Holocene Environmental Change at Groenvlei, Knysna, South Africa:

Evidence from Diatoms

Masters Thesis
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Abstract

Sediment cores extracted from a coastal lake along the south coast of South Africa provide a unique opportunity to assess environmental changes during two discrete periods of the Holocene. Conductivity and pH are reconstructed using a diatom inference weighted average model, ($r^2 = 0.76608$, RMSE = 0.47504) and ($r^2 = 0.7567$, RMSE = 0.50937), respectively. Other environmental parameters, including salinity, nutrient availability and water level changes are inferred using ecological indicator species within the diatom fossil assemblage. An age–depth model is developed through the combination of four radiocarbon (^{14}C) measurements and eleven optical luminescence dates from two cores in the lake basin. Cluster analysis and Principal Component Analysis identify four significant zones in the core, namely zone *a* (c. 4.2 – c. 4 ka), zone *b* (c. 4 ka), zone *d* (c. 0.7 – c. 0.33 ka) and zone *e* (c. mid 1600s AD – present). A depositional hiatus occurs between zone d and b causing an interruption in the sequence. The results indicate that variations in diatom assemblages are related to changes in external environmental factors. In summation; changes in the diatom assemblage in Zones *a* and *b* correspond to sea level changes and the remobilisation of sand dunes, while Zone *d* is associated with temperatures changes experienced during the Little Ice Age (LIA) episode. Zone *e* indicates a combination of extreme climates during the LIA and the later impacts of human activities within the catchment. This study demonstrates that diatom analysis of lake sediment can provide very detailed information on long and short term climate change, hampered only by inconsistent sediment accumulation at Groenvlei. Further work may provide insight to periods which were not covered in this study.

Key Words

Diatoms, Holocene, South Africa, pH, conductivity, Little Ice Age, sea level changes

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Quaternary based studies conducted throughout South Africa have shown that different regions have responded uniquely to changing global influences due to the steep biogeographical and environmental gradients across the country (Meadows and Baxter, 1999) (Talma and Vogel, 1990) (Holmgren *et al.*, 1999). In the quest to provide a more complete picture of the changes experienced in the different regions, the past two decades has witnessed an increase in long term palaeoenvironmental studies in a number of different disciplines. This has provided a more reliable assessment of the nature and scale of natural variability of the Earth's climate system, as well as the extent of human impacts on the present and future climate.

Palaeolimnology is one such discipline which has been indirectly utilised to determine climate change in numerous regions of the world (Wolin and Duthie, 1999), in addition to facilitating the monitoring of environmental transformations (Anderson, 1995). The sediments and fossils deposited in a lake system are intricately linked to the climate within the region, i.e. climate directly influences the hydrological budget of the lake with further implications on ecological and sedimentological characteristics of the system (Fritz *et al.*, 1999). The high potential of fossil preservation in sediments within a lake provides additional proxies to correlate to known climatic events and changing environmental conditions.

Diatoms in particular have proved to be a useful tool in reconstructions as they are widespread and abundant in almost all habitats where water is at least occasionally present and, moreover, are ecologically sensitive (Stoermer and Smol, 1999). Therefore, the stratigraphic sequence in lacustrine sediments can offer a valuable source of evidence for the reconstruction of high temporal resolution environmental change (Anderson, 1995). Recent advances in palaeolimnology from a primarily qualitative descriptive subject with basic depictions to a quantitative analytical science has provided in depth insight into rates of change and natural background conditions concerning the impacts of environmental changes on limnic systems

(Birks, 1998). These advancements have made it useful to revisit earlier works to further explore and quantify evidence obtained previously.

Although palaeoenvironmental studies in South Africa have been on the increase, there are still huge gaps in our knowledge of environmental change in the late Quaternary, as well as suggestions of inconsistencies between different regions across the country due to diverse climatic regimes. The opportunity to return to a study within the transitional rainfall zone of South Africa, which has laid the foundation for many studies since its publication, can present a quantitative view and offer added insight to a region that has had few feasible sites to study. Initial work on a coastal lake near Knysna by Martin (1956, 1959, 1962 and 1968) identified sediments rich in fossil materials, which spanned most of the Holocene epoch. This is an exceptional resource in the southern African context as the continuous accumulation of lake sediments is very rare (Scott and Lee-Thorp, 2004). The lake, Groenvlei, has shown alterations in its chemical and biological development through the Holocene which Martin (1959) attributed to possible marine transgressions at various times over the last few thousand years. The potential of the Groenvlei sediments to be rich in diatom fossils had already been demonstrated in Martin's work (1959); therefore revisiting this site to further study sediment chrono-stratigraphy and fossil diatom assemblage is a potentially rewarding exercise.

1.1 Aims and Objectives:

This project aims to develop, against a suitably accurate chronology, an understanding in the changes in the sedimentary sequence at Groenvlei in relation to evolution of the associated biological communities. Diatom analysis is used to determine environmental factors responsible for any observed changes. This analysis is expected to offer insight into the coastal lake's history during the Holocene, with particular reference to alterations in the physicochemical parameters of the water body. The ecologically based indicator study also provides indirect evidence of changes within the Groenvlei catchment area and a comparison with other proxies and previously published work reinforces the palaeoenvironmental reconstruction. The intention is to create a high temporal resolution study to present as much information on patterns of climatic variability in an extremely significant environmental area along the southern coast of South Africa.

In summary, the main objectives of this study are to:

- Reconstruct the water quality indices, pH and conductivity, quantitatively using diatom transfer functions with the intention of providing exact parameters of observed changes;
- Assess water quality changes of Groenvlei over time qualitatively by utilizing an indicator species approach as both a method to validate the quantitative reconstruction and relate the changes in the diatom assemblage to climatic changes;
- The overall aim relates to the evolution of Groenvlei based on theorised environmental changes already suggested in other studies with the hope of substantiating their findings and providing a foundation for the development of the southern coast of South Africa.

1.2 Project Outline:

The intention of the above introduction is to present a framework on which this project is based; in essence, establishing the fundamental principles required and the need for palaeo-based studies. Chapter Two investigates the importance of lakes and the broad application of diatoms as proxies to environmental change. A review on the literature available for the study site is presented in Chapter Three, outlining the contemporary setting and geological development of the physical environment in the region, based on climate, relief and ecology. Chapter Four describes the methods employed to produce the results and environmental reconstruction presented in Chapter Five. Chapters Six and Seven discuss and conclude the results introduced in the previous chapter and the project on the whole.

Chapter 2. Lakes and Diatoms

A closed lake, that is one without surface outflow (Fritz *et al.,* 1999), provides an archive of palaeoenvironmental data due to the response to changing hydrological inputs caused by natural climatic variability and/or anthropogenic activity (Austin *et al.,* 2007). These changes occur at a variety of timescales, either long or rapid periods of time or as a result of catastrophic events (Wolin and Duthie, 1999), that are recorded in the sedimentary record which vary according to the lake and its catchment (Battarbee, 1999). The strength of the sedimentary signal is dependent on the type of lake with shallow, closed basin lakes having the strongest (Wolin and Duthie, 1999). Lake sediments are a mixture of organic and inorganic material, typically derived from the lake itself or its catchment (Battarbee, 1999), the continued deposition of plant and animal remains and sediment inputs causes infilling of the lake basin, resulting in the lake becoming shallower over time (Wolin and Duthie, 1999). The rate of deposition can vary within and between lakes but are usually sufficiently rapid to allow for high temporal resolution analyses into environmental changes (Battarbee, 1999). It is for these reasons that lake sediments are analysed using a diverse range of physical, chemical and biological methods (Battarbee, 1999), as they contain a valuable record of changing hydrological conditions (Anderson, 1995).

Lake hydrology is intricately tied to climate, with the chemical response of a closed-basin lake being near instantaneous (Fritz, 1990). As a result, the palaeolimnological record should not suffer from time lags, as it is a direct, sensitive and powerful tool for palaeohydrologic and palaeoclimatic reconstructions (Fritz, 1990). An important factor to consider is a lake's hydrological sensitivity to any changes that do occur (Fritz *et al.,* 1999), as an individual lake's response is related to both the lake and the catchment morphometry, local hydrology and the position of the lake within the landscape (Anderson, 1995). However, the stability of the sediments and their resistance to erosion by such physical processes as tidal currents, wind-induced waves and bioturbation (Sullivan, 1999) allows for the use of palaeolimnology as a tool in identifying probable causes in change, either by reconstructing the history of individual sites or by the comparison between sites (Battarbee, 1999).

The climate, lake chemistry and lake levels of closed basin lakes are closely related (Anderson, 1995), hence several hydrological elements can be used to determine past climatic trends. Water levels and lake chemistry are a manifestation of moisture gains, i.e. inputs and moisture losses, i.e. outputs (Wolin and Duthie, 1999). Inputs include precipitation, stream flow, surface runoff and groundwater inflow (Fritz *et al.,* 1999) where outputs involve evaporation, stream outflow, groundwater recharge and in some cases deep seepage (Wolin and Duthie, 1999). Water level fluctuation is increasingly used in reconstructions for projecting climate change (Wolin and Duthie, 1999) and can provide a framework for understanding modern hydrologic responses (Fritz, 1990). Surface water hydrology, for example lake isolation or open versus closed basin, is not always the main cause behind changes to lake levels (Anderson, 1995) but can also be a function of a variety of geological, biological or climatic processes (Wolin and Duthie, 1999). However, in general, lake levels increase during wet periods and decline in drier periods leading to knock on effects on such parameters as thermal stratification, with the total loss of stratification and the resuspension of bottom sediments occur in shallow systems; in addition to increases in nutrient and chemical salt concentration with corresponding changes in pH (Wolin and Duthie, 1999). The inverse is true for higher lake levels (Wolin and Duthie, 1999).

Other factors influenced by changes in the inputs and outputs of a lake are salinity, the ionic composition and concentration and nutrient supply. Salinity varies in relation to the inflow of both freshwater and marine water, precipitation and evaporation and depending on the position of the lake salinity can vary from relatively stable to extremely unstable in time and space (Snoeijs, 1999). Brackish waters are the median between the two extremities of freshwater and marine water and can be subdivided into three major categories (Snoeijs, 1999. p. 298):

- "Transition zones between freshwater and marine habitats
- Transition zones between hypersaline waters and marine waters and
- Inland waters with higher salinities than freshwater"

Salinity can also be an indirect measure of climate, as lake water becomes more concentrated when regional climates become drier and lakes change to closed basin

(Anderson, 1995), however lakes that fluctuate between open and closed hydrology may exhibit large shifts in salinity which are not proportionate to climatic forcing hence a prior knowledge of the lake's development is required (Fritz *et al.,* 1999). Ionic composition of lakes is highly variable and may be dominated by carbonates, sulfates or chlorides in combination with major cations, such as Calcium (Ca), Magnesium (Mg) and Sodium (Na); the concentration of which is the result of the interplay between the chemistry of source water, groundwater flow and climate (Fritz *et al.,* 1999). An enrichment of inorganic plant nutrients into the lake system is termed eutrophication and may be caused by a multitude of factors but is regulated to a large extent by human activities, climate, morpho-edaphic conditions of the watershed and food web interactions (Hall and Smol, 1999). Eutrophication usually results in increased lake productivity (Hall and Smol, 1999).

An important factor to consider is the influence of humans on the natural processes occurring in the lake's catchment. In many regions, human activity has impacted lake development for a long time (Hall and Smol, 1999), typically resulting in acceleration in the natural processes by such activities as forest clearance, farming and nutrient inputs (Wolin and Duthie, 1999). These activities can alter or obscure the climatic signal present in the sedimentary record; by separating the anthropogenic signal from the natural, a clear indication of human versus natural modifications can be determined (Wolin and Duthie, 1999). Therefore changes in the hydrologic budget either natural or anthropogenic will affect physiological responses and species composition of the lake's biota (Fritz *et al.,* 1999). The microfossil record preserved in the sediments is used to identify early changes in the biological record, as the extent of these changes can be used to reconstruct changes in water quality; in particular diatom analysis is now sufficiently well established to allow for quantitative reconstructions (Battarbee, 1999).

Diatoms are microscopic algae found in almost all aquatic environments (Stoermer and Smol, 1999), their habitats range from marine to estuarine and shallow coastal environments (Sullivan, 1999) to freshwater lakes and rivers (Hall and Smol, 1999) where they are often the dominant component of the microalgal assemblage (Sullivan, 1999). Diatoms are typically abundant and diverse, occurring in a broad spectrum of lake trophic status (Hall and Smol, 1999), have high species diversity and niche specificity (Denys and de Wolf, 1999) with the community composition being generally related to the chemical, physical and biological variables present in their habitat (Fritz *et al.*, 1999). On an individual species level, each has a specific habit and water chemistry requirement (Hall and Smol, 1999). These requirements have allowed for diatoms to be used as a tool to explore and interpret many ecological and practical problems (Stoermer and Smol, 1999). Their sensitivity to different aquatic environments lead to their use as indicator organisms which reflect the ecological changes experienced (Wolin and Duthie, 1999), and allow for the changes to be tracked as algal productions shifts in response (Hall and Smol, 1999).

Biological communities are dynamic in nature (Snoeijs, 1999), therefore if a habitat varies in a short time period, even at a subseasonal scale the community will respond rapidly to the changes and adapt to the new conditions (Bradbury, 1999). With their short lifespans and capacity for rapid regeneration (Bradbury, 1999), diatoms make especially suitable indicators to track changes in the hydrological budget at a variety of temporal scales, whether be it short or long (Fritz *et al.*, 1999). The temporal scale is directly proportionate to the accumulation rate of the sediments, which are highly variable through space and time (Hall and Smol, 1999). It is important to note that accumulation rates are difficult to estimate accurately but remain the most accurate measure in diatom production (Hall and Smol, 1999).

On the basis of diatom life histories, habitats and ecological preferences, a wide variety of environmental parameters can be determined (Bradbury, 1999). A particular emphasis on past climate changes has been the subject of many recent diatom studies, these studies are based on interpreting past limnological conditions from fossil diatom records and subsequently extrapolating to the climatic environment responsible (Bradbury, 1999).

Diatom fossil deposits are often well preserved in the sediment record (Stoermer and Smol, 1999), reflecting years of sediment accumulation (Cooper, 1999). A diatom frustule (skeleton) is made up of two valves (Stoermer and Smol, 1999) composed of resistant opaline silica and it is these valves which are preserved in the sediment (Hall and Smol, 1999). The shape, size and sculpturing of the cell walls of the valves is taxonomically diagnostic (Stoermer and Smol, 1999), these distinctive features are well documented and aid in identification of species (Hall and Smol, 1999). The preservation potential of the fossil remains allows for the identification of each species within the assemblage which ultimately contributes clues about the past environment and with additional quantitative assessment and assemblage statistics additional information can be gained (Cooper, 1999) (Denys and de Wolf, 1999). The degree of preservation of the frustule may also contain additional information relating to the environment during deposition, for instance fractured or eroded valves may indicate intertidal exposure or abrasion whereas pristine valves may indicate rapid burial and little post-depositional disturbances in a low energy environment (Cooper, 1999). The analysis of the assemblage composition and knowledge of the relevant autecological characteristics of the taxa present aids in inferring environmental conditions (Denys and de Wolf, 1999).

2.1 Environmental Variables that Contribute to the Diatom Assemblage:

The main environmental variables that account for significant variations in diatom assemblages include conductivity, pH and cation and anion composition and concentration, that is the variation of positively- and negatively charged molecules within the water system and salinity (Fritz *et al.* 1999). Studies have shown that the distribution of diatoms is clearly correlated with pH in low alkalinity lakes and it has been shown to occur at the species and taxonomic level (Charles and Smol, 1988). The siliceous remains of the frustules, when well preserved in lake sediments can be used to infer long-term as well as short-term acidification trends (Charles and Smol, 1988). Many diatom species show a clear specificity for certain cation and anion compositions and concentrations and may be characterized by the levels of such ions as chlorides, carbonates or sulphates (Fritz *et al.* 1999); these specifications aid in the utilization of diatoms as bioindicators of water pollution or nutrient changes through time (Gélabert *et al.* 2006).

2.2 Diatoms in Relation to Sea Level and Climatic Changes:

Diatoms can be used to identify the stratigraphical levels where marine influences increase or diminish (Denys and de Wolf, 1999). The different stages that can occur within a water body, such as a lake that is affected by changes in sea level, specifically transgressions and regressions of the ocean, can be detected through the diatom microfossil assemblage, although early stages of sea level changes are often poorly represented in the diatom sedimentary sequence (Snoeijs, 1999). The changes in sea level can alter the tidal zones along a shoreline; hence environmental conditions, and subsequently diatom assemblage compositions, change most rapidly at the higher tidal elevations (Denys and de Wolf, 1999). For diatoms, the transition from fresh water to brackish water, the changing in the substrate characteristics and transportation by the tidal currents appears to be some of the most important determinants that characterise the assemblage (Denys and de Wolf, 1999). Diatoms can provide an indirect record of climatic change as they are known to respond to the physical and chemical attributes of a water body (Rühland and Smol, 2005); these attributes are a direct manifestation of the balance between inputs, e.g. precipitation and outputs, e.g. evaporation (Fritz *et al.* 1999), this can aid in tracing past climatic changes and the results of which can be useful for predicting expected future changes (Snoeijs, 1999).

Studies utilizing diatoms within sedimentary sequences have been conducted globally and these have aided in understanding changes in the local climate, sea level modifications and alterations in environmental systems. A study carried out along the Chilean coast showed that during the late Quaternary; there were strong palaeoproductivity variations that were associated to different physical mechanisms, forcing processes and climatic changes (Romero *et al.* 2005). Another study on Slipper Lake, U.S.A.; tracked a subtle, slow and natural pattern of increased acidity during the early history of Slipper Lake, with the most abrupt and noticeable change occurring within the last two centuries (Rühland and Smol, 2005). On the North American continent Quaternary hydrology and climate have been inferred from the diatom stratigraphy of closed-basin lakes; for example in glaciated regions, lake sediments recorded the pattern of limnological change following the retreat of the Laurentide ice sheet at approximately 12 ka (Fritz *et al.* 1999).

2.3 Environmental Factors:

As stated previously, diatoms have been used to determine various environmental variables, such as salinity, pH and productivity. Most studies incorporate classification schemes to group similar species together that share the same tolerances, as is the case with pH and salinity, or that have specific requirements for their existence, as is the case when trying to establish the palaeoproductivity. These classification schemes are discussed below.

2.3.1 Life Form and Water Level:

Life form relates to the changes in abundance of planktonic and benthic diatoms, these changes are interpreted in two ways; either as due to changes in the morphology of the lake basin as the lake fills in and/or to a change in productivity (Battarbee, 1986). Planktonic diatoms are those which are free floating living in the open lake water, whereas benthic diatom communities are those which are non-planktonic or littoral forms which live on the lake bottom (Wolin and Duthie, 1999). Tycoplanktonic forms are usually associated with the benthic or near shore community but can be easily transported into the planktonic community (Wolin and Duthie, 1999). Benthic diatoms are further characterised by the substrata they attach themselves to, for example epiphytes are attached to other plants (Wolin and Duthie, 1999), epilithic diatoms live attached to rocks, episammic diatoms are associated with sandy substrata and epipelic diatoms live on fine sediments (Hall and Smol, 1999). The knowledge of a dominant life form in the fossil assemblage can be beneficial in itself as each has an effect on the environment it inhabits, for example epipelic diatoms secrete a mucilage substance which prepares the way for the eventual colonisation by vascular plants (Sullivan, 1999).

Studies have shown that changes in the percentage of life forms from planktonic to benthic can indicate high or low lake levels (Wolin and Duthie, 1999). This is related to the assumption that during high water levels the percentages of planktonic forms are expected to increase and as lake levels fall, benthic and epiphytic life forms generally increase (Wolin and Duthie, 1999). Several environmental parameters are subject to vary as water levels fluctuate; these include changes in available habitat, chemical conditions, water stratification and to the mixing regime, also light penetration increases as lake levels drop (Wolin and Duthie, 1999). Although this ratio is highly useful, the same signal may be caused by other factors such as changes in nutrient inputs therefore multiple lines of additional evidence is required to support any proposed lake level fluctuations, this may include fine grained particle analysis, pollen analysis and stable isotope analysis (Wolin and Duthie, 1999).

The establishment of the dominant life form during a time period and the subsequent change to an alternative life form can be informative to the development of a habitat. The Chalie and Gasse (2002) study at Lake Abiyata, Ethiopia combined the abundance of taxa with the reconstructed chemistry of the lake water and the life form groupings to establish three major zones of environmental change over the past few centuries, these zones were then subdivided into several sub-zones. The subsequent limnological stages complemented millennial-scale environmental records available for the region and recognized variations in the lake water levels and salt balances.

2.3.2 Salinity:

Since the nineteenth century scientists have identified salinity as the major determinant of diatom distribution (Denys and de Wolf, 1999). The main salinity regulating factors within an aquatic system are the inflow of freshwater, the inflow of marine water, precipitation, evaporation and the extent of ice cover (Snoeijs, 1999). A freshwater body is separated from a saline water body by the salt deposits within its water column, it has been agreed that the boundary between freshwater and saline water is 3g/l (Fritz *et al*., 1999). Some species of diatoms are rare or absent above the 3g/l salt concentration mark, while others can only occur above this limit (Fritz *et al.* 1999). The diatom community structure is so sensitive to salinity changes that a one per mil (1‰) change in salinity can completely change the species composition within the water body (Snoeijs, 1999). In other words, the "series of species replacements along the salinity gradient" (Fritz et al., 1999, p. 63) make diatoms a leading indicator of chemical change within that water body which is driven by changes in hydrology and climate (Fritz *et al*., 1999). Although three factors must be taken into account when using organisms as environmental markers for salinity changes, as outlined by Snoeijs (1999, p. 298); those being:

1. "…In environments with fluctuating salinity regimes, the species are selected more according to their ability to cope with changing salinity (euryhalinity) than their salinity optima;
2. In environments with stable salinity regimes, evolutionary processes have resulted in various degrees of endemism depending on the geological age and stability of the water body and the degree of isolation from other populations of the same species; and

3. Species perform differently, that is physiologically and ecologically; in different brackish waters because they are, besides salinity, also affected by other environmental constraints; such as alkalinity, water temperature, light regime, nutrient concentrations, degree of exposure to wave action, biotic interaction etc…"

Lake water salinity becomes more concentrated as the local climate becomes drier and as lakes evolve from open basin to being closed basin (Anderson, 1995), therefore changes in salinity can be used to infer changes in climate. Diatoms are distributed into three major groups called a halobian system, which assists in identifying key periods in a lake's development. These groups were outlined by Battarbee (1986) and are stated below:

1. Euhalobous: diatoms that can tolerate salinities that range from 30 to 40 per mil
2. Mesohalobous: diatoms that can tolerate waters with a salinity range of 5 to 20 per mil
3. Oligohalobous: diatoms that can only tolerate salinities that are less than five per mil

The last group is subdivided into:

a) Halophilous: which are for diatoms that grow well in slightly brackish conditions
b) Indifferent: tolerant of brackish water but their optimum growth is in freshwater
c) Halophobous: these are the diatom taxa that can not tolerate even the smallest concentration of salts within the water column.

The reconstruction of climate change inferred from salinity records obtained from diatom analysis requires an understanding of the basin hydrology; due to the fact that the climate signal is affected by the contribution of the groundwater component in the water body's hydrologic budget (Fritz *et al.*, 1999). Significant limitations in salinity reconstructions occur when species diversity is low and the taxa that are present have a large salinity range (Fritz *et al.*, 1999), or if the assemblage is of a mixed origin where freshwater diatoms are brought into the system by rivers and marine species are transported in by tidal action (Cooper, 1999).

2.3.3 pH:

Numerous studies have shown that diatoms are good indicators of pH change over time (e.g. Nguetsop *et al.*, 2004, Huntsman-Mapila *et al.*, 2006, Chalie and Gasse, 2002). Species are typically divided into one of five categories according to their individual pH tolerances. These categories were outlined by Battarbee (1986) and are recounted below:

1. Alkalibiontic: these are the diatoms that occur at pH values over 7
2. Alkaliphilous: this category includes diatoms that occur at pH values at about 7 and with their widest distribution at pH > 7
3. Circumneutral/Indifferent: these are the diatoms that occur equally on both sides of pH = 7
4. Acidophilous: this category includes diatoms that occur at a pH value of about 7, but with the widest distribution at pH < 7
5. Acidobiontic: these are the diatoms that occur at pH values under 7, with the optimum distribution at pH = 5.5 and under.

There is an intricate relationship between pH values and water as indicated by Figure 1; hence by determining the changes in pH one can reconstruct the source water over time and the changes of these inputs in the evolution of a water body. For example, the study conducted by Nguetsop *et al.* (2004) established a link between the pH of Lake Ossa, Cameroon and precipitation rate, hence pH change over time was indirectly used as a proxy for past precipitation changes.

