

# **A Diatom-based Palaeoclimatic Reconstruction for the Border of Leribe-Makhotlong-Butha-Buthe Districts, Eastern Lesotho Highlands**

A Dissertation submitted to the Faculty of Science in fulfilment of the requirements for a Master of Science degree.

School of Geography, Archaeology and Environmental Studies

University of the Witwatersrand, Johannesburg

Lungile Ncube



*Butha-Buthe Maloti Mountains, Lesotho highlands.*

Supervisor: Prof. Jennifer M. Fitchett

Co-supervisor: Prof. Chris J. Curtis

July 2021

## DECLARATION

I fully understand the meaning of plagiarism, and I declare that this dissertation is my own work, save for which is properly acknowledged. This dissertation is submitted for the Master of Science degree at the University of the Witwatersrand in Johannesburg. I have not previously submitted this work for any purpose, including obtaining a degree or qualification at this or any other university.



\_\_\_\_\_  
Lungile Ncube

\_\_16/07/2021\_\_\_\_\_  
Date

## ACKNOWLEDGEMENTS

First and foremost, I would like to thank God for granting me an opportunity to further my studies and for also seeing me through it all!

To my loving and supportive fiancé, Nqobile – thank you for being there for me throughout this journey. Thank you for indulging in conversations regarding my research although most of it probably makes no sense to you as an engineer.

To my mother, Lindiwe and my sister, Simesihle I also want to thank you so much for your unwavering support, for always believing in me and encouraging me. You guys are absolutely awesome! To my son, Langa, you have been such a light in my life, I am so grateful for you!

A very big thank you to my supervisor, Prof Jennifer Fitchett, and my co-supervisor Prof Chris Curtis. Thank you for your guidance, input, and supervision. Also, thank you so much for making my fieldwork experience a beneficial (academically) and memorable one! You both are incredible people and remarkable scientists. I would further like to thank you Prof Fitchett for your support, for believing in me and my capabilities. Thank you for your close supervision in the laboratory, I have honestly learnt so much from you, you are amazing! In my books, you have gone over and beyond, thank you!

I would like to thank the iThemba laboratories for all their resources that allowed me to complete my AMS dates for this research. A very big thank you to Prof Stephan Woodborne along with his team - including Moshabi Silidi (whom I worked closely with), for their time and assistance in the laboratory. I acquired so many valuable skills while working there, thank you! The laboratories at the School of Geography, Archaeology and Environmental Studies (GAES) at Wits were also pivotal in the preparation and analyses of the results for this research, I am thankful for all the resources that were availed to me during the compilation of this research.

A very big thank you to Dr Sarah Roffe, for taking the time to read and give valuable feedback on some of the chapters in this dissertation.

I would like to acknowledge the DSI-NRF Centre of Excellence in Palaeoscience (CoE), for their financial support towards my Master's degree. I would also like to acknowledge the grant funding under my supervisor for funding all the fieldtrip expenses to Lesotho and laboratory (diatoms) resources for this research.

## ABSTRACT

The eastern Lesotho highlands presents an important site for palaeoenvironmental research in southern Africa, as it represents a niche environment which is enriched with a unique biodiversity and characterised by distinct climatic patterns strongly influenced by topography. Lesotho, with its montane wetlands, is invaluable to southern Africa as these form part of the Senqu-Orange River headwaters, one of the most important rivers draining the subcontinent. The region of Lesotho is also characterised by susceptibility to climate change and variability, moreover, the economy and livelihoods of communities in Lesotho depend on the environment. This presents a further need to better understand past climatic and environmental change at a higher spatio-temporal resolution, such information can be used to inform adaptation strategies to cope with the long-term effects of climate change. Although highly resolved reconstructions exist for the region, they are mostly clustered along the eastern escarpment, whereas this study focused on samples from the understudied northern region of Lesotho. Therefore, this study represents the first Holocene palaeoenvironmental reconstruction in the far northern part of the eastern Lesotho highlands. The reconstruction generated from this study is therefore developed from the diatoms and sediment analyses, which were performed on sediment cores from two high altitudinal wetland sites in the vicinity of the Afriski resort, with the first site being BLMA (~3,108 m.asl) and the second site, BLMB (~2,996 m.asl). The age of the sites were temporally constrained, spanning 4,200 cal yr BP for site BLMA and 1,450 cal. yr BP for site BLMB, based on Accelerator Mass Spectrometer (AMS) dating. The proxies used in this study indicate fluctuations between wet and dry conditions. ~4,200 – 3,200 cal yr BP is characterised by a wet period which is gradually progressed by a dry period at ~2,980 – 2,410 cal yrs. BP. ~2,400 – 1,145 cal yr BP is a wet period and another wet period begins for the region at ~1,145 – 750 cal yr BP with much warmer conditions than the previous wet period. At ~700 – 450 cal yr BP a dry period occurs and finally at ~400 cal yr BP – present day the diatoms suggest a wet period and a cold event ~200 cal yr BP. The results of this study indicate some similarities with other records from eastern Lesotho (Mafadi and Sekhokhong) and from palaeoenvironmental sites (Braamhoek and Ntsikeni Wetland) in South Africa. For comparisons on a global scale, the record shows evidence, or signals of the occurrence of global climatic events such as the '4.2 kyr' event, the '2.8 kyr' event, the Little Ice Age (LIA) and the Medieval Warming Period (MWP).

# Table of contents

<b>DECLARATION</b> .....	i
<b>ACKNOWLEDGEMENTS</b> .....	ii
<b>ABSTRACT</b> .....	iii
<b>Table of contents</b> .....	iv
<b>List of figures</b> .....	ix
<b>List of tables</b> .....	xi
<b>List of Naming and Style Conventions</b> .....	xii
<b>List of Acronyms and Scientific Terms</b> .....	xiii
<b>1. Chapter 1: Introduction</b> .....	1
1.1. Palaeoenvironmental reconstructions .....	1
1.2. Palaeoenvironmental proxies.....	3
1.2.1. Diatoms.....	3
1.2.2. Sediments.....	6
1.3. Understanding the Lesotho Highlands Environment .....	8
1.4. Rationale.....	10
1.4.1. Aims & Objectives.....	12
1.5. Structure of thesis .....	13
<b>2. Chapter 2: Literature Review</b> .....	15
2.1. Introduction.....	15
2.2. Early palaeoenvironmental work in southern Africa .....	15
2.2.1. Methodological advances.....	19
2.2.2. Various proxies used for palaeoenvironmental reconstruction in Southern Africa. ....	22

2.3.	Palaeoclimatic history of Lesotho .....	30
2.4.	Palaeoclimatic change in southern Africa .....	35
2.4.1.	Major climatic changes.....	35
2.4.2.	Major climatic shifts during the Quaternary .....	37
2.4.3.	Shifts in rainfall zones.....	40
2.5.	Diatoms In palaeoenvironmental reconstruction .....	41
2.5.2.	Global studies .....	41
2.5.3.	Southern African studies .....	46
2.5.4.	Palaeoenvironmental research in Lesotho studies .....	49
2.6.	Synthesis.....	56
<b>3.</b>	<b>Chapter 3: Study site.....</b>	<b>57</b>
3.1.	Lesotho .....	57
3.1.1.	Topography.....	59
3.1.2.	The Eastern Lesotho highlands.....	60
3.1.3.	Soils & Geology of Lesotho.....	61
3.1.4.	Climate.....	62
3.1.5.	Hydrology and Wetland properties.....	65
3.1.5.1.	Hydrology .....	65
3.1.5.2.	Wetlands.....	66
3.1.6.	Vegetation .....	69
3.1.7.	Environmental challenges .....	72
3.2.	Specific study sites.....	74

3.2.1.	Site one: BLMA .....	75
3.2.2.	Site two: BLMB .....	76
<b>4.</b>	<b>Chapter 4: Methodology .....</b>	<b>78</b>
4.1.	Fieldwork .....	78
4.2.	Laboratory work .....	81
4.2.1.	Laboratory samples .....	81
4.2.2.	Accelerator mass spectrometry (AMS) Dating .....	82
4.2.2.1.	Preparations for AMS dating .....	84
4.2.3.	Analysis of sediment.....	86
4.2.4.	Diatom preparation .....	89
4.3.	Microscope work.....	91
4.3.1.	Diatom identification.....	91
4.3.2.	Counting diatoms .....	92
4.4.	Statistical Analyses: .....	92
4.4.2.	Age-depth modelling.....	92
4.4.3.	Statistical analysis of diatom data.....	93
4.4.3.1.	Principal Component Analysis.....	95
4.4.3.2.	Clustering.....	95
4.4.4.	Visual representation .....	96
<b>5.</b>	<b>Chapter 5: Results.....</b>	<b>98</b>
5.2.	Site BLMB.....	98
5.2.1.	BLMB: Chronology and accumulation of sediment.....	98

5.2.2. BLMB: Stratigraphy and sediment analysis of profile .....	100
5.3. Site BLMA.....	106
5.3.1. BLMA: Chronology and sediment analysis profile.....	106
5.3.2. BLMA: Stratigraphy and sediment properties of profile .....	108
5.3.3. BLMA: Diatoms.....	114
<b>6. 6. Discussion .....</b>	<b>133</b>
6.1 Introduction.....	133
6.2. Palaeoenvironmental Reconstructions .....	133
6.2.1. Environmental variables.....	135
6.2.2. Multi-proxy environmental and climate reconstructions .....	137
6.3. Comparison of data to regional palaeoenvironmental sites. ....	144
6.4. Comparison of site to global climatic events .....	150
6.5. Limitations.....	156
6.6.1. Dating of samples.....	156
6.6.2. Diatoms as a proxy .....	156
6.6.3. Contamination of samples .....	158
6.6.4. Methods for preparation.....	159
<b>7. 7. Conclusion.....</b>	<b>160</b>
7.1. Achievement of objectives .....	161
7.2. Key Findings.....	163
7.3. Future Work.....	164
<b>8. References .....</b>	<b>166</b>
<b>9. Appendices.....</b>	<b>187</b>

9.1. Raw diatom data .....	187
9.2. BLMA sediment composition data .....	189
9.3. BLMB sediment composition data.....	190

# List of figures

Figure 1.1: Image showing a variety of diatom species under an electronic microscope adapted from (Du Buf, 2002; Jalba et al., 2004).....	4
Figure 1.2: The location of archaeological, geomorphological and palaeoenvironmental study sites in Lesotho from which published palaeoclimatic inferences have been made (Fitchett et al. 2016a). ....	11
Figure 2.1: Histogram showing the use of different types of proxies used in published studies over the years adapted from (Knight & Fitchett et al., 2019). Data from 1955 to 2019.....	23
Figure 2.2: Map of Lesotho showing the locations from which published palaeoclimatic inferences (Archaeological, geomorphological and palaeoenvironmental) have been made. ....	31
Figure 2.3: Southern African sites at which published diatom-based environmental .....	48
Figure 3.1: Study site map showing Lesotho, the border of Butha-Buthe and Afriski Resort in eastern Lesotho highlands.....	59
Figure 3.2.: Images showing the coring points for the sediment profiles BLMA coring site situated within a wetland.....	75
Figure 3.3: Images showing the coring points for the sediment profile BLMB coring site situated just outside a wetland.....	75
Figure 3.4: (a & b): images showing vegetation present at the study site in the vicinity of the wetland. (c): image showing Hummocks, called thúfur, are common microtopographical features on the mires of the Lesotho mountains. ....	76
Figure 3.5: (a) Image showing the type of vegetation dominant present in in the vicinity of the BLMB study site. (b) image showing an ice rats in the vicinity of the coring site.(c) image showing the highly disturbed core site and the actual coring points.....	77
Figure 4.1: Google Earth image showing the two study sites selected for coring (BLMA and BLMB). ..	79
Figure 4.2: Summary of three principal stages in the production of radiocarbon age. ....	86
Figure 4.3: Process of sediment preparation from sediment analysis to determine organic content, carbonate content and particle size (Adapted from Fitchett, 2015). ....	88
Figure 4.4: A Summarised process of diatom preparation (Adapted from Fitchett, 2015). ....	90
Figure 4.5: Image showing cover slips containing well mixed diatom suspension in preparation for mounting the diatom slides. ....	91
Figure 5.1: The BACON output for the BLMB profile showing interpolated ages for depth throughout the core. ....	100
Figure 5.2: Changes in sediment properties throughout the BLMB profile with depth. ....	102
Figure 5.3: Changes in sediment properties throughout the BLMB profile over time. ....	103
Figure 5.4: The BACON output for the BLMA profile showing interpolated ages for depths throughout the core. ....	108
Figure 5.5: Changes in sedimentary properties throughout the BLMA profile with depth. ....	109
Figure 5.6: Change in sedimentary properties throughout BLMA profile with time (age). ....	111
Figure 5.7: CONISS output showing the two separate zones within the Lesotho wetland profile, centred on the distribution of diatoms within the profile. ....	117
Figure 5.8: PCA bi plot for the Lesotho wetland profile, illustrating samples and taxa along the PC1 and PC2 gradient, with the explanatory power of the PCs 13.48% and 8%, respectively. ....	118
Figure 5.9: Silhouette plot for diatom samples in the BLMA profile.....	120

Figure 5.10: Stratigraphic diagram of the diatom results from the BLMA sequence, grouped according to specific habitats. .... 125

Figure 5.11: Stratigraphic diagram showing the total percentages of diatoms according to habitat. 128

Figure 5.12: Diatom and sediment stratigraphic plot for BLMA sequence. .... 130

Figure 6.1: Stratigraphic diagram showing dry and wet periods throughout the BLMA sequence..... 143

## List of tables

Table 2.1: Summary of literature reviewed of numerous proxy-based studies from southern African sites, placing emphasis on proxy diversity and reliability for southern Africa. Studies are arranged in descending order according to the time period covered.....	27
Table 2.2: Key events in the Southern African palaeoclimate in chronological order. ....	39
Table 3.1: Characteristics of the physiographic zones of Lesotho (adapted from Olutayo, 2019). ....	60
Table 3.2: Annual temperatures and rainfall occurring in the different physiographic zone of Lesotho (Adapted from Sood, 2007).....	63
Table 4.1: Coring sites coordinate with the respective altitudes of the sites. ....	80
Table 5.1: AMS radiocarbon dates acquired for the BLMB profile. ....	99
Table 5.2: Sediment properties for BLMB Lesotho profile.....	105
Table 5.3: AMS radiocarbon dates acquired for the BLMA profile. ....	107
Table 5.4: Sediment properties for BLMA Lesotho profile.....	113
Table 5.5: Diatom species of the BLMA profile with their respective average and maximum percentage representation. ....	115
Table 5.6: Key species and their preferred ecologies. ....	122
Table 6.1: Summary of the keys strands of evidence for inferring wet and dry conditions. ....	134
Table 6.2: Summary of comparison between regional sites. ....	149
Table 6.3: A summary of global climatic events (Chronological order- oldest to present).....	152

## List of Naming and Style Conventions

± cal. yr BP	calibrated AMS dates; years before present (calibrated years Before Present)
~ cal. yr BP	interpolated, calibrated AMS dates which were calculated using the BACON model; years before present (calibrated years Before Present)
yr BP	un-calibrated age-dates presented in publications (years Before Present)
Ka	Kilo annum, thousand years
Kyr	kiloyears, retained in the context of events by that name (e.g. '8.2 kyr' event)
m.asl	meters above sea level
g.mol <sup>-1</sup>	SI units for the measurement for amount of substance, molar mass.
rpm	Revolution per minute; a unit of rotational speed
CuO	Copper Oxide
Fe	Iron
H <sub>2</sub> O <sub>2</sub>	Hydrogen Peroxide
<i>Fragilaria pinnata/construens</i>	the group of morphologically indistinguishable and ecologically similar diatom species <i>Staurisorella pinnata</i> and <i>Fragilaria construens</i>
<i>sp.</i>	(singular) species of a known genus but cannot be specified.
<i>spp.</i>	(plural) indicates several species of the same genus

## List of Acronyms and Scientific Terms

ABA	Acid-Base-Acid
AMS	Accelerator Mass Spectrometer
AD	Anno Domini
CONISS	Constrained Incremental Sum of Squares
DAC	Drakensberg Alpine Centre
DEA	Department of Environmental Affairs
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GNA	Global Needs Assessment
GPS	Global Positioning System
HCl	Hydrochloric acid
LGM	Last Glacial Maximum
LHWP	Lesotho Highlands Water Project
LIA	Little Ice Age
LOI	Loss on Ignition
LMS	Lesotho Meteorological Services
MAP	Mean Annual Precipitation
MAR	Mean Annual Rainfall
MCA	Medieval Climate Anomaly
MWP	Medieval Warming Period
ND-GAIN	Notre Dame Global Adaptation Initiative
NRF	National Research Foundation
ORASECOM	Orange-Senqu River Commission
PC	Principal Component
PCA	Principal Component Analysis
ShCal13	Southern Hemisphere Calibration Curve 2013
SOP	Standard Operating Procedure
SRZ	Summer Rainfall Zone
WRZ	Winter Rainfall Zone
YRZ	Year-round Rainfall Zone
YD	Younger Dryas

# Chapter 1: Introduction

## 1.1. Palaeoenvironmental reconstructions

Palaeoenvironmental reconstructions refer to the results of investigations employed to determine the climate, vegetation, and environment at a specific time in a particular region in the past, usually prior to historical record keeping (Mackay et al., 2007; Parnell et al., 2011). Climatologists mainly utilise palaeoenvironmental data, to further understand how the environment, particularly the climate, has changed over time (Tuovinen, 2010). Archaeologists on the other hand, use palaeoenvironmental data to better understand living conditions at a specific time, that is, before, during and after site occupation (Dincauze, 1987, MacDonald et al., 2000). Ecologists use this kind of data to reconstruct past ecosystems, biota, and landscapes to further understand relationships between organisms and their environments (Birks, 2012; Bjune et al., 2015), while botanists use palaeoenvironmental data to understand processes of plant evolution (Scott & Smit, 1977).

Palaeoenvironmental records enable the analysis of past climatic and environmental conditions on a regional scale beyond the restricted period covered by instrumental measurements (MacDonald et al., 2000, Birks et al., 2003). These records contain information about past climate change and the way in which the ecosystem responds to these changes (Alverson et al., 2001). Forecasting future environments and ecosystems in light of climate change involves intensive considerations of the interactions between the changing climate and non-linear responses of ecosystems (Jones, 1996). In the Northern Hemisphere particularly, effects of climate change on ecosystems (mainly in lakes and wetlands) are highly complex and require more research. Over Holocene time scales, the development of aquatic communities

may have been influenced by processes relating to primary succession as a consequence of deglaciation (Engstrom et al., 2000).

The data collected and interpreted in palaeoenvironmental research are known as proxies. A proxy is essentially a substitute for the environmental variables that cannot be directly measured (Birks, 2020). It is impossible to travel back in time to measure the environmental variables such as the temperature, humidity, moisture, water levels of a given day, year or century, there also are no written records of climatic changes that would give us those details older than a couple of hundred years (Anderson et al., 2006; Birks, 2020). Due to these reasons, palaeoenvironmental researchers rely heavily on the biological, chemical, and geological traces of past events that were influenced by the climate to place future and current environmental change into context (Blaauw et al., 2020).

Palaeoenvironmental reconstruction methods offer a powerful tool for defining conditions of minimal anthropogenic impact (Bennion & Battarbee 2007). Palaeoenvironmental reconstruction utilises an extensive range of fossil indicators of past flora (such as diatoms, chrysophyte cysts, dinoflagellates, aquatic plant macrofossils, pollen) and past fauna (such as chironomids, ostracods, cladocerans, fish scales) known as proxies, to reconstruct the pre-pollution aquatic ecosystems and terrestrial environments (Bennion & Battarbee 2007). Additionally, the reconstruction of palaeoenvironments necessitates particular knowledge of the proxy's geographic ranges, environments, habitats, and ecological tolerances (Lyman, 2017). Through the use of palaeoenvironmental reconstruction, we are able to attain a clear representation of past conditions and therefore improve our understanding of the pathways that have resulted in the present conditions, as well as providing information required to predict for the future (Birks, 2020).

For example, southern Africa has experienced observed changes in climate over the last decade with a greater than 0.20 °C rise in temperature for most of the interior regions (Mapfumo et al., 2015; Kruger et al., 2019). Trends in increasing temperatures suggests that warmer conditions have been evident since the latter part of the 20th century (Kruger et al., 2019), due to anthropogenic influences, much pressure has been placed on the environment (Hansen et al. 2001; Lugina et al., 2005; Smith & Reynolds 2005; Lawal et al., 2019). The climate change phenomenon and evidence has led scientists to question whether these are as a consequence of natural climatic patterns which may have existed in the past, or just anthropogenic influences (Birks, 2020). This has placed great importance on palaeoenvironmental reconstructions and understanding past climates in southern Africa and the rest of the world in order to determine prominent climatic patterns (Fritz, 1996; Hassan et al., 2011; Caballeroa & Huberb, 2013). To efficiently manage, plan and adapt to climate change, it requires an understanding of the magnitude of past changes in the environment over long periods of time, solely because it provides evidence of patterns of variability, fluctuations as well as feedback systems (Meadows, 2014).

## 1.2. Palaeoenvironmental proxies

### 1.2.1. Diatoms

Diatoms are photosynthesising, unicellular, yellow-green to golden brown algae which comprise of a siliceous skeleton, which forms part of the cell walls. The cell walls consist of two valves, making up the frustule (Figure 1.1; Round, 1991). The siliceous cell walls are resistant to changes to pH and can therefore be preserved as fossils, if the conditions are favourable (Reid et al., 1995). Their ability to be preserved makes them particularly valuable in palaeoenvironmental reconstruction research (Round et al., 1990). These microorganisms vary

in shape and size, allowing for their identification to species-level, other physical characteristics assist in the identification process, and these include: the length, breadth, pattern of striations, frequency of striations and presence of a raphe (Jones, 1995; Taylor et al., 2007).

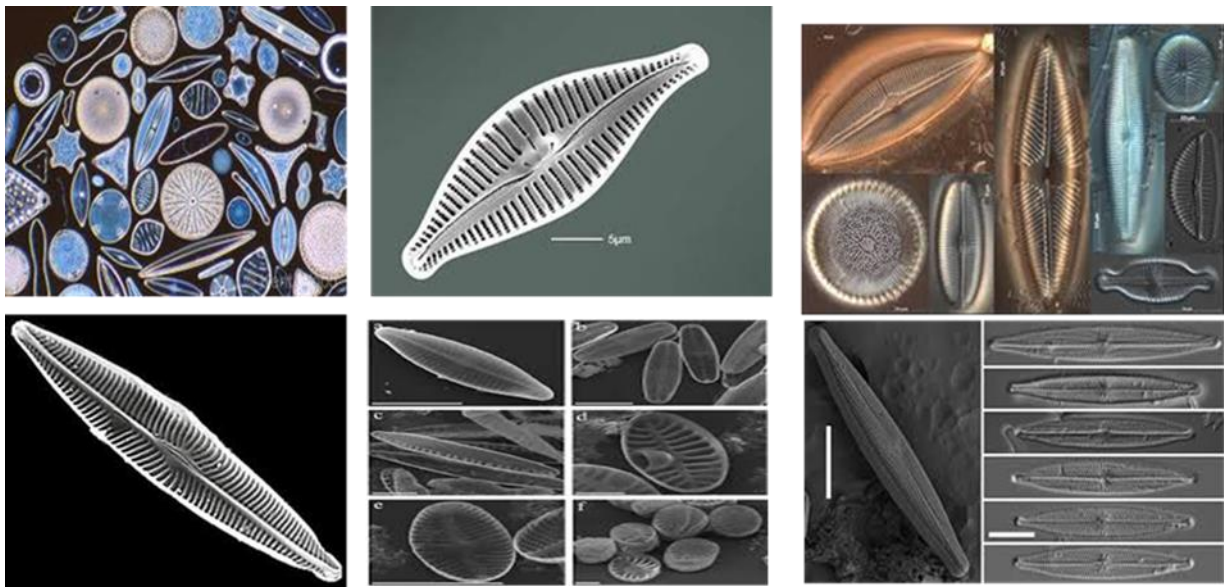


Figure 1.1: Image showing a variety of diatom species under an electronic microscope adapted from (Du Buf, 2002; Jalba et al., 2004).

