as interpreted from several of the analysed proxies. This general trend is decreased after c. AD 1500, where the dry adapted C\textsubscript{4}-Chlroidoideae increase briefly, after which the increasingly mesic trend continuous. The “LIA”, noticed in several records in southern Africa, was not shown as a significantly dry or cool period in the Lydenburg sequence.
The underlying assumption by Holmgren et al. (2003) that warming of the climate generally causes wetter conditions and cooler conditions cause’s drier conditions was not reflected locally at the Lydenburg fen. The results suggest that increased temperature, as inferred from results from the Makapansgat data, did not always entail wetter conditions and decreased temperatures did not always lead to drier conditions at Lydenburg fen. If this is due to local climate or hydrology changes, or has regional significance remains to be discovered.

A survey of liquid mediums showed that Entella is a suitable liquid mounting media for phytoliths. The results further emphasised the increased accuracy of phytolith identification obtained through the use of a liquid mounting medium.

The results from this study are in line with the results by Barboni and Bremond (2009) suggesting that small rondels should be excluded from fossil assemblages in sub-tropical settings.

**Future studies**

**Palaeoenvironmental reconstructions**
To get a more detailed knowledge of changes in climate related changes in grassland composition in the region, and especially to detect the driving forces of these changes, reconstructions from more wetlands (or other natural archives) needs to be conducted. Since many factors affect grassland composition, such as temperature, precipitation, fire frequencies, grazing by wild animals and livestock, and human activities, additional studies could hopefully help to detangle the different driving forces have been involved at different geographical places and through time.

For this particular study it would improve the quality of the interpretations if additional stratigraphy coring could be performed, in order to establish the actual depth of the basin. To also collect several cores, from several locations within the fen (for example site no 5, 6, 9 and 13) to perform analysis on would further improve the quality of the interpretations. The phytolith assemblage would benefit from increasing the number of levels studied, as well as the number of counted phytoliths for some particular levels. To increase the number of counted phytoliths for levels nearby events of particular interest, such as the “LIA” and
“MWP”, would be particularly interesting. More radiocarbon dates and by possibly applying OSL dating in the uppermost parts where calibration is difficult, would improve the quality of the age-depth model and timing of different events in the sequence. Since the Lydenburg fen have an accumulation rate of 1.9 mm / years the opportunity to get high resolution for palaeoenvironmental changes during the last 1,700 years from this site should be good.

When performing phytolith analysis it is recommended to commence a detailed vegetation survey and compare the contemporary vegetation with recent soil/sediment samples (eg. Piperno 1988; 2006). This was not done on the first field visit when cores was collected (December 2011), primarily related to limited time but also to that it at the time of core collection was not known what proxy would be analysed. A more detailed vegetation survey and analysis of recent samples would therefore be recommended in any future study in the Lydenburg fen.

Macro fossil analysis of the uppermost 150 cm of the Lydenburg fen would potentially give interesting information about the composition of the organic matter, which could also yield information about changes of the local vegetation other than grasses.

In this study the δ¹³C data was interpreted differently than how for example Holmgren et al. (2003) interpret variations in δ¹³C values. Here, a less depleted δ¹³C value occurred at the same time as the phytolith assemblage showed a distinct increase in C₄-Chloridoideae, leading to the interpretation that a significant drying occurred in zone 2. If only the isotope data was interpreted, with the same assumptions as used by Holmgren et al. (2003) the interpretation would have been of wetter conditions in zone 2 and increased drying upwards in the sequence. The lithology, carbon content, and increase of algae upwards also supports increasingly mesic conditions upwards. Testing the underlying assumption that enriched δ¹³C values indicate wetter conditions would therefore be an interesting scope for future studies. For example, through phytolith analysis of a peat core (or recent soil samples), in the area of Makapansgat. The results could then potentially be compared with the δ¹³C value from stalagmite data. This could potentially give interesting insights in weather the C₄ signal comes from C₄ Panicoideae or C₄ Chloridoideae grasses.
Identification of maize cultivation in the BoKoni region
No indication of maize cultivations was found in this study. To perform analysis on cores from other wetlands is one option for a future studies, preferably on sites where terraces and/or cultivation areas are confirmed to have occurred in the immediate surroundings of the wetland/fen. One potential new site was investigated during the second field visit in November 2012 at Verlorenkloof Estate (25°25’37.34"S 30°16’52.79"E). Traces of cultivated crops might be better represented at this site, either in the form of pollen and/or phytoliths. It might also be more likely to find traces of maize through a slightly different method design, where only certain pollen or phytoliths are searched for (for example only rondels and large crosses type phytoliths). Since the aim in current thesis was to both perform a grassland reconstruction and on the same time look for maize phytoliths the time spent on looking for maize phytoliths was limited. A future research design which only focuses on cultivated crops could increase the likelihood to find these pollen and/or phytoliths. In sites where archeological research have been performed other archives/sources could give interesting information about what crops was cultivated. Examples might be waste pits, tools, floors of storage buildings, etc.

Liquid mounting mediums
To compare the results when different mounting mediums have been used is a potential scope for future studies. Since it was evident during the analysis part of this thesis that phytoliths look very different depending on what view they are located in on the laboratory slide, it would be interesting to compare the results when using a permanent media with liquid mediums. To also evaluate the quality of the results, compared with how time efficient usage of different mediums is, could also yield interesting information. The result could potentially enable informed decisions to be made, when drawbacks and benefits of using different mounting mediums are better known.