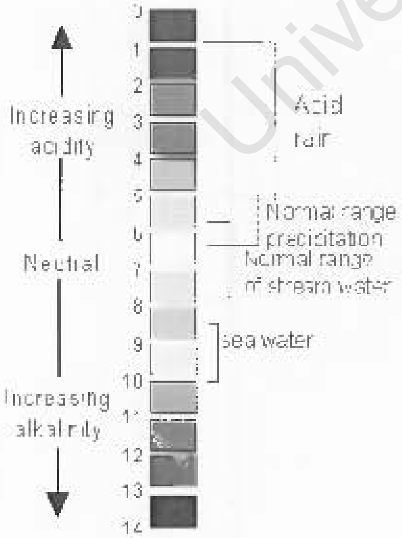

Figure 1: Relationship between pH and water sources (modified from http://www.ec.gc.ca/water/en/manage/qual/e_ph.htm)

Classification schemes aid in identifying periods of significance, ultimately assisting in inferring environmental and climate changes, however caution should be taken as local hydrological factors must be understood for a meaningful interpretation (Barker and Gasse, 2003). Another factor that plays an important role is that of adequate modern analogues which is required when utilising diatoms in such studies as reconstructing past environmental changes

2.3.4 Water Quality and Nutrient availability:

Water quality studies have increased in number and scope as human activities have continued to influence the environment (Sullivan, 1999). The nutrient signal in the diatom assemblage can be used to indicate human impacts or environmental changes within the lake basin (Wolin and Duthie, 1999). It works on the basis that diatoms are sensitive to changes in nutrient concentrations, supply rates and ratios; with each taxon having a specific range and tolerance (Hall and Smol, 1999). Therefore, the response time to changing nutrient availability and other water quality conditions is particularly rapid (Cooper, 1999). The combined shift in the relative proportion of inorganic nutrient concentration and increases in primary production usually indicates eutrophication (Snoeijs, 1999), although increases in primary production may be at a lag to the changing nutrient status due to the shading effect of the overstorey grass canopy (Sullivan, 1999). The other possibility when the ratio between nitrogen and phosphorus changes may be a shift from diatoms and other small edible algae to larger cyanobacteria, which may have ramifications on the higher trophic levels (Fritz *et al*., 1999).

Water quality indices have been formulated to quantify the concentration of chemical constituents present in the water body (Bate *et al*., 2004). In South Africa, benthic diatoms are utilised in water quality assessments since the 1950s (Bate *et al*., 2004), to determine environmental features such as lake water chemistry and conductivity to name but a few (Austin *et al*., 2004).

2.4 Limitations:

Diatom analysis has certain limitations and assumptions that need to be considered; firstly, mixing and transport of frustules before burial may cause distortion or inaccurate shifts in the diatom assemblage resulting in an imprecise environmental reconstruction (Fritz *et al.* 1999). Secondly, the selective removal certain taxa from the record may occur either through dissolution, i.e. the dissolving of the frustule into its constituent elements or diagenesis, i.e. the dissolving of the frustule into its constituent elements and the subsequent recombination of the elements (Fritz *et al.* 1999). Finally, the diatom assemblage composition can be affected by the physical processes within the water body, some of these processes being the changing velocity of the water currents, the intensity and frequency of upwelling events, the resuspension and erosion of particles; and biological processes, such as bioturbation (Snoeijs, 1999).

The importance of determining the ontogeny of the fossil assemblage has to be stressed; the possibility of transported material within the assemblage may represent species which never lived together in either space or time (Bradbury, 1999). Parautochthonous assemblages may also arise when different habitats occur close to each other, as is the case in some coastal situations (Denys and de Wolf, 1999). For this reason guidelines have been set out to limit the distortion of misplaced fossils when attempting a reconstruction; these include the consideration of life form, where sessile or benthic species are less likely to be transported than planktonic or tycoplanktonic species, the abundance or commonness of a species, valve preservation or the ecological compatibility within the assemblage and the consistency to the known palaeoecological trends for the region (Denys and de Wolf, 1999). However, small amounts of displaced species may provide valuable insight into environmental conditions during the time interval, for instance the occurrence of marine species in non-marine deposits that occur in close proximity to the sea may provide evidence of increased marine activity (Denys and de Wolf, 1999).

These limitations however do not outweigh the worth of this analysis. The primary value of palaeolimnologically based reconstructions of past hydrology and climate is to "establish natural patterns of climate variability at a variety of spatial and temporal scales" (Fritz *et al.* 1999, p. 45).

Chapter 3.   Study site

The dynamic nature of the south coast in relation to climate and landscape makes it a vital region for palaeoscientists to investigate environmental changes in the Holocene. Set in the transitional rainfall zone between the predominantly winter and summer rainfall zones, the Wilderness Embayment consists of several lakes of which Groenvlei is one (Figure 2). The following chapter gives an overview of the physical environment of the area and its development during the Holocene; all ages reported in various subsections have been calibrated to maintain consistency.

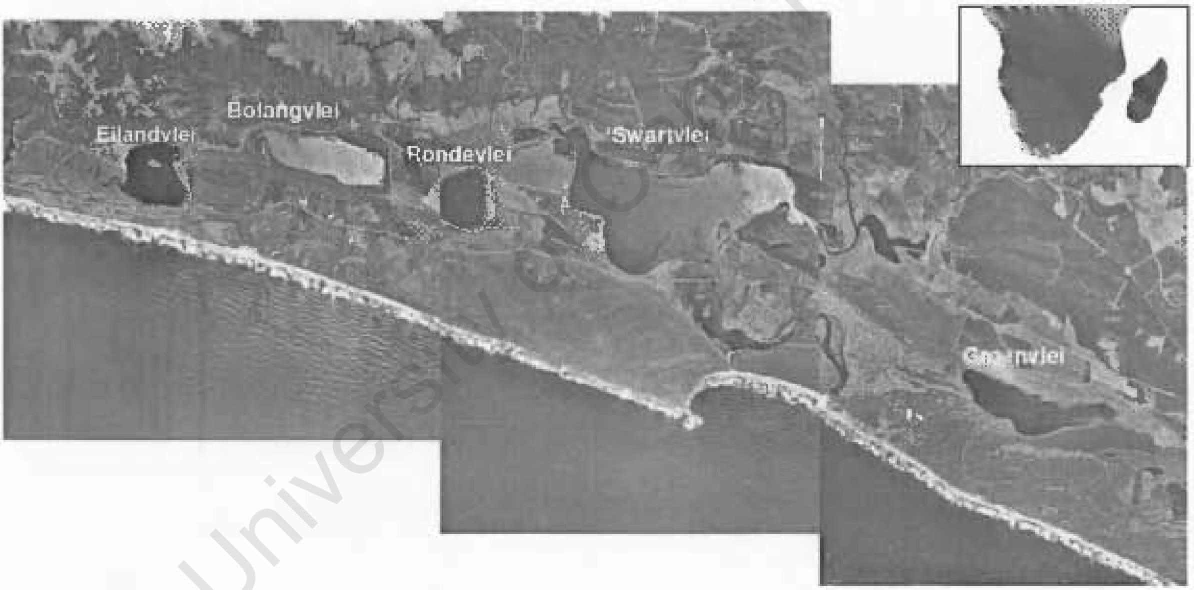

Figure 2: The location of Groenvlei (Composite Aerial Photograph) and the other Wilderness Lakes along the South Coast of South Africa (17.01.2004; Job 1075 Oudtshoorn, Strip 014, relative to southern Africa (inset)

3.1 Physical Setting:

The Wilderness region along the south coast of South Africa is defined by three physiographic elements according to Birch *et al.* (1978); these are the Outeniqua Mountains, the 200 m high Tertiary platform and the Wilderness-Knysna embayment. A prominent feature of the Wilderness-Knysna embayment is the 32 km stretch of coastal lakes (Martin, 1956) and marshes (Martin, 1962), beginning at Wilderness and culminating at the Goukamma River (Martin, 1959). These lakes lie in valleys between 200m high sand dunes and run relatively parallel to the coastline (Martin, 1962) (Figure 2). Behind the series of lakes coastal mountains rise to an elevation of about 1200 – 1500 m (Martin, 1959), at a distance of 13 – 25 km inland (Martin, 1960[a]). The mountains are of Pre-Tertiary origin (Martin, 1960[b]).

The region is dominated by Pleistocene and Recent coastal sands in the form of high rise dunes (Martin, 1956). The dune ridges are underlain by older dune rock showing aeolian cross-bedding (Martin, 1956). The underlying geology of the region is composed of igneous and metamorphic rock, predominantly quartzitic sandstones and shales of the Cape Supergroup (Irving and Meadows, 1997) and phyllites and granites of the Pre-Cape Group (Martin, 1960[a]). A peneplain, consisting of Table Mountain Group sandstone in the east and being the result of coastal erosion during the Tertiary (Martin, 1962), is dissected by several deeply entrenched, meandering, perennial rivers which are fed from the mountain (Martin, 1960[b]). The receding sea allowed for an erosive phase over the shore rejuvenating, deepening and broadening the coastal streams (Allanson and Whitfield, 1983).

Soils are derived from a variety of parent material (Martin, 1960[b]), however weathered Pleistocene and Holocene aeolianite make up a considerable percentage with dark alluvium, rich in organic matter located in larger river valleys (Allanson and Whitfield, 1983) (Martin, 1960[b]). Soils are generally acidic, leached, shallow and nutrient deficient (Irving and Meadows, 1997). One other feature that stands out along the coastline is the 7 – 8 m above sea level (a.m.s.l.) high terrace on both side of Swartvlei, and the two lower level terraces at 2.5 – 3 m a.m.s.l. and 1 – 1.5 m a.m.s.l., a remnant of past sea level transgressions (Martin, 1959).

3.2 Regional Climate:

The climate can be defined as mild and temperate (Allanson and Whitfield, 1983). The coastal mountains ensure high and evenly-distributed rainfall (Martin, 1960[a]), averaging between 700 mm to 1300 mm per annum (Martin, 1959). There is no dry season (Irving and Meadows, 1997), i.e. the region has year-round rainfall, however occasional dry spells or periods of torrential rain does occur (Martin, 1960[a]) (Figure 3). Temperatures are rather mild (Martin, 1959), with a mean daily maximum of 19.8

°C and a daily mean minimum of 13 °C (Allanson and Whitfield, 1983). Prevailing winds are southeasterly to southwesterly (Allanson and Whitfield, 1983); however the influence of the Berg Winds from the interior may cause widespread aridity (Duncan, 2006).

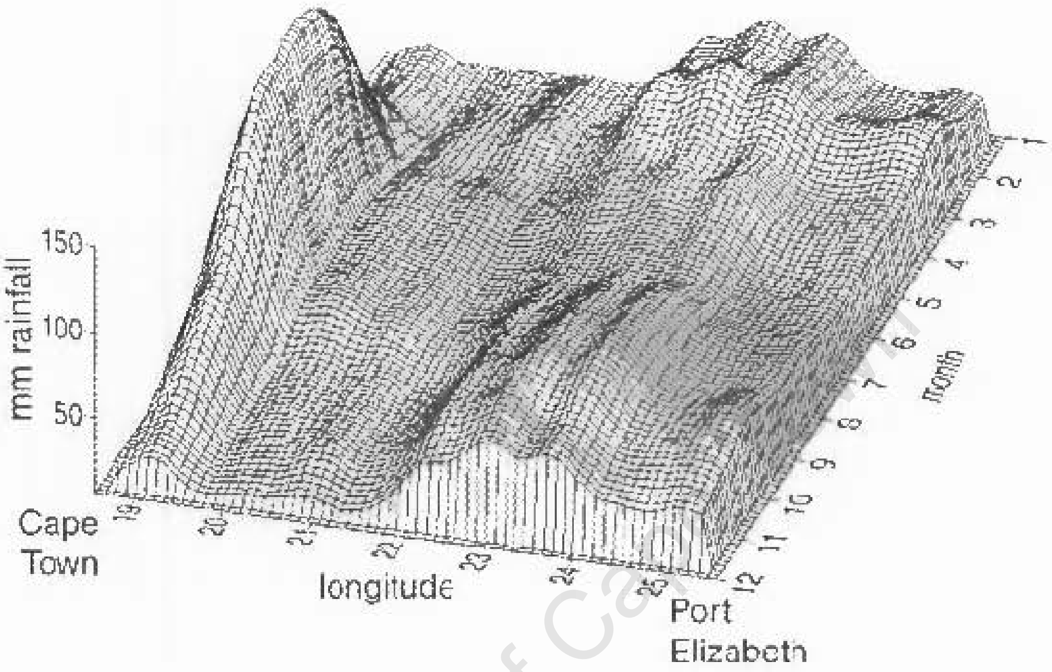

Figure 3: Transect from Cape Town to Port Elizabeth indicating total monthly rainfall in the winter rainfall zone and the transitional rainfall zone of southern Africa, the study site is located between the 22° and 23° longitude (Adapted from: Proches et al., 2005)

3.3 Environmental Changes during the Holocene:

The embayment is a wetland system which is ecologically based on fluctuations in natural processes (Allanson and Whitfield, 1983), which comprise of climatic mechanisms, including temperature and rainfall changes through time and oceanic forcing which consists of sea level variations and changes in sea surface temperatures. These natural processes are outlined below:

3.3.1 Climatic Mechanism:

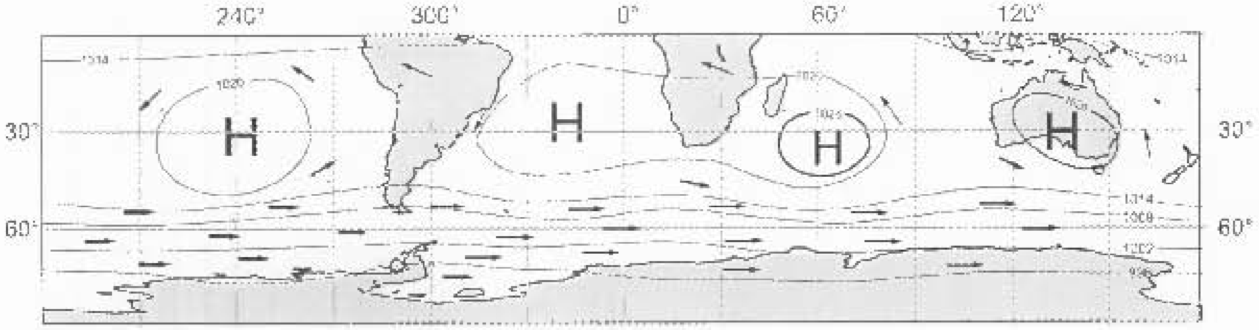

Figure 4: Schematic representation of the present-day position of high-pressure cells and general wind patterns on the Southern Hemisphere (Source: Stuut and Lamy, 2004, Pg 302).

Climate in southern Africa is dominated by two systems, the westerly belt and the tropical easterly winds; which is the result of the interplay of atmospheric and oceanic circulations along its coasts (Scott and Lee-Thorp, 2004) (Figure 4). These systems control moisture distribution across the continent, resulting in two rainfall regimes, the summer rainfall zone and the winter rainfall zone, with the Southern Cape region of South Africa being the current interface between the two zones (Bateman *et al.*, 2004) and receives year round precipitation. Less than 30 per cent of the subcontinent receives rainfall during the winter months which is derived from the passage of westerly low pressure systems originating in the South Atlantic Ocean (Partridge *et al.*, 2004). The origin of summer rainfall is the result of advection of moist air over the Indian Ocean by a High Pressure Cell to the southeast of the country (Carr *et al.*, 2006^{a}). The advection of moist air from the Indian Ocean is strongly influenced by sea surface temperatures and the intensity of the Low Pressure Cell which lies over the interior during the summer months (Scott and Woodbourne, 2007). Hence, cooler sea surface temperatures along the coast generally correlate with wetter conditions in the interior and drier conditions along the coast, as reduced sea surface temperatures lead to a decline in evaporation and lowered relative humidity corresponding to a decrease in cloud formation and precipitation (Duncan, 2006).

Fluctuations in sea surface temperatures (SST) are related to changes in the intensity of the cold Benguela Ocean Current system along the west coast and the strength of the warm Agulhas Ocean Current along the south eastern coastal margin (Partridge *et* *al*., 2004). Both of these ocean currents are modulated by fluctuations within the global thermohaline circulation (Partridge *et al*., 2004). Changes in the oceanic conveyor belt can result in changes in the global climate and local oceanic temperatures (Cohen *et al.,* 1992). As is the case during periods of reduced North Atlantic Deep Water (NADW) production, which results in cooler SST in the southern Benguela system as entrainment of warm Agulhas water around the Cape weakens and the southeastern Atlantic Ocean cools (Cohen *et al.,* 1992).

Wind intensity and direction plays an important role in the upwelling events of the two ocean currents, significantly contributing to the climatic variability and complexity of the area (Carr *et al.,* 2006[b]). In particular, the upwelling regime of the Benguela system and its associated atmospheric circulation system is strongly linked to coastal aridity along the west coast (Scott and Lee-Thorp, 2004). It is here that shifts in the easterly and westerly systems would affect climate both presently and historically (Scott and Lee-Thorp, 2004). Scott and Woodbourne (2007) state that an equatorward or poleward displacement of the westerly belt would alter the winter rainfall zone, whereas an eastward or westward displacement of the tropical easterly winds would alter advection of moisture over the Indian Ocean changing the summer rainfall zone's distribution. In general, precipitation in the winter rainfall zone would increase if the westerlies migrate equatorward and decrease in the summer rainfall zone, as would be expected if the easterlies migrated eastwards (Scott and Woodbourne, 2007). An example of a strong northward displacement of the westerlies occurred during the Little Ice Age (LIA) some 700 to 400 years ago; the Antarctic Circumpolar Vortex expanded pushing the westerly belt toward the equator, allowing cold air from the Southern Ocean to reach South Africa in the form of deep frontal systems (Duncan, 2006). This climatic event corresponds to decreases in upwelling events and the renewed introduction of warm Agulhas surface water plumes toward the coast by southwesterly winds leading to wetter coastal conditions and generally drier conditions in the interior (Duncan, 2006).

The contributing effect of the ocean, especially that of the Agulhas boundary current on the southeastern coast and the semi-arid nature of the region indicates that moisture is the more important climatic parameter over temperature changes (Scott and Lee-Thorp, 2004). Hence, changes in the Agulhas and Benguela currents related to their strength and position, together with variability of the wind systems in both direction and intensity will have considerable influence on moisture supply to the continent (Carr *et al.,* 2006[a]). Therefore by determining the spatial extent of the winter and the summer rainfall zones coupled with the timing and the magnitude of environmental changes within them, they can be used as vital indicators of the shifting positions of the temperate and subtropical mechanisms of the atmospheric circulation (Carr *et al.,* 2006[b]).

3.3.2 Holocene Climate Changes:

The Holocene was not exempt to climate variation, both temperature and precipitation patterns changed over the last 10 000 years. According to Partridge *et al.* (1999) temperature changes were of a modest extent and rather similar in amplitude over a wide geographical vicinity particularly for the coastal areas of the Southern Cape and KwaZulu-Natal, however rainfall trends are more complex in nature.

Temperature

Since the beginning of the Holocene epoch temperatures have generally increased, 8 to 6 kyr shows a warming of 1 to 2 °C in both the summer and winter rainfall regions of sub-Saharan Africa (Partridge *et al*., 1999), this warming trend reached a peak circa 7 – 6000 yrs BP (Scott, 1993) with evidence of warm, wet winters (Avery, 1993). A temperature increase of ~4 °C is documented in the dissolved gas temperature record from the Uitenhage aquifer at 6.3 kyr (Scott and Lee-Thorp, 2004). However, by 5.5 kyr marked cooling took place, which is in agreement with the Cango Cave $\delta^{18}O$ stalagmite record (Scott and Lee-Thorp, 2004) so that by 5000 yrs BP temperature essentially varied within +1 °C and -2 °C relative to present day temperature, these generally lower temperature values persisted until about 2000 yrs BP where evidence from the Cango Cave $\delta^{18}O$ stalagmite sequence indicates slightly higher temperature values (Talma and Vogel, 1990) (Figure 5).

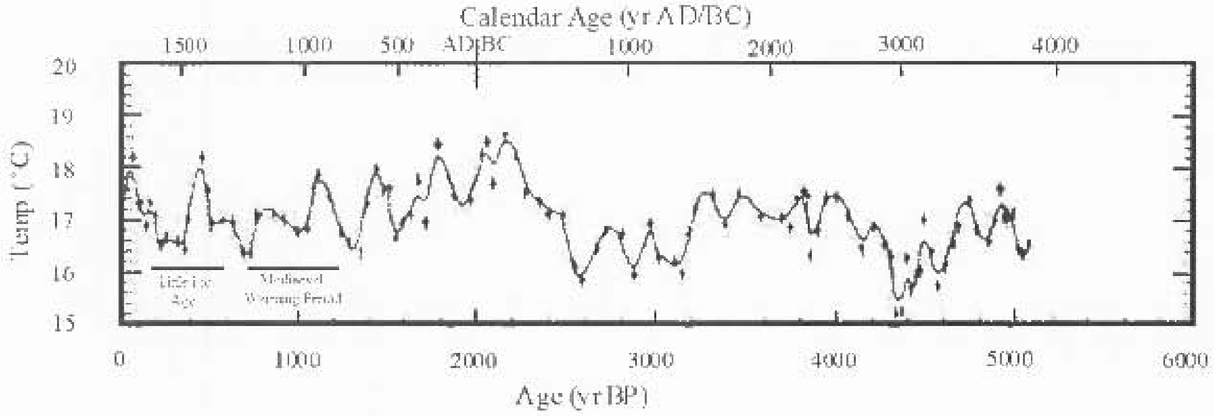

Figure 5: Late Holocene temperature curve derived from the Cango Cave $\delta^{18}O$ stalagmite sequence, indicating the Little Ice Age and the Mediaeval Warming Period (Modified from: Talma and Vogel, 1990, Pg 208)

Since then intermittent periods of warming and cooling have occurred, most notably the Mediaeval Warming Period from 800 to 1300 AD (Holmgren *et al.*, 1999) and the Little Ice Age (LIA) from 1400 to 1850 AD which was a global cooling period leading to deterioration of all vegetation types along the south coast (Holmgren *et al.*, 1999) and the development of lunette deposition on the Agulhas Plain (Carr *et al.*, 2004[b]). At the peak of the LIA, around the 1700s AD, cold and arid conditions prevailed over the interior (Holmgren *et al.*, 1999) (Figure 5), with Scott and Lee-Thorp (2004) concluding that ~1 °C temperature fluctuations occurred associated with drier, stormier and cooler conditions which culminated by 1750 AD.

Rainfall

Presently the south coast of South Africa lies in the transitional rainfall zone; that is there is no predominance of summer rainfall over winter rainfall and vice versa (Allanson and Whitfield, 1983) (Figure 6). Nonetheless, during certain periods of the Holocene a dominance of summer rainfall over winter rainfall or vice versa has occurred relating to shifts in atmospheric and oceanic circulation.

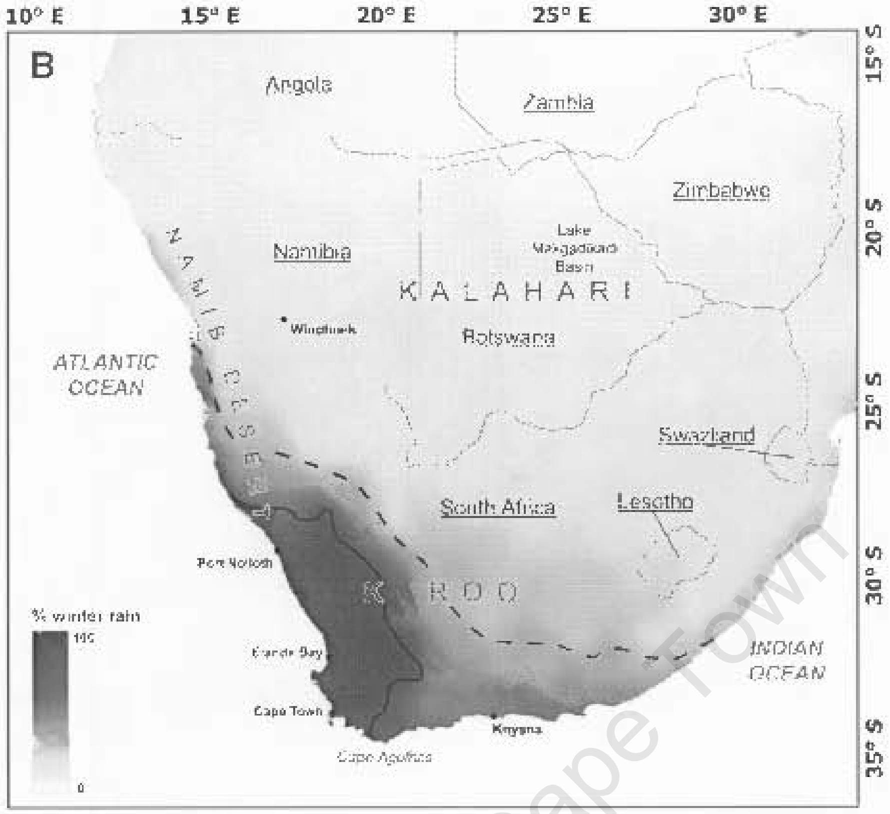

Figure 6: The division of the winter rainfall zone (bordered by solid line), the transitional rainfall zone (bordered by dashed line) and the summer rainfall zone (Source: Chase and Meadows, 2007)

In general, the early Holocene saw extensive aridification; with winter rainfall prevalent (Scott, 1993) and conditions sufficiently moist to support a hydrophytic element along the south coast (Duncan, 2006). By 7.5 kyr the summer rainfall region experienced some moisture improvement (Scott and Lee-Thorp, 2004). After moderately wet winters around 7000 yrs BP, a greater proportion of summer rainfall by 6200 yrs BP prevailed in the region indicated by an increase in graminoids, although year round rainfall is evident a decrease in winter seasonality occurred (Avery, 1993). Meadows *et al.*, (1996) suggest that the mid-Holocene was drier than present, with a tendency toward winter seasonality over the present all year round rainfall experienced in the area (Talma and Vogel, 1990). Soon after 5000 yrs BP, the subcontinent experienced widespread aridity (Scott and Lee-Thorp, 2004), as a shift from winter seasonality to summer dominance took place, the rising summer rainfall dominance peaked at around 2000 yrs BP, resulting in a dramatic decrease in winter seasonality (Scott, 1993); this trend is reinforced by high $\delta^{18}O$ values from ostrich eggshells from Elands Bay Cave indicating an arid period between 4.7 and 3 kyr

(Scott and Lee-Thorp, 2004). Since 3600 BP, rainfall has been on a general decline (Cornish-Bowden, 2005). Relatively moist conditions existed between 3200 BP and 2500 BP along the southern Cape region allowing for forest recovery (Avery, 1993; Lewis, 2008), but shifts towards drier conditions between 2.8 and 2.5 ka hampered the resurgence of forest flora (Carr *et al.*, 2004^b). Following this episode an increase in moisture availability as well as increased humidity began around 2 ka and lasted until 900 BP (Lewis, 2008; Carr *et al.*, 2004^b). Intermittent warming between 880 AD and 1320 AD, an expression of the Mediaeval Warming Period is evidenced in some palaeorecords (Tyson *et al.*, 2000); during which the interior experienced generally wetter conditions (Holmgren *et al.*, 1999) and coastal regions encountered increased aridity (Carr *et al.*, 2004^b). The Little Ice Age allowed for aridity on the interior of the country and relatively moist conditions along the coast (Duncan, 2006).