Diatoms have a variety of life forms (Mackay et al., 2003), with benthic diatoms as the ‘cornerstones’ of energy flow and all metabolic processes which occur in lakes and wetlands (Etrl & Tomajka, 1973). What makes diatoms suitable indicators for climate and environmental change, is that they are usually abundant in their habitats (mostly aquatic environments) and thousands of cells are produced within a few square centimetres of an aquatic system (Finlay et al., 2002; Pinseel et al., 2018). Diatom assemblages may also change over short distances if there is a marked environmental gradient (Pla-Rabes & Catalan, 2018). What this implies, is that an environment that has homogeneous ecological conditions will most likely be characterised by largely homogenous diatom communities (Hall & Smol, 1992). In a case where discrete pools within an aquatic system are dispersed spatially but possess that same

characteristics and tolerances, a single diatom sample from any pool is sufficient to show the conditions of the stream or wetland as a whole (Finlay et al., 2002).

Various studies show that diatoms are very sensitive to changes in their environment (e.g. Battarbee, 1997; Slingsers, 2015; Morin et al., 2016; Chonova et al., 2019), and therefore these microorganisms may be indicative of a wide range of environmental conditions such as moisture, organic enrichment, salinity, acidification and oxygen availability, to mention just a few (Korhola et al., 2000; Rosén et al., 2000; Bigler and Hall, 2002; Hargan et al., 2015; Papry et al., 2017). Diatoms have very short life cycles, meaning that they have the ability to rapidly colonise new habitats. The changes in diatom compositions therefore respond to the environmental and climatic changes which the diatoms are exposed to (Round, 1991; 1993; Pinseel et al., 2018). The time in which these microorganisms respond to changes in their environment, can be very rapid, the disadvantage being ecologically significant fluctuations may not be recorded (Round, 1993). Diatoms are largely cosmopolitan in distribution, and thus diatom species occurring across the Southern Hemisphere, for example, have similar ecological properties (Foged, 1978; Gell & Gasse, 1994).

Diatoms are among the most successful and important microorganisms to infer past environmental conditions, since they are well preserved in sediment, if subjected to suitable conditions (Mackay et al., 2003; Fitchett et al., 2016). Diatom taxonomy is largely based on the morphological preservations of silica valves, so, the fossil assemblages can be related to modern autecological data (Reid et al., 1995; Taylor et al., 2007). This allows for the reconstruction of water quality, climate and the environment from fossil diatom assemblages representing periods before the onset of anthropogenic impacts on aquatic ecosystems (Hall & Smol, 1992). Changes in the environment may inhibit the multiplication of certain species

while supporting or facilitating the multiplication of other species and thus the relative abundance of certain species within a community will be altered (Harding et al., 2005). These changes reflect the modifications in water, climate and environment in an integrated manner (Harding et al., 2005). These micro-organisms have been shown to be valuable in revealing and reconstructing past climates due to their abundance and ecological sensitivity, therefore contributing to palaeoenvironmental work around the world (e.g. Smol, 1985; Battarbee et al., 2001; Stoermer & Smol, 2012; Meadows and Finch, 2016; Fitchett et al., 2016; Summers et al., 2019). Diatom taxa all have very distinct tolerances to habitat conditions, their composition and assemblages change with every modification in the environment (Hall & Smol, 1992; Smol, 2004).

Living diatoms often have specific salinity, temperature and other environmental tolerances, this, together with the fact that a high proportion of fossil genera and species are still extant, makes it possible to use transfer functions to produce accurate palaeoenvironmental reconstructions (Stevenson et al., 1991; Hall & Smol, 1992; Fritz et al., 1993; Smol & Stoermer, 2010). Diatoms are also particularly advantageous for biostratigraphic studies of high latitude sediments where calcareous microfossils are often poorly preserved, sparse, or of low diversity (Round, 1993). Lastly, diatom taxonomy is well established and there are various complete and inclusive taxonomic papers available to assist in species identification (e.g. Hustedt 1930, 1959, 1961-1966; Patrick & Reimer 1966, 1975; Foged 1978; John 1983; Krammer & Lange-Bertalot 1986, 1988, 1991).

### 1.2.2. Sediments

Sediments form as a result of processes such as weathering, decomposition, and deposition, which are all processes influenced by the environment and climate conditions over time (Bell

& Walker, 2013). For many decades, sediments have been used as a tool to indicate past climates and environments, owing to the proxies they may possibly contain (Bell & Walker, 2013). Sediments themselves are also a powerful proxy for reconstructing past climates and environments (Briggs, 1977). The accuracy and reliability of the palaeoclimatic and environmental inferences from sediments is highly dependent on an understanding of how the sediment responds to the various environmental changes (Marker, 1994). In the southern African context, various studies reconstructing past environments have utilized the determination of particle size and Loss On Ignition (LOI) calculations mostly in their methodology and results, however only a few studies use the data in paleoenvironmental reconstructions and interpretations (e.g. Holmgren et al., 2012). Typically, literature which is dependent on interpretations of sedimentary properties are limited. For Lesotho this is not the case as many of the climatic inferences for the region from previous research have relied on sediment interpretations (e.g. Van Zinderen Bakker, 1955; Marker, 1994; Fitchett et al., 2016a). The composition percentages of sediments are particularly of interest when analysing sediment and the most commonly used is the organic content percentage (Heiri et al., 2001). The organic content percentage can be used to infer the available moisture for a specific time period (Meyers & Teranes, 2001), whereas the carbonate percentage in sediment is useful in potentially providing coarse information on relative temperature changes (Heiri et al., 2001). Sediments which are dominated by silt -sized and clay-sized particles are indicative of wetter conditions and larger sized sediment particles indicate drier periods, with limited vegetation (Bell & Walker, 2013). It is important to note that sediments cannot directly present information on changes in the environment, so they cannot be used in isolation as an environmental or climate proxy (Bell & Walker, 2013). Therefore, a holistic palaeoenvironmental reconstruction requires sediment composition to be paired with a proxy

such as diatoms for more direct information (Bell & Walker, 2013). Despite these limitations, sediments form an essential part of any type of environment at any period in time, and are, therefore, valuable for palaeoenvironmental reconstructions (Briggs, 1977).

### 1.3. Understanding the Lesotho Highlands Environment

Climate change research in Lesotho is a necessity as it allows for the formulation (and hopefully implementation) of adaptations to the region's fluctuations in the environment and climate (Gwimbi, 2017). The Kingdom of Lesotho is highly dependent on subsistence agriculture, this means that any changes in the climate and the environment could have adverse effects and pose a threat to the food security. With so much reliance on subsistence agriculture, the region's climate change also poses a huge threat on the economy. Lesotho provides a valuable and much needed source of water to southern Africa (Hoag, 2019; Braun, 2020). This is attributed to the country's high precipitation levels (Nthako & Griffiths, 1997; Grundling, 2015). Due to these reasons, palaeoenvironmental and palaeohydroclimatic research in Lesotho is crucial for understanding the unique hydrology of the region and this kind of research further contributes to the efforts made towards environmental conservation (Chatanga & Sieben, 2019).

The ecosystems of Lesotho are significant for supplying various ecosystem services and, environmental regulation, biodiversity conservation, livestock grazing and the harvesting of plants (Chatanga & Sieben, 2019). Additionally, Lesotho is particularly valuable to southern Africa due to its montane wetlands which form part of the headwaters of the Senqu-Orange River, one of the most important international river systems (ORASECOM, 2015). The wetlands of Lesotho play a vital role in the maintenance of water levels not only in dams of the Lesotho Highlands Water Project (LHWP), but also for the local communities of the region (ORASECOM,

2015; Chatanga & Sieben, 2019). It is pertinent to highlight that these wetlands are also crucial in the economy of Lesotho and contribute approximately 22% of the country's Gross Domestic Product (GDP) directly and indirectly- this includes improved water quality, flood control, wildlife, fisheries and recreational opportunities, just to mention a few (Department of Environment 2014). Therefore, any alterations in the hydrological system will significantly affect not only Lesotho but southern Africa. Lesotho hosts a highly varied climate, topography and associated vegetation thus providing specialised sites for palaeoenvironmental research (Fitchett et al., 2016a).

The protection and conservation of Lesotho's environment and its valuable water resource are imperative; however, this requires an understanding on how past and presently occurring- climate dynamics influence the geophysical landscape of Lesotho (Grab, 2010). With Lesotho being such a remote region, climate and meteorological data covering several decades is rather discontinuous, both spatially and temporally, when as compared to other regions and, in some cases, has been previously extrapolated from alpine regions in the Northern Hemisphere as well as in the lowlands and from surrounding regions of southern Africa (Boelhouwers et al., 2002; Borg, 2012; Hughes, 2016). Although extrapolation methods have proven to be valuable, the quantification of accurate rates of climate variation is not always achieved (Grab, 2013).

For regions similar to Lesotho, and particularly eastern Lesotho, palaeoenvironmental reconstruction using environmental and climatic proxies continues to be considered as an important task (Fitchett et al., 2017). This is because proxies offer the only source of long-term climate data (Fitchett et al., 2017; Norström et al., 2018). It is important to also note that the region's palaeoenvironmental studies can provide an understanding on specific details of

climate change, climate fluctuations as well as ecological alterations during the Holocene for southern Africa, due to its geographical positionality (Mills et al., 2012; Fitchett et al., 2017). The investigation of long-term climate and environmental change in this specific region is thus of particular interest and is of considerable value for developing adaptation mechanisms to climate variability and conservation of the ecological value of the region.

#### 1.4. Rationale

Several studies have demonstrated that diatoms are of value in the reconstruction of past climates and past environments (e.g. Finné et al., 2010; Stoermer & Smol, 2012; Meadows & Finch, 2016; Fitchett et al., 2016; Carballeira & Pontevedra-Pombal., 2020), however, when compared to regions in the Northern Hemisphere, southern Africa's palaeoenvironmental studies remain sparse, particularly for the Lesotho region. The majority of the Quaternary environmental reconstructions for Lesotho originates from the rich archaeological research (Figure 1.2) (e.g. Carter, 1976; Mitchell et al., 1998; Stewart et al., 2012; Roberts et al., 2013; Stewart et al., 2016). This archaeological work has included inferences of possible past climatic situations, but the temporal resolution and the quantification of past climates show a lack of detail (Fitchett et al., 2016a). High resolution proxy-based research in Lesotho has seen a lot of growth since the work of Fitchett (2015), as there is a confirmed presence and reliability of diatoms as well as other proxies, such as pollen. Additionally, this has also stimulated research which examines the palaeoenvironmental contexts of wetlands in Lesotho (e.g. Fitchett et al., 2016b, 2017b; Norström et al., 2018).

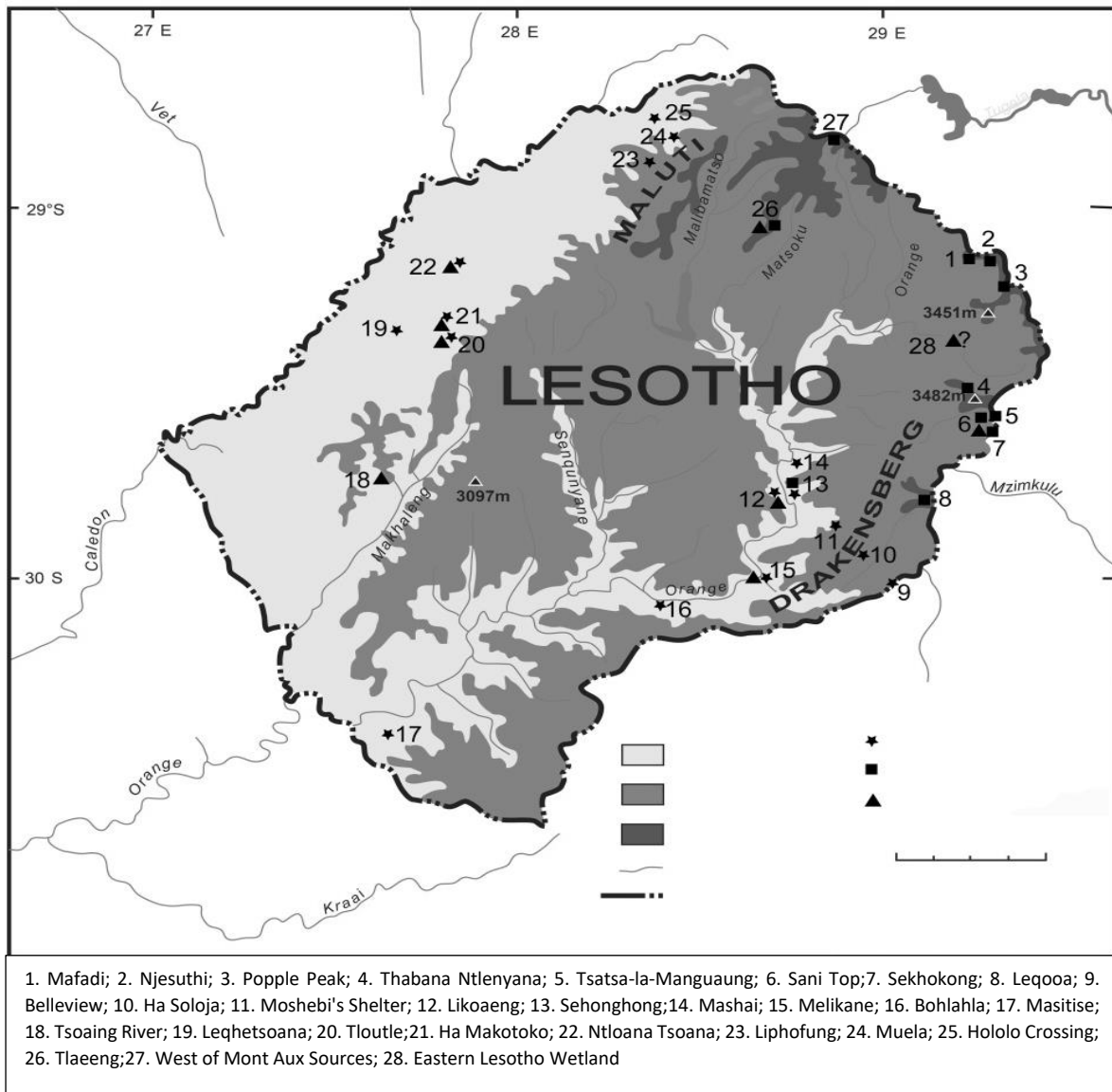


Figure 1.2: The location of archaeological, geomorphological and palaeoenvironmental study sites in Lesotho from which published palaeoclimatic inferences have been made (Fitchett et al. 2016a).

The region of Lesotho has a varied topography and distinct altitudinal variations and therefore much higher spatial resolution research is required to better understand the past climates and present environments. The Eastern Lesotho highlands holds an important environmental setting for palaeoenvironmental work due to the high altitudes, with a harsh climate and niche vegetation communities (Fitchett et al., 2016a; et al., 2018). The region is of great importance due to its role in water storage for the Lesotho Highlands Water Project (Quinlan & Morris, 1994; Haas et al., 2010). Understanding the palaeohydroclimate of eastern Lesotho highlands is thus of great value, it is also imperative that the spatial gaps existing in the research are

filled. The research presented here brings a new perspective to the past climates of the eastern Lesotho highlands as it is the first study conducted in the far northern region of the highlands and thus contributing to the spatial transect along the escarpment.

Diatoms are the most suitable proxy for the following research because they are able to reveal more information on the climate and environment when compared to other proxies such as phytoliths, pollen or isotopes (Meeker & Stager, 2002; Mackay et al., 2003; Reed et al., 2019). Diatoms are present in all aquatic environments and because of their successful preservation, they are often abundant in ocean, lake, and wetland sediments (Battarbee et al., 2001).

#### 1.4.1. Aims & Objectives

This study aims to reconstruct the palaeoenvironments and palaeoclimates of the northern region of eastern Lesotho. The work was undertaken through the extraction of peat sediment cores in the vicinity of Afriski resort, due to good road accessibility, at the border of Leribe, Butha-Buthe and Makhotlong districts. This was followed by the examination of peat sediment samples, with fossil diatoms subsampled at regular intervals of 2cm throughout the sediment cores.

The aim of this study will be achieved through the following objectives:

1. To obtain two peat cores from a wetland in the vicinity at the border between Leribe, Butha-Buthe and Makhotlong districts, at >3,000 m.asl.
2. To count and identify the diatom assemblages to explore the sedimentary properties, including organic and carbonate percentage and determine the particle size composition throughout the cores.
3. To develop an age-depth profile for the cores using AMS radiocarbon dating.

4. To infer the palaeoenvironment and palaeoclimate in order to identify the wet and dry periods from the diatom assemblages.

#### 1.5. Structure of thesis

**Introduction**: this introductory chapter presents a brief overview to the research and the need to conduct palaeoenvironmental research through the use of diatoms, the chapter further presents the general importance of a study of this nature for the northern region of Lesotho. Here the aims and objectives for this research are outlined.

**Literature review**: The literature review discusses the development of palaeoenvironmental research conducted in southern Africa, notably highlighting the various proxies which have been explored over the years. The chapter further explores the palaeoenvironmental evidence which is found in Lesotho and the reliability of these sources of evidence. The palaeoclimate of southern Africa is fundamental in understanding the climate, and the climatic dynamics of Lesotho. Thereafter, the use of diatoms in palaeoreconstruction is discussed focusing on research conducted globally, in southern Africa, and finally zooming into Lesotho and some of the key climatic events which have occurred in the region.

**Study site**: The study site chapter focuses on a detailed description for the regional setting of this study, that is, eastern Lesotho. The chapter commences with a description of the geography of the region, mainly concentrating on the geology, climate, hydrology, vegetation, and the environmental issues that Lesotho faces. The chapter also draws attention to the importance of the Lesotho wetlands, the specific coring sites, and their environmental setting.

**Methodology**: The methodology chapter presents a detailed account of all the methods used to enable palaeoenvironmental reconstruction. The chapter outlines the sampling field work

conducted to extract the sediment cores; the laboratory work to isolate and prepare diatoms; and identify the diatoms. The methods for AMS dating are also outlined as well as the statistical analyses for all the data in this research.

**Results:** the results chapter commences with the stratigraphic changes which occur in the diatom and sediment composition, which are plotted against depth and the age from the AMS dates for both study sites. Statistical analyses are presented by study site and the changes in each proxy are also presented independently for each site.

**Discussion:** The discussion chapter presents a detailed analysis of results and puts the data into context. The chapter commences with inferring palaeoenvironmental conditions for the sites. Further in the chapter, comparisons are made to similar palaeoenvironmental reconstructions undertaken in Lesotho and a relatively lower altitudinal site in southern Africa. The key climatic events detected in eastern Lesotho are further compared to those that have occurred globally. The chapter concludes with an overview of the limitations met by this study and finally the potential future work.

**Conclusion:** This chapter summarises the research and outlines how the objectives of the study were achieved.

## Chapter 2: Literature Review

### 2.1. Introduction

The geographical location of southern Africa spanning the tropical, subtropical and temperate climatic belts along with the oceanic, topographic and latitudinal influences result in very distinct rainfall zones, that is, the SRZ (Seasonal Rainfall Zone), WRZ (Winter Rainfall Zone) and YRZ (Year-round Rainfall Zone) (Tyson et al., 2005; Chase & Meadows, 2007; Mill et al., 2012). The region has a very rich biodiversity and highly distinct bioregions which have most likely undergone several shifts in the palaeoclimate throughout the Holocene (Chase & Meadows, 2007; Scott et al., 2012; Knight & Fitchett, 2019).

Climate and vegetation variability provide a great scope for palaeoclimatic and palaeoenvironmental work in southern Africa (Scott et al., 2012). However, the paucity in the information available is problematic, resulting in little work undertaken in the field in southern Africa, relative to other parts of the world, especially in comparison to the Northern Hemisphere regions, despite all the palaeoenvironmental evidence present (Scott et al., 2012; Knight & Fitchett, 2019). With more attempts at climatic reconstruction being executed through the use of palaeoenvironmental proxies, such as diatoms, more uncertainties continue to arise regarding past climates in southern Africa (Fitchett et al., 2016a). Palaeoenvironmental studies are vital in paving the way for future research, also emphasising the problems pertaining to lack of data availability (Sime et al., 2013; Fitchett et al., 2017).

### 2.2. Early palaeoenvironmental work in southern Africa

The first Quaternary studies were conducted from the 1950's onwards (Fitchett et al., 2016; Meadows, 2014; Meadows & Finch, 2016). However, in recent decades, noteworthy progress has been made in the field, through the reconstruction of climate, environments, vegetation,

and human occupation (Fitchett et al., 2017). The early development of palaeoenvironmental work in southern Africa has been critically reviewed by several researchers (e.g. Meadows et al., 2009; Meadows & Finch, 2016, Fitchett et al., 2017). The landscape of palaeoenvironmental sciences in southern Africa has evolved and continues to do so very rapidly (Bamford & Grab 2005; Fitchett & Bamford, 2017).

The pioneering studies and usage of proxies in southern Africa for palaeoenvironmental research began since the initial work of Van Zinderen Bakker (1955). His work was later followed by Martin (1959), Coetzee (1967) and Schalke (1973), amongst others. However, these pioneering studies were very restricted due to the shortage of accurate dating techniques (Kirsten et al., 2007). However, in the last few decades, one of the key researchers in the development of palaeoenvironmental work has been Louis Scott (Meadows, 2015). His work was pivotal in improving our understanding on how vegetation responds to climate dynamics and change of the late Pleistocene and Holocene. This research has also been important for understanding how plant microfossils could be used to reconstruct the changes occurring in the climate (Meadows & Finch, 2016). Louis Scott conducted early research on wetland and spring deposits in the former Transvaal province, from Lake Alexanderfontein where he examined the pollen deposits (Scott, 1976). Scott's study sites were strategically chosen, with most of them being localities appearing to offer favourable conditions for the preservation of microfossils, specifically pollen (Meadows, 2015).

The majority of the localities include water-logged sites which support the accumulation of organic material (Meadows et al., 2009). Scott then began to conduct research in rather unconventional localities in search of different kinds of deposits which may potentially contain pollen preservations for further vegetation history reconstructions, such as cave deposits in

Equus Cave (Scott, 1986), Sterkfontein and Swartkrans (Scott & Bonnefille, 1986). The results from these studies were promising and demonstrated an opportunity for palynology through the utilisation of alternative sources in localities which might have been previously ignored at the time (Scott & Bonnefille, 1986). While undertaking research in these localities, Scott was well aware of the potential challenges which may be faced at the sites such as the contamination of modern pollen (Scott & Bonnefille, 1986). Louis Scott was dedicated to exploring various types of sediment such as pan sediments and valley fill sediments, and thus adding the types of sediment as reliable materials for sediment analysis (Meadows, 2015). Scott's determination in enhancing palaeoenvironmental work in southern Africa, led to the identification of rock hyrax middens as a potential proxy (Scott & Bousman, 1990; Scott 1994, 1996).