**Acknowledgements**

I would like to thank my supervisors at Stockholm University, Elin Norström and Jan Risberg, for invaluable help, guidance and support in all different processes of this project. I especially appreciate been given enough freedom to pursue this project in an independent manner. I would also like to thank Mats Widgren, Stockholm University, for allowing funds from his VR project for travel, accommodation and radiocarbon dates. Alex Schoeman, Wits University, also offered invaluable assistance during our two field visits, but also throughout this project through supplying me with information and articles about Bokoni. I would also like to thank Jeannette Smith for supplying me with the stable isotope data and for discussing the interpretation of this data. I’m also grateful to Elinor Breman, Oxford University, for discussing her results with me and supplying me with invaluable information about GSSC phytolith interpretation in tropical and sub-tropical settings. I also owe a special thanks to JP Celliers at Gustav Klingbiel Reserve for arranging access to the Lydenburg fen as well as supplying information. I am also grateful to Anton Linstrom, wetland specialist in Mpumalanga, for taking time to talk with us about the fen and suggest new sites for further investigations. I am also grateful to Karin Holmgren and Hanna Sundqvist, Stockholm University, for informing me about speleothem interpretations. I would also like to thank Sven Karlsson, Shyrete Shala and Mats Regnell (Stockholm University) for helping me (among other things) to identify macrofossils for radiocarbon dating. Finally I would also like to thank friends and family for all the support.
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

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Burrough et al 2012


Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy


Jenny Sjöström


Norström. E. Holmgren, K. Mörth, C-M. (2008) A 600 year long δ18O-record from cellulose of


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Appendix A, Lithostratigraphical description

No 1
000 – 020 Sandy peat
020 – 030 Sandy silt

No 2
000 – 020 Sandy peat
020 – 050 Clayey silt
050 > 100 Sandy clayey silt

No 3
000 – 045 Sandy peat
045 – 145 Sandy clayey silt
At 95 – 100 cm a layer of clayey silt (darker colour).

No 4
000 – 050 Peat
050 – 150 Silty peat
Increasing minerogenic content downwards
150 > 200 Sandy clayey silt
Occurrences of iron nodules.

No 5
000 – 155 Peat
A band of peaty silt 130 – 135 cm
155 – 200 Clayey silt
200 – 280 Clayey peat / peaty clay
Alternating layers
280 > 300 Clayey silty peat
Highly decomposed. Black colour.

No 6
000 – 150 Peat
150 – 170 Silty peat
170 – 200 Peaty clayey silt
200 – 260 Clayey silt
Sand found at 256 – 260 cm.
260 – 265 Peaty clayey silt
265 – 290 Clayey silt
290 > 300 Clayey sandy silt

No 7
000 – 135 Peat
135 – 160 Silty peat
160 – 190 Clayey silt
190 – 200 Clayey sandy silt

No 8
000 – 025 Peat
025 > 050 Clayey silt

No 9
000 – 102 Peat
102 – 127 Silty peat
127 – 140 Sandy clayey silt
140 – 155 Peat
155 – 220 Pebbly peaty clayey silt
Increasing minerogenics downward
220 – 250 Gravelly sandy clayey silt
228 – 230 cm iron nodules.
250 > 300 Clayey silt

No 10
000 – 155 Peat
0 – 15 darker colour.
At 125 – 150; darker band.
155 – 250 Peaty clayey silt
Gradual increase of minerogenics downwards.
Occurrences of pebbles and gravel.
Brown colour indicates organics to 218 cm.
250 – 260 Peaty gravelly sand
260 > 300 Clayey silt

No 11
000 – 120 Peat
Uppermost 10 cm darker colour than 10-80 cm.
From 80 – 100 cm gradual change to darker colour.
120 – 148 Sandy clayey silt
148 > 150 Peat

No 12
000 – 067 Peat
0 – 25 cm darker colour.
067 – 112 Clayey silt
Gradual change from 67 cm towards minerogenics (clay)
112 – 150 Peat

No 13
000 – 005 Peat
005 > 050 Clayey silt

No 14
000 – 125 Peat
125 > 150 Silty clay
Gradual change from 125 cm from peat to clay dominance.

No 15
000 – 030 Peat
030 – 050 Clayey silt
A band of darker colour (black) between 138 – 140 cm.
050 > 150 Sandy clayey silt

No 16
000 – 030 Peat
030 – 050 Clayey silt
At 138-140 cm a band of darker colour (black) is found.
050 > 150 Sandy clayey silt

No 17
000 – 060 Peat
From 50 to 60 cm darker colour of peat (more decomposed)
060 > 100 Clayey silt

No 18
000 – 050 Peat
050 – 100 Clayey silt
Gradual change from peat to clayey silt starting from 50 cm.

No 19
000 – 050 Peat
050 – 100 Clayey silt
Appendix B, Radiocarbon calibration curves.

72-74 cm

111-113 cm
Late Holocene palaeoenvironmental reconstruction on a peat sequence from northeastern South Africa, using grass phytoliths as main proxy

150-155 cm

232-234 cm
282-284 cm
Appendix C, Counting sheet used during microscope analysis

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<td>Rectangular, granulate</td>
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<td>Square</td>
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