3.3.3 Oceanic Forcings:

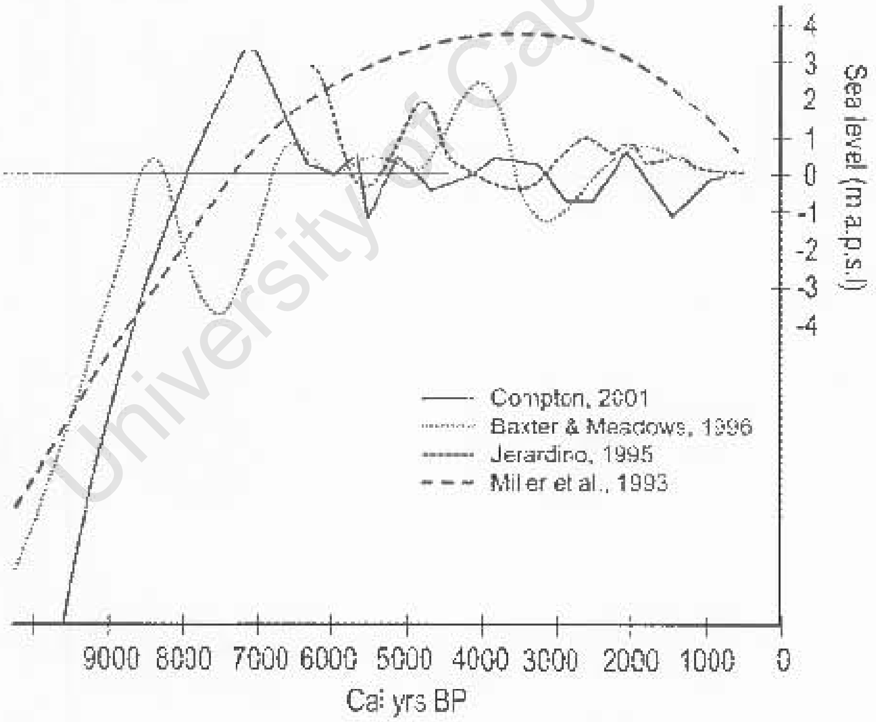

Figure 7: Sea Level Reconstructions as based on several studies along South Africa's Coast (Courtesy of Brian Chase)

All the Wilderness Lakes, including Groenvlei prior to its isolation owe much of their character, if not their continued existence to their close proximity to the ocean (Martin, 1962). Several marine transgressions and regressions have taken place during

Pleistocene and the Holocene, at some periods sea levels rose sufficiently to totally cover the Wilderness embayment (Allanson and Whitfield, 1983) (Marker and Miller, 1993). A large number of the topographic features along the south coast are related to these sea level changes; for instance a wave cut platform in the dune rock extending from the Wilderness Lakes to Cape St. Francis (Butzer and Helgren, 1972) or the seven metre high terrace-like feature on which the Sedgefield Village is situated (Martin, 1956). Miller *et al.* (1995) speculates that even a 2 – 3 m rise or fall in sea level would dramatically remodel the coastline; with local variations arising due to tectonism (Compton, 2001).

3.3.4 Sea Level Changes:

Since the end of the last glacial period sea level has been on an increase with a 120 m rise towards present day levels, this rise is termed the Holocene Transgression (Compton, 2001). Locally, sea level rise allowed for the complete covering of the coastal plain at the beginning of the Holocene (Allanson and Whitfield, 1983), Ramsay (1995) speculates that the sea continued to rise by 8mm.yr^{-1} between 9000 and 8000 BP with this initial transgression coming within a metre of present levels by 8000 BP (Baxter and Meadows, 1999), this trend continued throughout the 7000s BP, reaching a peak of 0 – 3 m above mean sea level by 6.8 ka (Compton, 2001). Sea level fluctuations during this time varied on a regional scale along the South African coast due to isostatic adjustment, ice volume changes and local tectonic movements creating a highly variable sea level curve (Compton, 2001) (Figure 7). A rapid regressive phase about 7000 BP occurred, with sea levels dropping 3 – 4 m only to experience a rapid advancement around 6000 BP (Baxter and Meadows, 1995). This mid-Holocene highstand, which persisted for 2500 years (Ramsay, 1995), is said to be of a magnitude of 1.5 m to 3 m above mean sea level (a.m.s.l.) (Marker and Miller, 1993) (Compton, 2001). Estuarine shells from the Sundays River suggest an elevation of 1.5 m a.m.s.l. (Marker and Miller, 1993); however other radiocarbon dated sea level indicators from the south coast suggest a magnitude of between 2.4 m and 2.8 m a.m.s.l. (Marker and Miller, 1993). This is consistent with the 2.5 m terrace on both sides of Swartvlei, an estuary near the town of Sedgefield, which probably formed as a depositional estuarine terrace (Illenberger, 1996). According to Ramsay (1995) sea level rose to a maximum of 3.5 m a.m.s.l. prior to the termination of the Holocene Hypsithermal Event, with Scott and Lee-Thorp (2004) suggesting a 2 m sea level higher than present before 5.6 kyr. The higher sea levels are attributed to warmer sea surface temperatures contributing to thermal expansion (Miller *et al*., 1995). Sea level slowly began to drop and reached 0 m a.m.s.l by 4200 BP (Miller *et al*., 1995), with a short lived rise around 4000 BP (Baxter and Meadows, 1999). Throughout the 3000s BP sea level regressed to within a metre of present datum (Compton, 2001), by around 3000 BP sea level had dropped to below 2 m a.s.l. (Ramsay and Cooper, 2002) with this lowstand maintained until approximately 2000 ka (Compton, 2001). By 2000 yrs BP sea level has risen again to close to its present level (Birch *et al*., 1978), temporarily rising above present day sea level, indicating a minor recovery from the regression (Baxter and Meadows, 1999). However, there are suggestions that sea levels began dropping again around 1.3 ka and continued to fall until 0.7 ka when it was 0.5 m lower than present (Compton, 2001). From 0.7 ka the sea has been rising to its present level (Compton, 2001); Scott and Lee-Thorp (2004) do suggest that sea levels were lower between 0.5 ka and 0.38 ka as an expression of the early phase of the Little Ice Age.

As stated by Compton (2001), variations between regional sea level reconstructions arise due to external environment processes, such as isostatic adjustment or tectonic activity, therefore it is rather complex to create one sea level curve for the entire South African coastline. However, the combination of several studies has hinted at generalized sea level fluctuations during the Holocene which are presented in Figure 7.

3.3.5 Holocene Sea Surface Temperatures:

Lower sea surface temperatures were experienced during the early Holocene, although prior to 7000 BP warmer sea surface temperatures (SST) of the adjacent ocean lead to an increase in rainfall possibly under the dominance of westerly circulation (Duncan, 2006), this may have persisted up to and beyond 6.8 kyr, from evidence of marine molluscs from Nelson's Bay Cave (Scott and Lee-Thorp, 2004), however, by 6300 BP SSTs had lowered (Duncan, 2006). Higher SSTs could be interpreted as intensified Westerly circulation bringing forth their associated frontal disturbances and slightly higher Agulhas Current influence (Scott and Lee-Thorp, 2004). The timing and duration of two episodes of isotopic enrichment in Antarctic ice cores over the last 4000 years, correspond to periods of Holocene Glacier expansion (Cohen *et al.*, 1992). The first of which occurred between 3 and 2000 yrs BP and relates to a worldwide neo-glacial advance, the second episode occurred between 750 and 400 yrs BP and is an expression of the Little Ice Age which reached a maximum 400 yrs ago (Cohen *et al.*, 1992). Both episodes are associated with lower annual inshore sea surface temperatures to the magnitude of one to two degrees lower than present day estimates typical of the west coast (Cohen *et al.*, 1992). A short lived occurrence of low summer and winter SST at around 1000 BP is thought to be an expression of the Mediaeval Warm Period, evidenced through forest decline prior to colonial influence (Duncan, 2006).

3.4 The Wilderness Embayment:

The Wilderness region has an extensive geomorphic history, relating to changes in various environmental factors, including tectonic deformation, eustatic fluctuations in sea level and changes in climate and vegetation (Butzer and Helgren, 1972). The embayment consists of palaeocliffs, a series of lakes and fossil dunes (Bateman *et al.,* 2004). The palaeocliffs form a northern boundary for the Touw River floodplain in which the lakes occur and is bounded along the south by high, consolidated, old sand dunes (Allanson and Whitfield, 1983). The Touw River floodplain is the most important wetland along the south coast (Allanson and Whitfield, 1983) and has been designated a RAMSAR site as of 1991 (Randall, 1990).

3.4.1 Lakes:

The Wilderness Lake System consists of several lakes lying in east to west valleys between sand ridges which rise to over 200 m in some places (Martin, 1956). The lakes, in order from west to east are Eilandvlei, Langvlei, Rondevlei, Swartvlei and Groenvlei (Figure 2), inland from these are the Karatara and Ruigtevlei (Martin, 1960^{a}). None of the lakes are above six metres above mean sea level and are the result of three phases of submergence and emergence, with the last stage occurring during the Holocene (Martin, 1962). These phases are linked to sea transgressions and regressions, of which the formation of the lakes during the Pleistocene was dependant (Martin, 1956). The present shape of the system formed in the Early Holocene, with estuarine conditions being established some 4 – 5 kyr ago (Allanson and Whitfield, 1983). This developmental phase commenced during the Late Pleistocene and coincided with the marine regression, water levels dropped considerably and in extreme cases lakes emptied and eroded, however with the Holocene Transgression reaching its peak during the mid-Holocene, interdunal depressions were once again flooded (Birch *et al.*, 1978), the marine tidal influence lasted throughout the Holocene up to the Present (Allanson and Whitfield, 1983). Freshwater enters the system via several rivers originating in the mountains, namely Touws, Duiwe, Diep, Hogekraal, Swart and Karatara Rivers (Martin, 1956). Inflowing freshwater is an important source of inorganic Phosphorous and Nitrogen, which may increase considerably during flooding episodes causing short-lived eutrophic conditions in the lakes, for example in Langvlei and Eilandvlei (Allanson and Whitfield, 1983). Flooding is the result of torrential rainfall episodes in the mountains, such as the major flooding events experienced in August, 2006 and November, 2007; which led to drastically altered water quality and levels. It is therefore apparent that the salinity status of these coastal lakes are directly related to the inflow of freshwater and evaporation rates (Allanson and Whitfield, 1983).

3.4.2 Dunes:

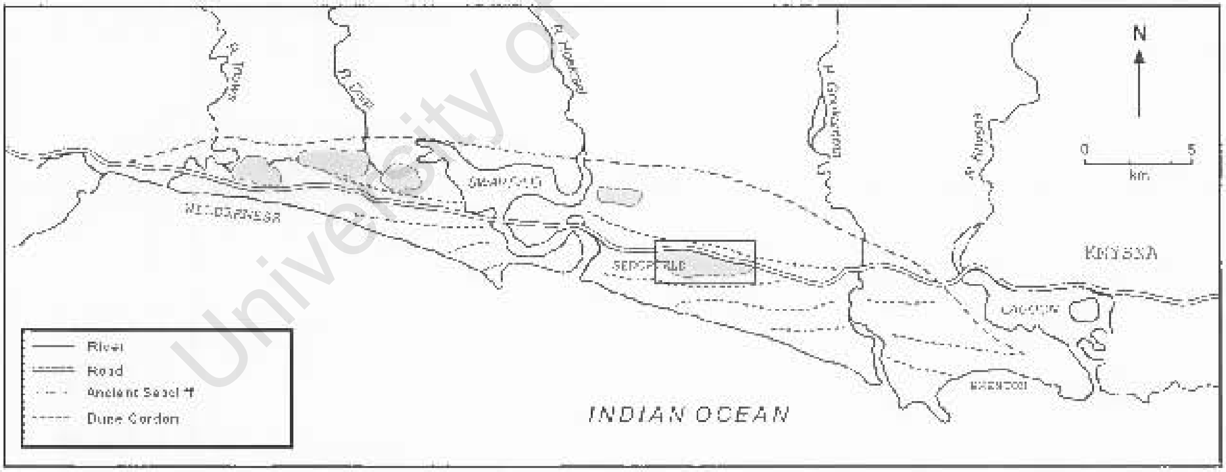

Figure 8: Dune cordons dissected by the major rivers in the Wilderness Region, also indicated is the ancient sea cliff. The square represents Groenvlei (Modified from Bateman et al. 2004).

Prominent topographic features of the landscape are the several dune cordons stretching from just west of the town of Wilderness (Martin, 1956) to the town of Knsyna (Illenberger, 1996) (Figure 8). Birch *et al.* (1978) identified two well developed dunal cordons onland and two offshore; however Illenberger (1996) identified three onland dune cordons. The coastal dunes are of Pleistocene origin

(Martin, 1956) which form steep ridges separated by the lakes (Illenberger, 1996) and dissected by a number of rivers originating in the mountains (Bateman *et al.*, 2004). The offshore dune cordons have recognised shorelines at their bases at depths of 40 m, 50 – 55 m and 65 – 75 m (Illenberger, 1996).

The oldest of these calcareous ridges have been cemented into aeolianite or dune rock (Martin, 1968). All onland dune ridges are underlain by the older dune rock showing aeolian cross-bedding (Martin, 1956) and covered by Holocene unconsolidated sand of variable thickness (Birch *et al.*, 1978). Soils present on the cemented dune deposits are in places ferroginised (Illeneberger, 1996). Sand deposits at the western end of the dune series forms a narrow belt in front of the Touw Estuary at Wilderness, gradually increasing in height and width further eastwards (Martin, 1962). At the eastern end sand spreads eight kilometres inland and forms a thin mantle over the older rocks (Martin, 1960^{a}). Deposits between these two points reach a thickness of 350 m (Illenberger, 1996). The dunes are more or less parallel to the shore converging towards the east (Illenberger, 1996) and reach up to a 200 m above sea level in height in some places (Bateman *et al.*, 2004) (Figure 10). Dunes are parabolic in form with their trailing arms orientated parallel to the predominant westerly palaeowind (Bateman *et al.*, 2004). The trailing arms form another topographical feature, creating ridges which are 15° - 30° to the shoreline and run diagonally across the seaward cordon (Illenberger, 1996).

The Holocene dun sand consists of 35% biogenic calcium carbonate, mostly shell fragments of marine molluscs (Illenberger, 1996). The calcium carbonate-poor system may be the result of a change in provenance or post depositional leaching (Bateman *et al.*, 2004). Gradual leaching in the fossil dunes is evident (Illenberger, 1996). The rate of leaching is climate dependent being directly proportional to temperature and rainfall (Illenberger, 1996; Raal and Burns, 1996). However, the Wilderness seaward cordon has not experienced much leaching as there is no evidence of calcification and lamellae show a subtle concentration of fines within the sediments (Bateman *et al.*, 2004).

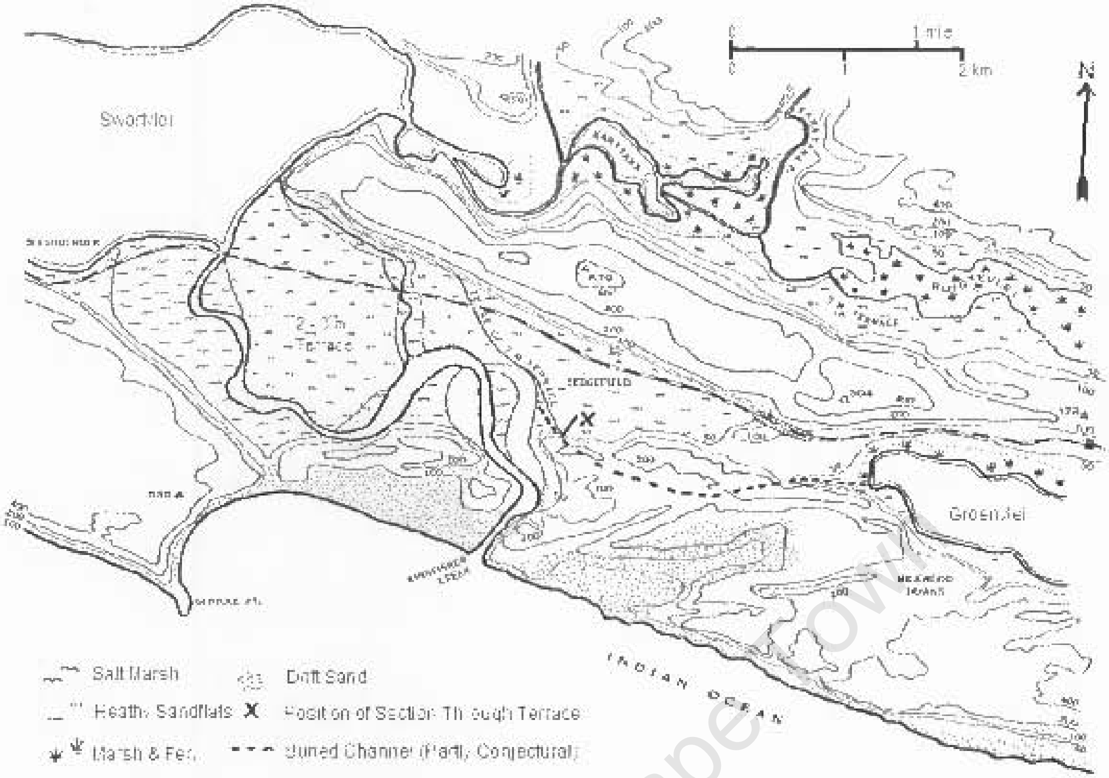

Figure 9: Groenvlei is in close proximity to the sea, the x y notation on the image indicates the proposed channel which linked Groenvlei to Swartvlei and the sea during the Holocene (Source: Martin, 1959)

The aeoliniatic ridge closest to Groenvlei reaches a maximum height of 200 m above sea level and is two kilometres wide (Birch *et al.*, 1978) (Figure 10), at its lowest point the ridge is 23 m above Groenvlei (Martin, 1959), the ridge is dissected by the Swartvlei Estuary in the west and cut at its eastern end by the Goukamma River but continues eastwards towards Walker Bay (Birch *et al.*, 1978). Directly north and south of Groenvlei towards Ruigtevlei and the sea respectively; multiple aeolianite ridges rise at their lowest point to about 46 m above mean sea level and at their highest to about 180 m above mean sea level (Martin, 1959). Leaching of surface carbonates along the northern shore dune ridges has left surface sediments slightly acidic, but the ridges to the south have a continuous mantle of pale calcareous sand with a pH of around 8.0 (Martin, 1968). The dunes are vegetated with dune heath comprised of ericoid and schlerophyllous scrubs which are gnarled and stunted by wind action (Martin, 1960^{a}). The heath vegetation remains the climax flora on sites which are climatically and edaphically less suited for tree growth, however woodland taxa are present in certain areas differing in species composition related to their position along the lake's shore; for example the southern shore is characterised by *Sideroxylon inerme* (White Milkwood) whereas the northern shore is characterised by *Afrocarpus falcatus*[1] (Sickle-leaved Yellowwood) and *Celtis rhamnifolia* (Martin, 1960[a]).

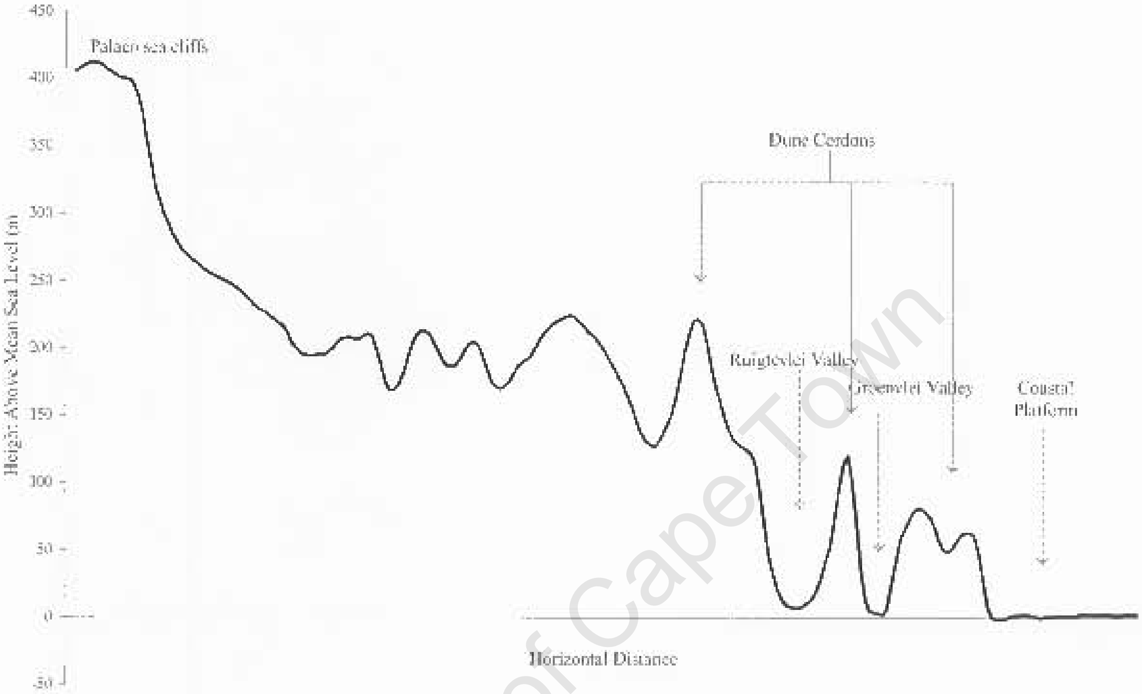

Figure 10: North to South Cross Section through the aeolianite ridges closest to Groenvlei, indicating lake valleys, dune cordons and coastal platform (Courtesy of Frank Eckardt)

Dune Development

The development of the Wilderness dune cordons is related to wind action (Hellström, 1996) and changes in sea level (Martin, 1962) over two glacial-interglacial cycles (Bateman *et al.*, 2004). The series of dunes are complex in origin (Martin, 1962) with each cordon forming at different ages and sea levels (Illenberger, 1996). Each new line started further west that the preceding one, the easterly trend observed is due to the prevalent southwesterly gales (Martin, 1962). The initial pulse in dune building was probably in form of transgressive dune fields, with the prevailing westerly winds creating the presently observed parabolic dunes (Illenberger, 1996). A constant supply of sediments was provided by these dominant winds and the west to east longshore drift, allowing for the northeasterly dune migration (Hellström, 1996).

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[1] *Afrocarpus* was designated a separate genus from *Podocarpus* based on genetic variability (Barker *et al.*, 2004).

The carbonate-rich sediments are derived from the coastal plain during periods of changing sea level (Bateman *et al.*, 2004). Butzer and Helgren (1972) state that these cordons could only have formed during periods of high sea level, during the earliest stages of a developing regression or during the later stages of a renewed transgression, sentiments which were first expressed by Martin (1962) in a prior study. The thickness of the aeolianite deposits has been interpreted by Bateman *et al.* (2004) as indicative of high palaeowave energy levels along the south coast. The combination of easterly littoral drift, which caused the eastward propagation of the dunes and the receding sea allowed for each new line of dunes to start from a point further to the west than the preceding one (Birch *et al.*, 1978).