A key limiting factor in palaeoenvironmental reconstruction has been obtaining sequences with consistent organic accumulations, primarily because of the highly varying and seasonal climatic condition in most sites of southern Africa, the arid to semi-arid climate. Finally, much of SA's landscape history has been dominated by erosion and wiping away of sediments (Meadows, 2015). However, the discovery of pollen-bearing peat deposits at or nearby the thermal spring in Wonderkrater opened new possibilities for the reconstruction of the late-Pleistocene and the Holocene palaeoenvironments of the region (Scott, 1982). The deposits were a significant addition to the few palynological sites available in southern Africa (e.g. Van Zinderen Baker, 1957; Martin, 1968; Schalke, 1973; Scott, 1982; Scott et al., 2003). Scott and Vogel (1978) conducted preliminary work in Wonderkrater which provided the first Quaternary pollen data for the former Transvaal region and revealed considerable vegetation changes which took place over the last 25,000 yr BP. Many years later, in the early 1980's, Scott revisited the site and reanalysed the data in much greater detail (Scott, 1982). In the

study, the sediment core covered a much longer period than thought, that is, ~35,000 yr BP, providing evidence for an early, moist cool phase with mesic bushveld and expanded montane forest in the central Transvaal, with temperatures probably 5-6°C cooler than present-day temperatures (Scott, 1982).

The first long Quaternary pollen sequences in South Africa are from Wonderkrater. This study site has become crucial in palaeoenvironmental reconstruction, having been revisited several times over the years by Scott (1982a,b; 2003), Backwell et al. (2014) and other researchers (e.g. Brook et al., 2010; McCarthy et al., 2010; Truc et al., 2013). Pollen sequences from the Wonderkrater spring have played a vital role in shaping our understanding of past vegetation during the late Quaternary (e.g. Scott, 1982; 1999; 2003; Scott & Thackeray, 1987). Tswaing Crater presented the longest and most continuous record of precipitation in South Africa, and the region also gained high levels of interest from researchers as it potentially offered a more consistent record (up to ~200,000 years). However, the pollen microfossils were not well-preserved resulting in only the uppermost parts of the deposits facilitating pollen analysis (Scott, 1999). The Quaternary shed light on the challenges facing vegetation and climate change in the region, moreover, sediments from the region also aided in documenting hydrological changes in southern Africa over the last 200 Ka, using basic geochemistry (Kirsten et al., 2007). Tswaing Crater has been revisited in recent years by researchers collaborating with Scott mainly to reconstruct palaeoenvironments at a higher resolution (e.g. Metwally et al., 2014; Schmidt et al., 2014).

Scott (1999) further compared the pollen data from both Wonderkrater and Tswaing Crater for vegetation history and climate in the Savanna biome, and the palaeotemperature trends from the two regions allowed for a new regional palaeoenvironmental reconstruction.

Notably, the pollen sequences overlapped between upper ca. 25 m of the Tswaing Crater and the Wonderkrater sequence. The correlation of the two sequences suggested that the Wonderkrater sequences are a quarter of the time period than that from Tswaing Crater, also, the combined sequences suggest fluctuations between cold and warm periods (Scott, 1999). However, both the records were not continuous due to either sediment breaks or pollen decomposition (Scott, 1982; 1999; 2016).

Over the years, Scott has collaborated with various researchers (e.g. Norström et al., 2009; Neumann et al., 2010; Quick et al., 2011; Scott et al., 2006; Roberts et al., 2017), resulting in an influx of people conducting research pertaining to palaeoenvironmental reconstruction in southern Africa. Also, this resulted in a research focus shifting from inland sites to more coastal regions (e.g. Scott & Skeenkamp, 1997), especially along the Western Cape coast (e.g. Scott, 1994; Scott, 2006; Scott & Woodborne, 2007). It is important to also note that there has been a shift in the types of study sites over the years, previously, work was mainly carried out on the best available sediments which were rare organic spring deposits (Scott, 1982). Over time more attention has been given mainly to lakes (Holmgren et al., 2003; Chase et al., 2012; Ekblom et al., 2012), because they have been recognised as sentinels for regional climate and environmental change (Adrian et al., 2009). Additionally, estuaries (e.g. Carr et al., 2015) and wetlands (e.g. Finne, 2010; Fitchett et al., 2016a, b; Truc et al., 2013; Norström et al., 2018) are also considered as a potentially reliable source of microfossils.

#### 2.2.1. Methodological advances

Initial palaeoenvironmental and palaeoclimatic research was largely challenged by the significantly rich, varied flora of southern Africa and uncertain chronologies (e.g. Martin 1959; 1968; Coetzee, 1967; Scott, 1976). In the recent years, studies have benefitted from access to

increasingly precise and affordable dating facilities, which was previously a great limitation. There has also been a noted increase in large diatom, pollen and phytolith collections (Meadows, 2014). Highly-resolved palaeoenvironmental reconstructions (e.g. Valsecchi et al., 2013; Quick et al., 2018) play a key role in meeting the environmental challenges facing the future (Meadows, 2012). Further development in both methodology and data quality should remain a priority in southern African Quaternary research (Meadows & Finch, 2016). Advances in methodology and the continuous growth in proxy availability have contributed to various collaborations between archaeologists and palaeoecologists (Meadows, 2014; Fitchett & Bamford, 2017).

Access to affordable radiocarbon dating has been a great limitation because any palaeoscience research lacking robust age models presents insufficient evidence of the past (Meadows, 2014). An important methodological development has been the access to regional radiocarbon dating facilities which have enabled cost-effective palaeoclimatic and palaeoenvironmental research within southern Africa (Meadows & Finch, 2016). The calibration of  $^{14}\text{C}$  is a necessity to the conversion of radiocarbon ages into calendar ages (Meadows, 2014). Due to the several challenges facing southern African terrestrial sediment deposition, attributed to the arid, semi-arid and highly seasonal climate, alternative forms of dating material have emerged, such as luminescence dating (Meadows & Finch, 2016). This form of dating is mostly applied to studies focused on reconstructing environments in dunes, especially the Kalahari and Namibia region (Meadows, 2012). This method determines how long ago sediment particles were exposed to sunlight using various techniques to stimulate and measure luminescence (Preusser et al., 2009). According to Meadows & Finch (2016), this method has also been beneficial to coastal geomorphological research (e.g. Botha, 2008).

The Wonderkrater spring deposits were revisited by Backwell, in collaboration with Terrance McCarthy, Christine Steininger and others in a multiproxy study on Quaternary climate change, and the study also simultaneously focused on the human use of the area (Backwell et al., 2014). According to Meadows and Finch (2016), this study propelled and stimulated an interest specifically at the development of complex modern behaviour (e.g. Thomas & Burrough, 2012; Chase, 2014), as well as the necessity in understanding the role of climate change (e.g. Carr et al., 2016; Quick, 2016) and sea level change (e.g. Wündsche et al., 2016; Loftus et al., 2017; Cooper et al., 2018).

Huntley (2012) highlights that there are various challenges facing the use of fossil evidence for the Quaternary climate, with the biggest one being able to understand which variables influence the distribution and abundance of biological proxies, especially since there are numerous factors attributed to this (Meadows, 2014). The use of multi-proxy research has been beneficial in addressing this challenge, along with the developments of Bayesian statistical modelling frameworks which offer the possibility of contemporaneous reconstructions of two or even more variables for various samples in a specific sequence (Meadows & Finch, 2016). Developments in statistical analysis have allowed for improved interpretations of environmental changes through pollen or other biological proxies such as diatoms, phytoliths and biomarkers (Meadows & Finch, 2016).

Regarding improvements in microfossil identification, there has been potential for technological development, particularly aimed at automated fossil identification since the 1970s (Meadows, 2014). There have been various attempts to pursue such, however, progress for automated systems has been very limited (e.g. Kaya et al., 2013). Research towards automated systems has yielded insignificant potential to advance and improve

palaeoenvironmental reconstruction (Meadows, 2014). With that considered, it is, however, important to note that the introduction of automated systems for extracting microfossils effectively from sediment would save time, increase efficiency, and lower costs (Meadows, 2014).

#### 2.2.2. Various proxies used for palaeoenvironmental reconstruction in Southern Africa.

The absence or lack of instrumental data have been a key catalyst in reconstructing past climates and environmental conditions through the use of proxy or indirect data sources (Knight & Fitchett, 2019). Southern Africa is poorly suited for the same methods used in Europe and Northern America due to its highly variable climate (Meadows, 2014). Given the challenges facing the field of Quaternary palaeosciences in southern Africa, additional and alternative proxies have become a focus (Fitchett & Bamford, 2017) and these various proxies have been critically reviewed (e.g. Meadows, 2014). Southern Africa contains an impressive range of proxies which have been used for palaeoenvironmental reconstruction, and these include pollen, phytoliths, diatoms, isotopes, and geochemistry, among others (Figure 2.1; Fitchett & Knight, 2019). From Figure 2.1, it is evident that the use of various proxies has significantly increased over the years.

The continuous discovery of archives coupled with the technological advances related to the biological proxies are leading to high resolution and detailed reconstructions of environments (Meadows, 2014; Fitchett et al., 2017). The variety of proxies found in the region are uniquely distributed spatially according to their environment of formation, thus increasing their value in research (Meadows, 2014). An improved understanding of long-term past climatic changes is essential, which is why reviewing recent development of palaeoenvironmental proxies is

relevant as they play an important role in high resolution palaeoenvironmental reconstructions (Meadows & Finch, 2016).

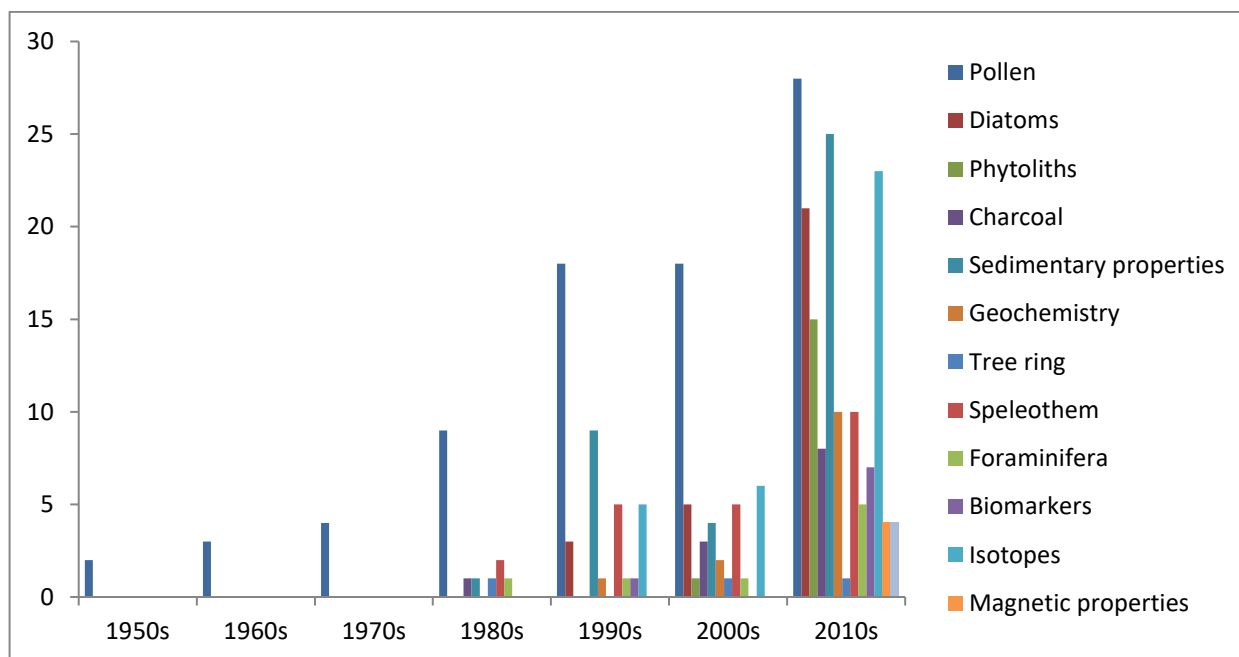


Figure 2.1: Histogram showing the use of different types of proxies used in published studies over the years adapted from (Knight & Fitchett et al., 2019). Data from 1955 to 2019.

Research pertaining to palaeoenvironments has experienced incredible growth over the past few decades, specifically in the number of proxies used and sites explored since the pioneering work of Van Zinderen Bakker (Meadows, 2014; Fitchett et al., 2017). This can be attributed to the growth of palaeoenvironmental researchers over the years due to the array of proxies available and another reason for this growth is the changes in technology, along with improved methodology of extraction and radiometric dating (Knight & Fitchett, 2019). Additionally, increased availability of funds and international collaborations also contribute to the wide diversity of proxies utilised in published research (Chase & Meadows, 2007; Fitchett et al., 2017).

One of the most commonly and extensively used proxies for palaeoenvironmental reconstructions is pollen (e.g. Scott, 1982; 1999; 2002; Partridge et al., 1993; Finch & Hill, 2008; Brook et al., 2010; Chase, 2010; Truc et al., 2013, Norström 2009; 2014; Quick et al., 2018; Combrink et al., 2020), and this is because pollen is produced in great quantities and distributed by wind and animal vectors. Additionally, preserved pollen fossils have important information on vegetation, flora, environment, and climate associated with processes of the past (Fargri et al., 1989). Figure 2.1 demonstrates that although a diversity of proxies exists, pollen remains the most used proxy. However, it is important to note that over time more attention has been given to diatoms, sediments, geochemistry, and isotopes (Chase & Meadows, 2007). There has also been a particular increase in the use of speleothems as a palaeoenvironmental archive because this proxy provides highly-resolved isotope analyses which, when supported by well constrained chronologies, have yielded significant environmental changes (e.g. Talma & Vogel, 1992; Holmgren et al., 2003; Finch et al., 2001). Additional use of other proxies increases diversity, thus enabling investigation of a wider range of palaeoenvironmental variables (Meadows, 2014), it also enables for various tipping points and/or stressors to be analysed, and facilitates multiproxy research (Meadows et al., 2014; Fitchett et al., 2017). Multiproxy research allows for the investigation of a wider range in environmental conditions.

Certain proxies are favoured in palaeoenvironmental research, however, studies utilising more uncommon proxies, such as foraminifera do exist (e.g. Strachan et al., 2014; Strachan et al., 2017; Bergh, 2019). In southern Africa, the use of foraminifera as a proxy has been restricted to research only pertaining to temperature change, stratigraphy, sedimentology, and marine records, however, in the study by Strachan et al. (2014) this biological indicator was introduced as a sea-level change proxy. The list of uncommon proxies further includes phytoliths

(Burrough et al., 2012), dinoflagellate cysts (Dupont et al., 2004), biomarkers (Carr et al., 2015; Norström et al., 2017) and hyrax middens (Chase, 2010; Chase et al., 2009; 2012) which have proven to be particularly valuable archives.

The use of hyrax middens materials is not new in the southern African context (e.g. Scott, 1999), however, there have been improvements in sampling methods, which have led to high resolution chronologies. Hyrax middens also contain a considerable number of proxies, these include pollen, microcharcoal, phytoliths, plant biomarkers and stable isotopes (Chase et al., 2012). For example, phytoliths, pollen, charcoals, and diatoms at Braamhoek signalled wetter conditions which may be connected to the northward shift of the Westerlies from ~14 ka, with fynbos pollen indicating persisting cold conditions (Finne et al., 2010; Norström et al., 2014). The ensemble of proxies at the Braamhoek site confirms southern Africa's wealth of palaeoenvironmental proxies (Chase & Meadows, 2007; Meadows, 2014).

With increases in proxy-based research in southern Africa, there are a variety of sites which have received attention due their potential wealth of palaeoenvironmental proxies (Fitchett, 2016). Site selection for palaeoclimatic and palaeoenvironmental research is also highly dependent on ease of access, apart from the potential ensemble of proxies (Fitchett et al., 2016b). The late Quaternary vegetation and climate change of the southern Africa biomes can be derived from pollen sequences, that is, the Wonderkrater and the Tswaing Crater sites (Meadows, 2014), because these provide evidence of vegetation and climate in greater detail than isotopic and geological proxies. Studies conducted in Tswaing Crater (e.g. Kristen et al., 2010; Metwally et al., 2014; Schmidt et al., 2014) and Wonderkrater (McCarthy et al., 2010; Truc et al., 2013; Backwell et al., 2014; Chevalier & Chase, 2016) along with the new interpretations of both the records continue to raise questions relating to their significance for

the palaeoenvironmental history of the region (Scott, 2016). The results of the multi-proxy datasets extracted, along with the revision of palynological data, clarify the questions and conflicting interpretations about the regional palaeoenvironmental history (Schmidt et al., 2014; Scott, 2016). These sites are of importance because they provide more information about the Holocene (Partridge et al., 1993).

Another pivotal site is the Braamhoek wetland, where analysis of sediment gives information about the palaeovegetation and palaeoclimatic conditions (Norström et al., 2009; Finne et al., 2010). The region has great potential for retrieving these kinds of conditions because of its high-altitude grasslands and the nearby escarpment which hosts afro-montane forest trees and an array of fynbos vegetation (Coetzee, 1967). The ensemble of proxies present provide insight on palaeoenvironmental conditions and the summer rainfall region in South Africa (Norström et al., 2009). Studies conducted in the south coastal plain of southern Africa (e.g. Kirsten, 2007; 2008; Carr et al., 2015; Quick et al., 2018) reveal that a complex interplay of climate, geology and topography have contributed to a vastly diverse vegetation matrix and therefore, also potentially containing a wealth of proxies.

Table 2.1: Summary of literature reviewed of numerous proxy-based studies from southern African sites, placing emphasis on proxy diversity and reliability for southern Africa. Studies are arranged in descending order according to the time period covered.

Years (cal. yr BP)	Period	Author	Title	Site	Proxies	Environmental conditions
75,000	Pleistocene	Scott (2016)	Fluctuations of vegetation and climate over the last 75 000 years in the Savanna Biome, South Africa: Tswaing Crater and Wonderkrater pollen sequences reviewed	Tswaing Crater & Wonderkrater	Pollen	Dominance of peats, sands and clay indicating fluctuations in moisture availability at ~ 60,000 cal yr BP.
44,000	Late Pleistocene	Finch & Hill (2008)	A late Quaternary pollen sequence from Mfabeni Peatland, South Africa: Reconstructing forest history in Maputaland.	Mfabeni Peatland, Maputaland	Pollen	Cool and wet period at ~44,000 cal. yr BP. 33,000 cal. yr BP presented warm, wet conditions. Cool, dry conditions existed thereafter, possibly indicating onset of LGM.
35,000	Late Pleistocene	Scott (1982)	A late quaternary pollen record from the Transvaal bushveld, South Africa	Transvaal bushveld	pollen	Early moist, cool period existed ~30,000 cal r BP. A dry period then existed until approximately 25,000 yr B.P. 11,000 yr B.P and the temperatures were probably 5°–6°C cooler than at present, After 6,000 yr B.P conditions became slightly wetter. After 2,000 yr B.P conditions became much warmer.
32,000	Late Pleistocene	Van Zinderen Bakker & Coetzee (1988)	A review of late Quaternary pollen studies in east, central and southern Africa.	Numerous, east, central, and southern African sites	Pollen	From ~32,000 – 28,000 yr BP the period was warmer and more humid. From ~ 28,000 to 20,000 yr BP there was higher precipitation in East Africa and Kalahari. The LGM is inferred to have occurred from 20,000 to 16,000. The period 14,000 yr BP was characterised by dry conditions. From 12,000 yr BP warmer and humid conditions were prominent in East Africa. Holocene humid conditions existed and continued in East Africa until 4,000 yr BP, then a drying period commenced.
25,100	Late Pleistocene & Holocene	Combrink et al. (2020)	A late quaternary palaeoenvironmental record from Ntsikeni Wetland, KwaZulu-Natal Maloti-Drakensberg, South Africa	High altitude wetland, Maloti-Drakensberg, southern Africa	pollen	Record begins with cold conditions associated with the LGM. From ~7500 to 5500 cal BP the period consisted of warm and moist conditions. From ~13,500 cal BP, ~8500 cal BP the conditions were characterised by cold periods and ~4000 cal BP with temperature fluctuations. The periods ~19,600–18,000 and ~6500-4900 cal BP were two distinct dry periods.
25,000	Late Pleistocene & Holocene	Holmgren et al. (2003)	Persistent millennial-scale climatic 300 variability over the past 25,000 years in Southern Africa.	Makapansgat Valley, South Africa	Speleothems, Isotopes	1300 - 1800 AD was the Little Ice Age. The period 1, 000 cal yr BP consisted of a wet period. Evidence from Makapansgat Valley suggest that 8,500 cal yr BP was a cooler period and from 6,500 - 500 - cal yr BP warming occurred.
20,000	Late Pleistocene & Holocene	Truc et al. (2013)	Quantification of climate change for the last 20,000 years from Wonderkrater, South Africa: Implications for the long-term dynamics of the Intertropical Convergence Zone.	Wonderkrater	Pollen, Speleothems	Temperatures during both the warm and cold seasons were $6 \pm 2$ °C colder during the LGM and Younger Dryas, and the rainy season precipitation during the Last Glacial Maximum was ~ 50% of the precipitation during the mid-Holocene.
16,000	Late Pleistocene	Finné et al. (2010)	Siliceous microfossils late Quaternary palaeoenvironmental indicators at Braamhoek wetland.	Braamhoek	Diatoms, phytoliths	Dry conditions at ~13,600-10,400 cal. yr BP and an occurrence of a wet event at 11,300 cal. yr BP. At ~8,000 – 2,000 cal yr BP there were dry conditions. From 1,500 cal yr BP -present evidence from diatoms and phytoliths suggest conditions are wet.