The cordons are the result of their proximity to the beach and a plentiful supply of sand (Butzer and Helgren, 1972), having functioned more or less naturally for the last 4000 to 6000 years (Hellström, 1996). Large scale movements of dunes south of Groenvlei have occurred during the Holocene (Martin, 1968), with cave profiles from Nelson's Bay Cave and East Guanogat on the Robberg Peninsula (Plettenberg Bay) documenting major activity around 6000 BP and partial stabilisation shortly before 4200 BP (Butzer and Helgren, 1972). Illenberger (1996) agrees that cordon growth restarted about 7000 BP when sea levels returned to near present levels in the Holocene and that this phase started with a large extensive sediment pulse which is in accordance with the cave profiles. Aeolian contributions to the dunes may have decreased due the dunes becoming vegetated (Birch *et al.*, 1978).

Human Influence

Dunes are still active presently, albeit constrained due to human activities (Illenberger, 1996). Human interference occurred during the mid 1800s with the introduction of an Australian *Acacia* species to prevent the movement of mobile coastal sands, by 1921 dune stabilisation became general policy under the perception that the mobile transverse dunes in the Goukamma Nature Reserve would eventually block the Goukamma River mouth and cover the forest and fynbos vegetation (Hellström, 1996). *Acacia cyclops* and *Ammophila arenaria* were introduced as part of the dune reclamation programme transforming the mobile dune fields into a stable vegetated coastal platform (Hellström, 1996).

3.4.3 Vegetation:

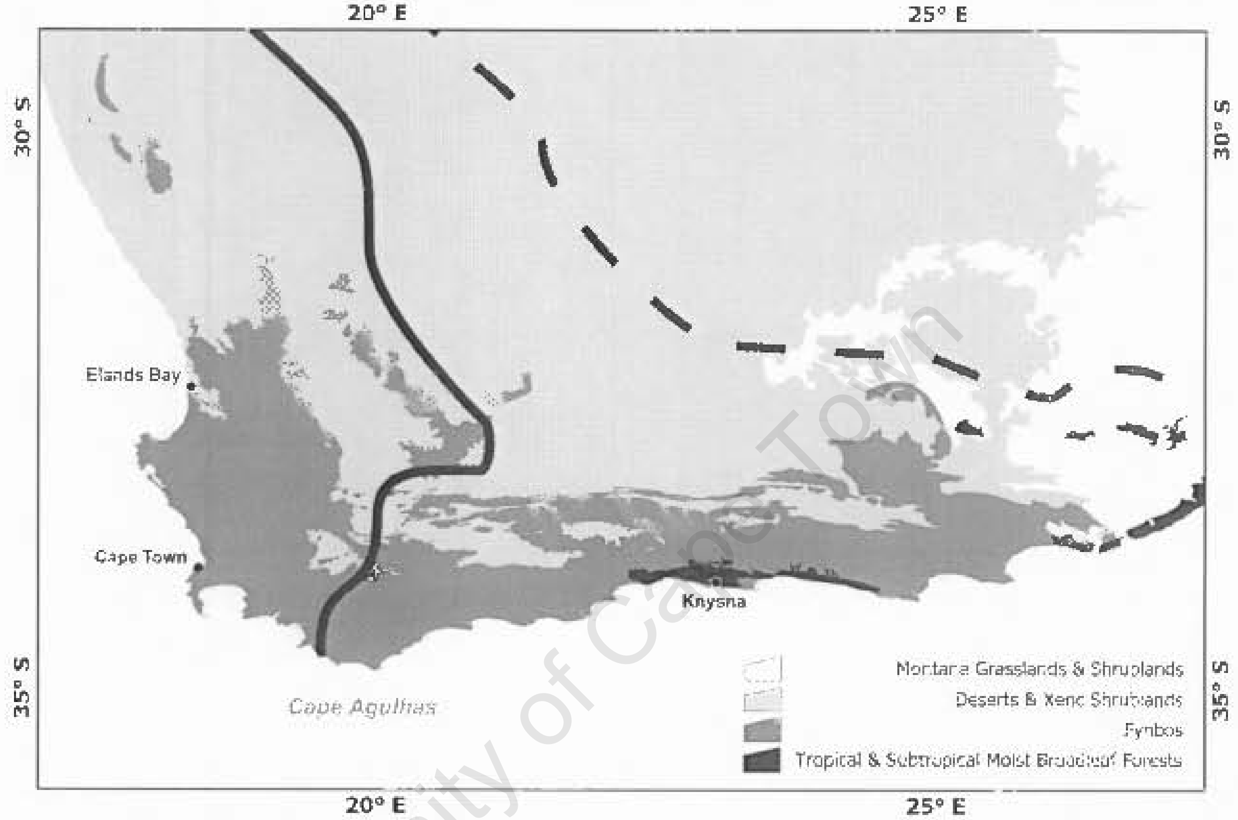

Figure 11: The vegetation that comprises the South and Southwestern Cape within the winter rainfall zone (solid line) and the transitional rainfall zone (dashed line) (Source: Chase and Meadows, 2007)

The interplay of climate, topography and soil patterns has resulted in a complex vegetation matrix (Raal and Burns, 1996) (Figure 11). Allanson and Whitfield (1983, p. 23) consider the Wilderness system to be made up of three major vegetation components, these being "aquatic plants of the lakes and channels, semi-aquatic flora of the low lying areas adjacent to the lakes and channels and degraded coastal Fynbos". Raal and Burns (1996) state that the Cape Flora is well represented with many different Fynbos communities identified, they conclude that the most important vegetation along the southern Cape coast is the mosaic of xeric transitional thicket and limestone Fynbos, Afromontane forest and mesic mountain Fynbos.

Forests

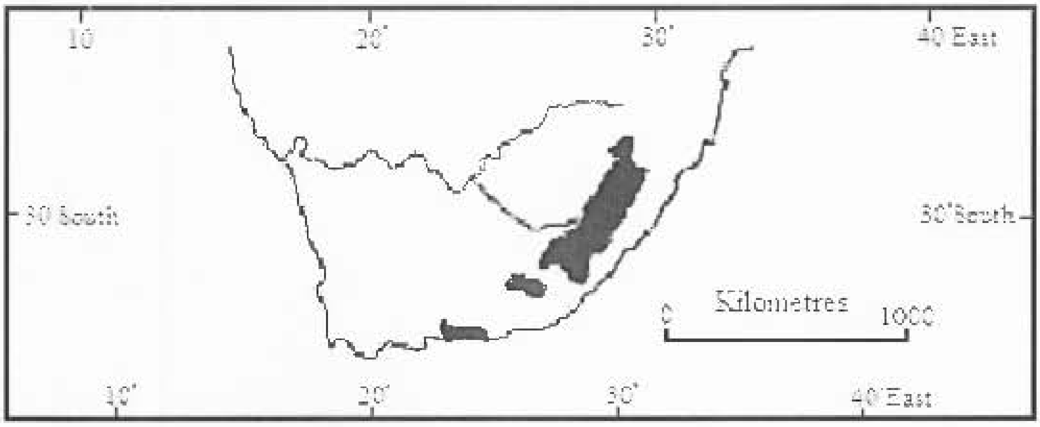

Figure 12: Shaded areas indicate the extent of the Afromontane vegetation in South Africa (Modified from: Meadows and Linder, 1993).

The forest is the most extensive of its kind in South Africa, although presently fragmented the forests used to be more extensive spatially (Martin, 1968), this decline may be partly due to the combination of Berg Wind related fires and topography (Duncan, 2006). The Afromontane vegetation is an assortment of dry and wet forest types, grassland and small-leaved ericoid and schlerophyllous plant elements (Martin, 1968) (Meadows and Baxter, 1999). Temperate rain forests are located in a narrow zone on the coastal plain and on the seaward slopes of the Outeniqua and Langekloof mountains (Martin, 1968) (Figure 12). The forests generally have an altitudinal limit of about 800 m and restricted in three directions by the sharp climatic gradient towards aridity; they are also topographically bounded in the west by the Gouritz River valley and to the east by the Gamtoos River valley (Martin, 1968). Therefore, areas of high forest coverage occur on the southeastern facing slopes and ravines, on sandstones of the mountains and coastal uplands (Meadows and Baxter, 1999), on the peneplains and in patches along the shore (Martin, 1968). At sea level the forest gives way to scrub (Martin, 1968). The forest element does appear to be the climax community; and may be the reason behind the low local endemism of the Cape heath species (Martin, 1968). This trend is particularly true for periods of climatic shifts towards wetter conditions and reduced sand mobility where plant progression from herbaceous dominated environments to woodland taxa is prevalent (Duncan, 2006).

3.4.4 Fauna:

The Wilderness Lakes wetland system is an important region for avian habitat, for both resident and migrant species (Allanson and Whitfield, 1983). The site is a significant area for Palearctic migrant waders, southern African waterfowls undergoing moult migration, large populations of herbivorous and piscivorous birds and a refuge and food supply for seabirds during unfavourable weather conditions (Allanson and Whitfield, 1983).

3.5 Groenvlei:

3.5.1 Geomorphic Evolution:

Groenvlei's origins are founded in the Early Pleistocene during a lower sea level, allowing for the calcification of the aeolinitic ridges north and south of Groenvlei (Martin, 1959), followed by a rise in sea level drowning the depression between the two aeolinite ridges, which lie parallel to the coast (Martin, 1960^b). Martin (1960^b) outlines four developmental stages of the Holocene epoch relating to the Holocene marine transgression prior to this Groenvlei was a freshwater system. The first stage occurred approximately 6900 yrs BP and lasted until 4000 yrs BP, and it typified by the peak of the transgression (Martin, 1960^b). The "marine" stage was followed by the "lagoonal" stage from 4000 yrs BP to 2200 yrs BP based on a decline in marine influence, from 2200 yrs BP Groenvlei was once again transformed to a freshwater system, with peat formation in the last 900 yrs (Martin, 1960^b). The climatic conditions associated with these stages are suggested to be, for both the marine and lagoonal stages, either drier and hotter or wetter with increased sand mobility; neither of which are favourable to forest spread, this was followed by more effective moisture allowing for an increase in the forest element with the onset of drier conditions about 900 yrs ago (Martin, 1960^b). Cornish-Bowden (2005) also suggests a series of changing environments which appear to coincide with the stages Martin (1960^b) proposes, the onset of which may have resulted in the development of a depositional environment within the lake by means of wind-blown sand from the surrounding dunes and influx of in-washed sediments from the surrounding environment (Cornish-Bowden, 2005).

Marine Intrusions

Evidence relating to marine tidal influence throughout the Holocene can be found at Groenvlei, the filled in basin includes marine sediments (Martin, 1962), occurring on top of peats which suggests that the sea entered Groenvlei periodically (Birch *et al.,* 1978). Martin (1959) proposed that Groenvlei's link to the sea lay through Swartvlei, an estuary situated directly to the west of Groenvlei (Figure 9). The connection takes the form of a channel which was first cut during the second marine recession of the current interglacial period (Martin, 1962). The channel is cut below the level of the 7 m terrace and into the 2.5 m terrace and is currently overlain by a recent dune of unleached, calcareous sand (Martin, 1959). The sea level highstands in the final stages of the Holocene Transgression increased tidal action and enhanced sediment influx into Swartvlei, as a more direct link to the ocean must have been prevalent during these periods (Birch *et al.,* 1978). Birch *et al.* (1978) states that a 5 m rise in sea level would undercut the seaward dune ridge and engulf Groenvlei and Langvlei, possibly transforming the dune into an elongate island making both lakes relatively open marine embayments. However, Martin (1956) maintains that there is no implication that the sea was above its present level when it entered Groenvlei. As the sea receded the marine influence on the lake decreased with the lowering of sea levels as well as with the migration of the mouth of Swartvlei eastwards creating a more tenuous link with the sea (Birch *et al.*, 1978). It was during these times that an initial increase in sand mobility started filling in the channel, causing a limited amount of water interchange between the two lakes (Illenberger, 1996).

3.5.2 Contemporary Groenvlei:

Groenvlei is a shallow, coastal lake with a surface area of approximately 248 hectares, which is relatively large considering its catchment area of about 956 hectares (Martin, 1956). Its catchment area consists entirely of coastal sand dunes, stabilised heath and woodland taxa (Martin, 1960[b]). Groenvlei is only 2.2 m above mean sea level and has a maximum depth of 5.6 m; yet its depth rarely exceeds 3.7 m (Martin, 1956) (Figure 13). The lake floor rapidly increases to a depth of 2.5 m, progressing slowly to a maximum depth then gently shelving up to 2.5 m before rapidly reaching the lake margin on the southern shore (Martin, 1960[a]).

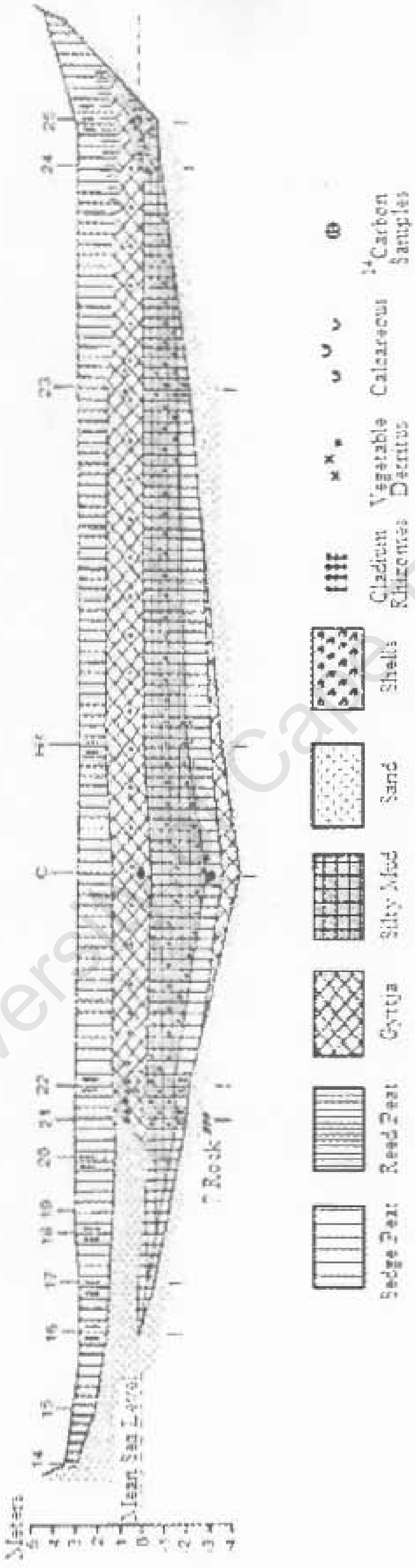

Figure 13: Transverse profile through Groenvlei, indicating sedimentary deposits, elevation above mean sea level and Martin's coring sites (Source: Martin, 1959)

Groenvlei is isolated from Swartvlei in the west by drift sand and alluvium (Martin, 1960^a). A fen has developed on the eastern shore, separated from the greater majority of the lake by a hummock, giving the fen a fairly separate drainage basin (Martin, 1960^b). The northern shore is bordered along its entire length by a 180 m broad sand platform of whitish to grey sand, on which peat bearing fen vegetation occurs (Martin, 1960^a). The southern shore has a narrow reed shelf resting on sand dune (Martin, 1960^a). Soils are generally waterlogged being organic and alkaline to neutral in nature (Martin, 1960^b). Near the margin, the bottom sediments is mainly sandy but with increasing depth bottom sediment is variable consisting of a pale buff-coloured marl with diatom frustules constituting a large portion of surface lake mud (Martin, 1960^a) (Figure 13). The sand which makes up the bottom sediments are continuous with that of the dunes, both the lake and the fen have been subjected to intrusions of sand in the past but little evidence in the present suggests that this is still occurring (Martin, 1960^a).

Water Quality

The lake is fed by rainfall, seepage, springflow, runoff and groundwater and is without outlet; hence water level is dependent on the inflow and evaporation rates (Martin, 1956 and 1960^{a+b}). Water level is highest during the winter season, where levels can increase by more than 0.7 m (Martin, 1956). The summer water table is close to or conforming to ground level (Martin, 1956).

All lakes in the Wilderness embayment are slightly saline, which is related to their historical development and a low precipitation to evaporation ratio (Martin, 1962). Groenvlei does have a salinity gradient with its western end tending to be more saline than the eastern end and is generally eutrophic (Martin, 1959). Lake water is calcareous in nature as a response to the leaching of the surrounding calcareous dunes (Martin, 1960^b). Water contains very little organic matter in suspension or in colloidal solution (Martin, 1960^a), although lake water is rich in solutes, the main ions present are chloride, sodium, bicarbonate, sulphate and magnesium (Martin, 1960^b). The relatively high proportion of chloride ions is not derived from the freshwater streams which enter Groenvlei at the foot of the dunes along the northern shore, as these streams are poorer in solutes than the lake (Martin, 1960^b). It has been hypothesised that the high chloride content of the water is attributable to one of several sources; these theories include the possibility of the concentration of salts by evaporation or possibly salt accumulation derived from sea spray (Martin, 1960[b]). These are all viable options and none can be discounted. A highly stable buffering system maintains the pH within the alkaline range of 8 to 9, it is presumed to be a calcium and magnesium carbonate to bicarbonate system (Martin, 1960[b]). Magnesium replaces calcium as the chief basic ion due to the high precipitation of calcium carbonate by the algal photosynthetic community (Martin, 1960[b]). Water depth is not so great to allow for complete mixing of the water column; however during warm, still weather temporary thermal stratification occurs (Martin, 1960[a]). The water is generally well oxygenated, even though *Chara*[2] beds only grow down to a depth of four metres possibly indicating a minor oxygen-deficiency (Martin, 1960[a])

Vegetation

The plant community surrounding Groenvlei is fen (Martin, 1956), with narrow sections of swamp and saltmarsh along the southern and western shores (Martin, 1968), the eastern shore is covered by grass meadow on peat due to grazing (Martin, 1956). Martin (1960[b]) states that primary succession is generally from sedge fen to fen scrub or carr. However with the increasing utilisation of the area by humans related to grazing and ground trampling, secondary succession leads from fen carr toward meadow fen and salt marsh-like communities (Martin, 1960[b]). The lake's proximity to the sea affords for wind pruning of the vegetation by the prevailing southerly wind off the Indian Ocean (Martin, 1968). Vegetation is also prone to desiccation during summer months (Martin, 1960[b]).

The vegetation of the lake and its margin is relatively species-poor, having only two major growth forms, those being the elodeiod and the reedswamp types (Martin, 1960[a]). The reedswamps occur along the outer most edge of a sandy platform and consists of *Typha capensis* (Martin, 1960[a]). Peat deposits and marginal flora are well developed amid local abundance of *Phragmites* and *Chara* species in varying densities covering the greater part of the lake floor (Martin, 1960[a]). Bottom-living and

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[2] *Chara* is a common alga found in lakes with growth is directly proportional to nutrient and oxygen availability (State of Michigan, Department of Environmental Quality Water Bureau, 2005)

epiphytic diatom species are common, sharing the bottom mud sediments of the lake with blue-green algae (Martin, 1960^{a}).

Lacustrine Fauna

Prior to the introduction of the exotics, *Lepomis macrochirus* (Blue Gill Sunfish) and *Huro salmoides* (American Black Bass) primarily for angling (Martin, 1960^{a}), the dominant fish species were *Gilchristella aestuarius* and *Hepsetia breviceps* (Allanson and Whitfield, 1983). All marine and estuarine fish species disappeared when Groenvlei lost its link to the sea (Allanson and Whitfield, 1983). Invertebrates include the mollusc, *Burnupia capensis* and the isopod, *Pseudosphaeroma barnardii* (Martin, 1960^{a}). Mole rats and moles occur along the eastern shore in sandy soils (Martin, 1960^{a}).

3.6 The Human Factor:

Human activity has clearly affected the region (Meadows and Baxter, 1999). The present degraded state of the vegetation along the south coast of South Africa in general is directly related to human occupation of the region (Allanson and Whitfield, 1983). Colonial settler influence in the area began late in the 18th century, evidenced through increased charcoal remains in the sedimentary record relating to the exploitation of the forest, as well as the introduction of exotics such as pine in the late 19th century (Duncan, 2006). The first cattle farmers appeared some time between 1730 and 1750 AD in the Knsyna and Tzitzikamma forests with the first permanent settlement occurring near Plettenberg Bay in the late 1780s AD (Butzer and Helgren, 1972).

3.6.1 Groenvlei Catchment

Human disturbance is directly linked to the resources within the floodplain and its adjacent area and remains a major determining ecological element (Allanson and Whitfield, 1983). The increased pressure for development along the coast of South Africa for tourism and recreational pursuits are on the rise (Raal and Burns, 1996), the effects of which are already observed in the area.

3.7 Conclusions:

As outlined above the Wilderness region has experienced striking environmental fluctuations during the Holocene and continues to be affected during the present day by human activity. It is expected to follow then, that these changes will be expressed in the lacustrine deposits which can be indirectly utilised to measure the magnitude of the afore mentioned environmental changes. Therefore, to establish the development of Groenvlei various methods are employed to ascertain the extent of these changes on the local surroundings.

Chapter 4. Methodology:

The aims of this project are to reconstruct the floristic composition of the lake diatom communities through the Late Holocene and hence indirectly establish the lake water quality and the palaeoenvironment during the Holocene; this includes the pH, alkalinity, the nutrient status, life form and the salinity of the lakes within Groenvlei as part of the Wilderness Lake system. To achieve these aims suitable methods were undertaken to ascertain the changing nature of the lakes.

4.1 Sediment Sampling:

Sediment cores were extracted from several sites within the Wilderness Lakes system with the use of a vibracorer in the late summer of 2005. The vibracorer is the most effective way to extract deep, continuous sediment sequences for investigation. Modifications on the vibracorer by Smith (1984, as cited in Baxter, 1996) and Baxter (1996) on the initial design by Lanesky *et al.* (1979, as cited in Baxter, 1996) allowed for the greater accessibility to a variety of depositional terrains, including fluvial, lacustrine and in estuarine environments (Baxter, 1996). The only requirement for its effective use is that the sediments are unconsolidated and water saturated (Baxter, 1996). The vibracorer works on the basis of continuous source, high frequency vibrations which creates a low amplitude standard wave throughout the core (Baxter, 1996). A portable generator supplies power to the vibracorer, for this study the University of Cape Town's vibracorer was powered by a 144cm^3, 3.7kW Yanmar GE 50 motor (Baxter, 1996). The core tubing used in this study was standard thin-walled aluminium 'irrigation' tubing, which is available in 6 m lengths, with a diameter of 7.8cm (Baxter, 1996).

Figure 14: The vibracoring process a) equipment set-up; b) pushing core down into the sediment; c) wrenching core out using a tripod and d) sealing and labelling cores

The vibracorer facilitated the extraction of four cores from three of the Wilderness Lakes; namely two from Groenvlei and one each from Rondevlei and Bo Langvlei respectively, with minimal disturbance to the sediment (Figure 14a to 14c) (Irving and Meadows, 1997). Following the retrieval of each core, they were sealed, labelled GK1, GK2, RV1 and BLV (Figure 14d), respectively and transported back to the laboratory, where upon the aluminium tubing of each core was split lengthwise for stratigraphical description based on texture, colour and organic content. The splitting of the aluminium cores was performed in dark room conditions so that sand samples could be extracted for optically stimulated luminescence (OSL) dating. Other suitable samples were submitted to the Radiocarbon Dating Lab of the CSIR in Pretoria.

4.1.1 Dating Methods

Two methods of sediment age determination were utilised in this study, namely radiocarbon dating and optically stimulated luminescence (OSL) dating. The OSL dating method determines when last material was exposed to daylight. It is based on the assumption that materials contain naturally occurring radionuclides and are subject to increasing levels of radiation build up over time (Walker, 2005). The resulting radiation remains as structurally unstable electron traps within the mineral grains, the electrons are then released by shining a beam of light onto the material, the measure of which provides an indication of the time that has elapsed since the last exposure to daylight (Walker, 2005). Optical dating offers a direct measure of the last time the sediment was exposed to daylight and can provide ages up to ~800 ka (Jain *et al.*, 2004; Lepper, 2007). In contrast to OSL dating, radiocarbon dates can be obtained on a range of biogenic material (Walker, 2005). The radiocarbon method is based on the rate of decay of the radioactive or unstable carbon isotope 14 (^{14}C) in organic material (Walker, 2005). The rate of radioactive decay of the unstable isotope is constant; therefore by measuring the amount of ^{14}C remaining in a sample of fossil material and comparing to modern ^{14}C material an age can be determined (Walker, 2005). The half-life of the radioactive isotope is ~5730 years, giving an upper dateable age limit of approximately 45 000 years (Walker, 2005).

4.1.2 The Groenvlei Cores

Table 1: Summary of the allocated Munsell notation and their descriptive colour to depositional zones

Depth	Munsell Notation	Colour
0 - 200	7.5YR2.5/1	Black
200 - 330	10YR5/2	Grayish/brown
330 - 830	5Y6/1	Gray
830 - 925	5Y7/2	Light Gray
925 - 1050	5Y5/2	Olive/Gray

The core's stratigraphy was described based on the colour of the sediments using the Munsell Colour Notation (Table 1), the texture and the presence of organics (Irving and Meadows, 1997). The Troels-Smith scheme for stratigraphic notation as described by Birks and Birks (1980) was used to indicate changes in lithology within the first metre of the core (Figure 15). The organic content of the GK2 core is relatively low, most of which occurs most prominently in the surface section, which is a representative of more recent accumulation (Charter *et al.* 2005). Other than these principal surface organics, other sediment of presumed organic nature occur discontinuously throughout (Charter *et al.* 2005); one of these sections occurs near the base of GK2 at a depth of 4.27 m and corresponds to an age of 8.173 ka (Kirsten, 2005). Apart from these sections the cores are predominantly made up of sand of varying shades of grey which range from coarse to fine grained sands (Cornish-Bowden, 2005).

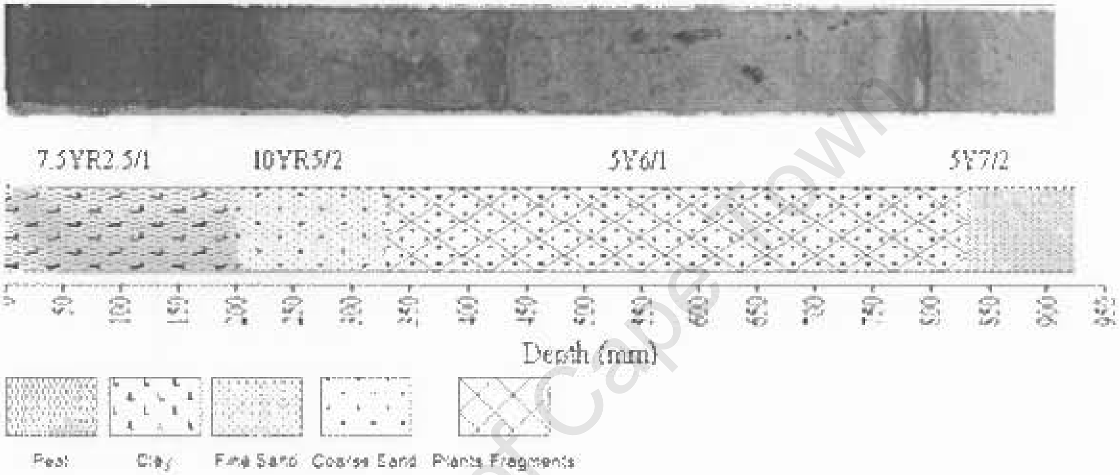

Figure 15: Annotated diagram indicating Lithology using Troels-Smith Description and related Munsell Colour Notation for the top metre of the GK2 core

4.1.3 Core Site (34° 01' 515" S; 22° 50' 069" E)

Upon inspection it was shown that diatoms occur throughout much of the GK2 core, although their stratigraphic distribution is discontinuous. Much of the lower portions of the GK2 core exhibited post depositional mixing or discontinuous sedimentation, therefore the upper metre of the 4.8 m core was sampled as it showed evidence of continuous sedimentation. The core site is located on the south western shore of Groenvlei. It is about 50 m from the Lake Pleasant Holiday Resort reception area and approximately 20 m from the water's edge (Charter *et al.* 2005). The core was taken from within a *Phragmites* stand about 15 m from the grass bank at the edge of Groenvlei (Charter *et al.* 2005).

The core tube penetrated quite easily to a depth of 5.45 m, with a sample length of 4.8 m; indicating a compaction factor of 0.65 m or ~12% (Charter *et al.* 2005). The resorts influence is noted through the existence of exotic vegetation that surrounds the

Phragmites stand (Charter *et al.* 2005). This vegetation takes the form of palm trees and *kikuyu* grass (Charter *et al.* 2005).

4.2 Diatom Analysis:

The larger the stratigraphic sample thickness the more time will be averaged in the prepared sample material and the more difficult it will be to relate the fossil assemblages to modern diatom communities and populations (Bradbury, 1999) therefore, a sub-sample with the thickness of 5mm was extracted from the core at 20 – 30 mm intervals; however the sampling was ultimately dependent on changes in lithology and sedimentation rates. This generated approximately 30 to 35 samples from the GK2 core, giving a detailed temporal scale of environmental change at periods through the Holocene. The extraneous materials required removal so as to concentrate the diatom sample; this included salts, organic matter and minerogenic matter. The main objective in chemically treating the samples extracted from the individual cores was to obtain satisfactory microscope slides for analysis. For this to succeed certain steps were undertaken for the effective extraction of the fossils, these steps are outlined below (as adapted from Battarbee, 1986) and displayed in Figure 16:

1) The sediments were initially treated with hot 10% HCl to remove all carbonates from the sample. This was achieved by placing a small quantity of sediment into a beaker, covering it with 10% HCl and heating gently for 15 minutes while swirling the contents. This was repeated until all carbonates were dissolved.

2) Following this, the residue was diluted with distilled water and allowed to settle overnight, with excess supernatant liquid removed through pipetting the following morning.

3) The sample was then washed in 20ml of 30% H_2O_2 and heated gently in a water bath until all organic matter was removed, this was repeated several times to ensure complete removal of organic matter.

4) To remove coarse organic matter, e.g. roots; the residue was sieved through a 0.5mm screen.

5) The resultant residue was centrifuged and washed with distilled water at least three times.

6) Coarse mineral matter was removed by sieving through a mesh size not less than 0.5mm with deionised water.

7) The subsequent sample may have contained clays and finer mineral matter, by swilling the residue in a beaker, clays were removed by allowing the diatoms to sediment before decanting and discarding the suspended clay.

8) Following these steps, a final wash with deionised water was performed.

9) The prepared sample was checked by preparing wet mounts to ensure an adequate removal of diluent material and a proper separation of frustules into single valves.

10) Following these steps, 3 drops of the diatom solution was pipetted onto a clean cover slip (Battarbee, 1986) and diluted with a few drops of deionised water (Barnett, 1997); the solution was then been allowed to settle (Battarbee, 1986).

11) The water in the solution was left to evaporate on a hot plate at a low temperature (~40°C).

12) Lastly, after all the water had evaporated, the coverslip was mounted onto the microscope slide using a "resin of high refractive index" (Battarbee, 1986, p. 531) for this purpose Pleurax (R.I. = 1.73) was utilised.

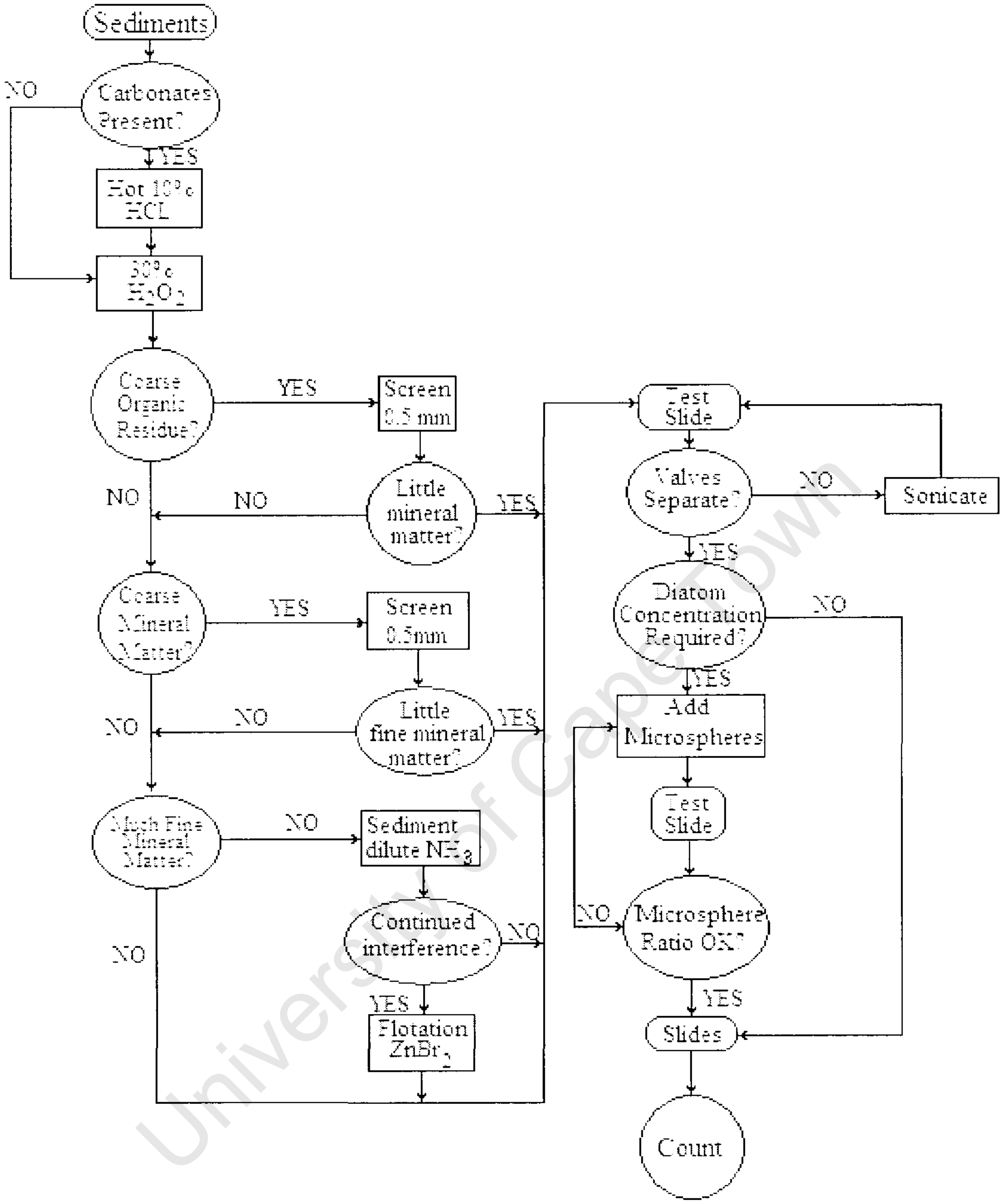

Figure 16: Summary of laboratory preparation of lake sediments for diatom analysis (Source: Battarbee, 1986, p. 531)

4.3 Counting and Identification:

After mounting the slide, diatoms were counted under a light microscope at a magnification of up to X1250 (Lowe and Walker, 1984). To improve precision and significance a count of approximately 500 diatom valves was undertaken, however 500 counts per slide was not always possible, hence a lower limit of 300 individuals had to be present on the slide before it was decided upon for the sample to be included in the analysis. Fragments were also included in the count; but to avoid double counting, only fragments that include the valve centre or a single characteristic feature of the valve were included. A larger count is necessary due to ecologically important taxa being obscured by mass occurrences of more common taxa (Battarbee, 1986). Identification of diatom species was based on type collections, keys and photographs in diatom manuals and catalogues, for example Bate *et al.*, (2004); Schoeman and Archibald (1997); Kelly *et al.*, (2005) and Taylor *et al.*, (2007) (Lowe and Walker, 1984). Once identified the diatom assemblage was analysed and displayed using the TILIA programme (Grimm, 1997, as cited by Szkornik *et al.*, 2006).

4.4 Statistical Analyses:

The Jaccard Index compares the species diversity between two different samples or communities, and is defined as follows:

$$\text{Jaccard Index} = (j / r) * 100.$$

and is "...calculated by dividing the number of species found in both of two samples (j) by the number found in only one sample or the other (r) and then multiplying by 100," [3]. The Jaccard Index gives a percentage of faunal similarity, but is sensitive to differences in sample size. Two other statistical techniques were utilised to identify group classifications within the fossil diatom assemblage namely Cluster Analysis and Principal Component Analysis (PCA) using the program *Statistica 7.0*. Cluster analysis using Ward's Algorithm identifies relationships between the diatom species and defines them into specific groups. Principal Component Analysis aids in establishing relationships between environmental parameters as well as identifying the most influential environmental factor.

4.4.1 Weighted Averages

The weighted average method assigns each species an optimum and a tolerance for the given environmental variable hence the weighted average optima and tolerances can be used to determine the desired variable for the study site with weighted average calibration (Reavie *et al.*, 2004). Weighted Averaging (WA) reconstructions take averages twice, once in the regression and once in the calibration, this can result in a

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[3] Meyer, 1998. http://www.cals.ncsu.edu/course/ent591k/gcextend.html#diversity

reduction in the range of inferred values, therefore the application of linear deshrinking is required as a correction (Birks *et al.*, 1990). This is achieved through the use of a linear regression model which regresses the initial inferred values of the training set on the observed values; this is termed a classical regression (Birks *et al.*, 1990). The classical regression has a tendency to take inferred values further away from the mean, whereas an inverse regression minimizes the root mean squared error (RMSE) in the training set (Birks *et al.*, 1990). The RMSE gives a measure of the 'apparent' error (Roberts and McMinn, 1998); hence the value of the RMSE evaluates how well a model can be expected to function as a predictive tool (Birks *et al.*, 1990). The Jackknife can be used to derive errors of prediction, where the jackknifed RMSE gives an indication of the "true predictive ability of a transfer function [and can provide a] realistic predictive correlation and error estimate between observed and diatom-inferred" (Roberts and McMinn, 1998, p. 104) parameters. In this study, Conductivity and pH were reconstructed using the EDDI (European Diatom Database Initiative) Combined Salinity training set in the reconstruction software called ERNIE available from the Newcastle University website (Juggins, 2001). The ERNIE program allows diatom-based transfer functions stored in the European diatom database to be applied to core or fossil samples. The dataset is an amalgamation of those established for Spain, North and East Africa and the Caspian region and consists of 652 species from 387 lakes. All that is required is to align the diatom species of the core to that of the training set, "this means that the taxon codes used in the core and training set must match in terms of the codes themselves and in the taxonomic concepts applied to the codes" (Juggins, 2001, p. 14). A weighted averaging reconstruction with inverse deshrinking was chosen for the analysis and was evaluated using jackknifing to determine diatom species relationships to pH and Conductivity.

4.5 Conclusions:

The analysis of the various methods incorporated and outlined above will provide a framework on which changes in natural processes can be measured. The interpretation of these methods will aid in the understanding of any variations in the diatom community observed over time and lead to inferences on environmental changes.

Chapter 5. Results

5.1 Chronology:

Two dating methods were utilised to create a chronology for the Groenvlei cores, namely radiocarbon dating and optical luminescence dating. The radiocarbon dates were determined by the Quaternary Dating Research Unit (QUADRU) at the CSIR in Pretoria and were calibrated using the program CaLib Version 5.0 (Stuiver and Reimer, 1993) with the calibration dataset SHCal04 for Southern Hemisphere terrestrial samples (McCormac *et al.*, 2004). Probabilities are ranked to a 95.4% confidence interval, i.e. 2σ (sigma) with the relative area under the probability curve calculated and normalized to one (Stuiver *et al.*, 2005). The number of calibrated ranges is related to the relative area covered by the probability curve and in cases where more than one range is reported Stuiver *et al.* (2005) suggests that the extremes of the ranges can be given. Hence, in Table 2 below, the extremes of the lower and upper calibrated range is reported when more than one range is produced as well as the median probability over all ranges.

Table 2: The radiocarbon dates of both cores calibrated to the SHCal04 curve indicating the upper and lower calibration range in units, BP with their median probability and corresponding depths

Lab Code	Sample Code	Depth (mm)	Radiocarbon age, yrs BP	No. of ranges	lower cal range BP	upper cal range BP	median probability
9491 Pta -	GK1.31-36	340	580 ± 40	2	504	631	543
9481 Pta -	GK1.158-163	1600	7410 ± 70	1	8016	8337	8170
9497 Pta -	GK1.400-405	4020	7630 ± 130	4	8049	8631	8378
9487 Pta -	GK2.425-430	4270	7400 ± 20	2	8032	8286	8158

Several sand samples from the Groenvlei cores, GK1 and GK2 were extracted for luminescence dating, which was carried out at the Centre for the Environment, Oxford University (Table 3). Prior to determining the ages several corrections need to be made, one of which is for dose rate. The environmental dose rate is a measure of the radiation per unit of time since the zeroing of the luminescence clock, which is "calculated from an analysis of the radioactive elements within the sample and its surroundings" (Walker, 2005, p. 98). In this study Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and X-Ray Fluorescence (XRF) for the elements uranium (U), thorium (Th) and potassium (K) determined the dose rate. The ages and accompanying depths are summarised in the table below:

Table 3: OSL dates with their corresponding depths within the Groenvlei cores

GK 1 Sampled Dates		GK 2 Samples Dates	
Depth (mm)	Age (ka) and error	Depth (mm)	Age (ka) and error
730	3.58 ± 0.58	440	4.13 ± 0.27
840	7.39 ± 0.43	790	4.19 ± 0.74
1000	9.41 ± 1.83	1280	8.11 ± 1.48
1560	8.53 ± 1.68	2290	6.45 ± 1.15
3350	8.43 ± 0.51	3920	8.49 ± 0.59
4280	31.22 ± 5.65		

The OSL ages coupled with the radiocarbon ages from both cores aid in deciphering the chronological sequence of events indicated by the sedimentary sequence. To estimate relative ages for sampled material, the OSL ages and calibrated radiocarbon ages from the sampled depths of 340 mm, 730 mm, 840 mm, 1000 mm and 1560 mm in GK 1 and 440 mm, 790 mm and 1280 mm from GK2 were graphed with the assumption that the top of the core (contemporary sediment surface) equates to present-day deposition and has an age of zero (Figure 17). For depths not dated by either method an age-depth model is incorporated to present a means of interpolation of ages and to estimate sedimentation rates.

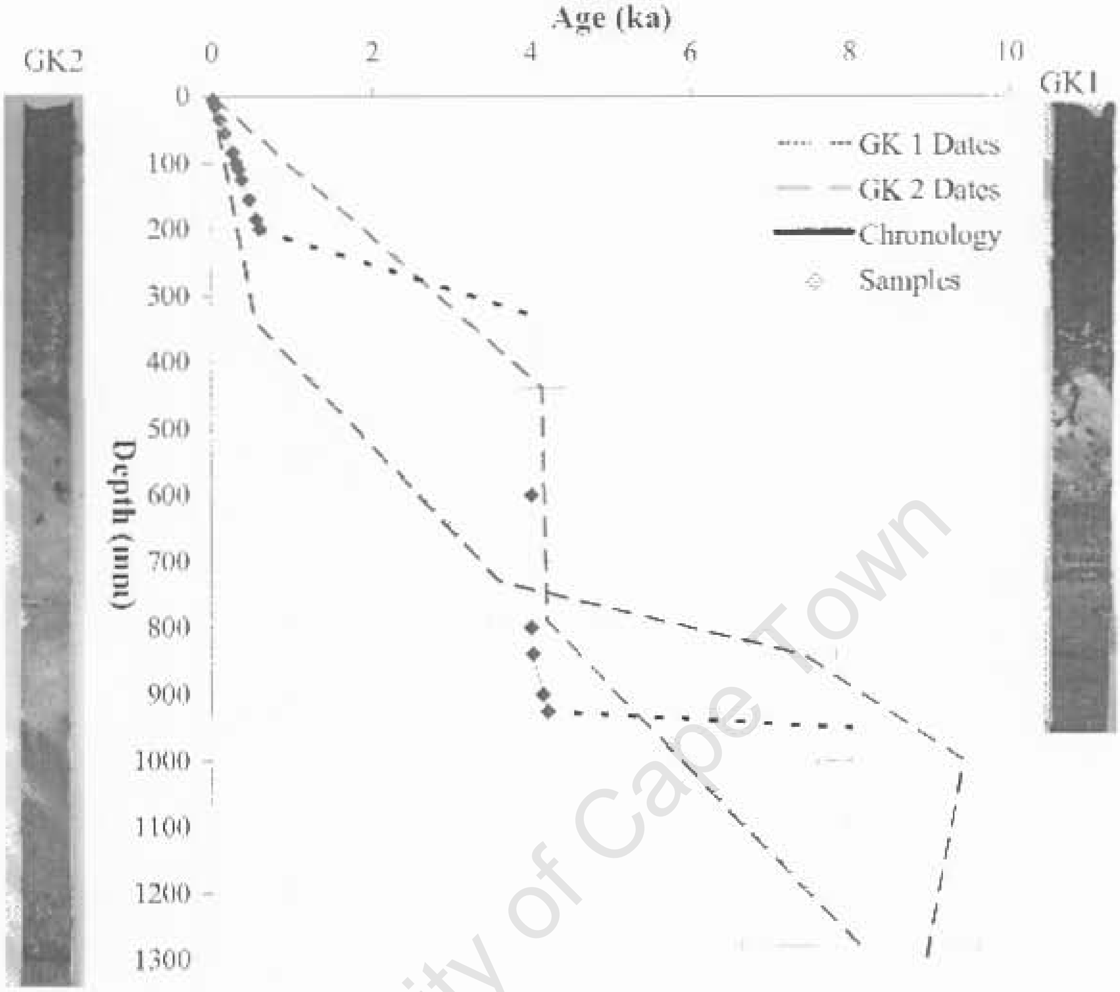


Figure 17: Age-Depth Model incorporating OSL dates and calibrated radiocarbon dates with errors for both Groenvlei cores alongside the GK 2 core, including age estimates of sampled material (diamonds). Depositional hiatuses are indicated by a black hashed line on the age depth model

A root mat occurs in both cores, extending from the surface to 340 mm in GK 1 and 200 mm in GK2, the base of which is estimated to be around 600 years old; this would imply that the rate of deposition of the most recent phase of deposition for the area around the GK 2 core site is about 0.3 $mm.yr^{-1}$ (Figure 17), although is it worth noting that the area near the site is next to a recent construction during which the location may have been disturbed; moreover, modern roots constitute some of the mat which may cause contamination of samples extracted for analyses as well as disturbance to the stratigraphy. However, even with this in mind it is still possible to consider that the root mat represents a coherent phase of recent deposition, as pollen analysis shows the introduction of the exotic genus *Pinus* during part of this period

(Duncan, 2006). The introduction of *Pinus* into the region is known from historical records having occurred during the early stages of the 20th century and provides an excellent chronological marker (Duncan, 2006). Lower down the cores, two probably short-lived episodes of very rapid sediment deposition occur at depths equating to approximately 4 ka and 8 ka (Figure 17). The most recent episode spans from ~ 830 mm to ~ 330 mm in the GK 2 core and consists of light grey, coarse sand; the horizon of which merges with the root mat dated at around 600 BP. Sediments of the period connecting the sand bar with the formation of peat underwent post depositional erosion, therefore sediments and fossils are thus indistinguishable in age. It can be said that the transition from the ~ 4 ka episode and the root mat having experienced removal of sediment over the 3500 year gap left behind 130 mm of trace material in the GK2 core between the two sedimentary zones (Figure 17). The time between the two rapid deposition events from ~ 4 ka and ~ 8 ka also appears to have been associated with either a depositional hiatus or a continual removal of sediment possibly by wave action over the 4000 year gap, leaving behind approximately 200 mm of trace material in the GK2 core (Figure 17). Mid-Holocene high sea levels may have contributed to the removal of sediment from the GK 2 area as the core site is near the proposed channel connecting Groenvlei to the sea via Swartvlei. Sea levels returned to present levels around 4200 BP (Miller *et al.*, 1995), just prior to the ~ 4 ka event; possibly allowing for 200 years of sequential deposition of sediment before its onset. A new depositional stage occurring between 925 and 830 mm is evident in the stratigraphy and may substantiate the 200 year deposition event as pinkish, grey sand with clear laminations are observed; this would suggest that the rate of deposition near the GK 2 site during this stage would be close to 0.5 mm.yr^{-1}.

5.2 The Fossil Assemblages:

5.2.1 Cluster Analysis

Cluster Analysis incorporates a number of methods to develop group classifications in datasets. Its main objective is to assemble items into groups through the use of some measure of similarity or distance. Ward's Algorithm was used in this analysis as it identifies relationships between the variables although Ward's does not recognize outliers well. The analysis generated three clusters and one possible outlier; these clusters were further subdivided as discussed below (Figure 18).

Figure 18: Cluster analysis on 38 diatom species using Ward's Algorithm, which created three main clusters with subdivisions (squares) and a single outlier

The first cluster consisted of species that are rare or do not occur in the upper ten samples of the core, such as *Amphora veneta*, *Campylodiscus clypeus* and *Mastogloia smithii*. The second cluster was subdivided into three groups *a*, *b* and *c*. Group *a* consists mainly of aerophilic species and occur throughout the core increasing in the top two samples of the core towards the present. Group *b* is dominated by epiphytic, fresh brackish species that increase in surface samples. Group *c* also consists of epiphytic species preferring alkaline waters but generally decrease towards the surface. The exception to this is the diatoms *Mastogloia elliptica* (Figure 21m) and *Amphora commutata*; the former only occurs between the depths 125 mm to 220 mm and the latter is consistent throughout the core. The third cluster is also subdivided into three groups, namely *d*, *e* and *f*. Group *d* includes three benthic species, namely *Cocconeis engelbrachtii*, *Mastogloia braunii* and that dominate the lower half of the core from depths 600 mm to 925 mm (Figure 18). Group *e* comprises three diatoms, namely *Cocconeis placentula*, *Rhopalodia gibberula* and *Rhopalodia gibba*; that live attached to other plants in fresh brackish water that have notable appearances in the lower quarter of the core from 800 mm to 925 mm. The last subdivision, Group *f* features *Pinnularia* cf. *viridiformis*, *Pseudostaurosira brevistriata* and *Staurosirella pinnata* are fresh brackish (Table 8), basic water species occurring in the top half of the core from depths 220 to the surface and are subdominant to *Staurosira elliptica*, the outlier identified in the analysis. *Staurosira elliptica* prefers a fresh brackish, alkaline habitat living on fine sediments or on sandy substrata (Kelly *et al*., 2005).