16,000	Late Pleistocene	Fitchett et al. (2016b)	A multi-proxy analysis of late Quaternary palaeoenvironments, Sekhokong Range, eastern Lesotho	Alpine wetland, Sekhokhong	Diatoms, pollen, sedimentary characteristics	From ~16,450 -14,440 cal yr BP wet period occurred and was interrupted from ~16,350 -15,870 cal a BP by drier conditions. Much drier conditions occurred at ~14,150 - 8,560 cal yr BP. Proxies inferred warmer, dry conditions 8,560–7,430 cal yr BP, followed by cold, wet conditions from ~7,280-6,560 cal a BP. ~6,560-3,640 cal yr BP conditions were dry and warmer, from ~3400-1200 cal yr BP period was cool and wet, followed by progressive drying ~1,110 cal a BP
16,000	Late Pleistocene	Norström et al. (2009)	Reconstruction of environmental and climate changes at Braamhoek wetland, eastern escarpment South Africa, during the last 16 000 years with emphasis on the Pleistocene-Holocene transition.	Braamhoek	Pollen, Charcoal, Isotopes	Drier period for 16,000 – 13,700 cal yr BP. Wetter conditions 13,700 – 12,800 cal yr BP, dry conditions ~ 12,800 – 1, 500 cal yr BP. 10,500 – 9,500 cal yr BP was a wet period, and 9,500 – 8,200 cal yr BP was a dry period. Wet conditions occurred from ~1,500 cal. yr BP – present.
16,000	Late Pleistocene	Norström et al. (2014)	Late Quaternary vegetation dynamics and hydro-climate in the Drakensberg, South Africa.	Braamhoek	Charcoal, pollen biomarkers, mineral magnetic properties	From 13,800 – 12,000 cal yr BP and 10,200 – 8,500 cal yr BP period is characterised by increased wetness. Warmer temperatures from ~8,500 cal. yr BP. One wet event during the Holocene at ~2,000 cal yr BP till present. The Younger Dryas 12,600 – 11,300 cal yr BP came with much drier conditions
13,000	Pleistocene	Chase et al. (2011)	Late glacial interhemispheric climate dynamics revealed in Southern African hyrax middens	Cederberg Western Cape Province	Hyrax middens (Isotopes)	High-resolution isotope (stable nitrogen & carbon) records from a rock hyrax midden, show the Younger Dryas (YD, 13–11.5 ka) from the southern African subtropics. Results from this study provides key evidence for the influence of the YD, also suggesting that a subtropical-temperate transition zone existed along the oceanic Subtropical Front across the Southern Hemisphere.
12,000	Holocene	Grab et al. (2005)	Holocene palaeoenvironments inferred from a sedimentary sequence in the Tsoaing River Basin, western Lesotho	Tsoaing River Basin	Pollen, phytoliths & sediment	Wet conditions at ~12,200-9,000 cal. yr BP and at 8,600- 8,450 cal. yr BP. Drier conditions at 7, 000 cal yr BP mid-Holocene Altithermal and 4 500 cal. yr BP.
11,700	Holocene	Chase et al. (2009)	A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa.	central Namib Desert	Hyrax middens	Record indicates phases of relatively humid conditions from 8700–7500, 6900–6700, 5,600–4,900, and 4,200–3,500 cal yr B.P., with a distinct period of aridity which occurs from 3,500 until ca. 300 cal yr B.P.
10,200	Holocene	Neumann et al. (2010)	A Holocene sequence of vegetation change at Lake Eteza, coastal KwaZulu-Natal, South Africa.	Lake Eteza, KwaZulu-Natal	Diatoms, Pollen, sediment	~10,200 – 6,800 cal yr BP from wetter woodland to drier grass, increased precipitation occurred at ~6,800 – 3,600 cal yr BP, high sedimentation rates at 6500 and 4000 cal yr BP. 3,600 – 2,500 cal yr BP was a dry period, dramatic vegetation changes to grass at 700 cal yr BP.
9,000	Holocene	Metwally et al. (2014)	Holocene palynology and palaeoenvironments in the Savanna Biome at Tswaing Crater, central South Africa.	Tswaing Crater	Pollen, charcoal, alkanes	Generally dry at ~9,400 -7,200 cal. yr BP, driest at 7,800 cal. yr BP. ~7,000-6,600 cal. yr BP increases in moisture availability. 3,750-1,800 cal. yr BP dry event and fluctuating moisture.
8,900	Holocene	Quick et al. (2018)	A high-resolution record of Holocene climate and vegetation dynamics from the southern Cape coast of South Africa: pollen and microcharcoal evidence from the southern Cape coast of South Africa:	Eilandvlei, Southern Cape coast	Pollen & microcharcoal	The data indicates that cool, seasonal and moderately dry conditions existed at the Wilderness Embayment from ~8,900 to 8,000 cal a BP. Afrotemperate forests expanded from ~8,000 cal a BP until 4700 cal a BP. This humid period is followed by indications of more arid and seasonal conditions until 3,500 cal a BP. A long-term increase in forest taxa as well as increased moisture availability throughout the late Holocene.

			pollen and microcharcoal evidence from Eilandvlei			
8,000	Holocene	Scott (1989)	Climatic conditions in southern Africa since the last glacial maximum, inferred from pollen analysis.	Various sites	pollen	Wet conditions during the LGM, and dry conditions during the Early Holocene 8,000 yr B.P, which were followed by progressively moist conditions peaking soon after the development of a temperature optimum ca. 6,500 yr. B.P.
8,000	Holocene	Fitchett et al. (2016)	Holocene climatic variability indicated by a multi-proxy record from southern Africa's highest wetland	Mafadi Wetland	Diatoms & Pollen	Fluctuations of wet & dry throughout the mid to late Holocene. ~8,140 – 7,580 cal. yr BP and ~5,600 – 1,100 cal. yr BP were wet periods. dry periods ~7,520 – 6,680 cal. yr BP, ~6,160 – 5,700 cal. yr BP and from ~1,000 cal. yr BP, cold period at ~8,140 cal. yr BP.
4,000	Holocene	Kirsten (2008)	Holocene Environmental Change at Groenvlei, Knysna, South Africa: Evidence from Diatoms	Coastal lakes Groenvlei, Knysna	Diatoms	c.4,2- c.4,0 ka is characterised by sea level changes. c.0,7- c.0,33 ka the period is associated with changes in temperature similar to those experienced during the Little Ice Age (ILA). C.mid 1,600s AD – present, conditions were a combination of extreme climates and impacts of human activities on catchments.
2,600	Late-Holocene	Kirsten & Meadows (2014)	Late-Holocene palaeolimnological and climate dynamics at Princessvlei, South Africa: Evidence from diatoms	Princessvlei, Cape Town	Diatoms, sediment	Dry conditions from ~2,400 cal yr BP and 2,100 cal. yr BP. Wetter conditions at ~2,000 cal. yr BP. South Atlantic anticyclones becomes the principal climatic force at ~1,200 -920 cal yr BP. Progressive wetness from 600 cal. yr BP.
1,700	Late-Holocene	Sjöström (2017)	Late Holocene palaeoenvironmental reconstruction from Mpumalanga Province (South Africa) inferred from geochemical and biogenic proxies.	Lydenburg fen, Mpumalanga Province, South Africa	Geochemical proxies, grass phytoliths, diatoms	From the geochemistry ( $\delta^{13}C$ ) and phytolith there were past shifts in hydrology and vegetation of the region. The proxies indicated dryness from AD 1,250–1,350, followed by conditions with moderate amounts of moisture.
1,600	Late-Holocene	Norström et al. (2018)	Late-Holocene climate and vegetation dynamics in eastern Lesotho highlands	Ladybird wetland, Eastern Lesotho Highlands	Isotopes	Higher temperatures during this phase, synchronous with the Medieval Climate Anomaly (MCA). After AD 1,200, local conditions transitioned gradually from purely terrestrial, towards the typical wetland environment prevailing today.
1,200	Late-Holocene	Kirsten (2014)	Late Holocene diatom community responses to climate variability along the southern Cape coastal plain, South Africa	Lakes along the southern Cape coastal plain	Diatoms	Notable shifts in precipitation which overlap with the global climatic phenomena, such as the MCA (~1200 - 700 cal yr BP) and the Little Ice Age (~700 - 125 cal yr BP).
1200	Late-Holocene	Strachan et al. (2014)	A late Holocene sea-level curve for the east coast of South Africa	Kariega Estuary, South Africa	Foraminifera	Transgression before 1,100 cal years BP relates with existing palaeoenvironmental literature from southern Africa. ~1,100 to ~300 cal years BP sea level oscillations are evident. After 300 cal years BP, relative sea level has remained relatively stable

### 2.3. Palaeoclimatic history of Lesotho

The late Quaternary palaeoenvironmental record for most parts of Lesotho remains somewhat inconsistent and uncertain, and this is mostly due to the varied topography of the region (Roberts et al., 2013). Prior to the high-resolution multiproxy-based palaeoenvironmental research in the region (e.g. Fitchett et al., 2016 a, b), as well as existing literature for the region was largely based on the archaeological and geomorphological evidence (Fitchett et al., 2017). Therefore, most of the evidence of past climates which exists for Lesotho is derived from evidence based on the periods where occupation occurred at the specific site or the glacial and periglacial activity of the region. Palaeoenvironmental reconstruction research in Lesotho has been frequently conducted in the eastern parts of Lesotho (Figure 2.2), where the Sub-Alpine (2,000 -3,000m) and Alpine (>3,000m) zones lie. Fewer studies have been conducted in the western and central parts of the region which are dominated by the Montane Zone (1,500-2,000m). High lying regions are of interest for palaeoclimatic and palaeoenvironmental research due to the ecological significance, and the eastern Lesotho highlands exhibit specific sensitivity to climate variability and climatic changes (Grab & Knight, 2018).

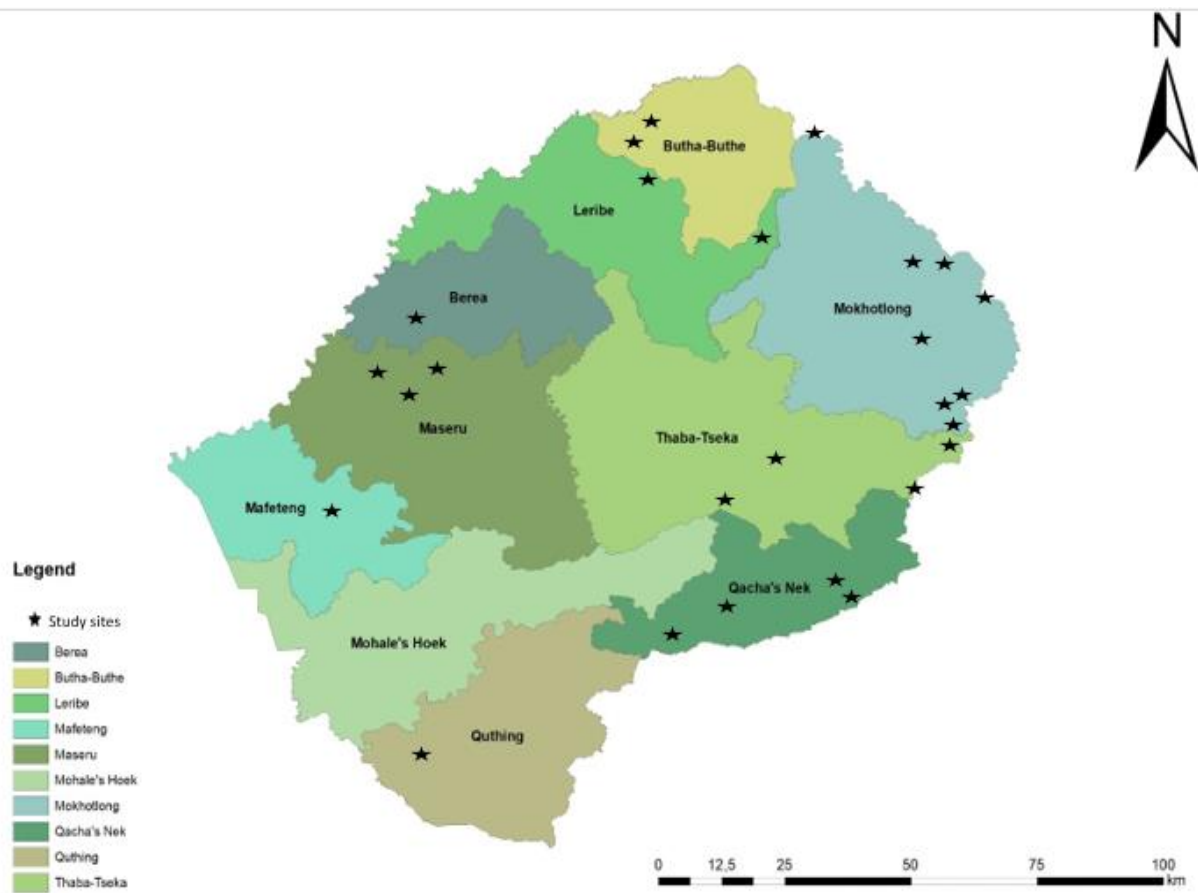


Figure 2.2: Map of Lesotho showing the locations from which published palaeoclimatic inferences (Archaeological, geomorphological and palaeoenvironmental) have been made.

Palaeoclimatic inferences in the region of Lesotho have been fundamental and continue to improve our understanding of the climatic dynamics of the region (Fitchett et al., 2017a; Mills et al., 2009). The inferences made for eastern Lesotho through palaeoclimatic evidence indicate that very cold conditions were prominent during the late Pleistocene, and during certain periods of the Holocene (Fitchett et al., 2016). The evidence presented by Stewart & Mitchell (2018) shows that the LGM brought about much warmer and summer-like conditions, thus supporting various types of flowers and vegetation. Additional studies on the eastern Lesotho highlands contradict this and instead emphasise the cold conditions of the LGM, and report that the LGM and Holocene neoglacial episodes may have occurred at ~4,000 yr BP, and 3,000 to 2,000 yr BP respectively (Stewart et al., 2012; 2016). Mills et al. (2009)

have identified palaeoglacial structures which they suggest developed during the LGM and LIA have indicated that present conditions are much warmer than periods before, they suggest erosional structures, such as solifluction mantles, also show that cold and dry conditions were prevalent during the time of formation. The occurrence of erosional structures are thought to be indicative of relatively wet conditions during the colder periods (Mills et al., 2009; 2017).

There have been debates concerning the palaeoglacial structures and the type of climatic conditions they are indicative of. These debates emerged due to research conducted in the Mafadi Summit, where the structures indicate high moisture availability and seasonal precipitation (Mills et al., 2017). The snow accumulation required to support the occurrence of these glaciers implies that the LGM brought about higher precipitation to the mountainous areas such as the Maloti-Drakensberg region, and possibly the wider SRZ (Mills et al., 2012). Although the glacial landforms located in the Drakensberg of eastern Lesotho demonstrate that the LGM in the region spanned for a very short period (Mills et al., 2012). The existence of the niche glaciation indicates the glaciers may have occurred where factors such as snowblow and topographical shading were key influencers and thus creating microclimate niches (Mills & Grab, 2005; Mills et al., 2009a, b; Mills et al., 2012). These structures may have occurred under various possible climatic conditions in the Lesotho highlands, and the glaciers may have possibly developed where the temperature was between 4-6°C or where a decrease in temperature would facilitate the possibility of an increase in precipitation and seasonal shifts towards cold-season precipitation (Mills et al., 2012). This implies a shift in rainfall seasonality meaning that increased precipitation occurred during the much colder months at regions of higher altitudes (Mills et al., 2012). The trends identified can be linked to the frequent occurrence of westerly wave disturbances as a consequence of pressure belts

shifting northward, thus increasing precipitation in form of snow at high altitudes (Mills et al., 2012).

The Pleistocene and Holocene periods were characterised by fluctuations between warm and cold conditions indicated by the archaeological evidence, with more prolonged warm conditions during the mid-Holocene. Higher altitudinal sites in the eastern Lesotho highlands were characterised by extremely cold and dry conditions which may have prevented the growth of plants and moisture availability (Carter, 1970; Mitchell, 1996; Grab & Nash, 2010). The much lower sites, such as Sehonghong, are indicative of much more tolerable cold conditions as there was evidence of occupation even during the LGM (Mitchell, 1996; Plug & Mitchell, 2008; Pargeter et al., 2017). Palaeoenvironmental reconstructions in the region that are continuous and highly detailed are inadequate as they are not highly resolved, however, the research that is available, although incomplete, has been valuable in further understanding the past climates of Lesotho (Fitchett et al., 2016).

Sediment analysis of samples at Sani Top were indicative of a cold period before ~13,500 cal yr BP, followed by a wet, warm period at ~13,500 to 9,000 cal yr BP, thereafter, drier colder conditions were prevalent from ~9,000-5,000 cal yr BP (Fitchett et al., 2016). Pollen, phytoliths, isotopes and charcoal have also contributed to early palaeoenvironmental reconstructions conducted for the region (e.g. Van Zinderen Bakker & Coetzee, 1988; Smith, 1997; Scott, 2002; Parker et al., 2011). Data collected from the phytoliths show rapid fluctuations between dry and wet conditions from ~8,600 to 8,450 cal yr BP and ~7,000 cal yr BP, respectively (Grab et al., 2005). For the period ~12,110 to 8,370 cal yr BP, evidence from charcoal indicated dry and cold conditions and increases in moisture availability at ~10,000 cal yr BP (Steward et al., 2016). The region was also characterised by progressively

warming conditions from ~16,000 cal yr BP to 6,000 cal yr BP, this was indicated by isotope data with more stability in temperature attained at ~9,500 cal yr BP (Norström et al., 2018).

The archaeological, palaeoenvironmental and geomorphological evidence emphasise the variability of temperature and precipitation evident throughout the Holocene in Lesotho (Fitchett et al., 2016). These three sources of evidence (archaeological, palaeoenvironmental and geomorphological) do have contradictory interpretations in their records, and this can be attributed to low resolution long-term records failing to detect the detail and intricacy of the higher resolution records (Fitchett, 2015). Archaeological evidence tends to be more accurate in reflecting periods of warmer temperatures, whereas geomorphological features reflect much colder periods (Roberts et al., 2013). The two sources of evidence (archaeological and geomorphological data) are not capable of fully reflecting the climatic history of the Lesotho region, however, these can be used to infer the timing of warm and cold events (Parker et al., 2011). This kind of evidence has great limitations in that climatic and environmental conditions cannot be accurately inferred but are rather identified from the broader characteristics (Fitchett et al., 2016a), therefore well-dated palaeoecological records are crucial in determining the nature of climate change and the environments associated with the extreme events which took place at relatively high resolution (Grab et al., 2005). Employing multiple proxies in eastern Lesotho has been fundamental to unravelling the relative influences of the climate dynamics of the region (Roberts et al., 2013; Fitchett et al., 2016a).

## 2.4. Palaeoclimatic change in southern Africa

Southern Africa encounters a variety of climatic regimes (Mills et al., 2012). The region's climate is mainly controlled by oceanographic, topographic, and latitudinal influences, resulting in highly distinct rainfall zones and seasonality (Fitchett & Bamford, 2017). The subtropical location, and the convergence of the Indian Ocean and Atlantic Ocean, consisting of warm and cold currents, respectively, creates a longitudinal gradational effect, resulting in aridity in the west of the region to more humid conditions in the east of southern Africa (Carr et al., 2006; Chase & Meadows, 2017). Alongside the influence of global ocean variability, several studies (e.g. Partridge & Williams, 1993; Kirsten & Meadows, 2016; Knight et al., 2018) have highlighted the significance of landcover and dynamic feedbacks on climate (Jury, 2014).

### 2.4.1. Major climatic changes

In the past, a significant amount of work has been conducted and reviewed (e.g. Preston-Whyte & Tyson, 1988; Deacon and Lancaster, 1988; Partridge et al., 1990; Tyson and Lindsay, 1992; Fitchett et al., 2017), with the aim of clarifying the phenomena of climate change and the underlying processes which drove it during the Quaternary and Holocene periods in southern Africa. Climatic changes during the Quaternary were fundamental in moulding the land surfaces, environments, and ecosystems in southern Africa for the present day (Knight & Fitchett, 2019). In the Northern hemisphere, this period was pronounced by cycles of cold ice ages and much warmer interglacials (Tyson et al., 2000). The Quaternary in southern Africa was subtler compared to the Northern hemisphere, however, it can be properly explained through the use of various palaeoenvironmental and palaeoclimatic proxies (Knight & Fitchett, 2019). The palaeoenvironmental records indicate that regional fluctuations in

moisture availability, changes in sea levels and temperature were the key outcomes of the global scale climatic changes (Knight & Fitchett, 2019).

Over the past two million years, global circulation patterns have changed resulting in changes in the oceanic currents, leading to shifts in the precipitation patterns (Holmgren et al., 2003; Mills et al., 2012). Significant climate changes in southern Africa may be also attributed to the glacial periods (Tyson, 1999; Mills et al., 2012; Jury, 2014). During these periods, the expansion of the Antarctic sea ice forced both oceanic and atmospheric frontal systems of the southern ocean to move northwards, potentially altering climatic patterns (Bard and Rickaby, 2009). Moreover, changes in the westerly belt influenced the occurrence and intensity of mid-latitude cyclones apparent in the interior parts of southern Africa during the Pleistocene, and records from the Braamhoek wetland through diatom, pollen and phytolith analysis provide evidence for this (Norström et al., 2014; Finné et al., 2010). Interestingly, this evidence is synchronous to the eastern Lesotho highlands climate, based on palaeogeomorphological evidence which indicated an increase in mid-latitude cyclones during the same period (Mill et al., 2009). The changes which have occurred in temperature and precipitation rates due to shifts in climatic dynamics have largely impacted weathering rates, erosion rates as well as on the river regime fluctuations (Norström et al., 2009). During the Quaternary, the diverse fauna and flora of southern Africa have experienced various climatic fluctuations, and these fluctuations were attributed to climatic drivers including the equatorial shifts of the Westerlies, changes in temperature, moisture, the extent of glaciation during the LGM, the Younger Dryas (YD) and the Holocene Thermal Maximum (Table 2.1; Neumann et al., 2010; Norström et al., 2014).

#### 2.4.2. Major climatic shifts during the Quaternary

The mechanisms behind climate change during the Quaternary are debatable; Bond et al. (2001) argued that the abrupt climate shifts during the deglacial and the Holocene cooling events occurred at intervals of 1,500 years. During this period, global warming commenced after the LGM event, and all the components of the climate system experienced large-scale modifications (Bond et al., 2001; Clark et al., 2012). The most significant climatic events (Table 2.1) to occur in the Southern Hemisphere since the LGM event includes the LIA (Tyson et al., 2000; Holmgren et al., 2003), the African Humid Period (Chase et al., 2009), the YD (Holmgren et al., 2003; Truc et al., 2013) and the '8.2 kyr' event (Smith et al., 2002). Regarding the African Humid Period, much of the evidence for the event is apparent in the western coast of southern Africa and East Africa, indicating a rapid decrease in vegetation, grasses, trees and lakes in the early Holocene at ~14,800 to 5,500 cal yr BP (Chase et al., 2009; Burrough & Thomas, 2013; Holmes, 2017).

For southern Africa, much of the evidence for the LIA is largely founded on the analysis of isotopes, with most of the evidence demonstrating varying climatic conditions between the WRZ, SRZ and the YRZ. (Table 2.1; Tyson et al., 2000; Neumann et al., 2010; Stager et al., 2012). A considerable amount of evidence for southern Africa exists for this period, with studies dating back to the 1990's (e.g. Talma & Vogel, 1992; Tyson & Lindesay, 1992; Brook et al., 1999) providing evidence generally indicating much wetter conditions in the WRZ and dry conditions during the period in the SRZ. Out of the significant events which have occurred in southern Africa, the LIA had a great influence on climatic shifts (Chase & Meadows, 2001; Mills et al., 2012), with research (e.g. Neumann et al., 2014; Fitchett et al., 2016a, b) suggesting much drier conditions during the period. Moreover, temperatures during the LGM

were much cooler with temperatures reported to lie slightly below 6°C (Engelbrecht et al., 2019). According to Scott et al. (2012), 24,000 and ~17,000 cal. yr BP were representative of the two coldest periods during the LGM for southern Africa.

Recently, a pioneering study by Engelbrecht et al. (2019) used dynamic regional climatic modelling to further analyse the LGM conditions over southern Africa, and here the simulations suggest a northward reach of the frontal rainfall, thus confirming the inferences attained from proxy records (e.g. Thackeray and Scott, 2007; Norström et al., 2014; Neumann et al., 2014). Rainfall seasonality is projected to have been very distinct from the current day, with a high probability of all-year rainfall extending as far north and east as the present-day Free State and Gauteng provinces of South Africa (Engelbrecht et al., 2019). The projections further indicate highly increased rainfall for the Cape Fold Mountains, while the Cape south coast region projected decreased rainfall (Engelbrecht et al., 2019). With regards to temperature, it is projected that temperatures were significantly low during the LGM as compared to present-day, with annual average temperatures ranging between 4 to 6 °C, much lower along the eastern escarpment and more than 6 °C lower along south-north aligned Cape Fold Mountains and western escarpment (Engelbrecht et al., 2019). When the assessments and evaluations of the downscaling of the LGM climate are compared with proxy records from published research for the LGM (Table 2.1) (e.g. Scott, 1982, 2012; Holmgren et al., 2003; Carr et al., 2006; Chase and Meadows, 2007; Thackeray and Scott, 2007; Mills et al., 2012; Norström et al., 2014), it was demonstrated that the information is synchronous with only a few slight deviations.

Table 2.2: Key events in the Southern African palaeoclimate in chronological order.

<b>YEARS (APPROXIMATED AGE)</b>	<b>PERIOD</b>	<b>CLIMATE CONDITION (SOUTH AFRICAN)</b>	<b>AUTHORS</b>
<b>24,000-17,000 cal. yr BP</b>	Last Glacial Maximum (LGM)	Conditions during the period were mainly characterised by glaciation.	Partridge et al., 1999; Scott, 1982, 2012; Holmgren et al., 2003; Carr et al., 2006; Chase and Meadows, 2007; Thackeray and Scott, 2007; Mills et al., 2012; Norström et al., 2014; Neumann et al., 2014
<b>~14,800 -5,500 cal. yr BP</b>	African Humid Period	Period was characterised by very moist conditions, the Northern parts of Africa were much wetter than presently.	Chase et al., 2009; Burrough and Thomas, 2013
<b>~13,000-11,500 cal. yr BP</b>	Younger Dryas (YD)	Conditions varied regionally during this period, and there were fluctuations between dry and wet.	Holmgren et al., 2003; Thackeray and Scott, 2006; Truc et al., 2013
<b>8,400-8,000 cal. yr BP</b>	'8.2 kyr' event	Generally, the event is associated with dry periods for southern Africa, indicated by low lake levels and other indicators in lake sediments, is likely correlative to the 8kyr event	Gasse, 2000; Smith et al., 2002; Fitchett et al., 2016b
<b>4.500 cal BP-650 cal BP</b>	Neoglacial	Period consisted of significantly decreasing trends in temperatures	Porter and Denton, 1967; Jerardino, 1995; Porter, 2000
<b>AD 1,800 - 1,300 (South Africa)</b>	Little Ice Age (LIA)	Climatic conditions during this period were unclear. The WRZ characterised by wet conditions and the SRZ was very dry.	Tyson et al., 2000; Holmgren et al., 2003; Fitchett et al., 2016b
<b>AD 1,500 - 800</b>	Medieval Warming Period (MWP)	Period came with drier climatic conditions	Lamb, 1965; Tyson et al., 2000

### 2.4.3. Shifts in rainfall zones

As already mentioned, southern Africa's climate can be separated into three distinct rainfall zones, the SRZ which extends to the interior of South Africa, Lesotho and Swaziland, the YRZ which spans most of the southern coast and WZR which is restricted to the southwestern Cape (Chase & Meadows, 2007; Engelbrecht et al., 2015). The WRZ is of key interest in the climate of the late Quaternary of South Africa, as this zone is an important geographical region, and is characterised by Mediterranean-type climate which is characterised by the occurrence of dry conditions in summer and mid-latitude cyclones in winter (Chase & Meadows, 2007; Quick et al., 2016).

There have been significant concerns that should the Westerlies retreat poleward under present-day climate change, a greater frequency of drought in the WRZ may occur (Stager et al., 2012). Thus, various debates exist concerning shifts in the position of the Westerlies (Fitchett & Bamford, 2017). Some of the early studies conducted by Van Zinderen Bakker in the 1980s suggested that the stronger Westerlies may have occurred during the LGM, and their research also indicated that the westerly belt and the related vegetation did not extend far north (Van Zinderen Bakker, 1983). On the contrary, in a later study, Chase and Meadows (2007) suggested that the westerly belt and the WRZ did extend to the far north but towards the east. There have been several studies that have emerged over the last couple of years introducing high resolution records than those that existed (e.g. Chase et al., 2011; Neumann et al., 2011; Carr et al., 2015; Quick et al., 2015). Even with these advances, questions pertaining the past dynamics of tropical and temperate systems

persist, specifically at the WRZ–SRZ interface, as well as their influence on regional environments and climates (Chase et al., 2018).

Debates regarding the LGM also exist, and the period is of great significance in the palaeoclimate of southern Africa, a significant amount of evidence is provided in literature for the occurrence of this event (e.g. Holmgren et al., 2003; Carr et al., 2006; Chase & Meadows, 2007; Thackeray & Scott, 2007; Mills et al., 2012; Norström et al., 2014; Neumann et al., 2014). Although sufficient evidence for the occurrence of this period, there are uncertainties regarding the timing and moisture variability during this time (Fitchett et al., 2017), with the period constrained to varying time periods, e.g. ~21,000 to 18,000 cal yr BP (Partridge et al., 1997) and 20,000 to 16,000 cal yr BP (Deacon & Lancaster, 1988).

Recent palaeoenvironmental-based research (e.g. Tyson et al., 2000; Fitchett et al., 2017) in southern Africa, in comparison to previously published work, provides evidence for synchronous climate events for the Southern and Northern Hemisphere, however, the exact dates in which the events occurred and the specific temperature changes during the climatic events are debatable (Fitchett et al., 2017).

## 2.5. Diatoms In palaeoenvironmental reconstruction

### 2.5.2. Global studies

The environmental reconstruction approach using sedimentary diatoms in the Northern Hemisphere, began in the 18<sup>th</sup> century, where most of the early work focused on taxonomic analysis (Vyverman et al., 2007). By the mid-19<sup>th</sup> century pivotal palaeoenvironmental reconstruction research was initiated by Nipkow (1920), with research conducted in Lake Zurich, Switzerland. Deevey (1942) and Pennington et al. (1943) then signified and

emphasised the importance of diatoms extracted from sediment cores. The increased precision in sediment dating have enabled sediment as a fundamental tool for the reconstruction of limnological and environmental change (Flower et al., 2005). On much longer time scales, diatom species at the bottom of longer cores have enabled palaeoclimatic inferences to be made for several millions of years. For example, Crampton et al. (2016) conducted a study in Antarctica, examining diatom response to climate change in the southern high latitudes over a period of ~15 million years.

There have been various studies where diatoms have played a significant role in the reconstruction of past climate changes, with these microorganisms being utilised as a proxy to reconstruct Holocene climate variability in every continent (Mackay et al., 2003). Most of the global studies focusing on diatom-based reconstructions apply quantitative multivariate techniques to construct past environmental variables associated with climate, either directly such as surface-water temperature (e.g. Rosén et al., 2000; Bigler & Hall, 2002; Brown, 2019) and indirectly through the reconstructing of, for example, salinity (e.g. Fritz et al., 1991; Verschuren et al., 2000; Warnock, 2020). Majority of diatom-based palaeoclimatic research is conducted in the Northern Hemisphere, hence the natural climatic cycles and past environmental dynamics remain poorly understood for most of the regions in the Southern Hemisphere (Villalba et al., 2009; Fritz et al., 2018).

#### 2.5.2.1. Global examples of diatoms in palaeoclimate reconstruction

Studies which utilise diatoms within sedimentary sequences have been conducted globally and these have contributed to the understanding of the changes which may have occurred in local climate, sea level changes and environmental changes beyond regional scales (e.g.

Palmer & Abbott, 1986; Denys & Wolf., 1999; Tyson et al., 2000; Romero et al., 2005; Gaiser & Rühland, 2010; Birks et al., 2012; Horton & Sawai, 2016). It is evident that lakes and wetlands are considered to be a useful resource in reconstructing palaeoenvironments as they are known to host diatoms particularly sensitive to even modest changes to the climate in various regions (Metcalf et al., 2000; Mackay et al., 2003; Gaiser & Rühland, 2010; Brown, 2019).

For example, diatom assemblages in north-eastern Siberia indicate minor shifts between ~12,600 and 12,100 cal. BP suggesting conditions became cooler and drier during this period (Laing, 1999). The diatom assemblages further indicated significant limnological changes at 9,100 cal. yr BP and then a return of colder climate at approximately ~3,800 cal. yr BP (Laing, 1999). Minor shifts in diatoms over the last 400 years are indicative of the influx of organic material coupled with warm climatic conditions in north-eastern Siberia (Laing, 1999). Bigler (2001), explored the potential of diatoms as indicators of the Holocene climate and environmental change in northern Sweden. The diatoms suggested a linearly decreasing trend in temperature (by 1.5°C) from 6,000 cal. yr BP. For this region, the early Holocene (10,600 to 6,000 cal. yr BP) was a problematic period, as there were abrupt climatic fluctuations, which resulted in various uncertainties in the reconstruction (Bigler, 2001).

Over 200 diatom-based records from various lakes across the Northern Hemisphere demonstrated similar taxon-specific shifts since the 19<sup>th</sup> century (Ruhland et al., 2008), and the changes in the diatoms were linked to hemispheric warming trends. There were clear implications of substantial warming over time and long-term changes in air temperature, which correlates with evidence from other studies, for example, diatom data from Lake of

the Woods (Canada) (Ruhland et al., 2010). In a more recent diatom-inferred high-resolution study of the mid to late Holocene climates, diatoms suggested major shifts in climatic conditions revealing that conditions were drier and that lakes in the Yellowstone National Park, USA, were high in phosphorus between ~7,682 to 1,600 cal. yr. BP (Browns et al., 2019).

Moreover, diatoms have been of key importance in understanding the palaeoclimates of extreme climatic conditions such as Antarctica, providing high-resolved information on climatic modifications (Crampton et al., 2016). Three main climatic changes, specifically for the Quaternary can be identified through diatom assemblages in the region, that is, LGM, mid-Holocene climatic optimum and Neoglacial cold event (Bak et al., 2007). In West Antarctica, diatom assemblages that have been deposited in variable sea ice conditions over the last 25,000 years which indicate dense sea cover over the region, with an increase of ice-tolerant species such as *Actinocyclus actinochilus*, *Eucampia antarctica*, *Fragilariopsis curta*, and *Fragilariopsis cylindrus* (Bak et al., 2007). This finding marks a significant response to climate change in the region.

For the Northern Hemisphere various studies have been conducted at high altitudinal lakes and the diatoms in the mountainous regions (such as the Alps) have shown to be valuable indicators of environmental change (Lotter & Bigler, 2000; Lotter et al., 2010; Rott et al., 2006; Fritz et al., 2015; Sochuliaková et al., 2018). Additionally, interactions between diatom assemblages and snow cover in extreme environments have been examined in the continental regions (e.g. Mackay et al., 2003) and the Arctic (e.g. Smol, 1988; Douglas & Smol., 1995; Barinova & Stenina, 2013). The Arctic specifically is of interest due to polar

amplification effects (Engelbrecht et al., 2019), the region changes faster than any other region in the Northern Hemisphere and sediment records from Arctic regions consist of highly distinct records (Serreze & Barry, 2011). Proxies such as diatoms provide accurate data as the community composition of these microalgae can rapidly mirror the environmental change due to their short life cycles (Sienkiewicz et al., 2017).

#### 2.5.2.2. Evidence of the LIA using diatoms and other proxies

Climate changes of the last millennium have been reviewed (e.g. Jones et al., 2009; Wilson et al., 2016) and the climatic events which were observed in the Northern Hemisphere have been described in great detail, including the MWP (900 to 1,500 AD), LIA (1,500 to 1,900 AD) and modern warming (1,900 to present AD) (Jernas et al. 2013). The LIA climatic event in the Northern Hemisphere is particularly of interest as it has been characterised by very dry and cold conditions in most palaeoclimatic reconstructions (e.g. Grove 1988; Bradley & Jonest 1993), where this has been largely based on data from the regions of Western Europe. However, several studies have disputed these findings and indicate that the LIA, although a cold period, was rather characterised by increased precipitation especially in the tropical regions (Nesje & Dahl, 2003; Wang et al., 2013). Diatoms from the Arctic suggest that the LIA environmental conditions were relatively stable, and that the summers in the region were not characterised by cold conditions, although glaciers occupied their maximum Holocene extent (Sienkiewicz et al., 2017).

The LIA is well documented for the Northern Hemisphere and the European Alps, however, uncertainties pertaining to the regional spatio-temporal patterns in temperature changes continue to persist (Ilyashuk et al., 2019). Progress has been made in terms of assessing the

spatial extent and timing of the event using several proxies, including diatoms (e.g. Schmidt et al., 2007), speleothems (e.g. Mangini et al., 2005), tree-ring data (e.g. Nicolussi et al., 2009; Klusek et al., 2015) to reconstruct temperature for the period from continental to more global scales (Mann et al., 2008; Bertler et al., 2011; Christiansen & Ljungqvist, 2012; Xing et al., 2016). The available proxy records, although not evenly distributed (spatially), can represent climate variability (Huntley, 2012).

When comparing the Southern Hemisphere (specifically Africa) and the northern Hemisphere, the tropical African climate response at the time of LIA cooling in the Northern Hemisphere appears to correspond to the proposed cool conditions which occurred in the Last Glacial Maximum (Johnson et al., 2002). The centennial variability of the LIA is often identified by rapid shifts toward the cold state, and abrupt shifts which are identified by the doubling in diatom productivity in just a few decades (e.g. at 1,370 to 1,390 cal yr BP and at 1,740 to 1,770 cal yr BP), with the cold conditions alternating with relatively steady shifts towards the warmer conditions (Brown & Johnson, 2005).

### 2.5.3. Southern African studies

Diatoms in southern Africa have been mainly used in biomonitoring (e.g. Schoeman & Archibald, 1976; Bate et al., 2002; Matlala, 2010), because of their rapid response to the environment (Round, 1993), as well as their sensitivity to biotic and abiotic factors (Weckström et al., 1997). There has been a tremendous increase in the use of diatoms for palaeoenvironmental reconstructions in southern Africa over the past two decades, particularly within multi-proxy studies (Figure 2.3) (Knight & Fitchett, 2018; Quick et al., 2018). The efficient use of these microorganisms as proxies is usually inhibited by poor

preservation in most regions (Gordon et al., 2012). Moreover, the silica which the diatoms are composed of dissolves easily when exposed to alkaline water, and in the Tswaing Crater this was a great limitation (Fitchett et al., 2016a). The diatoms can possibly be destroyed through the siliceous uptake during plant growth which may have affected diatom counting in the Braamhoek wetland (Finne et al., 2010). In addition, recent work undermines the potential value of these climate and environmental proxies through focusing only the ecological divisions and often restricts the analysis to one key environmental shift (Fitchett, 2016a). The location of studies using diatoms for palaeoenvironmental work in southern Africa is presently limited almost entirely to lakes, wetlands, and coastal sites (Kirsten, 2014; Fitchett et al., 2016a; Norström et al., 2018). Given that diatoms are of immense value to understanding the environmental history at such sites, increased inclusion of diatom proxies at inland wetland localities is encouraged, in particular with greater emphasis to explore changes across a broader range of ecological affinities (Norström et al., 2018).

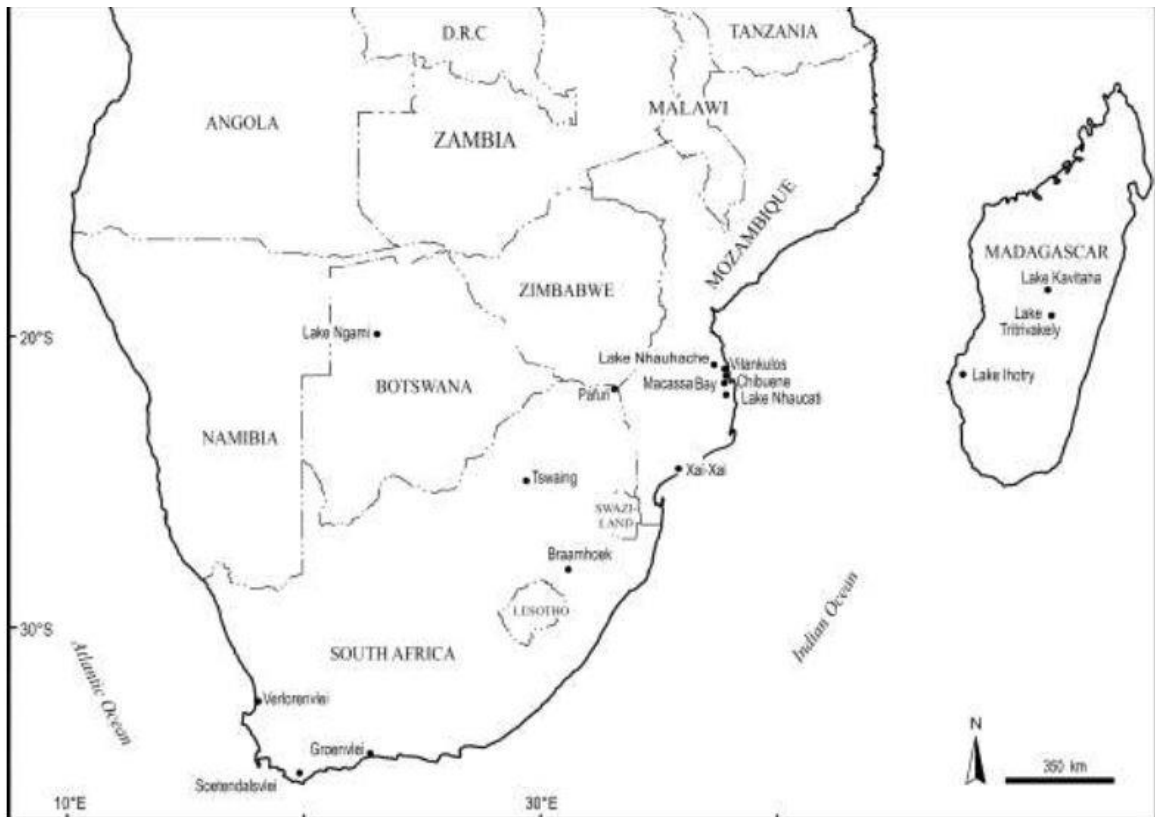


Figure 2.3: Southern African sites at which published diatom-based palaeoenvironmental reconstructions have been undertaken (Fitchett, 2015).

The analysis of inland wetlands has been restricted to environmental reconstruction at Tswaing Crater (Partridge et al., 1993; Metwally et al., 2014) and Braamhoek Wetland (Finné et al., 2010). In these studies, various proxies were utilised such as diatoms, pollen, isotopes, charcoal, and biomarkers. These two studies indicated major environmental shifts which correlated; however, the period of the late and middle Holocene raises more ambiguity because the results reflected by the proxies were inconsistent to each other (Fitchett, 2016a). Diatoms have shown to be useful in revealing water changes, moisture conditions and more information on the Holocene (Finné et al., 2010).

The analysis of sediment comprising of diatoms can provide very detailed information on both short-term and long-term climate change (Kirsten, 2008). The only prohibiting factor

in collecting accurate records from sites is the inconsistency in sediment accumulation, especially in coastal regions (e.g. Kirsten, 2008; Carr et al., 2010; Kirsten, 2014). However, at Groenvlei, South Africa, although a coastal site, changes observed in the diatom assemblages suggested that the region experienced striking climate and environmental change throughout the Holocene (Kirsten, 2008). Sites along the south of southern Africa have demonstrated great potential for analysis (Martin, 1956; Jerardino, 1995; Carr et al., 2006; 2010; Kirsten, 2014), where these records offer details of short and long-term climatic and environmental changes experienced in the region.

#### 2.5.4. Palaeoenvironmental research in Lesotho studies

Lesotho provides a very distinctive setting for palaeoenvironmental research. This is due to the region being characterised by the distinctly high altitude consisting of a harsh climate and niche vegetation communities (Fitchett et al., 2016a). The high altitude plays a key role in exploring various altitudinal rates of species relocation during periods of climate change (Noström, 2018).

Prior to studies by Fitchett (2015), continuous records of proxies for palaeoenvironmental reconstruction were scarce and were mainly impeded by various methodological challenges. The use of diatoms in palaeoenvironmental reconstructions has been largely restricted to lakes (Scott & Lee-Thorp, 2004; Chase et al., 2010; Fitchett et al., 2016a). The palaeoenvironmental contexts of eastern Lesotho's wetlands have received attention over several decades but have only recently been examined in detail (e.g. Fitchett et al., 2016a,b). Studies done by Finné et al. (2010), Fitchett et al. (2016a, 2016b) and Norström

et al. (2018) have shown that wetlands are also valuable sources of information for reconstructing past climates.

The eastern Lesotho region hosts a variety of palaeoenvironmental and palaeoclimatic proxies such as diatoms, pollen, and isotopes. One of the key studies in the region consisting of the longest and continuous multi-proxy palaeorecord was based on sedimentary characteristics, pollen fossil and diatoms from an alpine wetland near the Sekhokhong Range (Fitchett et al., 2016). The record for the region begins in the late Pleistocene with a wet period from ~16,450 to 14,440 cal. yr BP, then followed by very dry conditions from ~16,350 to 15,870 cal yr BP. From ~14,150 to 8,560 cal. yr BP the assemblage was dominated by much drier conditions and thereafter a cold, wet period from ~ 7,280 to 6,560 cal. yr BP (Fitchett et al., 2016a). The dry warmer period at ~6, 560 to 3,640 cal. yr BP was indicated by all the proxies used, those are, diatoms, pollen, and sedimentary records. The record also indicated progressive drying from ~6,000 cal. yr BP period.

In the Sekhokhong profile (Fitchett et al., 2016), diatoms played a significant role in detecting the extremely cold events in the record. The diatoms demonstrated shifts from an environment dominated by *Fragilaria pinnata/construens*, which is characterised by icy, unstable, and unpredictable conditions, to an environment dominated by snow-tolerant, benthic diatoms such as *Fragilaria famelica* (Schmidt et al., 2004; Ohlendorf et al., 2009; Wang et al., 2013). The analysis of the diatoms also revealed that the profile represented undisturbed conditions and periods of increased pollution with wetland disturbances (Fitchett et al., 2016). The interpretations of the diatom results were mainly associated to

their habitat with distinctions in the profile of periods dominated by aerophilic species relative to those dominated by planktonic and benthic species. The relative abundance of *Fragilaria* species is very significant in understanding the past climate of Lesotho, and this is due to their tolerance to seasonal ice and snow, with this tolerance as a result of their high adaptive capacity to respond to the surrounding environment (Schoeman, 1973). A more recent study in Sekhokong, focused on the late glacial period using mainly pollen, total organic carbon, total nitrogen and stable carbon isotopes ( $\delta^{13}\text{C}$ ) as proxies, reveal that the period was characterised by complex changes in thermal and moisture conditions (Kylander et al., 2021). For the region, the data suggests that a humid environment existed, with cold precipitation around  $\sim 17,000$  cal yr BP. From  $\sim 15,600$  to  $15,030$  cal yr BP, warmer conditions were prominent and a shift to summer dominated rainfall and colder, drier conditions with winter precipitation starting at  $\sim 14,380$  cal yr BP (Kylander et al., 2021). Generally the proxies indicate the late glacial period was marked by considerable climatic fluctuation and bi-directional environmental change (Kylander et al., 2021).

The Mafadi wetland profile was reconstructed to track changes in the Holocene period through diatoms and pollen (Fitchett et al., 2016a). The diatoms provided valuable information on the past climates in the region, regarding moisture (Fitchett et al., 2016a). The diatoms reflect distinct climate and environmental shifts in the Mafadi wetland (Fitchett et al., 2016a). This study site is of significant interest because it is the highest studied wetland in southern Africa, and therefore it presented a chance to discuss marginal and threshold conditions associated with climate change through the Holocene. However, although the wetland is isolated by its altitude, no endemic diatom species were present

unlike in other alpine wetlands (e.g. McGlynn et al., 2010). The presence of two diatom communities (*Fragilaria sp.* and *Aulacoseria ambigua*) was significant in the inference of the palaeoclimates and palaeoenvironments. The first species is the *Fragilaria sp.* which are r-strategists, meaning they are able to withstand strongly harsh conditions such as ice and snow cover (van Dam, 1982; Weithoff, 2003). The presence of these diatoms support inferences of colder temperatures in the region such as the LIA. The second species is *Aulacoseria ambigua* and other aerophilic diatoms, which are known to be indicative of periods of fluctuations in wet and dry conditions (Finne et al., 2010).