5.2.2 Principal Component Analysis:

Principal component analysis aids in revealing patterns within a dataset and is useful when trying to determine underlying aspects of the data. Three eigenvalues were extracted from the analysis which covered nearly 90% of the explained variance. The Eigenvalues generated three Factor Loadings which were rotated; using Varimax Normalised Rotation. In the factor loadings there are three factors, of which fourteen variables are present; Factor One incorporates ten variables with two variables in each of the second and third Factors. The Factor Loading was considered to be significant if greater than 0.7, which explains 50% of the squared variance.

Factor Loadings

Factor One incorporates the top ten samples from the dataset from depth 220 mm to the surface, all of which are directly proportional to each other (Figure 19c). This implies that during this phase, which lasted approximately 700 years, conditions were rather steady allowing for a period in which a stable diatom community could be establish. Although certain species appear and disappear during this time the conditions in which they occurred remained rather constant and that it is possible that these samples are linked by an underlying environmental condition. Factor two incorporates the samples 600 mm and 800 mm (Figure 19b). This agrees with the Jaccard index which identified a separation between samples at 800 mm and 840 mm. The two samples are directly proportional to each other but inversely proportional to the other two factors. This may be the start of declining environmental conditions during the mid-Holocene resulting in shifts in the diatom community as a response. As in Factor Two the total variance for Factor Three is explained by two variables, those being samples 900 mm and 925 mm (Figure 19a). Both samples are directly proportional to each other. This stage appears to be a near stable period just prior to environmental deterioration of the mid-Holocene.

One sample is left out of the loadings, namely 840 mm; which appears to be an intermediate between factor two and factor three. This could possible be seen as the transition between a near stable environment to a modifying environment only tolerated by diatoms with a wide ecological amplitude.

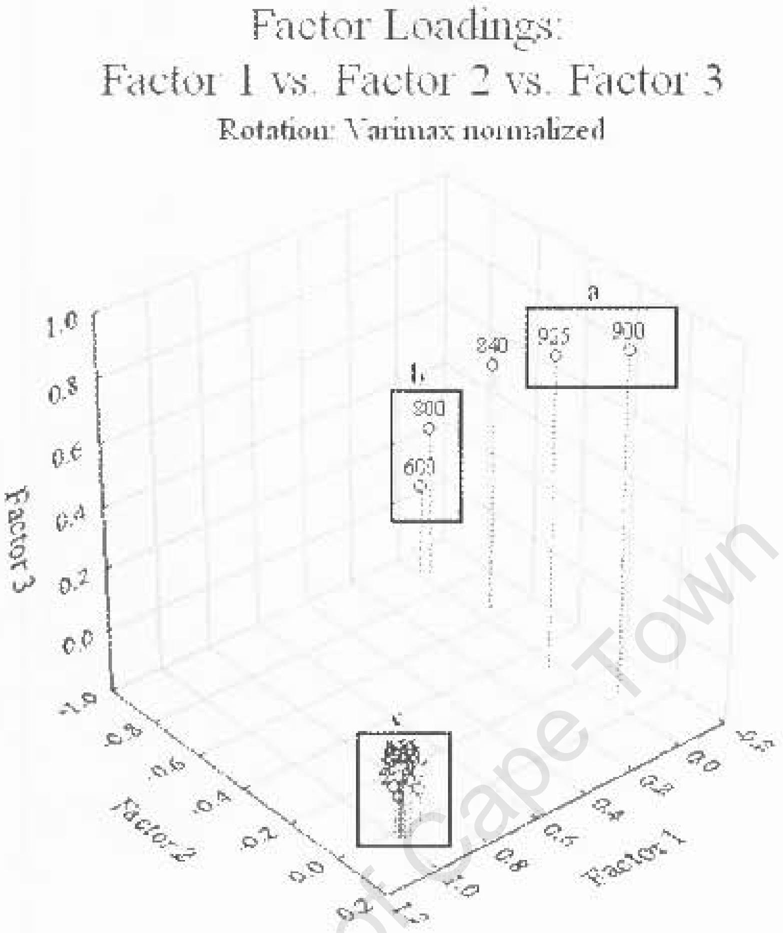


Figure 19: Three dimensional plot of factor loadings generated by Statistica v7.0, indicating the relationship of sampled material to each other; (a) relates to factor loading 3, (b) relates to factor loading 2, (c) relates to factor loading 1 and the intermediate sample of 840 mm

In this analysis, component scores above the value of one were identified as significant in relation to the Rotated Factor as discussed previously. As the factor score relates to the cases in the dataset it will therefore relate to the diatoms that the case represents.

Factor Scores

The diatoms *Pinnularia* cf. *viridiformis*, *Pseudostaurosira brevistriata* and *Staurosira elliptica* are shown as significant in relation to Factor One. Of these cases it is *Staurosira elliptica* which has the greatest significance with a factor score of 6.08 (Figure 20), this is translated to the dominance of the species in the assemblage in the top 220 mm of the core, the other two diatoms are subdominant to *Staurosira elliptica* occurring in quantity in all samples from 220 mm to the surface. With respect to

Factor Two the following diatoms were shown to be of significance; *Rhoicosphenia abbreviata* (Figure 21o), *Anomoeoneis sphaerophora*, *Navicula cryptocephala* and *Rhopalodia gibba* with *Rhoicosphenia abbreviata* being the most significant with a factor score of -5.97 and *Rhopalodia gibba* being inversely proportional in significance to the afore mentioned diatoms (Figure 20). *Rhoicosphenia abbreviata* is a dominant species in the lower half of the core which tolerates alkaliphilous, inland brackish waters of electrolyte rich content (Kelly *et al*., 2005). *Cocconeis placentula, Amphora commutata. Rhoicosphenia abbreviata Mastogloia braunii. Cocconeis engelbrachtii* and *Rhopalodia gibba* are positively significant and *Anomoeoneis sphaerophora* is inversely proportional to the aforesaid species in factor three (Figure 20). *Anomoeoneis sphaerophora* can tolerate critical levels of pollution in brackish-saline coastal waters therefore as these criteria are met *Anomoeoneis sphaerophora* (Figure 21c) will increase and the afore mentioned diatoms will decrease and vice versa.

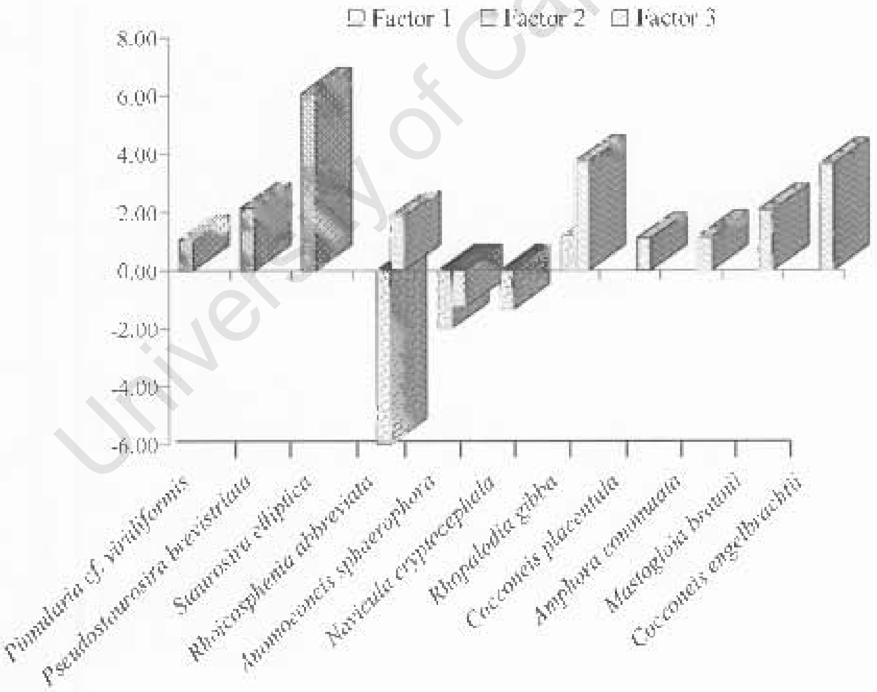


Figure 20: Visual representation of Factor Scores generated during Principal Component Analysis

Therefore, with the aid of the above analyses it is possible to determine statistically significant changes in the fossil diatom assemblage and establish zones of similarity within the core. Alternatively, the combination of cluster analysis and principal component analysis can be used to identify dissimilarity between samples and aid in classifying zones in the assemblage. For example, PCA has clearly defined a separation between samples 800 mm and 840 mm as did cluster analysis. Consequently, the assemblage has been divided into five zones based on a combination of cluster analysis, PCA and the Jaccard index, which is used to verify changes between limnological stages, as well as to determine similarity/dissimilarity between the different communities prevalent in the fossil assemblage (Meyer, 1998). The five zones are provided with interpolated ages based on the age-depth model (Figure 17). The fossil assemblage is characterised by two diatom fossil depositional periods and are further subdivided into five zones between the time intervals of 4.2 ka to 4 ka and 0.7 ka to the present. A hiatus occurs between the two periods and has been designated as *Zone c*. The separation between the two time intervals lasts 3.5 thousand years which corresponds to active sand movement in the area during this time. Diatom frustules are not well preserved in a coarse sand matrix, this fact may be the reason behind highly fragmented diatom frustules in the samples from the hiatus period. The only fragments which are discernible come from the diatom *Campylodiscus clypeus*, a planktonic species which favours inland waters with high conductivity as well as inland saline waters and weakly brackish waters (Wasylikowa, 2006) (Figure 21b). A description of each zone and their prevailing environmental nature with notable diatom species occurrence is given below with a more detailed table of the dominant and subdominant species per time step displayed in Table 4.

5.2.3 4.2 ka – 4 ka:

The time period spanning from 4.2 ka to 4 ka corresponds to the depths 925 mm to 600 mm and is divided into two zones. Zone (a) occurring from depths 925 to 800 mm spans about two hundred years; whereas Zone (b), from depth 800 to 600 mm, corresponds to at best a few decades and appears to occur concurrently with major aeolian activity. Dominant and subdominant species for both Zones are summarised in Table 4 below.

Zone a

A mixed assemblage with *Rhopalodia gibba*, *Cocconeis engelbrachtii* (Figure 21d), *Cocconeis placentula* (Figure 21c), *Mastogloia braunii* (Figure 21g) and *Rhoicosphenia abbreviata* (Figure 22) being most prevalent. All species prefer alkaliphilious water and live either attached to rocks or filamenteous algae (Kelly *et* *al*., 2005) (Table 8). *Cocconeis engelbrachtii* is endemic to South Africa, preferring brackish waters with highly elevated electrolyte content (Taylor *et al*., 2007). Just prior to the 4 ka event, most of these species have steadily dropped in abundance, with other species like *Achnanthidium minutissima* occurring. *Achnanthidium minutissima* is abundant in fresh to brackish waters which are circumneutral or alkaline in nature with low or moderate concentrations of nutrients and organic material (Kelly *et al*., 2005; Telford, 2001) (Table 8). Planktonic and aerophilous taxa are minimal, suggesting moderate water levels which is optimum for a benthic diatom community.

Table 4: Summary of the dominant and subdominant diatom species for Zones a and b as recognised by TILIA, included are those species which were identified as significant by the Principal Component Analysis

Sample		**Species**
600	Dominant	*Rhoicosphenia abbreviata, Anomoeoneis sphaerophora, Navicula cryptocephala, Amphora veneta*
800	Dominant	*Rhoicosphenia abbreviata*
840	Dominant	*Rhoicosphenia abbreviata, Cocconei engelbrechtii, Achnanthidium minutissima*
	Subdominant	*Rhopalodia gibba*
900	Dominant	*Rhopalodia gibba*
	Subdominant	*Amphora commutata, Cocconeis engelbrechtii, Rhoicosphenia abbreviata*
	PCA	*Cocconeis placentula, Mastogloia braunii, Anomoeoneis sphaerophora*
925	Dominant	*Mastogloia braunii, Cocconeis engelbrechtii*
	Subdominant	*Rhoicosphenia abbreviata, Cocconeis placentula, Rhopalodia gibba*
	PCA	*Anomoeoneis sphaerophora, Navicula cryptocephala*

Zone b

Zone b represents a very short time interval with dynamic changes in the assemblage due to the rapid changes occurring in the environment at around 4 ka. *Rhoicosphenia abbreviata* peaks at 800 mm (~ 4000 yrs ago), comprising nearly 80% of the diatom assemblage (Figure 22). *Rhoicosphenia abbreviata* (Figure 21o) is commonly found attached to filamentous algae or to rocks (Kelly *et al*., 2005) and is indicative of slightly brackish conditions (Hedenstrom and Risberg, 1999) (Table 8). *Rhoicosphenia abbreviata* diminishes in numbers to ~45% at 600 mm, giving way to two epipelic and one epilithic species, namely *Anomoeoneis sphaerophora* (Figure 21e), *Navicula cryptocephala* and *Amphora veneta*, respectively (Kelly *et al*., 2005; Poulíĉkova and Mann, 2006) (Table 8). *Anomoeoneis sphaerophora* is typically found in littoral zones of waterbodies with moderate to high electrolyte content (Kelly *et al.*, 2005) and is classified as a brackish lagoonal taxon by Hedenstrom and Risberg (1999). The dominant species for this zone all extend into brackish waters and are tolerant to heavy degrees of organic pollution (Kelly *et al.*, 2005). All other species previously observed have disappeared from the assemblage.

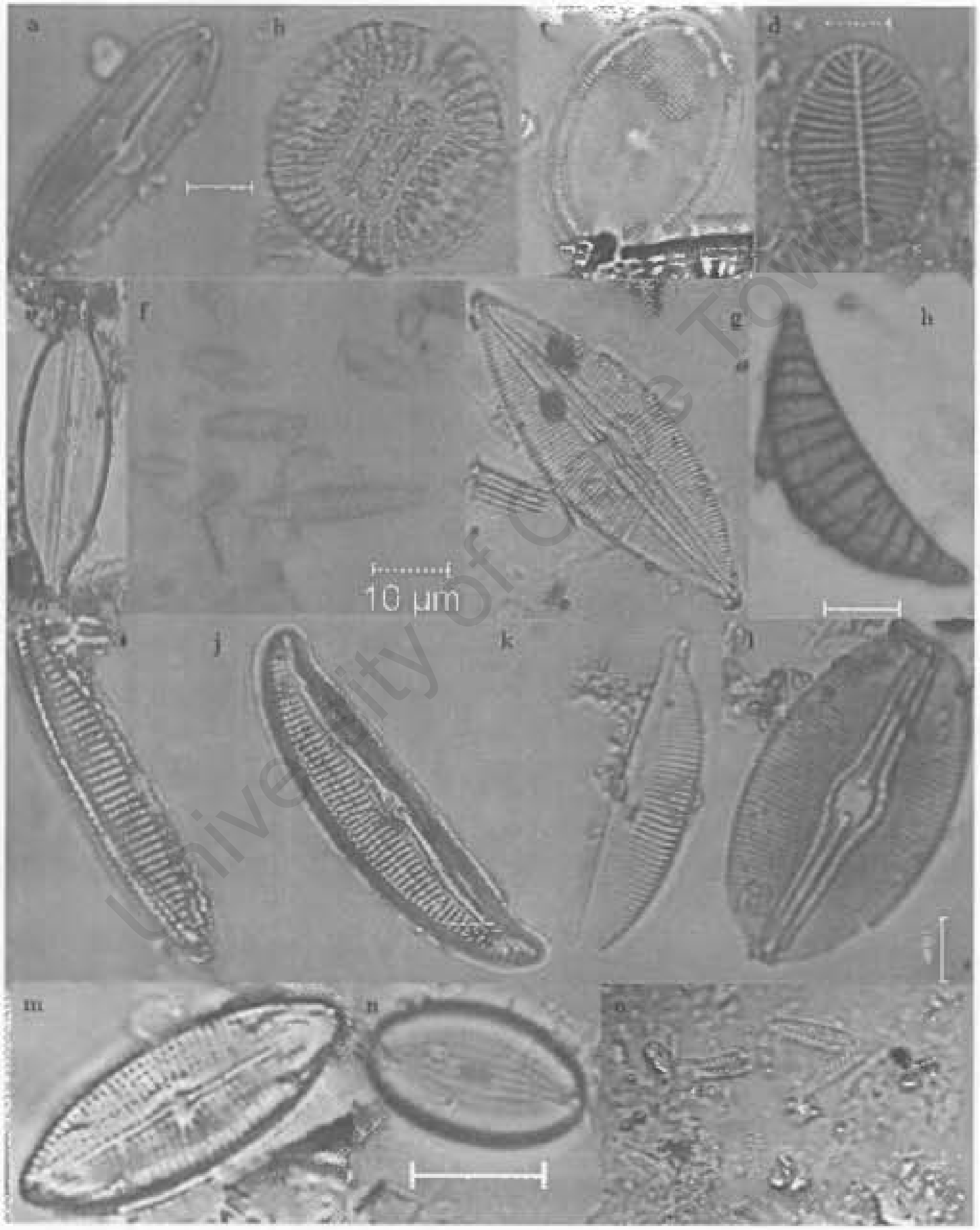


Figure 21: Some diatoms present in the assemblage – scale represents 10µm where indicated: (a) Pinnularia cf. viridiformis, (b) Campylodiscus clypeus, (c) Cocconeis placentula, (d) Cocconeis engelbrachtii, (e) Anomoeoneis sphaerophora, (f) Pseudostaurosira brevistriata (elongate) and Staurosirella pinnata (rounded), (g) Mastogloia braunii, (h) Rhopalodia gibberula, (i) Nitzschia cf. amphibia, (j) Amphora ovalis, (k) Amphora coffeaeformis, (l) Diploneis ovalis, (m) Mastogloia elliptica, (n) Fallacia pygmaea and (o) Rhoicosphenia abbreviata

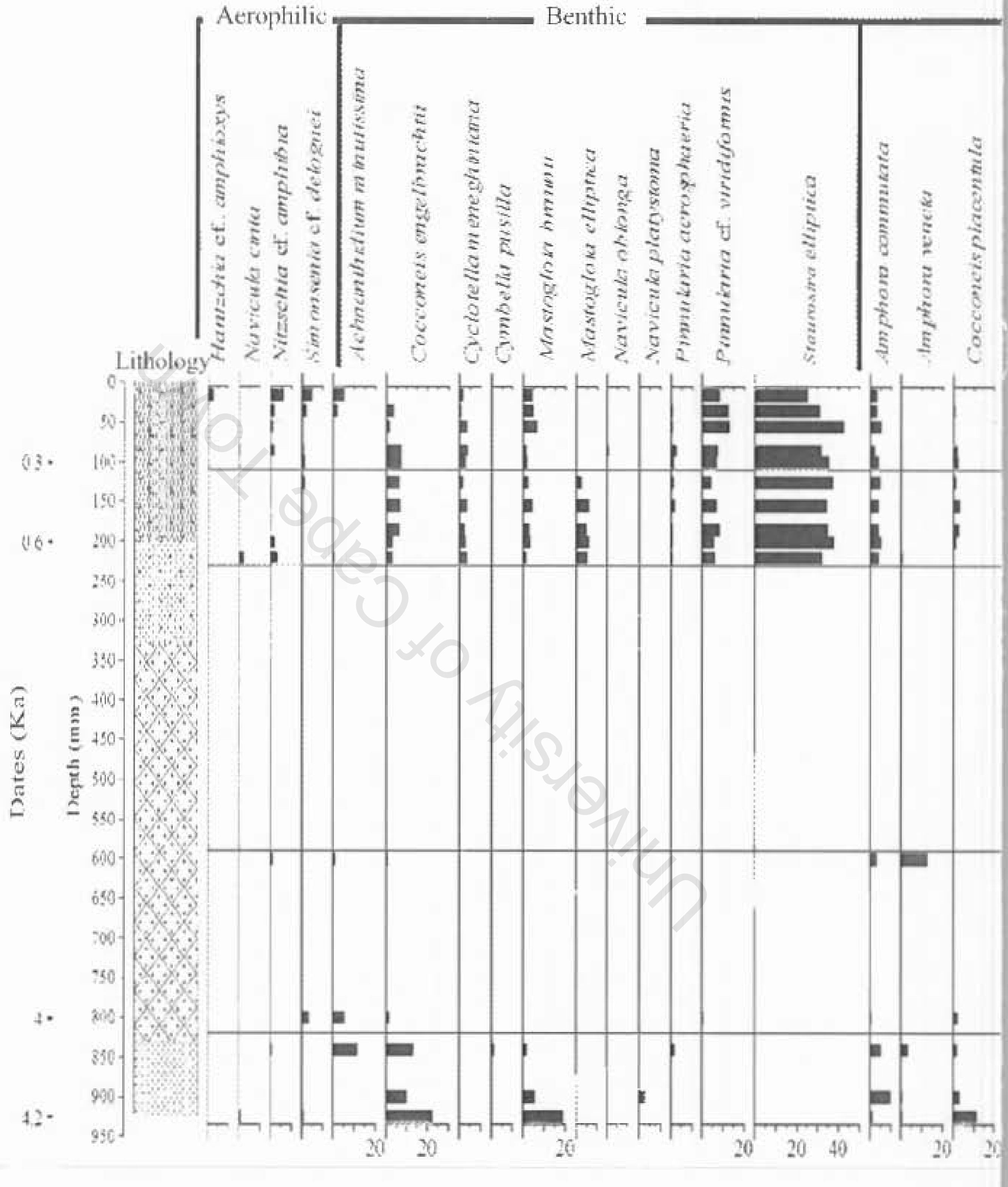
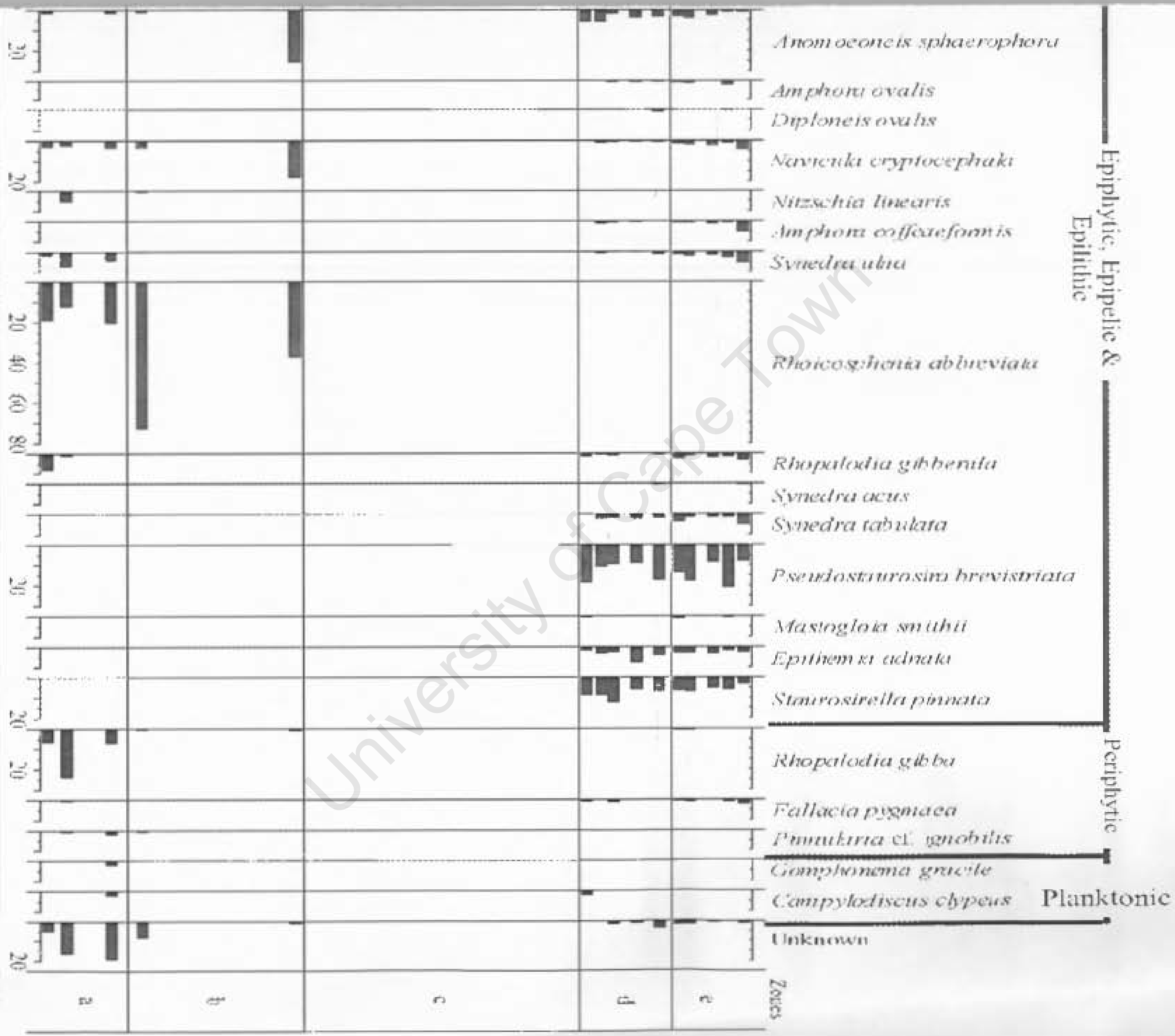


Figure 22: Tilia Graph indicating changes in the diatom assemblage represented in percentages through time, grouped by pre



ferred life form; including the zonations a – e and changes in lithology.