The period ~8,140 to 7,580 cal. yr BP was characterised by cold wet conditions with very low temperatures, and therefore inhibiting plant growth which explains why no pollen was present in the record (Fitchett, et al., 2016a). The diatoms suggested persistence in shallow water depth likely to be covered by ice. The emergence of pollen suggests localised wet patches, drier and warmer conditions indicated by a decrease in *Fragilaria sp.* and increases in the relative abundance of aerophilic species such as the *Eunotia praerupta*, ~7,520 to 6,680 cal. yr BP was also characterised by weak rainfall seasonality shifts and thus declining water levels (Norström et al., 2009). Conditions in ~6,610 to 5700 cal. yr BP were much warmer than in ~7,520 to 6,680 cal. yr BP, indicated by a low proportion of the ice-tolerant *Fragilaria sp.*, where the warming in eastern Lesotho overlaps with the Holocene Altithermal (Fitchett, et al., 2016a). The period from ~5,600 -1,100 cal. yr BP is dominated by summer rainfall which can possibly be attributed to the weakening of Westerlies (Norström et al., 2009). In the more recent years (~1,100 cal. yr BP to present), diatoms have suggested reduced rainfall and decreasing strength of the Westerlies, moisture

fluctuations and changes in hydrology were prevalent in the period (Norström et al., 2009). Evidence of the cold event is apparent at approximately the same time as the beginning of the LIA (Tyson et al., 2000).

The wetlands of the Lesotho highlands have high hydrological value as they are capable of storing and regulating large reservoirs of water (Grab, 2010). In the Mafadi wetland and Sekhokhong mountain range, eastern Lesotho region, palaeoenvironments were reconstructed through the use of multiple proxies, with heavy reliance on diatoms and pollen (Fitchett, 2015). Studies in Mafadi, Sekhokhong and Ladybird confirm the fluctuations in moisture availability in the eastern Lesotho highlands in cycles of approximately 2,000 years (Fitchett et al., 2016b; Norström et al., 2018). Fluctuations between wet and dry climate throughout the mid-late Holocene commencing with cold, wet conditions from ~8,140 to 7,580 cal. yr BP were revealed by proxies used in the studies, mainly diatoms and pollen (Fitchett, 2015). Findings from various other studies (e.g. Fitchett et al., 2016b; Mills et al., 2012) also suggest changes in the seasonality of precipitation in the region. The Lesotho lowland sequences suggest that the period ~11 200 to 9500 cal. yr BP was characterised by fluctuations of temperature, and the fluctuations in temperature are consistent with evidence from two other sites in the region thus revealing the accuracy in the shifts (Roberts et al., 2013). Importantly, proxy data from the Maloti-Drakensberg region reinforce the SRZ as being characterized by increased moisture availability and cold-phase precipitation may have possibly spread throughout the years (Steward et al., 2012).

#### 2.5.4.1. '8.2 kyr' EVENT

The '8.2 kyr' event is defined as an abrupt cooling period, with a cooling of 1-3°C across most parts of the Northern Hemisphere, lasting for approximately 160 years (Matero et al., 2017). The event is often assumed to have had a significant influence on the Northern Hemisphere climatic conditions, where this short-lived cold period was stimulated by large water pulses which occurred in the northern Atlantic Ocean (Mayewski et al., 2004). This was a result of the meltwater outflow into the northern Atlantic Ocean (Rohling & Pälike, 2005). Research by Smith et al. (2002) presented the very first confirmation of the '8.2 kyr' event across southern Africa, on the basis of isotopic analysis and radiocarbon dating from archaeological sites. The results revealed a significant appearance of  $C_3$  plants, suggesting climatic shifts to cooler conditions coincided with the occurrence of the 8.2kyr climatic event (Smith et al., 2002). The extremely cold conditions documented in the Mafadi wetland were evident from ~8,140 to 7,850 cal. yr BP (Fitchett et al., 2017). The increased surface depth favourable to planktonic diatoms and a specific dominance of *Fragilaria sp.* in the Mafadi sequence around 8,140 cal. yr BP are indicative of the persistent cool conditions after the '8.2 kyr' event (Fitchett et al., 2017).

#### 2.5.4.2. THE LITTLE ICE AGE

The multi-proxy analyses using sediment sequences, synthesised signals from Ladybird wetland proxies suggest that stable terrestrial and hydrological conditions were prevalent between AD 400 - 800 (Norström et al., 2018). The LIA is less distinct in the Ladybird proxy record, suggesting a gradual development from purely terrestrial conditions towards a wetland environment from around AD 1,200 until the 20th century (Norström et al., 2018). However, reconstructions from Mafadi and Sekhokhong presented relatively strong

evidence for the LIA (Fitchett et al., 2016). Periglacial features in the eastern Lesotho Highlands are believed to have been reactivated by the LIA (Boelhouwers & Meiklejohn, 2002; Grab & Mills, 2011). Proxies from many regions in southern Africa link the LIA to relatively cooler and drier conditions (e.g. Ekblom & Stabell, 2008; Holmgren et al., 2012; Siteo et al., 2017), however, in eastern Lesotho there are inferences of increasing effective moisture (Norström et al., 2018). The increased moisture may possibly be attributed to the frequency of mid-latitude cyclones over the LIA period, resulting in increases in precipitation during autumn, winter, and spring (Norström et al., 2018). The climatic and environmental conditions inferred for the region during the LIA, are a response to regionally low temperatures which are experienced in the Lesotho highlands along with the reduced evaporative processes (Fitchett et al., 2017). The low temperatures and reduced evaporation processes create an environment supporting the formation of wetlands (Norström et al., 2018). In the profiles taken in Lesotho (e.g. the Mafadi Wetland and Sekhokong; Fitchett et al., 2016a, 2017), there is a noticeable dominance of *Fragilaria pinnata/constuens*, which is an indication of extremely cold conditions, and this species is common in the east African alpine lakes (McGlynn et al., 2010; Wang et al., 2013). This is thus inferred as a marked cold period (at ~160 cal. yr BP), which presents evidence for a LIA in the region of eastern Lesotho.

The palaeoenvironmental reconstruction for the region of eastern Lesotho over the past few years has presented very strong evidence for the '8.2 kyr' and the LIA cold events, particularly for Mafadi and Sekhokong (Fitchett et al., 2016a; 2016b). However, the region

does not contain strong evidence for warmer events such as the Holocene Altithermal, which occurred ~at 7,460 cal. yr BP, and for the Medieval Warm Period.

## 2.6. Synthesis

Studies conducted in the Southern and Northern Hemispheres reveal that several climatic shifts and fluctuations occurred throughout the Holocene (Quick et al., 2018). From these studies, it is evident that diatoms are a valuable proxy in tracking and reconstructing past environments and climatic changes which may have occurred (Chase et al., 2009; Kirsten, 2008; Quick et al., 2018). The significant relationships which exist between diatoms and climatically-driven environmental variables inspire the application of diatom-based reconstruction methods for the Quaternary climate (Hassan et al., 2011; Fritz et al., 2018). The various studies presented in this literature review indicate that globally the climate and environment have undergone various changes during the Quaternary, and therefore an understanding of the nature and rate of climate change is of considerable value. The eastern Lesotho Highlands presents a variety of palaeoenvironmental evidence allowing for reconstruction of past climates, however, there are considerable gaps in the research which can be attributed to the high spatial variability in the region influencing the great variation in the climate which is apparent in the region. Diatoms in Lesotho have shown to be valuable in revealing climates and past environments, specifically moisture availability and cold events such as the Younger Dryas, the '8.2 kyr' event and the LIA (Fitchett et al., 2017).

## Chapter 3: Study site

This study presents a palaeoclimatic reconstruction for the northern region of the eastern Lesotho highlands. The field work for research was undertaken in the vicinity of Afriski resort, which is close to Butha-Buthe. The altitudinal and topographic variability of eastern Lesotho and Lesotho as a whole provides considerable choice in site selection for this study. This also presents a need for greater understanding of climatic and environmental change at a much higher resolution. Generally, the primary challenge in study site selection in Lesotho is access to remote regions, which archive undisturbed sediment profiles that contain satisfactory proxy records. However, eastern Lesotho although a remote region, is accessible and does contain uninterrupted sediment profiles (Fitchett et al., 2016). Potential for palaeoenvironmental work in southern Africa has been restricted mainly by arid environments, and because of a lack of sites with well-preserved proxy records (Neumann et al., 2008). Eastern Lesotho however has sufficient precipitation to support a large network of wetland systems which have been established as maintaining particularly well-preserved pollen and diatom assemblages (Schwabe, 1995; Grab, 2010).

### 3.1. Lesotho

The Kingdom of Lesotho is a sovereign, independent country and democratic monarchy which has an unusual distinction of being an enclaved country (Figure 3.1). The country is completely surrounded by provinces of the Eastern Cape, Free State and KwaZulu-Natal of the Republic of South Africa (Ramaili, 2006). The country has a population of approximately two million people and is classified as a lower-middle-income country (Tromp, 2006; Maro, 2016; Damane et al., 2018). According to Ramaili (2006), Lesotho is an excellent example of

the larger socio-economic challenges faced by southern Africa. The country is plagued by a wide range of environmental, physical, political, social, and economic problems, these include the inefficiency in resource management, lack of infrastructure, poverty, agricultural deterioration, and environmental degradation (Majara, 2005; Maurya & Letsie, 2017).

Lesotho is situated between 28°30'30"40"S and 27°00'29"30"E, it lies outside the subtropics (Grab & Linde, 2014). Lesotho has a terrestrial area of approximately 30, 555 km<sup>2</sup>, and is the only country in the world which has all its land lying at altitudes greater than 1500m.asl; it is a land of heights and extremes (Figure 3.1; Grab & Linde, 2014). These heights play a significant role in temperature regulation in the region, such that higher altitude areas are much colder than the lower lying summer rainfall areas of southern Africa (Roberts et al., 2013).

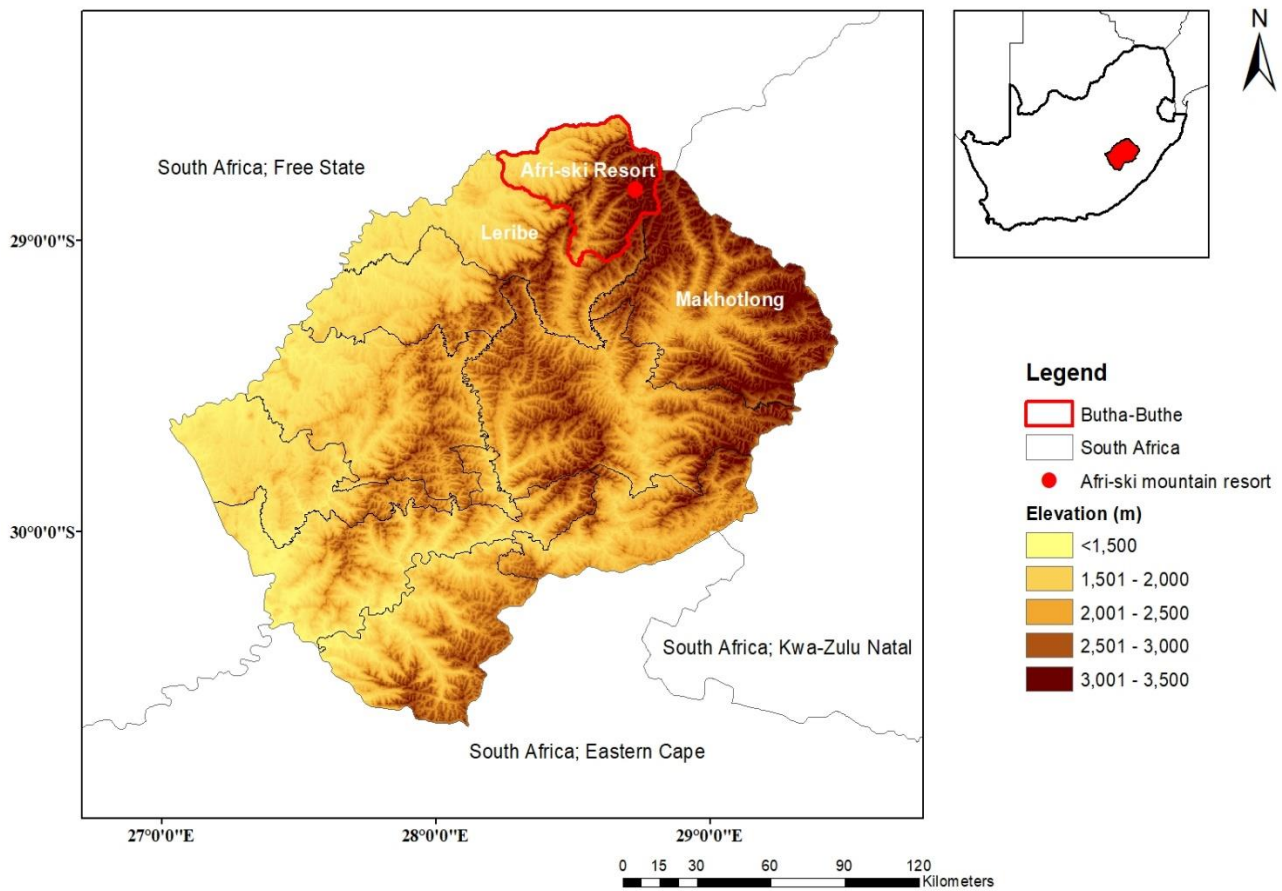


Figure 3.1: Study site map showing Lesotho, the border of Butha-Buthe and Afriski Resort in eastern Lesotho highlands.

### 3.1.1. Topography

Lesotho is comprised of the Drakensberg range and the Maloti range (Letsie & Grab, 2015). The Drakensberg Mountains rise in the east of the South African border (Guillarmod, 1968). The Maloti Mountains are situated in the centre of Lesotho, joining the Drakensberg range in the north. The country is classified into four main physiographic zones (Table 3.1), that is, the western lowlands (17%) with an elevation ranging from 1,500 -1,800m.asl, the foothills (15%) ranging from 2,000-2,500m.asl, the Senqu River valley (9%) and the mountains (59%) which mainly include the Eastern Highlands with elevations exceeding 2,500m.asl (Smit, 1967; Saha, 2011; Grab & Linde, 2014). Lesotho is evidently very mountainous, and the

extremely diverse topography of the region results in diverse rainfall patterns throughout the region (Hoag, 2019).

*Table 3.1: Characteristics of the physiographic zones of Lesotho (adapted from Olutayo, 2019).*

<b>Physiographic zones</b>	<b>Area (km<sup>2</sup>)</b>	<b>Topography</b>
Lowland	5,200	Flat to gentle
Foothills	4,588	Steep rolling
Senqu river valley	2,753	Steep sloping
Mountains	18,047	Extremely steep, bare rock and gentle rolling valleys

### 3.1.2. The Eastern Lesotho highlands.

The Eastern Highlands constitutes 75-80% of the total land area, the vast majority of the population of Lesotho lives in the lowlands (Moeletsi, 2004; Majara, 2005). The lowlands are highly suited for agricultural practices due to the climate, topography, and soils (Mitchell, 1992; Grab & Linde, 2014). Southern Africa's highest mountain range is in eastern Lesotho, with the highest peak of 3,483m.asl at Thabana Ntlenyana (Grab et al., 2009). The topography and high altitude evident in eastern Lesotho largely contribute to the distinct flora and fauna found in the region (Acocks, 1953). More efforts are constantly being made to protect the biodiversity of eastern Lesotho which forms a major part of the Drakensberg Alpine Centre (DAC) (Carbutt & Edwards, 2006). The DAC is renowned for its species rich flora and high levels of endemism (Carbutt & Edwards, 2004). In a study conducted by Carbutt and Edwards (2004), the DAC was shown to support over 2,800 specific and infraspecific native taxa.

The elevated landscape throughout eastern Lesotho, the unfavourable soil and marginal winter climate conditions account for why only 10% of the terrestrial land of Lesotho is

cultivable (Letšela, 2008). However, despite the limited amount of cultivable land, subsistence agriculture and livestock farming greatly contribute to the livelihoods of the population (Bisaro et al., 2010; Mpholo et al., 2012).

### 3.1.3. Soils & Geology of Lesotho

Sedimentary units and basaltic lavas of the Karoo Supergroup underlie much of the region of Lesotho (Stockley, 1947). The eastern Lesotho Drakensberg is a plateau that is deeply dissected, having elevations ranging from 2,290 to 3,484 m.asl (Magill, 1987). The underlying and exposed rock in the eastern Lesotho Drakensberg forms part of the Karoo Supergroup, which includes the Drakensberg Group flood basalts of Upper Triassic to Jurassic age, intruded by fine grained dolerite dykes, underlain by the Stormberg group of sandstone including the Clarens Formation, which is exposed to an altitude of 2,500m.asl, and the underlying Elliot and Molteno Formations (Schmitz & Rooyani, 1989). The Drakensberg Group basalts stretch to a maximum thickness of 1,600m, covering the eastern Lesotho Highlands, with the remaining eroded basalt plateaus forming the Maluti and Drakensberg ranges (McCarthy & Rubidge, 2005).

Most of the soil types found in Lesotho are formed from sediments and basaltic lavas of the Karoo Supergroup (Marake et al. 1998). The sediments of the Karoo Supergroup in this region include the Clarens Formation, Elliot Formation, Molteno Formation and Beaufort Group (Marake et al. 1998). The soils found in the region of Lesotho are characterised by low phosphorus levels, relatively low organic content, and a low base saturation (Ranthamane, 2005). At the lower altitudes of the region, Karoo sedimentary rocks with igneous intrusions, formed by Clarens Formations and covered by alluvium, colluvium and

aeolian deposits are highly dominant (Chakela et al. 1986). The soils in the lowlands and foothills are considered to be acidic, with a pH of 5.3 and 4.4, respectively. The soils in the Highlands at high altitudes are considered to be more neutral (Ranthamane, 2005). According to Cregan (1981) acidic soils are generally problematic and potentially limit productivity.

Soil characteristics, climate, and relief are significant factors and influencers of land degradation, including soil erosion. In Lesotho, the majority of croplands in the lowland region are covered by infertile and vulnerable alfisols (National Report on Climate Change, 2000). These are highly erosive and significantly contribute to gully erosion in the lowlands. Young and shallow soils as well as young and deep vertisols, which are clayey, are largely distributed in Lesotho (Ranthamane, 2005). The vertisols are generally susceptible to erosion because of the dominance of steep slopes – mainly in the highlands, as it is characterised by poor structures with high potassium content and low organic content (Ranthamane, 2005).

#### 3.1.4. Climate

There is a paucity of climate data for Lesotho and particularly eastern Lesotho (Mulder & Grab, 2009). This remains true due to poor coverage of weather recording stations relative to the climatic variety across the region (Pryor, 2018). Although the lack of climatic data is an inhibiting factor in accurately determining the climatic conditions of the region, several studies have been conducted and written on the climate and climate change of Lesotho (e.g. Hudson, 1938; Killick, 1978; Ziervogel & Calder, 2003; Grab & Nash, 2010; Grab & Linde, 2014; Norström et al., 2018).

The temperate climate of Lesotho with its well-defined seasons is as a consequence of the country lying outside the tropics (Grab, 2010). The present-day climate of Eastern Lesotho can be best described as a seasonal alpine climate with cool wet summers and cold dry winters (Grab, 2010). The Eastern Lesotho Highlands have climatic patterns which are distinct from the surrounding lower altitude regions (Fitchett et al., 2016a). Temperatures along the Eastern Lesotho Highlands to the western lowlands tend to increase whereas the rainfall and humidity decreases (Sood, 2007). Climate in the eastern highlands of Lesotho is largely influenced by the altitude (Table 3.2; Sood, 2007; Roberts et al., 2013; Hughes et al., 2018). In the mountains, the climate exhibits rapid changes in temperature and cold-air drainage which can be attributed to temperature differences occurring between the valleys and high slopes (Guillarmod, 1965; 1971). The altitudinal influences result in the region experiencing some of the coldest temperatures in the whole of southern Africa. The altitudinal influences also result in the different temperatures and rainfalls of the physiographic zones of Lesotho (Table 3.2; FAO, 2011).

*Table 3.2: Annual temperatures and rainfall occurring in the different physiographic zone of Lesotho (Adapted from Sood, 2007).*

	<b>Highlands (Mountains)</b>	<b>Foothills</b>	<b>Lowlands</b>	<b>Senqu River Valley</b>
<b>Temperature range (°C)</b>	-8 to 30	-8 to 30	-11 to 38	-5 to 36
<b>Average Temperature (°C)</b>	13	14	17	16
<b>Annual Rainfall (mm)</b>	1,000 – 1.300	900 – 1,000	600 – 900	450 – 600

The lowland mean temperatures range from 8°C in winter to 24°C in summer (Sood, 2007). It is considerably colder in the mountains where conditions change very quickly, especially in winter (Malebajoa, 2010; LMS, 2013). Winter in the region of eastern Lesotho is governed by the presence of high-pressure systems resulting in dry, cold conditions with very limited

rainfall (Grab and Linde 2014). Eastern Lesotho is characterised by strongly seasonal rainfall, with almost 80% falling between November and March, and less than 10% between May and August (Malebajoa, 2010; Linde, 2011). Southern Africa's highest rainfall occurs in the mountainous region (DEA, 2013; Roberts et al., 2013). The orogenic rains of the mountain area are vital for irrigation in arid regions; the runoff from the Drakensberg-Maluti mountains of Lesotho is fed via tunnels to irrigate both lower and central Orange River areas (DEA, 2013). The annual precipitation of the region is said to lie between 750mm per year and 1,600mm per year in the northern mountains and averages 500 mm per year in the extreme west regions of the country (Grab, 2002; Malebajoa, 2010; Linde, 2011). The influx of moist air from the Indian Ocean, during summer along with orographic uplift result in the regular formation of thunderstorms, which are a key source of summer rainfall in Lesotho (Nel & Summer, 2008; LMS, 2013). Tropical temperate troughs, which are cloud bands connecting a tropical low and a temperate low, are very important systems producing summer rainfall in Lesotho (Hart et al., 2013).

The region experiences an estimated five to ten snowfalls during the colder months from April to October, these snowfalls are generally associated with the passage of cold fronts (Linde, 2011; Mills et al. 2012; Grab et al., 2017). Typically, the first frosts occur on the Lesotho plateau for approximately 180 frost days per annum from mid to late April and ending in October (Mills et al., 2009). Most of the precipitation above 3,000m.asl between May and September falls as snow and that accounts for 10% of the total precipitation (Nel & Sumner, 2008).

### 3.1.5. Hydrology and Wetland properties

#### 3.1.5.1. Hydrology

The poor conversion ratio of the Mean Annual Precipitation (MAP) to Mean Annual Runoff (MAR) is problematic in southern Africa and the rest of the continent (Africa), resulting in only 20% of water reaching water systems such as rivers, dams, lakes (Turton, 2008). Eastern Lesotho, however, has the only catchment in southern Africa where annual precipitation exceeds evaporation rates (Zunckel, 2003). The Lesotho highlands receive a dependable amount of rainfall from the moisture uplift of the Indian Ocean coastal air masses over the Maloti-Drakensberg in summer. This rainfall also provides water to the lower-lying and western regions through run-off (Tyson and Preston-Whyte, 2000).

There is thus a considerable surplus (at times) of water in the region, which is why Lesotho supplies neighbouring countries, particularly South Africa. Surface water hydrology of Lesotho is defined by three major rivers, that is, the Mokokare in the far west; Makhaleng in the central area; and Senqu in the far east (FAO, 2011), these rivers meet forming the Orange-Senqu River which flows into South Africa, begins across the dry interior plateau and flows eastwards to the Atlantic Ocean (Loftus et al., 2015). The Orange River System's water balance has and continues to be altered significantly since the establishment of the Lesotho Highlands Water Project (DWA, 2013).

The region sources the Tugela, and Orange (Senqu) Rivers, with run-off from smaller tributaries in the eastern Lesotho highlands (Letšela, 2008). To Lesotho, water is a very profitable export and has boosted the economy (Smith, 1999; Ramaili, 2006). Despite having a considerably small portion of Lesotho that is covered in water, the rivers that run across

the country are an important part of Lesotho's economy. More than 50% of the country's export income can be accredited to water resources in the region, and much of its power comes from hydroelectricity (FAO, 2011). The Drakensberg mountains in north-eastern Lesotho give rise to the Orange River which flows across the entire length of the country before exiting to South Africa. Therefore, the country has become a very reliable source of freshwater for water-stressed and water scarce regions in southern Africa (Arthur et al., 2011; FAO, 2011).

#### 3.1.5.2. Wetlands

A wetland is land that predominantly consists of hydric soils or is inundated or saturated by surface or ground water (Ramsar, 2006). The soils are saturated to the frequency and duration sufficient to support a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions (Ramsar, 2006). Wetlands are very beneficial to the environment, resulting in climate regulation through carbon cycling, absorption of toxins, flood control, erosion reduction, maintaining groundwater levels and water purification (Ramsar, 2006).

Southern Africa's high-altitude areas consist of unique wetlands particularly in terms of their hydro-geomorphology and botany (Sieben et al., 2010; Grab & Knight, 2018). The region of Lesotho consists of wetlands of varying types (Schwabe, 1995; Grab & Knight, 2018), of the five wetland systems found in Southern Africa (marine, estuarine, riverine, lacustrine, and palustrine). Three of these systems are predominant in Lesotho, that is, palustrine, lacustrine, and riverine systems (Du Preez & Brown, 2011). The Lesotho wetlands can be classified into the organic rich bogs, in which atmospheric water only, is able to exit

and enter the system as well as the minerogenic fens that receive water from the surrounding soils (Schwabe, 1995). Several alpine wetlands in eastern Lesotho are experiencing transitions from bogs to fens due to the warming of the climate and increases in erosion resulting in the organic content and hydrological input being affected (Grundling et al., 2015).

Wetlands in Lesotho are widely distributed, varying in sizes ranging from several square meters to square kilometers (Du Preez & Brown, 2011). Most of the wetlands in Lesotho are situated in high precipitation areas of the mountain region and are found in the headwaters of catchments and are origins of the major river systems (Schwabe, 1995). The wetlands in the region can be classified into five main types: mires, marshes, artificial impoundments, natural lakes, and rivers (Schwabe, 1995).

Structurally and floristically, the wetlands found in eastern Lesotho are distinct as compared to those in other parts of the region, the soils and vegetation of these wetlands are different from any other (Grab & Knight, 2018). Attempts have been made at characterising wetlands of Lesotho, however, these attempts have been limited to vegetation and biodiversity (Schwabe, 1995).

Montane wetlands of Lesotho serve multiple hydrological, socio-economic, lithological, and biological functions, some of these include (Grab & Knight, 2018):

1. Hydrological: Regulating flow and channelling floods during heavy rainfall events.

2. Socio-economic: Wetlands play a socio-economic role, that is, providing clean water to downstream communities, and wetlands also provide a grazing resource for livestock and regulate clean water for storage dams and support hydro power.
3. Lithological: Wetlands in the region assist with sediment retention and stabilisation.
4. Biological: The wetlands facilitate the production of organic matter and transfer of nutrients. The wetlands also host several near-endemic, endemic, and rare vegetation species.

Eastern Lesotho has extensive networks of wetlands which are located across the landscapes, occurring at altitudes exceeding 2,750m.asl (Grab, 2010). These wetlands are omnipresent due to the moist, cool climatic conditions in the region of eastern Lesotho, as well as the variety of springs (Grab, 2010). Many of the wetlands in eastern Lesotho are alpine and affect the hydrological system and the organic content input (Schwabe, 1995). The montane wetlands of Lesotho are usually dominated by endemic vegetation species, this is attributed to the isolated high altitudinal habitats they are present in (Junk et al. 2013; Chatanga & Sieben, 2019).

The wetlands of the Lesotho highlands are significantly important to southern Africa's hydrology because they act as storage systems, also regulating large reservoirs of water (Grab, 2010). The highly saturated condition of the wetlands of Lesotho along with the relatively low temperatures throughout the year, facilitate and enable the preservation of organic material and inhibits decomposition (Grundling et al., 2014; Fitchett et al., 2016b). Despite the proven importance of the Lesotho wetlands, an estimated 65% of these wetlands are damaged, with 49% of the damaged wetlands suggesting disturbance

(Schwabe, 1995), mainly as a consequence of livestock grazing and trampling (Brown et al. 2013). It is therefore important that wetland conservation is made a priority, not only in eastern Lesotho but in southern Africa at large, because Lesotho is an important hydrological reservoir and watershed for several countries (Nüsser & Grab 2002; Chatanga & Sieben, 2019).

### 3.1.6. Vegetation

Empirical evidence demonstrating vegetation changes in Lesotho does not demonstrate explicit trends (Marake et al., 1998). However, more historical observations have demonstrated contrary and interesting trends of vegetation change for the region (Ellenberger, 1992; Marake et al. 1998; Norström et al., 2018). Lesotho is a dominantly grassland country, with limited naturally growing trees in the western lowlands, because it is too dry and cold to allow for tree development (Acocks, 1953). The lowlands consist of *Themeda-Cymbopogon-Erograstis* grassland type (Acocks, 1953; Chakela et al., 1986), while the higher lying regions are covered by shrubs and vegetation such as *Helichrysum trilineatum*, *Chrysocoma ciliata*, *Cussonia spicata*, *Euclea ramosa*, *Ocotea bulleata* and *Aloe capensis* (Nüsser, 2002; Mucina, 2006; Chatanga, & Sieben, 2019; Smit & van Rensburg, 2020). The grasslands, unlike trees, give very limited protection against soil erosion, especially since the country's rainfall is concentrated during particular months of the year and thus further promoting erosion (Carroll & Bascomb, 1967; Maro, 2011). Most of southern Africa's vegetation patterns are largely influenced by the seasonality and amount of rainfall received, however, in Lesotho vegetation is structured by altitudinal temperature gradients (Loftus et al., 2015).

It is evident that the vegetation in the region of Lesotho is specifically impacted by physiographic and temperature regimes (Vogel et al., 1978). Topography further influences the spatial distribution of plant species, through the modification of factors such as temperature, soil moisture and light, which directly affect the plant (Morris et al., 1993; Morris, 2017; Chatanga et al., 2019). Eastern Lesotho has very rich, diverse vegetation and hosts a number of endemic and near endemic species, this diversity is due to the high altitude, rapid changes in aspect and high levels of moisture (Carbutt & Edwards, 2004). The climatic differences between the eastern Lesotho highlands and western lowlands are accountable for the vegetation gradient across Lesotho (Carbutt & Edwards, 2004; Bentley et al., 2019). Eastern Lesotho is characterised by wet conditions, with several high-altitude wetlands which comprise of grasses, sedges and mosses (Grab, 2002; Carbutt & Edwards, 2006), on the other hand, western Lesotho is much drier, with lower altitudes and therefore has the capacity to support the growth of scrub forests (Van Zinderen Bakker, 1955; Mucina & Rutherford, 2006; Clark et al., 2011). Trees are only found in the valleys of western Lesotho, where altitudes do not exceed 2,200m.asl. while the shrubs in eastern Lesotho do not reach heights exceeding 0.5m as a result of altitudinal limitations (Plug, 1997; Nüsser & Grab, 2002). At the highest altitudes, above 3,400m.asl, plant cover is particularly sparse and, in some cases, completely absent (Killick, 1978; Morris, 2017). The composition of vegetation species in the eastern highlands of Lesotho is largely determined by altitudes, slope aspect and climatic conditions, leaving soil type with very little influence on vegetation (Carbutt & Edwards, 2004). According to Morris (1993) Eastern Lesotho has five main vegetation communities which lie in the alpine and subalpine belt (Killick, 1963). The alpine belt consists of temperate sedgeland, temperate grassland and mixed grasslands, the

subalpine belt consists of two types of subtropical grassland (Killick, 1963). The terms alpine and subalpine are commonly used to define the major vegetation belts occurring in the Natal Drakensberg and Maluti (Killick, 1963; Zunckel, 2003).

Reeds are a common type of vegetation, the region is also dominated by *Phragmites communis* which frequently occurs along rivers in the lowlands (Schoeman, 1973; Bentley, 2019). The reeds are useful in the region due to their ability to bring about silt deposition and slowing down flood waters (Guillarmod, 1962). Schoeman (1973) further emphasised the importance of this vegetation type as an aid of biological self-purification of the rivers in the lowlands, as the majority of these waters were polluted.

Vegetation present in the wetlands of Lesotho includes Poaceae (~20%), Asteraceae (~19%), Cyperaceae (~14%), Scrophulariaceae (~4%) and Polygonaceae (~4%) (Chatanga & Sieben, 2019). The vegetation composition in the wetlands are generally influenced by various factors, including altitude, soil depth, slope, and wetness (Meakins & Duckett 1993; Chatanga & Sieben, 2019). The vegetation from the Lesotho highlands has exhibited a dominance of C<sub>3</sub> plants (i.e. sedges, trees, shrubs and cool season grasses) and the lowlands are dominated by C<sub>4</sub> (i.e. tropical savannah grasses and sedges), thus there is a distinct difference between wetlands in the highlands and lowland in terms of the vegetation species that make up the communities and the structure of communities (Nüsser 2002; Chatanga & Sieben, 2019). High altitudinal wetlands of Lesotho are notably more diverse than the lowlands which may only be dominated by just one or two species (Boutin & Keddy 1993). This vegetation pattern that exists in the region contradicts the general ecological

law, where species richness is expected to decline with altitude (Rosenzweig, 1995), this further contributes to the uniqueness and importance of the region.

#### 3.1.7. Environmental challenges

The eastern Lesotho highlands is identified as one of the most endemic-rich regions within the DAC, however, only 1% of the Grassland belt of the Lesotho highlands is conserved (Dayaram et al., 2017). Most of the country has decreased natural grass cover due to uncontrolled grazing and fast flowing surface water which contribute to erosion (Low & Rebelo, 1996; Dayaram et al., 2017). Some of the primary environmental related problems include population pressure forcing settlement into marginal areas which results in overgrazing, inappropriate agronomic practices, severe soil erosion, soil exhaustion and desertification (Dayaram et al., 2017). In an attempt to combat these issues, the Lesotho Highlands Water Project committed to better methods of storing, controlling, and redirecting water to South Africa (Tromp, 2016). The environmental challenges, combined with the effects of climate change and the socio-economic issues surrounding the country, threaten the sustainable production of food, thus affecting food security (Nusser & Grab, 2002). This is problematic because more than half of the population of Lesotho rely on some form of subsistence farming, and therefore the economic prospects of the country and the lives of many citizens are intimately linked to the state of the environment (Maro, 2011; Molaoa, 2016).

The landscape of eastern Lesotho and its mountainous topography means that any type of farming occurring in the region is undertaken on slopes characterised by delicate soil formations resulting in excessive levels of soil erosion caused by water run-off (Majara,

2005; Bentley et al., 2019). Over the years, soil loss and land degradation have accelerated, this can be attributed to the increasing pressures of arable and livestock production, characterised by overgrazing, over-cultivation, and forest conversion, with ongoing urbanisation and deforestation (Majara, 2005; Hoag, 2017).

The alarming state of land degradation in Lesotho dates back to the 1800s, with reports of the development of gullies caused by soil erosion noted in literature (Staples & Hudson, 1938; McVean, 1977; Majara, 2005). Presently, the region is considered as one of the most eroded countries in the world, with an estimated 40 million tonnes of soil lost per year, the resultant sedimentation affects river ecosystems while also exacerbating both air and water pollution (Majara, 2005; Hoag, 2017; Khaba & Griffiths, 2017). Lesotho is highly vulnerable, ranking 2/3 on the Global Needs Assessment (GNA) Vulnerability Index and 3/3 on the Global Needs Assessment (GNA) Crisis Index, and this is problematic as it indicates that the majority of the population does not have sufficient adaptive capacity or resilience to environmental and climate change. Hence the region is more vulnerable to negative impacts, such as droughts and floods, associated with the climate change (LMS, 2017). Water resources including perennial dams, rivers and springs have greatly deteriorated, while agriculture, which is an important source of rural livelihoods, continues to decline steadily (Maro, 2011; Hoag, 2017).

Various climate change projections indicate that Lesotho is likely to experience increased temperatures and rainfall variability including extreme and erratic climatic events (Bentley et al., 2019). The manifestation of climate change and environmental dynamics in Lesotho continue to have direct and indirect consequences on natural resources, infrastructure as

well as in human communities (Maro, 2011; Molaoa, 2016). The Notre Dame Global Adaptation Initiative (ND-GAIN) Country Index ranks Lesotho the 14th most vulnerable and susceptible to climate change, and it is the 51st least ready country to improve resilience to climate change (LMS, 2017). Therefore, much intervention through investments, innovations and research is required urgently in order to improve and curb the environmental and climatic issues that the region faces (Mapfumo et al., 2015).

### 3.2. Specific study sites

#### 3.2.1. Site Selection

This study is conducted at altitudes >3,000 m.asl, and this is to enhance the understanding of both environmental and climatic lapse rates, for the present time and the past. The region is alpine and thus plays a key role in exploring different altitudinal rates of species relocation during periods of climate change (Noström, 2018).



Figure 3.2.: Images showing the coring points for the sediment profiles BLMA coring site situated within a wetland.

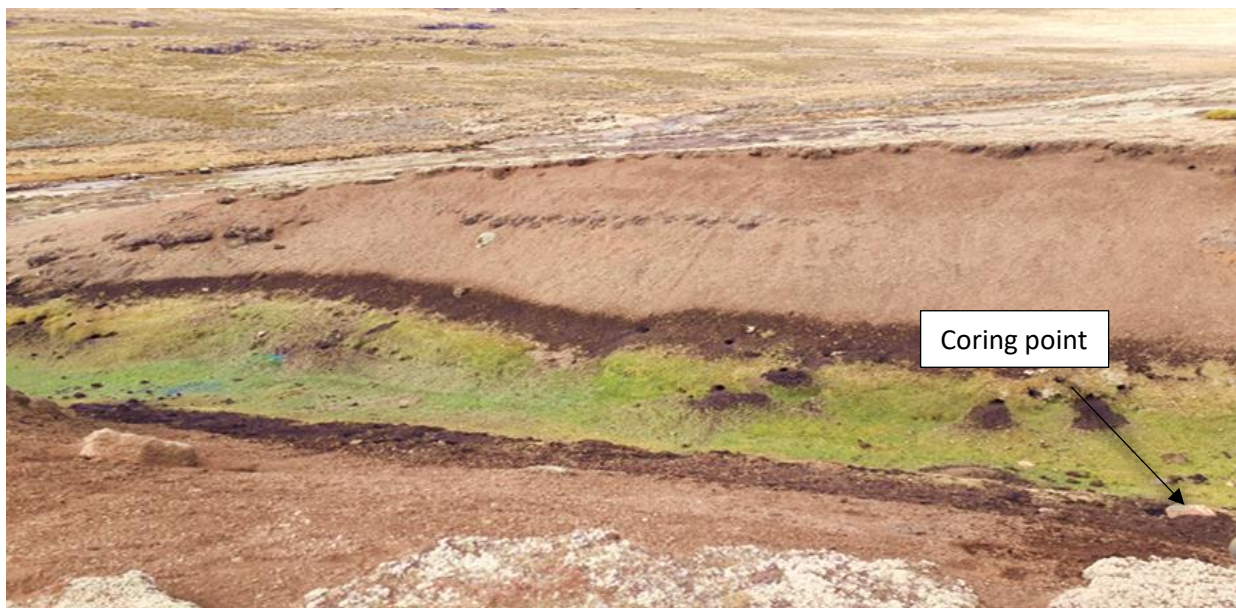


Figure 3.3: Images showing the coring points for the sediment profile BLMB coring site situated just outside a wetland.

### 3.2.1. Site one: BLMA

The GPS (Global Positioning System) coordinates for the first study site were 28°54.6034'S; 28°49.0743'. The site also has an altitude of 3,108 m.asl, lying on a highly steep west-facing slope. The point of coring identified was half-way down the slope within the wetland. The site is characterised by short grasses and vegetation such as *helichrysum* shrubs, the

vegetation on site is larger and denser towards the river with a presence of trees. The area is also dominated by frost hummocks which are periglacial structures (Figure 3.2). These structures are usually dome-shaped vegetated hummocks, with a diameter of about 30 to 50 cm, and around 20cm in height (Schunke & Zoltai, 1988). Earth hummocks play a vital role in hydrology by obstructing water flow paths, and increasing the water-table elevation in the inter-hummock areas (Grab, 2005). A variety of processes which include the cryoexpulsion of clasts, hydrostatic and cryostatic pressure, cellular circulation and differential frost heave may be attributed for the formation of earth hummocks (Van Vliet-Lanoë, 1991; Van Vliet-Lanoë & Seppälä, 2002; Grab, 2002).



(a)

(b)

(c)

Figure 3.4: (a & b): images showing vegetation present at the study site in the vicinity of the wetland. (c): image showing Hummocks, called thúfur, are common microtopographical features on the mires of the Lesotho mountains.

### 3.2.2. Site two: BLMB

The second coring site's GPS coordinates were 28°50.7356'S; 28°45.6581'E at an altitude of 2,996 m.asl. The coring site (figure 3.3) was located just meters outside a wetland, on a south-facing slope. The sediment from the site contained fossilised organic material and is

characterised by segments of red coloured soil and dark clay. The vegetation of the site is very similar to the previous site, characterised by short grasses and shrubs, however, shrubs are more abundant in this site and there were no trees. Hummocks are barely present in the site. The study site also shows evidence of extensive erosion, and this has been attributed to the harsh climate, highly steep slopes, thin regolith cover and agriculture at the site (Showers, 1989; Calles & Stalnacke, 2000). The site also had the presence of ice rats which may have contributed to land disturbances through burrowing. There has also been continuously growing pressure to utilise alpine and sub-alpine vegetation for grazing for much longer periods (Quinlan & Morris, 1994; Grab & Nusser, 2001).



(a)

(b)

(c)

Figure 3.5: (a) Image showing the type of vegetation dominant present in in the vicinity of the BLMB study site. (b) image showing an ice rats in the vicinity of the coring site.(c) image showing the highly disturbed core site and the actual coring points.

## Chapter 4: Methodology

### 4.1. Fieldwork

#### 4.1.1. Sediment extraction

The fieldwork for this study, took place 2019, May 27 to 28. During the field trip, two sites suitable for coring were identified (Figure 4.1). The first day of field work was allocated to identifying the coring sites for this study. Sediment profiles of 95cm and 150cm depth were extracted, from two selected study sites, respectively. The core site were mainly selected by the presence of a wetland and accessibility , as the area is quite remote. The second day of field work was allocated for the extraction of the sediment profiles. The samples for the first core (BLMA) were taken adjacent a wetland in the vicinity of Afriski and the samples for the second core (BLMB), that is were taken on a downhill slope just outside the wetland, which was a few kilometres away from the BLMA (Table 4.1).



Figure 4.1: Google Earth image showing the two study sites selected for coring (BLMA and BLMB).

Table 4.1: Coring sites coordinate with the respective altitudes of the sites.

Site	Co-ordinates	Altitude
<b>BLMA</b>	28°54.6034'S; 28°49.0743'E	3,108m.asl
<b>BLMB</b>	28°50.7356'S; 28°45.6581'E	2,996m.asl

The extraction of well-preserved sediment was conducted from exposed gully walls at both study sites, this is the same method utilised by Grab et al. (2005) and Fitchett (2015) among others. To commence with the sediment extraction these steps were followed: 1) a clean vertical profile was exposed, and this was to ensure minimal contamination. 2) To collect sediment, a polyvinyl chloride (PVC) core was hammered into the ground a few centimetres away from the gully face. 3) Using a stainless-steel scraper horizontal sections of excess sediment material is removed, and the PVC tube containing intact core was dug out and extracted. 4) The PVC core with sediment material was then covered using cling-wrap and heavy-duty aluminium foil, labels were also added for the top and bottom of the core.

This method was useful when extracting sediment from the first study site, resulting in a largely continuous sequence of the sample. For the second study site, extracting sediment proved to be rather challenging, therefore adaptations had to be made to the method used for the first study site. The site contained highly disturbed sediments, and the sediment was characterised by a 'crumbly' texture. Due to the texture of the sediment most of sediment material was extracted by removing a layer of the exposed sediment from the gully face. A stainless-steel scraper was then used to extract sediment, this process was repeated at 2cm consecutive intervals throughout the depth of the exposed gully, the sediment was then

placed into zip-lock bags and properly sealed, this was to ensure minimal contamination. Finally, the samples were labelled and properly packed.

## 4.2. Laboratory work

### 4.2.1. Laboratory samples

After the collection of sediment in the field, the sediment samples were further subsampled to proceed with sediment analysis, diatom analysis and for AMS radiocarbon dating. Samples of 1g were portioned for diatom preparation, 8g was retained for AMS dating and about 10g for the sediment analyses. These subsamples were stored in sealed test tubes and refrigerated at a temperature of  $\sim 4^{\circ}\text{C}$ , until they could be processed, to prevent decay and microbial activity (Faegri et al., 1989; Stager et al., 2003).

To prevent contamination and ensure reliability of results, clean PVC corers were used for coring at each site. The sediment was collected in clean, clear zip-lock bags. Following the technique of Stager et al. (2003), the subsampling of sediment was conducted in the GAES laboratory, and samples were scooped with a stainless-steel spatula from the sample bag into an appropriately labelled receptacle. The spatula was washed and rinsed with distilled water between each sample. Any sediment that was in contact with either the PVC tube, or on the exposed face was removed using the scalpel and discarded, to reduce the risk of contamination (Renberg, 1990). The scalpel was washed and rinsed with distilled water between each use to prevent contamination (Renberg, 1990).

For this study, it is important to acknowledge that bioturbation may have occurred at the sites resulting in disturbances in sediment and thus contamination. However, since eastern Lesotho is a very remote area, this would be limited to animal trampling and burrowing,

which has only intensified in the past 100 years. Burrowing could be issue because it is not related to human activity in the last 100 years.

#### 4.2.2. Accelerator mass spectrometry (AMS) Dating

AMS dating for this research was conducted at the iThemba labs of the NRF (National Research Foundation). Altogether, fifteen samples were prepared and dated using AMS dating, eight from the first core (BLMA) and seven from the second core (BLMB). iThemba labs is a laboratory with an established track record in technical competence in measuring natural levels of radiocarbon using Accelerator Mass Spectrometry (AMS). Normally samples are packed and sent to a laboratory, however, for this research, access to use the lab was granted and training was conducted, therefore dating preparations were personally performed by the researcher at iThemba laboratories (more detail in subsection *4.2.2.1.Preparations for AMS dating*).

It is important to date the sediment material, because although the material can be assumed to be from the Holocene, it is necessary to validate and confirm this. Dating sediment material is necessary to determine whether there is an intact stratigraphy and attach a chronology to any observed changes and patterns. There are various dating methods which can be used for dating material, however, AMS dating is most-suited for this study because the wetland sediment is expected to be less than 50,000 cal yr. BP and it contains organic material (Kolstrup, 2007).