5.2.4 0.7 ka – present:

The last 700 years of the regions history is represented by the top 220 mm of the core and is divided into two zones. Zone (d) extends from 700 to 330 years ago, covering 120 mm of sediment from 220 to 100 mm; whereas Zone (e), from 100 mm to the surface, spans approximately 330 years. Neither zones d nor e are completely dominated by one species, but rather a composition of taxa. Previously dominant species, *Rhoicosphenia abbreviata*, *Rhopalodia gibba* and to a lesser degree *Amphora veneta* do not occur in either Zone d or e (Figure 22). *Anomoeoneis sphaerophora* and *Navicula cryptocephala* which peaked prior to the hiatus, are still present in both zones but at no level do any of these diatoms exceed 5% of the total diatom assemblage on an individual basis. A summary of species, which are dominant or subdominant in each zone, are indicated in Tables 5 and 6 below.

Zone d

Zone (d) post dates aeolian activity and the hiatus and is viewed as a recovery stage for the diatom community (Figure 22). At least 60% of the diatom community during this time period is comprised of the benthic diatoms, *Staurosira elliptica* and *Pseudostaurosira brevistriata* (Figure 21f) with *Pinnularia* cf. *viridiformis* (Figure 21a) and *Staurosirella pinnata* (Figure 21f) making up another 25% (Figure 22) (Table 5) (Kelly *et al.*, 2005) (Edwards *et al.*, 2006). *Mastogloia elliptica* makes its only appearance in the assemblage during this stage; a species which extends into brackish water bodies, requires non-acidic conditions and can be sensitive to pollution (Kelly *et al.*, 2005) (Table 8). *Epithemia adnata* also makes its first appearance and reaches a peak around 450 years ago; it lives attached to macrophytes and other solid substrata; generally found in neutral to high pH environments and is tolerant of elevated water temperatures (Taylor *et al.*, 2007) (Kelly *et al.*, 2005). *Epithemia adnata* is apparently capable of Nitrogen fixation via endosymbiotic blue-green algae, which may be beneficial for the later colonisation by vascular plants (Kelly *et al.*, 2005). One eutrophic diatom able to survive critical levels of pollution makes an appearance during this period (Kelly *et al.*, 2005); *Cyclotella meneghiniana* has a cosmopolitan distribution in the benthos and plankton of electrolyte rich rivers, streams and lakes (Taylor *et al*, 2007). Aerophilic species such as *Rhopalodia gibberula* (Figure 21h) and *Synedra tabulata* also start making an appearance after the hiatus. Aerophilic taxons are dependent on free oxygen or air and therefore can survive periods outside the water body.

Table 5: Summary of the dominant and subdominant diatom species for Zone b as recognised by TILIA, included are those species which were identified as significant by the Principal Component Analysis

Sample		**Species**
125	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Staurosirella pinnata, Pinnularia cf. viridiformis*
	Subdominant	*Cocconeis engelbrechtii*
155	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Staurosirella pinnata, Pinnularia cf. viridiformis*
	Subdominant	*Mastogloia elliptica, Cocconeis engelbrechtii, Epithemia adnata*
185	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Staurosirella pinnata, Pinnularia cf. viridiformis*
	Subdominant	*Mastogloia elliptica, Amphora commutata, Cocconeis engelbrechtii*
200	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Staurosirella pinnata, Pinnularia cf. viridiformis*
	Subdominant	*Mastogloia elliptica, Amphora commutata, Anomoeoneis sphaerophora*
220	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Staurosirella pinnata, Pinnularia cf. viridiformis*
	Subdominant	*Mastogloia elliptica, Amphora commutata, Anomoeoneis sphaerophora, Cyclotella meneghiniana*

Zone e

The last 330 years exhibits a general decrease in planktonic species and increases in aerophilic taxa. Benthic diatoms are still dominant, of which the majority live on or in fine sediments or on hard surfaces such as rocks. *Staurosira elliptica*, *Pseudostaurosira brevistriata* and *Pinnularia* cf. *viridiformis* are still the dominant species during this period (Table 6) and are accompanied by *Synedra acus*, *Synedra tabulata* and *Synedra ulna* (Figure 22); all three *Synedra* species are epiphytes, preferring fresh brackish, alkaliphilous waters (Kelly *et al.*, 2005) (Table 8). *Simonsenia* cf. *delognei* has been increasing since the start of this period and reaches a maximum of nearly 5% of the total assemblage about 50 years ago; it is typically associated with strong river influence and low productivity (Hay *et al.*, 1997); at the same time *Hantzchia* cf. *amphioxys*, an aerophilic species makes its first appearance. *Navicula cryptocephala* shows a slight recovery towards the present, with *Anomoeoneis sphaerophora* steadily decreasing towards the present as does *Amphora commutata*. *Achnanthidium minutissima* makes a re-emergence near the end of the stage possibly indicating a return to fresh water conditions (Kelly *et al*., 2005). Both *Cocconeis* species disappear from the top samples, reiterating changes in water conditions from previously brackish fresh to possibly fresh to fresh brackish (Kelly *et al*., 2005).

Table 6: Summary of the dominant and subdominant diatom species for Zone e as recognised by TILIA, included are those species which were identified as significant by the Principal Component Analysis

Sample		**Species**
15	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Pinnularia cf. viridiformis, Staurosirella pinnata*
35	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Pinnularia cf. viridiformis, Staurosirella pinnata*
55	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Pinnularia cf. viridiformis, Staurosirella pinnata*
	Subdominant	*Cyclotella meneghiniana, Amphora commutata, Mastogloia braunii*
85	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Pinnularia cf. viridiformis, Staurosirella pinnata*
	Subdominant	*Cocconeis engelbrechtii, Cyclotella meneghiniana*
100	Dominant	*Staurosira elliptica, Pseudostaurosira brevistriata, Pinnularia cf. viridiformis, Staurosirella pinnata*
	Subdominant	*Cocconeis engelbrechtii, Synedra tabulata*

5.3 Environmental Variables:

The classical species orientated approach places taxa in general autecological classifications which reflect the behaviour of species groups with similar requirements (Denys and de Wolf, 1999). Environmental variables were determined through these classifications grouping diatoms into categories; in this analysis variables include salinity, pH and life form. Salinity has four groupings, in order of highest to lowest salinity; they are brackish, brackish fresh, fresh brackish and fresh. pH also has four categories, which include alkalibiontic, alkaliphilous, circumneutral and indifferent. Life form has five divisions, namely aerophilous, periphytic, epilithic and epiphytic, benthic and lastly planktonic. All environmental variables have an unknown category which includes unknown species and species with an unknown preference related to the particular variable. Variables are presented in percentages which were determined by the addition of individual species related to the specific category divided by the total number of species within the sample.

5.3.1 Salinity:

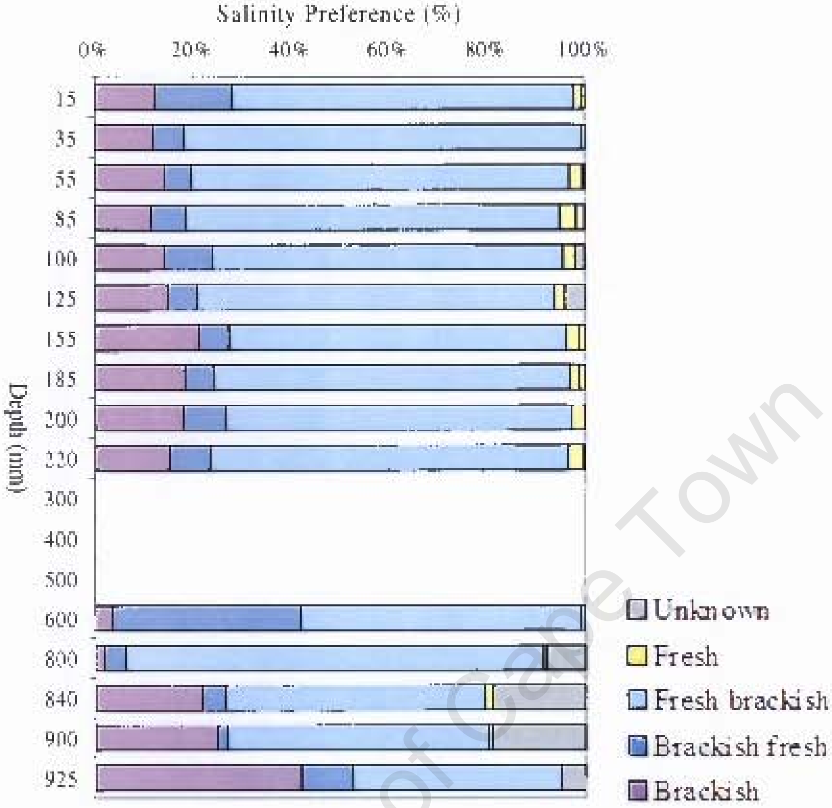


Figure 23: Percentage representation of salinity preferences of individual species over depth in GK2

Initially, conditions are more brackish to brackish fresh, with just over 50% of the assemblage boxed into this category but by ~ 4000 years ago (800 mm) only ~6% of the fossil assemblage remain in this category as the situation becomes increasingly fresh brackish, implying a trend towards a fresher environment (Figure 23). However just prior to the hiatus, the trend reverses and circumstances revert towards brackish fresh with an increase of ~35% in the species preferring brackish/brackish fresh conditions, implying either a decrease in freshwater supplies or an increase in saline water. After the hiatus towards the present, approximately 70% of the assemblage tends toward fresh brackish, accompanied by fresh water individuals but these diatoms are minimal. The brackish/brackish fresh component of the assemblage is still evident and at certain phases strengthens but does not return to dominate. Near the surface, an increase of 10% in individuals preferring brackish/brackish fresh conditions may indicate the beginnings of brackish conditions.

5.3.2 pH:

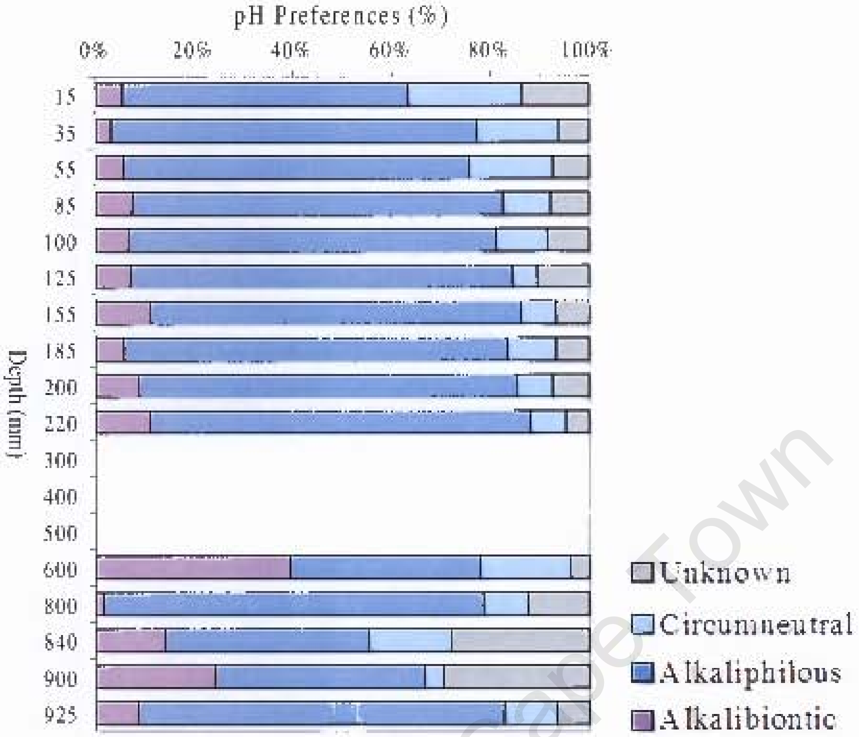


Figure 24: Percentage representation of pH preferences of individual species over depth in GK2

At no point in time is the water chemistry in Groenvlei acidic. Strongly alkaline conditions are prevalent throughout the fossil diatom assemblage both prior and post the hiatus. Of particular interest, is the phase approximately 4000 years ago (800 mm) as circumneutral individuals decreased by 5% as well as a decrease by more than 10% in alkalibiontic species resulting in an increase to 80% for alkaliphilous species, probably indicating a shift towards weakly alkaline water. In spite of this inclination, just prior to the hiatus about 4000 years ago (600 mm), a return of alkalibiontic species is observed, an increase of nearly 40% is evident possibly indicating an increase in pH to strongly alkaline conditions. Subsequent to the hiatus conditions are strongly alkaliphilous to alkalibiontic with diatoms occurring at pH values at about seven or with their widest distribution at pH greater than seven. These taxa dominate the assemblage with an overwhelming ~90% which steadily decreases to just over 60% near the surface, approximately 50 years ago. The decrease in strongly alkaline dominant species gives way to cirumneutral individuals able to tolerate a wider spectrum of the pH scale on either side of seven; this may imply that waters are tending toward neutral but remaining basic in nature at present.

Weighted Averages Method

Of the 40 known species recorded in the fossil samples 34 were found in the modern calibration set in EDDI. The mean jackknife estimates of pH correlate well ($r^2 = 0.7567$, RMSE = 0.50937) with the weighted average (inverse deshrinking) pH estimates. The general trend observed in the reconstruction corresponds well with both this study (Figure 24) and the analysis conducted by Cornish-Bowden (2005).

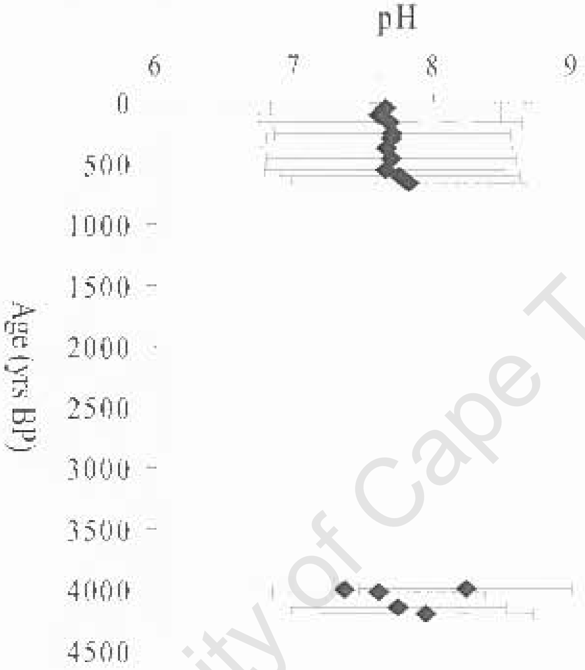


Figure 25: pH reconstruction with errors, using diatom reconstruction program ERNIE indicating general trend of changing pH over time (yrs BP)

As in the species classification above (Figure 24), the reconstructed values indicate a rather alkaline environment decreasing towards neutral by ~ 4 ka then a sudden and rapid increase towards a more alkaline environment is detected (Figure 25). The more alkaline conditions may have prevailed during the hiatus but without more information, this remains speculative, although Cornish-Bowden's (2005) study does suggest the same trend for changes in pH over this interval. The last 700 years sees relatively stable pH conditions fluctuating within 0.1 units of 7.5, with a downward trend in the most recent samples.

5.3.3 Life Form:

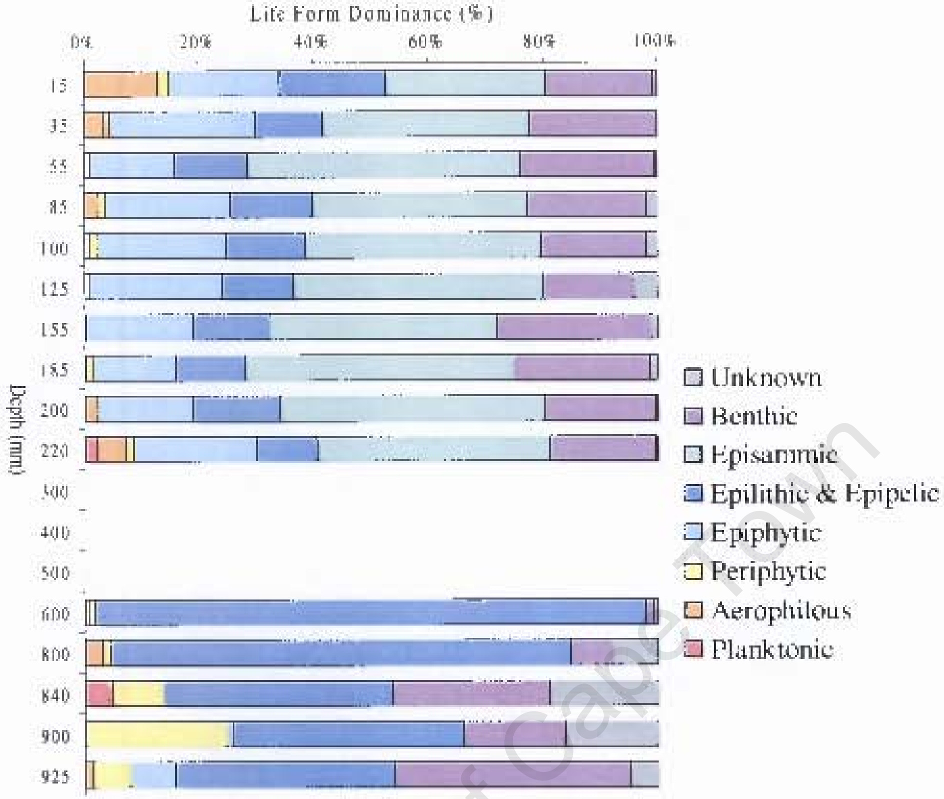


Figure 26: Percentage representation of life form salinity preferences of individual species over depth

Planktonic species are rare in the fossil assemblage only occurring twice, once just prior to the onset of the ~4 ka event (840 mm) and then again about 700 years ago (220 mm). These two episodes may indicate periods of increased water levels. Other than these two exceptions, the fossil diatom assemblage is dominated by typically benthic flora. A shift toward predominantly epipelic and epilithic diatoms occurs by about 4000 years ago (600 mm), these taxa are found attached to rocks or living on fine sediment and at one point comprise nearly 95% of the assemblage. Prior to this dominance, a notable portion of the fossil diatoms were sessile organisms living on the bottom of the lake but are eventually outcompeted by the epipelic and epilithic component. After the 3300 year gap in the sedimentation, the flora is predominately comprised of benthic organisms; with epipelic and epilithic species still major constituents. These three categories combined, vary between 100% and 85% of the assemblage from 700 years ago to the present. The decrease in the benthic flora near the surface of the core is not contributed to an increase in the periphytes nor to the planktonic component but rather to the emergence of aerophilic species which are able to survive outside the water; this may indicate a gradual lowering in water level. The trend observed can be subdivided into two groups; the first incident spans from 700 years ago (220 mm) to 450 years ago (155 mm) where aerophilous taxa initially contribute approximately 5% towards the diatom assemblage only to gradually disappear by 450 years ago. The second incident spans from 400 years ago to present and sees the re-emergence of the aerophilic taxa from just above zero percent to nearly 15% of the total taxa present.

5.3.4 Conductivity:

Conductivity is the measure of the ability of water to pass an electrical current. Several factors affect the conductivity of water these are the presence of inorganic dissolved solids such as chloride, nitrate, sulfate and phosphate anions or sodium, magnesium, calcium, iron and aluminum cations; organic compounds such as oil, phenol and alcohol, changes in temperature and the underlying geology (USEPA, 2006). Therefore, low conductivity may be the result of either cold water temperatures, a large amount of organic pollution or a low concentration of inorganic ions and vice versa. A measure of conductivity is useful in determining the electrolyte content (USEPA, 2006); as a result high electrolyte content would be correlated to high conductivity.

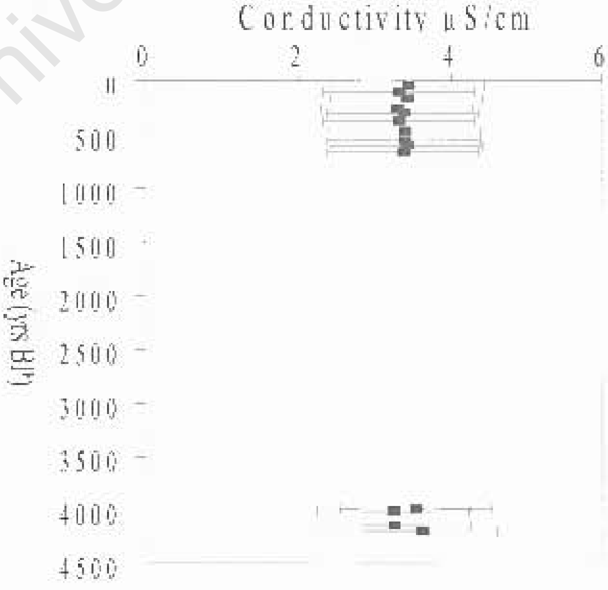


Figure 27: Conductivity reconstruction with errors, using diatom reconstruction program ERNIE, indicating general trend of changing conductivity over time (yrs BP)

To determine conductivity two methods are employed, the one is based on the specific requirements of taxa present per sample and the other uses weighted averages to reconstruct inferred values over time. The same training set was used to reconstruct conductivity as that used for pH. The mean jackknife estimates of conductivity correlate well with the weighted average (inverse deshrinking) conductivity estimates, with an r^2 of 0.76608 and a RMSE of 0.47504. However, the reconstruction appears to markedly underestimate Groenvlei's conductivity through time, indicating values which closely resembles those of distilled water (Figure 27). The examination of the diatom community suggests that, for the time period ~ 4.2 ka to ~ 4 ka, electrolyte content was relatively high, with species such as *Cocconeis engelbrachtii* and *Rhopalodia gibba*, which enjoy water habitats with highly elevated electrolyte content being most abundant (Bate *et al.*, 2004). Following the hiatus, electrolyte rich waters are inferred by the dominance of taxa such as *Staurosira elliptica* and *Staurosirella pinnata* (Kelly *et al.*, 2005).

5.4 Conclusions:

The water chemistry of Groenvlei during the period spanning from ~ 4.2 ka to ~ 4 ka experiences rapid changes in all determined parameters suggesting a dynamic system responding to changing environmental conditions during the mid-Holocene. On the contrary, over the last 700 years conditions appears to have remained relatively stable in all environmental variables; including pH, salinity and conductivity.

Chapter 6. Discussion

6.1 Introduction:

When attempting to reconstruct past environments certain fundamental principles are applied, the most well known being the uniformitarian approach, which implies that fossil organisms have the same biological and environmental requirements as their modern day counterparts (Lawrence, 1971). Thus, by transferring an organism's modern ecological situation to its fossilised occurrences within the palaeorecord, one can create a snapshot of the environment at the time of deposition and with it resolve external environmental factors relating to climate and distribution. The paleorecord may manifest itself in various forms, although as demonstrated in this thesis, lake sediments have shown particular promise in this regard. Changes within a lake related to environmental drivers are usually rapid and normally have knock on effects on the biological community; in this way, the examination of fossil assemblages can provide key insights into changes in the environment and their related causes.

The development of an acceptable chronology using two dating methods in this study has allowed for a detailed environmental reconstruction using diatoms as a proxy. However, sand movement during certain periods of the Holocene has disturbed the preservation of fossil material, resulting in two discrete units of fossil assemblage accumulation for analysis. These units span from depths 925 – 600 mm and 220 mm to the top of the core and correspond to interpolated ages of ~ 4.2 ka to ~ 4000 years BP and 700 years ago to present, respectively.

Both periods are of interest to the development of Groenvlei and the evolution of the region. The lower unit spans two previously identified limnological stages (Martin, 1968); this transitional period from Marine Stage II to Lagoon Stage I was associated with one of two climatic alternatives as expressed by the pollen sequence. The pollen evidence suggests an environment that was not conducive to forest spread, being either too dry or too warm, although Martin (1968) proposes a second possible explanation: that of a wetter climate than present with forest vegetation being restricted by active sand movement. Pollen (Duncan, 2006) and sediment analysis

(Cornish-Bowden, 2005) on the same Groenvlei core presented in this study offer support for the latter suggestion, with both Cornish-Bowden (2005) and Duncan (2006) presenting evidence indicating higher rainfall in the area during this time. Indeed, the region was "...potentially influenced by warm sea surface temperatures of the adjacent ocean, [and] under [the] dominance of westerly circulation" (Duncan, 2006, p. 99). The division from the marine stages to the lagoonal stages represents successively lower salinity levels, although salinity varied considerably during this time the separation between the two stages is co-incident with the ultimate extinction of marine diatom species (Martin, 1959)

The upper unit encompasses the last 700 years and includes recent climatic events which have been indicated in other palaeoclimatic studies such as those conducted in the Cango Caves (Talma and Vogel, 1992) and Makapansgat Valley (Holmgren *et al.*, 1999). Both speleothem records point to 16th and 17th century (0.45 ka and 0.35 ka) cooling during what is now termed the Little Ice Age and intermittent 10th century (1.1 ka) Mediaeval Warming, although the exact nature and extent of these events are uncertain both in terms of timing and amplitude of temperature change. The upper fossiliferous depositional zone at Groenvlei begins around the time of the termination of the Mediaeval Warming Period (around 630 cal yrs BP) and encompasses the whole of the Little Ice Age (Holmgren *et al.*, 1999) and the expansion of colonial influence since the mid 18th century (~150 cal yrs BP) (Duncan, 2006).

The geological development of the Groenvlei system over the last 4500 years has been intermittently recorded in the fossil diatom assemblage. Through the assessment of the fossil assemblages, it is possible to correlate and determine changes in the Wilderness Embayment through time and relate this to changes in climatic influence and the environment as well as indicating changes in water chemistry, water temperature and water level. The interpretation below is, accordingly, compared with other Holocene palaeoenvironmental records within the region.

6.2 Synthesis:

6.2.1 ~ 4.2 ka to ~ 4 ka:

The depositional unit spans for approximately 200 years and indicates radical changes in the physiochemical parameters of Groenvlei around the time. The period commences after the partial stabilisation of the coastal dunes in the region (Butzer and Helgren, 1972) and terminates at about 4000 yrs BP when dunes once again became unstable (Martin, 1968). The lake substratum appears to be consistent with fine sediments providing a suitable environment for diatoms to prosper. The diatom assemblage suggests that conditions were initially alkalibiontic and brackish to brackish fresh with high mineral content. Over the next 200 years salinity becomes highly variable but with an overall trend toward a fresh brackish habitat; pH follows suit as water alkalinity advances toward neutrality. Water levels appear to be higher than presently observed, as witnessed through the abundance of diatom fossils some distance from the present day shoreline and remains relatively stable during this period; that is until the transition from the marine stage to the lagoonal stage; where an increase in planktonic species occurs directly followed by the appearance of aerophilic taxa. The planktonic component coupled with the declining pH toward neutral may allude to increases in rainfall resulting in a rise in water levels within Groenvlei (see Chapter 2.3.3); allegedly the climatic mechanism behind the wetter climate during this period is the greater influence of Atlantic cyclones to the south-western Cape (Hassan, 1997). Whereas the sudden increase in the aerophilic component at the expense of planktonic taxa directly afterwards indicates a shift toward a drier climate. Scott and Lee-Thorp (2004) suggested that around 4000 BP a short-lived dry spell occurred, which could possibly be the reason behind the growth of aerophilous taxa as water levels would drop due to decreases in rainfall. Evidence from the transitional period implies an intensely dynamic environment responding to changes in source water supply. The changes in the source water may have led to increases in organic concentration coupled with decreasing conductivity which is evident during this period as species, such as *Amphora veneta* and *Rhoicosphenia abbreviata* which are tolerant of moderate to heavy concentrations of organic material are dominant (Kelly *et al.*, 2005); this could be in response to changes in rainfall increasing runoff from the surrounding terrain (Lewis, 2008). Much of this episode may be interpreted as the response of the lake to the marine intrusions which frequently entered Groenvlei creating a slow flowing tide as shown by the subdominance of *Rhopalodia gibba* in the earlier stages (Kelly *et al.*, 2005). Isotopic analysis on molluscan shells from the Groenvlei core, GK2, showed a correlation between the $^{12}C/^{13}C$ and $^{18}O/^{16}O$ signal which was attributed to the mixing of two fluids with different isotopic composition (Kirsten, 2005); this correlation may confirm the sea water intrusions as well as the full mixing of the other source waters in the lake creating the brackish to brackish fresh environment. The later stage, as depicted by Zone b, occurred concurrently with the 4 ka event and shows the struggle between two natural forcing factors, viz the rapid rise in sea level at around 4000 yrs BP (Baxter and Meadows, 1999) and the remobilisation of the sand dunes (Martin, 1968). The interplay between these processes seems to have affected the salinity and pH of the lake and brought on its isolation from Swartvlei to the west, effectively filling in the channel and creating a lagoonal environment which was in full effect at the end of the period as shown by the dominance of *Anomoeoneis sphaerophora* (Hedenstrom and Risberg, 1999). The increase in epilithic taxa near the end of the period is also indicative of an enhancement in sediment movement and dune instability.

6.2.2 ~ 4 ka to 0.7 ka:

Little can be said about this period as the preservation of fossil material was minimal. Indeed, sediments of this age are not sampled in the Groenvlei cores. Duncan (2006) encountered the same problem during her pollen analysis, stating that the sand section imposed a "significant hiatus in the record" and declined to make any environmental inference. Therefore, it would be unwise to make assumptions about the environmental conditions on the basis of the diatom remains that do occur in this facies. It may be that the occurrence of *Campylodiscus clypeus* frustules in the sedimentary sequence during this period indicates increased salinity, a pH greater than seven and increased water levels due to the planktonic nature of the species. In fact, the material making up the sand bar, which extends from 830 mm to 330 mm is consistent with aeolian sedimentation as noted in Kirsten (2005) and Cornish-Bowden (2005). It is, therefore, likely that diatom remains were transported by wind into the Groenvlei catchment during the active dune destabilisation period and cannot be used to infer environmental conditions during this time.

6.2.3 ~ 0.7 ka to the present:

The discussion below is subdivided into two time periods; one relating to the Little Ice Age and the other correlating to the period of European occupation along the south coast of South Africa.

Little Ice Age Period (1300 – 1800 AD)

The Little Ice Age is a global climatic phenomenon which lasted five centuries terminating by about 1810 AD (140 yrs BP), although it has rarely been observed in the southern African palaeorecord (Holmgren *et al.*, 1999). While it is generally accepted that the Little Ice Age is evident in some records across South Africa its influence on different regions has been variable (e.g. Talma and Vogel, 1990; Holmgren *et al.*, 1999; Tyson *et al.*, 2000). The Makapansgat Valley stalagmite record suggests that this period was associated with lower than average temperatures and drier conditions related to the regional expansion of the circumpolar westerlies (Holmgren *et al.*, 1999). During the dry spells an increase in frequency of deep, intense thunderstorms and hail is experienced over the interior as oppose to the "…persistent warm rainfall from middle-level stratiform cloud bands associated with tropical-temperate troughs" which occurs during wetter periods (Holmgren *et al.*, 1999, p. 303). However, through pollen analysis of the GK1 core Duncan (2006) proposed that this period was rather moist due possibly to increased frontal systems trailing across South Africa owing to the expansion of the circumpolar vortex resulting in reduced upwelling and the introduction of warm Agulhas current surface water plumes towards the coast. Duncan's (2006) analysis attributed the decline in vegetation around the Groenvlei site during the Little Ice Age to the significance of changing temperatures on the physiological needs of the vegetation.

The palaeorecord at Groenvlei based on the diatom assemblages recommences around 1300 AD (650 yrs BP) with conditions appearing to be rather brackish fresh tending toward fresh brackish, strongly alkaline, with a pH value nearing eight and moderately high mineral content. Groenvlei's ecology during the Little Ice Age (LIA) is principally dominated by four species which frequent alkaliphilous, moderate to high electrolyte content and fresh brackish habitats (Kelly *et al.*, 2005). Two of these species, namely *Staurosira elliptica* and *Staurosirella pinnata* are episammic (Sylvestre *et al.*, 2001; Kelly *et al.*, 2005), a clear indication of the sandy matrix within the root mat. The sub-dominance of *Anomoeoneis sphaerophora* and *Cyclotella meneghiniana* may be suggestive of high levels of organic loading and even eutrophication (Kelly *et al.*, 2005). It is important at this point to specify that Groenvlei today is without outlet and is mainly fed by groundwater and surface runoff the chemistry of which is related to changes in the watershed. The wetter conditions during the Late Holocene would have increased surface runoff causing widespread erosion leading to changes in the water chemistry (Lewis, 2008); hence altering biological community. A sudden and dramatic increase of *Epithemia adnata* about 450 years ago is consistent with a warming phase during the mid 1500s AD; this was also evident in the Holmgren *et al.* (1999) $\delta^{18}O$ analysis of the Makapansgat Valley stalagmite which indicates a slight warming between 1500 and 1675 (450 yrs BP and 275 yrs BP). The warming phase was coupled by a minor reinforcement in alkalinity and salinity as well as the renewed introduction of aerophilic taxa implying a drop in water levels; this could be interpreted as a decrease in rainfall as the circumpolar vortex weakened. The aerophilic component remains until the mid 1600s then diminishes in presence as the species are replaced with benthic taxa relating to a recovery of water levels equivalent to that experienced prior to the warming phase. Many species preferring brackish waters do not re-emerge after the warming period and water conditions appear to be eutrophic, tending more toward fresh brackish and alkaliphilous. The near disappearance of *Epithemia adnata* and *Rhopalodia gibberula* by the early 1700s AD corroborates other records suggesting remarkable cooling during the early half of the 18th century which has been associated with sunspot activity minima (Tyson *et al.*, 2000).

During the first half of the 18th century, Groenvlei remains relatively stable with respect to water quality boundaries and lake levels, however with the increasing human influence over the next two and a half centuries conditions start reflecting the changes occurring in the watershed of this coastal lake.

Period of Human Occupation (1750 – present)

Historical records indicate human activity within the region by the mid 18th century as resources in the floodplain and its adjacent areas became apparent (Allanson and Whitfield, 1983). By 1730 AD cattle farmers infiltrated the Knysna/Tzitzikamma Forests and by 1790s permanent settlements were established (Butzer and Helgren, 1972). The value of the forest was apparent to these early settlers who began intrusive logging operations and section clearing of the biome by the late 19th century introducing exotic plant species, changing the vegetation composition and altering the watershed regime, the magnitude of which Duncan (2006) likened to that seen during the Little Ice Age.

The baseline conditions which were present during the Little Ice Age are still prevalent during this period, with the same four species dominating the assemblage. However, the occurrence of the episammic species, *Staurosira elliptica* and *Staurosirella pinnata*, which remained relatively stable during the previous stage; begin to dramatically decrease in the later phase of the sequence toward the present day indicating a reduction of coarse sediment supply into the lake. Cornish-Bowden's (2005) sediment analysis showed a considerable decrease in the sand constituent of the textural composition of the Groenvlei core but increases in mud and organic matter. The changes in the diatom assemblage relating to sediment supply shifts pertain to the timing of human interference in the natural dune activity of the region through the introduction of alien vegetation and dune stabilisation programs since the mid 1800s (Hellström, 1996) (see Chapter 4.3.2).

Water quality is variable; salinity appears to be increasing toward brackish to brackish fresh conditions, pH is on a very minor downward curve but still remaining strongly in the alkaline range and water levels drop significantly as aerophilic species quadruple in frequency towards the present. The increase in taxa which favour periodically dry habitats is directly related to the dropping water levels and the receding shoreline of Groenvlei coupled with the advance of the reed swamp presently observed around the periphery of the lake. A decidedly electrolyte-rich environment is established, as changes in the watershed alter the chemical make up of runoff water into the lake. Runoff is one of the main inlet water sources into Groenvlei. The change in the runoff water chemistry as well as an upward inclination in eutrophic and hypertrophic species, such as *Hantzchia* cf. *amphioxys*, *Pseudostaurosira brevistriata* and *Nitzschia* cf. *amphibia* is discernible, emphasizing the increase in nutrients into the lake system possibly due to modified farming techniques occurring on the fen along Groenvlei's eastern shore and within its catchment (Martin, 1960[b]; Duncan, 2006). Duncan (2006) goes as far as stating that the selling off of allotments within the Groenvlei catchment for agricultural purposes probably disturbed the rather sensitive nutrient cycle, causing ramifications in plant succession, thus altering runoff and groundwater quality ultimately affecting the biological community of Groenvlei.

It is clear, however, that not all changes observed in the assemblage are solely attributable to human interference as changes in the climate over the last 250 years could be an additional underlying mechanism as witnessed throughout the remainder of the sequence. However, the complexity involved in trying to disentangle the climate signal from human influence on the environment is beyond the scope of this study and further research is required to achieve an indication of the course of both natural and artificial processes present in the region. It could be presumed that climatic conditions post LIA set the course in Groenvlei's modification as detailed previously and human influence amplified the signal.

Chapter 7. Conclusions

The fundamental objective of this study was to supply an accurate account of the changes in natural processes over time by using the fossil diatom assemblage preserved in the lake sediments of Groenvlei as a medium. For this to be achieved an acceptable chronology was constructed using two dating methods on which the variations in the fossil assemblage could be correlated. By undertaking both quantitative and qualitative approaches several environmental parameters where determined, aiding in developing a detailed environmental reconstruction for the south coast region. Salinity, pH, water levels and conductivity were determined through an ecologically based indicator study using species classification schemes as a means to ascertain variations on the environment. Conductivity and pH were further analysed quantitatively, offering a specified numerical range to the changes in the physiochemical parameters and were verified by the classification schemes previously undertaken. The outcome of the combined techniques has supplied a reasonably high temporal resolution study against which information on patterns of climatic variability could be assessed.

Groenvlei has proven to be a vital source of information pertaining to the evolution of the Wilderness region during the Holocene and has demonstrated itself to be an excellent receptor to changes in external environmental processes, documenting these variations in fossil rich sediments. The development of Groenvlei would best be described as cycles of accumulation and erosion of sediment through time. Two such events of accumulation are those labelled as the ~ 8 ka and ~ 4 ka events where rapid and near instantaneous deposition of sand disturb the preservation of fossil material. Both events are preceded by extensive erosion lasting a few millennia then by continuous sediment deposition lasting a few centuries. It was during these short lived depositional phases that fossil rich sediment was laid down and provides the focus of this study.

Groenvlei in itself exists on an environmental gradient related to the proximity of the lake's ecosystem to sources of marine water and freshwater; in particular the core site examined in this study has shown a direct relationship between its proximity to the proposed channel linking Groenvlei to the sea via Swartvlei and environmental changes experienced during the mid-Holocene. Of the two discrete depositional units analysed, that corresponding to the period of ~ 4.2 ka to ~ 4 ka demonstrated the full effects of sea transgressions and regressions on a coastal lake. Ramifications of which were felt throughout both the abiotic and biotic constituents of the ecosystem as altering salinity, pH, nutrient availability and water levels resulted in the modification of the biological community in response. This two hundred year episode saw the metamorphosis of a lake from a marine embayment to a coastal lake caused by the remobilisation of local dunes and minimised marine influence due to the filling in of the channel. The second unit spanned the last seven hundred years and extended the full length of the Little Ice Age, as well as the beginnings of human interference in the region since the mid 1700s AD. The natural climate phenomenon identified as the Little Ice Age caused widespread cooling and wetter conditions along the coast resulting in increased water levels and fresh water conditions; it is however, punctuated by a warming period approximately 400 years ago causing a decrease in rainfall and hence in water levels and increased water temperatures. The onset of human occupation within the region exacerbated conditions leading to increases in nutrient availability and dropping water levels, these changes in the catchment relating to forestry and agriculture can not be solely attributed to Groenvlei's environmental state as further investigations are required to ascertain climatic forcings during this period.

The changes observed during this analysis appear to be the result of the interplay of natural processes within the watershed and the region during the Holocene and increased human influence over the last two and a half centuries. While this project has contributed knowledge of environmental conditions during certain periods of the Holocene; a substantial hiatus in the palaeorecord between the depositional units analysed still poses questions on climatic causes and effects during these phases. Lastly, the possibility of overlapping previous studies to provide an outline of natural circumstances where this study has fallen short is an option in addition to the possibility of substantiating the findings of this study.

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Appendix:

Table 7: GK2 Total Diatom Counts.

Species	15	35	55	85	100	125	155	185	200	220	600	800	840	900	925	1000
Hantzchia cf. *amphioxys*	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Achnanthes sp	0	0	0	3	0	4	2	3	0	0	0	0	0	0	0	0
Achnanthidium minutissima	24	7	0	0	0	0	0	0	0	1	2	30	40	0	0	0
Amphora coffeaeformis	26	3	7	4	5	0	2	4	6	0	0	0	0	0	0	0
Amphora commutata	14	15	25	12	19	23	20	20	26	12	10	2	19	26	5	0
Amphora ovalis	0	11	0	8	5	3	5	6	0	1	0	0	0	0	0	0
Amphora veneta	0	0	0	0	0	0	0	0	0	1	44	0	11	1	2	0
Anomoeoneis sphaerophora	4	4	12	18	14	15	18	10	28	18	91	7	6	0	8	0
Campylodiscus clypeus	0	0	0	0	0	0	0	0	0	7	0	0	8	0	0	0
Cocconeis engelbrachtii	1	15	8	35	35	29	32	30	13	8	2	8	45	26	107	0
Cocconeis placentula	0	2	0	8	11	5	14	12	4	0	0	12	6	8	55	0
Cyclotella meneghiniana	7	3	14	16	13	6	14	10	12	10	0	0	0	0	0	0
Cymbella pusilla	1	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0
Cymbella sp	4	0	2	6	0	4	3	3	0	0	0	0	0	3	3	0
Diploneis ovalis	0	1	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Epithemia adnata	12	6	16	13	14	19	36	12	15	5	0	0	0	0	0	0
Fallacia pygmaea	10	4	0	4	3	0	1	6	0	3	0	0	0	1	0	0
Gomphonema gracile	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0
Hanneae sp	0	0	0	0	0	0	0	0	0	0	0	0	0	20	12	0
Mastogloia braunii	19	21	31	6	9	9	19	12	13	3	0	0	5	14	92	0
Mastogloia elliptica	0	0	0	0	0	11	30	24	30	17	0	0	0	0	0	0
Mastogloia smithii	0	3	0	0	5	0	0	0	0	1	0	0	0	0	0	0
Melosira sp	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0
Navicula cinta	0	0	0	2	0	0	0	0	0	6	0	0	0	0	3	0
Navicula cryptocephala	21	7	13	10	9	4	3	5	6	0	63	20	12	7	14	0
Navicula oblonga	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
Navicula platystoma	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0
Navicula sp 1	0	0	0	0	10	2	0	0	0	0	0	0	0	0	0	0
Navicula sp 2	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
Navicula sp 3	0	0	0	0	0	0	0	0	0	1	2	30	40	0	0	0
Nitzschia cf amphibia	29	7	4	7	0	0	0	1	9	10	3	0	2	0	0	0
Nitzschia cf. *chasei*	21	9	1	3	5	4	0	0	1	0	0	18	0	0	3	0
Nitzschia linearis	0	0	0	0	0	0	0	0	0	0	0	2	0	13	0	0
Pinnularia acrosphaeria	0	3	2	11	5	4	6	3	2	2	0	0	5	0	0	0
Pinnularia cf. *ignobilis*	0	0	0	0	0	0	0	0	0	0	0	4	6	2	0	0
Pinnularia cf. *viridiformis*	39	59	64	34	33	19	31	40	26	18	0	1	0	0	0	0
Pinnularia sp	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Pseudostaurosira brevistriata	38	100	42	86	68	83	44	47	53	58	0	0	0	0	0	0
Rhoicosphenia abbreviata	0	0	0	0	0	0	0	0	0	0	130	411	73	32	92	0
Rhopalodia gibba	0	1	0	2	3	0	0	0	0	1	3	2	25	62	32	0
Rhopalodia gibberula	16	7	9	4	11	2	1	4	3	4	0	0	0	3	38	0
Rhopalodia sp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
Staurosira elliptica	121	148	215	155	181	180	167	171	183	101	0	0	0	0	0	0
Staurosirella pinnata	13	27	25	33	32	32	28	59	42	28	0	0	0	0	0	0
Synedra acus	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Synedra tabulata	25	7	7	6	18	8	11	9	11	0	0	0	0	0	0	0
Synedra ulna	26	14	8	12	8	7	3	3	5	2	0	2	15	19	11	0
Unknown sp 1	0	0	0	0	0	0	0	0	0	0	1	15	15	6	5	0
Unknown sp 2	0	0	0	0	0	0	0	0	0	0	0	0	4	14	0	0
Total	485	484	505	500	516	488	490	494	489	318	351	566	355	264	486	0

Table 8: Summary of Life Form, Salinity and pH, referenced

Species	Life form	Salinity	pH
Achnanthidium minutissima	Benthic (Taylor *et al.*, 2007)	Fresh brackish (Kelly *et al.*, 2005)	Circumneutral (Kelly *et al.*, 2005)
Amphora coffeaeformis	Epipelic, Epiphytic or aerophilous (El-Awamri *et al.*, 2007)	Brackish (Sylvestre *et al.*, 2001)	
Amphora commutata	Epilithic (Camargo and Jiménez, 2007)		
Amphora ovalis	Epipelic & Epilithic (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Amphora veneta	Epilithic (Edwards *et al.*, 2006)	Brackish fresh (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Anomoeoneis sphaerophora	Epipelic (Kelly *et al.*, 2005)	Brackish fresh (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Campylodiscus clypeus	Planktonic (Kelly *et al.*, 2005)	Brackish (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Cocconeis engelbrachtii	Benthic (Taylor *et al.*, 2007)		
Cocconeis placentula	Epilithic & Epiphytic (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Cyclotella meneghiniana	Benthic & Planktonic (Yacobaccio and Morales, 2005)		Alkaliphilous (Yacobaccio and Morales, 2005)
Cymbella pusilla	Benthic (Saros and Fritz, 2000)	Fresh brackish (Sylvestre *et al.*, 2001)	
Cymbella sp	Epipelic and Epilithic (Kivrak and Gürbz, 2005)		
Epithemia adnata	Epiphyton or Epilithon or Periphyton (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Fallacia pygmaea	periphyton (Hassan *et al.*, 2006)	Brackish fresh (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Gomphonema gracile	Phytoplanktonic - Epiphytic (Lane and Brown, 2007)	Fresh brackish (Kelly *et al.*, 2005)	Circumneutral (Kelly *et al.*, 2005)
Hantzchia cf. amphioxys	Aerophilous (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Circumneutral (Kelly *et al.*, 2005)
Mastogloia braunii	Benthic (Edwards *et al.*, 2006)	Brackish (Edwards *et al.*, 2006)	
Mastogloia elliptica	Benthic (Edwards *et al.*, 2006)	Brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Mastogloia smithii	Epiphyton (Lane and Brown, 2007)	Brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Navicula cinta	Aerophilous & Epipelon (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Navicula cryptocephala	Epipelic in F/water (Poulíĉkova and Mann, 2006)	Fresh brackish (Kelly *et al.*, 2005)	Circumneutral (Kelly *et al.*, 2005)
Navicula oblonga	Benthic (Jacobs *et al.*, 2007)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Navicula platystoma	Benthic (Korol, 2005)	Indifferent (Korol, 2005)	
Nitzschia cf amphibia	Aerophytic, planktonic or benthic (El-Awamri *et al.*, 2007)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Nitzschia linearis	Epipelic in F/water (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Pinnularia acrosphaeria	Benthic (Caljon and Cocquyt, 1992)		
Pinnularia cf. ignobilis	periphyton (Cremer *et al.*, 2001)	Fresh (Cremer *et al.*, 2001)	
Pinnularia cf. viridiformis	Benthic (Nguetsop *et al.*, 2004)		
Pseudostaurosira brevistriata	Epiphytic or tychoplankton (Yacobaccio and Morales, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Rhoicosphenia abbreviata	Epiphyte & Epilithon (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Rhopalodia gibba	Periphytic (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkalibiontic (Kelly *et al.*, 2005)
Rhopalodia gibberula	Epiphytic (Yacobaccio and Morales, 2005	Brackish Fresh (Yacobaccio and Morales, 2005)	Circumneutral (Yacobaccio and Morales, 2005)
Simonsenia cf. delognei	Aerophilous (Kelly *et al.*, 2005)	Brackish fresh (Kelly *et al.*, 2005)	
Staurosira elliptica	Episammic or tychoplanktonic (Sylvestre *et al.*, 2001)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Staurosirella pinnata	Episammic or Epipelon (Kelly *et al.*, 2005) (Hassan *et al.*, 2006)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Synedra acus	Epiphytic (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)
Synedra tabulata	Epiphytic (Vos and de Wolf, 1988)		
Synedra ulna	Epiphyte & Epilithon (Kelly *et al.*, 2005)	Fresh brackish (Kelly *et al.*, 2005)	Alkaliphilous (Kelly *et al.*, 2005)