During the dating process, relative abundances of carbon isotopes ( $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{14}\text{C}$ ) were compared to each other. Carbon isotopes  $^{12}\text{C}$  and  $^{13}\text{C}$  are stable and  $^{14}\text{C}$ , the heaviest isotope, is radiocarbon and thus radioactive.  $^{14}\text{C}$  is produced in the upper atmosphere when

the neutrons from cosmic rays and  $^{14}\text{N}$  react,  $^{14}\text{C}$  then oxidizes to produce  $^{14}\text{CO}$  (Leese, 1995).  $^{12}\text{CO}$ ,  $^{13}\text{CO}$  and  $^{14}\text{CO}$  are widely distributed throughout the atmosphere and used by plants during the process of photosynthesis (Leese, 1995). Once oxygen becomes limited when a plant dies,  $^{14}\text{C}$  becomes more dominant as decay occurs, and once radioactive decay begins, the half-life of  $^{14}\text{C}$  is 5,730 years  $\pm$ 40 years (Walker & Walker, 2005).  $^{14}\text{C}$  varies in the atmosphere, and it is unstable in the atmosphere, thus calibration is required to ensure the correct ratio is used (Walker & Walker, 2005).

To guarantee correct atmospheric  $^{14}\text{C}$  data was used, a calibration curve was constructed by using dendrochronology, and the data is then calibrated to 1950, thus resulting in dates reported as calibrated years before present (Walker & Walker, 2005). The individual atoms of the carbon isotopes ( $^{12}\text{C}$ ,  $^{13}\text{C}$  and  $^{14}\text{C}$ ) were counted and the level of decay was calculated using the concentration ratio of isotopes (Brown et al., 1992). According to Hogg et al. (2013), there is an apparent difference in carbon isotope ratios, where these differences are attributed to the ocean to land ratio. The land and ocean affect the isotope ratios because of the organic matter produced by land and ocean plants (Rullkötter, 2003). In the Southern Hemisphere, the ocean to land ratio is much greater than in the Northern Hemisphere, however, the calibration curves between the Northern and Southern Hemispheres are generally similar, resulting in synchronous Southern Hemisphere dates being found to be decades older, when compared to the Northern Hemisphere dates (Hogg et al., 2013).

The wetlands found at the border of Leribe-Makhotlong-Butha-Buthe districts, are situated in the Southern Hemisphere and the ages of the sediment sequences are assumed to be

younger than 50,000 cal yr. BP, therefore the dates for the two sediment cores were calibrated through the use of ShCal13 (Southern Hemisphere Calibration Curve 2013).

#### 4.2.2.1. Preparations for AMS dating

All preparations for AMS dating were conducted at iThemba labs, with the main stages of this preparation depicted in Figure 4.2. To prepare samples, standard procedures were used, and following (Chappell & Polach 1972; Brock et al., 2010) adaptations were made where necessary. Prior to treating the samples, they were visually inspected under the microscope to ensure any waste or material (such as grass roots) is removed to limit contamination. The sediment samples selected for AMS dating were pre-treated, to get rid of all possible contaminants particularly mineral carbon (carbonates) (Chappell & Polach 1972). The pre-treatment chemical method used was the acid-base-acid (ABA) method. This process involved material subsampled into beakers and acid (HCl) was added to cover the sample. The samples were then placed in a hydro sonic water bath in the fume cupboard for about 45 minutes, and the samples were stirred every 10 minutes using a spatula, following the process of Brock et al. (2010). NaOH was then added to the sample to remove humic acids. This was followed by rinsing with deionised water till the sample was neutral. Acid (HCl) is then added again onto the sample, to ensure that the acid had reacted with all the sediment particles.

To prevent contamination, the spatula was cleaned between every stir using a paper towel. After 45 minutes the samples were rinsed with distilled water. This process was repeated three times for each sample. All the sample material was placed in test tubes, centrifuged for 1 minute at about 1,000 revolutions per minute (rpm) and rinsed. This is done to ensure

the useful material was not lost during the rinsing process of the samples in the beaker. The samples were then dried in the oven overnight at 70°C, however, for the wetter samples, methodological adaptations were made to allow samples to dry completely. Therefore, the samples were placed in the oven for longer, depending on how wet they were. Once the samples were dry, they were then gently crushed, and a sample mass of 100mg was weighed into a test tube. Thereafter 89mg of Copper Oxide (CuO) and 1.5mg of Iron (Fe) and pure Silver (Ag) were added to the 100mg sample. The CuO, Fe and Ag were added to facilitate combustion (Tripp et al., 2004). The samples were weighed into clean tin capsules and then placed in test tubes for measurement of their stable isotopic composition and the carbon and nitrogen content, as well as their ratio (Brock et al., 2010). Vacuum conditions were created, and each sample was sealed. Each sample was combusted in a furnace and then graphitised according to Dee & Bronk Ramsey (2000). After combustion, most of the samples placed in the test tubes indicated that the copper oxidised completely to copper (II) oxide, which meant the samples contained sufficient carbon dioxide for dating (Polach & Golson, 1966; Fewlass et al., 2019). Graphitization involved the separation of gases to extract carbon dioxide (CO<sub>2</sub>) from the samples (Dee & Bronk Ramsey, 2000). Once the preparations were completed, samples were sent off for AMS dating. It is important to note that careful attention was given to handling the samples and the materials used (Polach &

Golson, 1966, Fewlass et al., 2019, Reimer et al., 2015; Fayle & Gerrard, 2002).

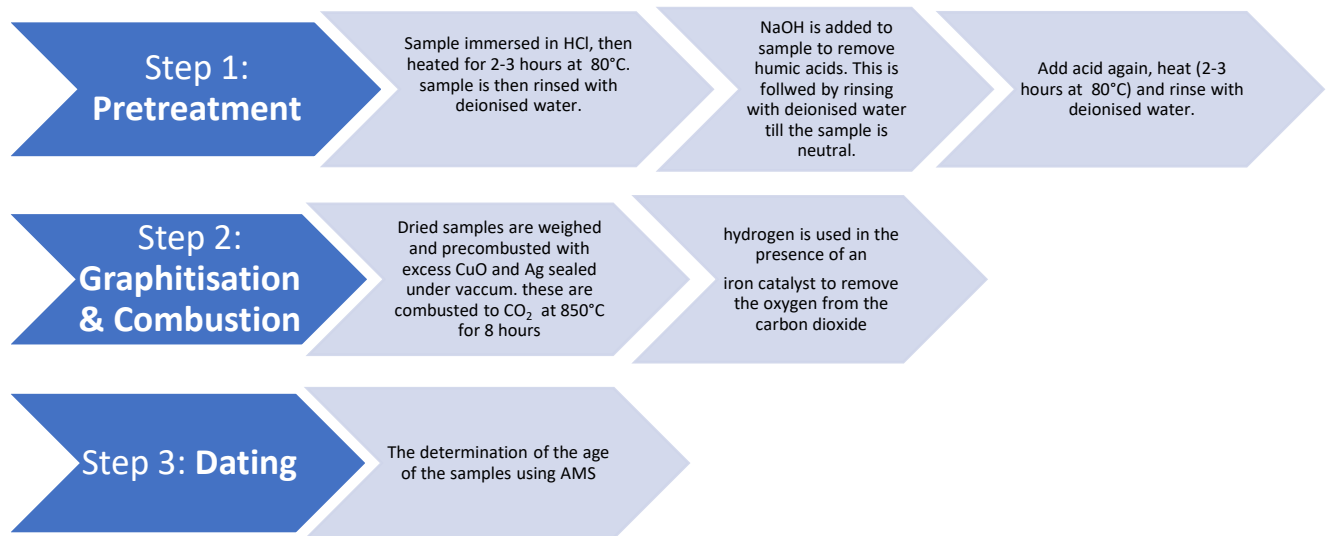


Figure 4.2: Summary of three principal stages in the production of radiocarbon age.

#### 4.2.3. Analysis of sediment

The sediment that was obtained from the two sites (BLMA & BLMB) were classified using a specific criterion, that is, carbonate content, organic content, size of particle and the colour of the sediment. This was done to aid in deducing the periods of climatic changes which may have occurred through analysing composition and weathering processes (Abby & Tauber, 1974; Barber, 1981).

The sediment was classified according to the organic content of each subsample from both cores (Ball, 1964; Ellison, 2008), and the total organic content was determined using the LOI (Loss on Ignition) process. This process (Figure 4.3) involves the burning off of organic content and then weighing the difference (before and after the organic content is burnt off) (Heiri et al., 2001). The general equation for determining organic content is as follows:

$$LOI_{550} = (Dw_{105} - Dw_{550} / Dw_{105}) \times 100$$

Where:

$LOI_{550}$  *LOI at 550 °C (as percentage)*  
 $Dw_{105}$  *represents the dry weight of the sample before combustion*  
 $Dw_{550}$  *dry weight of the sample after heating to 550 °C*

In the southern African context, the change in organic content percentage can be used as a proxy to estimate moisture levels. Since high organic content is an indication of high humidity and low organic content indicates much drier periods (Marker, 1994).

The second step to determining the organic content available in the sediment samples, was the quantification of the weight of carbonates. When preparing the diatoms, the reactions which occurred from the addition of hydrochloric acid (HCl) signified the presence of carbonates (Battarbee & Kneen, 1982 Battarbee, 2001). Carbonate content percentage composition further gives information on the general conditions under which the sediment formed.

The mass of the carbonates ( $Mass_{CO_3^{2-}}$ ) was approximated (assumption: molecular mass for  $CO_2$  of 44g.mol<sup>-1</sup> and for  $CO_3^{2-}$  of 60g.mol<sup>-1</sup>) (Heiri et al., 2001). This was done to facilitate the determining of the carbonate content percentage, using the following equation:

$$LOI_{950} = (Mass_{CO_3^{2-}} / Dw_{105}) \times 100$$

$$\text{where } Mass_{CO_3^{2-}} = (Dw_{550} - Dw_{950}) \times 1.36$$

$LOI_{950}$  *LOI at 950 °C (as percentage)*  
 $Dw_{550}$  *represents the dry weight of the sample after combustion*  
 $Dw_{950}$  *dry weight of the sample after heating to 950 °C*

In the equation, the weight loss by LOI at 950 °C is always multiplied by 1.36 so that it theoretically equals the weight of the carbonate in the original sample (Bengtsson, 1986; Heiri et al., 2001).

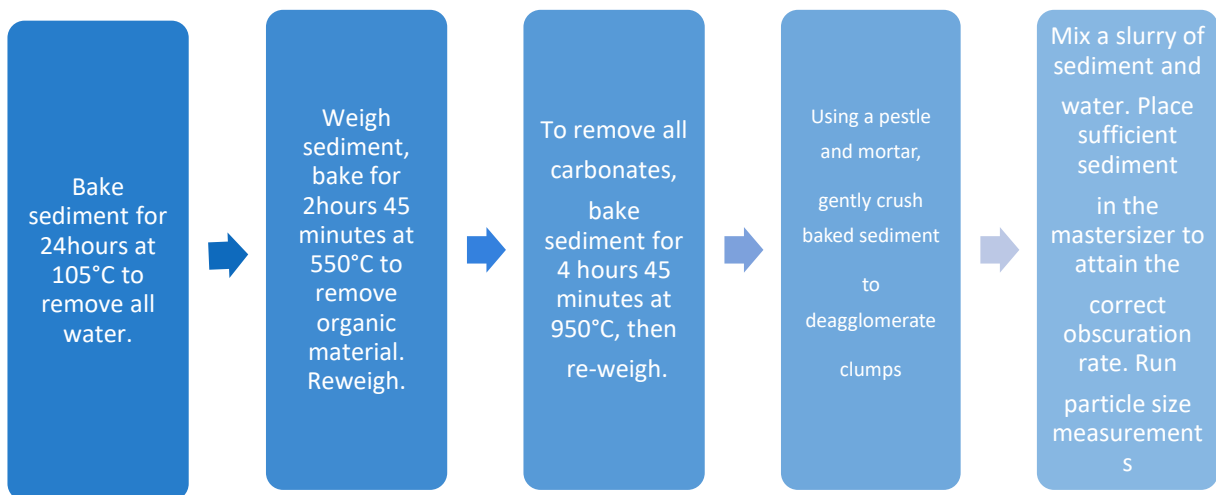


Figure 4.3: Process of sediment preparation from sediment analysis to determine organic content, carbonate content and particle size (Adapted from Fitchett, 2015).

The third step to analysing the sediment for this research focused on the particle size distribution of the sediment. Particle size was measured using a Malvern Mastersizer 3000©, where this equipment uses laser diffraction (Figure 4.3). The standard particle size ranges for granule, sand, silt, and clay are as follows; 2-4 mm, 0.5-1mm, 3.9–62.5 µm and 0.98–3.9 µm, respectively. The sediments used for determining the particle size, were the sediments which had undergone LOI. The sediment was put in water and dispersed using ultrasonic stirring enabling the measurement of resultant refraction of light in both blue and red by passing a set of lasers (Sperazza et al., 2004). The light scattered is converted into a measure of the number of particles within each of the particular size categories. For this research, a single Standard Operating Procedure (SOP) was utilized for all of the

samples, to ensure consistency between measurements (Sperazza et al., 2004). The results produced from the mastersizer for each of the samples were analysed in order to establish sediment processes which may have occurred in the past and to also determine changes in particle size.

#### 4.2.4. Diatom preparation

Diatom preparation for this study was conducted in the GAES (Geography, Archaeology & Environmental Studies) laboratories of the University of the Witwatersrand. The diatoms were prepared for the BLMA core only. This is because the BLMB site indicated extensive bioturbation and therefore the diatoms may not be reliable. Methods for isolation for the identification of diatoms were very similar to what has been outlined in the studies of Fitchett (2015), Andren et al. (2007) and Setty (1996). These methods were adapted for the use of a water bath in preparation for the large (4samples) samples (Battarbee, 1982). For the samples which were organic rich, slides were produced with the solutions diluted by 10x. This was to prevent crowding the slides with clay particles or diatoms, this is also very useful in making more accurate identifications of the diatoms (Fitchett, 2015). To prepare the diatoms, wet sediment was weighed (0.1g) into centrifuge tubes, hydrogen peroxide ( $H_2O_2$ ) was added to the sediment and samples were placed in a test tube rack in the water bath (water temperature set to 90°C) in the fume cupboard (Renberg, 1990; Taylor et al., 2007). The samples were left in the heated water bath, making sure water levels were maintained, for about 5 days, to remove all the organic material. Once the samples were removed from the water bath, 3-4 drops of HCl were added to each sample to remove all the remaining  $H_2O_2$  and carbonates, however, for samples with high clay content, double

HCl rinses were completed to remove the iron oxides.  $\text{NH}_3$  was used in the final wash to keep the clays in suspension. The samples were then topped up with distilled water and centrifuged at 1,200 rpm for four minutes. The liquid floating above the sediment material was decanted off, making sure the sediment material was not disturbed, the diatoms were re-suspended in distilled water, and the washing process was repeated a further four times.

The procedure followed for preparing the slides for this study was adapted from standard procedures (Renberg, 1990; Harding et al., 2007; Taylor et al., 2007; Franchini, 2013; Fitchett, 2015). Using a 1ml pipette, 0.5ml of well-mixed diatom suspension was placed on each cover slip and dried overnight in a covered tray to avoid dust contamination (Figure 4.4). Once the samples had dried, leaving only the diatom material on the cover slip, the hotplate was heated in the fume cupboard at  $130^\circ\text{C}$ . On the glass microscope slides, one drop of Naphrax was placed. The coverslip was inverted with the dried diatoms. Thereafter, the slide was heated on a hotplate for about 15 minutes, to remove the toluene from the Naphrax. The slide was finally allowed to cool, during this time it was ensured that the cover slip does not move. Figure 4.2 below presents a brief summary of the procedure.

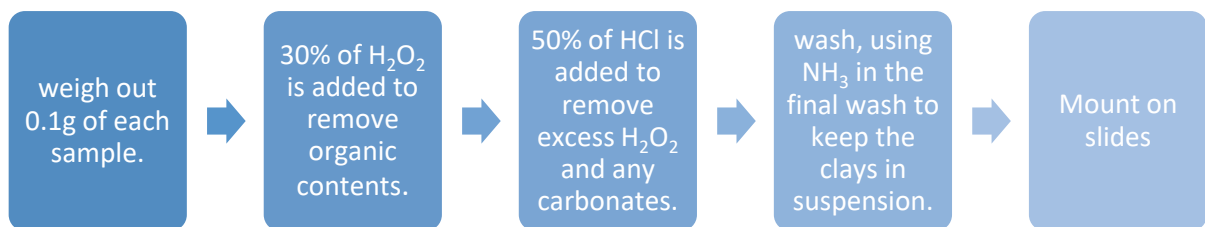


Figure 4.4: A Summarised process of diatom preparation (Adapted from Fitchett, 2015).

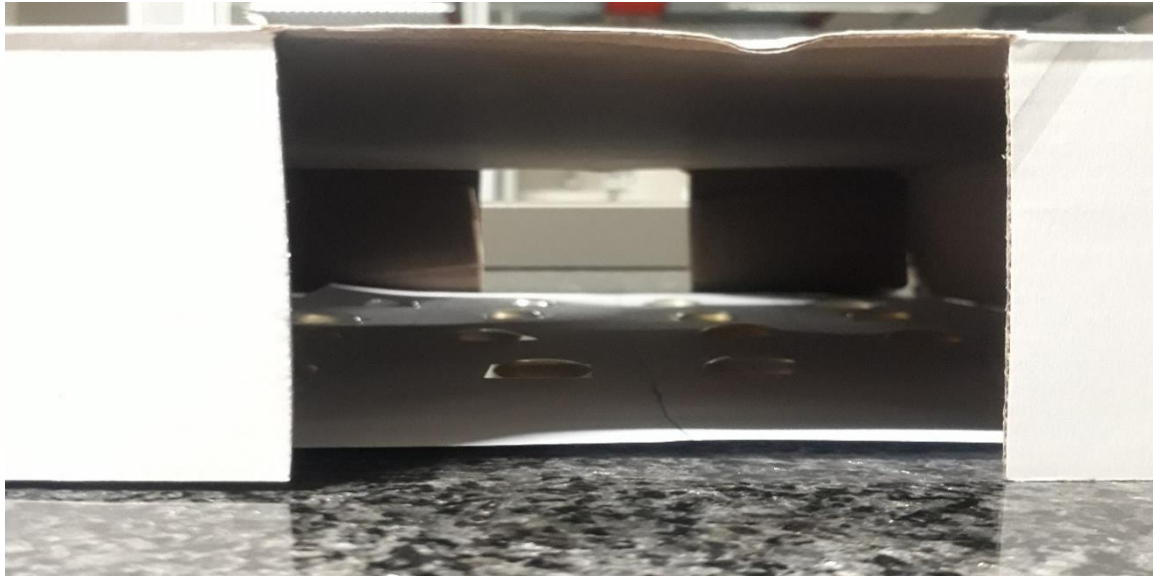


Figure 4.5: Image showing cover slips containing well mixed diatom suspension in preparation for mounting the diatom slides.

#### 4.3. Microscope work

##### 4.3.1. Diatom identification

To identify the species of diatoms, a light microscope with oil immersion objective lens was used at a magnification of 100x (Fitchett, 2015). Specific focus was placed on the frequency of striae, length, breadth, pattern of the striae and the presence of a raphe (Battarbee et al., 2001). These features or characteristics enable discrimination between the different species in the identification process (Taylor et al., 2007). The identification of the species of diatoms was made by comparing samples with diatom reference material from Lesotho (Schoeman, 1973), southern Africa (Matlala et al., 2011; Harding & Taylor, 2011) and internationally (Patrick & Reimer, 1975; Snoeijs & Balashova, 1998), where it was necessary to do so. During the identification of the diatoms online references (e.g. <http://diatoms.org>; [www.algaebase.org](http://www.algaebase.org)) were also consulted.

#### 4.3.2. Counting diatoms

Diatom valves are fragile and can be broken or deteriorate in water before sampling or during cleaning, thus it is important to establish a consistent approach to count the diatom valves (Serieyssol et al., 2010). If more than a half a valve was found, it was to be counted as one valve. This also applies to the central fragments of centric diatoms (Taylor et al., 2007). According to Battarbee et al. (1986), there are marked differences in the percent frequency of dominant taxa between a count of 100 and 200 valves. However, for the valve count between 400 and 500, the change in the percent frequency of dominant taxa was marginal/insignificant and therefore a count between 300 and 600 comes highly recommended for most analyses (Battarbee et al., 1986). Thus, in this study, a minimum of 300 diatom valves were counted for each sample, and the diatom valves were counted in a transects across the slide.

#### 4.4. Statistical Analyses:

##### 4.4.2. Age-depth modelling

The type of Bayesian age-depth model which was used in this study is the Bayesian accumulation model (BACON). This model was used because it is a simple autoregressive time series (prior accumulation is based on previous sedimentation rates), and it assists in displaying accurate natural changes in accumulation rates (Blaauw & Christen, 2011). The model is very useful because it addresses uncertainties and approximate sedimentation rates, and it also accounts for the spanned depth of the sample and radiocarbon uncertainties which may occur (Parnell et al., 2011). This model addresses these uncertainties through a

Markov Chain Monte Carlo algorithm, which is a class of algorithms for sampling from a probability distribution (Parnell et al., 2011).

Linear interpolation and linear regression methods have been the conventional methods for generating age-depth models (Parnell et al., 2011), but have several limitations, one being that the model is forced to pass through radiocarbon dates (Parnell et al., 2011). Secondly, the methods uses a central point from the calibrated radiocarbon dates, thus the probability of distribution for date ranges is not acknowledged (Telford et al., 2004). Lastly, the methods do not provide a statistical way to address outliers because sedimentation rate is considered as constant (Telford et al., 2004).

The Bayesian calibration of radiocarbon dates were advantageous, because the Bayesian age-depth model considers variables such as stratigraphy as well as other historical dates (Blaauw & Christen, 2011). The use of the model results in more refined and highly resolved date range. The model's ability to detect outliers and account for errors in the calibration process, allows for the researcher to compare dates between age-depth models (Blaauw & Heegard, 2012). According to Telford et al. (2004), the most substantial benefit of a Bayesian age-depth model is that the model is sensitive to sedimentation rate changes.

#### 4.4.3. Statistical analysis of diatom data.

The aim of statistical analysis in this study was to determine any of the trends which may have occurred, that is, environmental and climatic changes which may have been stable or may have fluctuated over a specific period (Fitchett, 2015). Clustering and ordination assists in making changes and trends visible and allow for statistical investigation. This was possible through the clustering of samples which exhibit the greatest similarities in diatom species

distribution (Legendre & Birks, 2012a). Statistical analysis of the data was conducted using ordination, performing Principal Component Analysis (PCA) and classification using CONISS (Constrained Incremental Sum of Squares) (Grimm, 1987). These analyses allow for periods of change to be compared with local, regional as well as international periods where climatic or environmental change has occurred. The statistical analysis of the data, through the plotting of the relative abundance of diatom species in each specific sample allowed for the visual exploration of changes that may have occurred.

In order to prepare for statistical analysis, the diatom species which accounted for less than 2% of relative abundance were excluded from the data set the site, to limit distortion of results due to the occurrence of rare or uncommon species (MacKay et al., 2012). A mean depth is added to a table for each of the samples. Prior to the analysis a square root transformation was performed in order to ensure the disproportionately high species counts do not influence the environmental gradients (Lepš & Šmilauer, 2003). The data for the sample counts was recorded using *Microsoft Excel* in order to determine the count percentage per taxon per sample and the average occurrence of the species. The data were compiled into a comma separated version (.csv) file. The interpolated ages were then added to the .csv file which was then used for ordination, PCA, clustering and graphical representation in *C2* software. To further analyse the diatoms various literature was reviewed (e.g. Chalnoky, 1968; Schoeman, 1973; Taylor et al., 2007; Walsh & Wepener, 2009) in order to determine the ecology and tolerances of each diatom species as well as the preferred habitat of each. This assisted in more detailed visual representations and increased the reliability of inferences made through diatoms.

#### 4.4.3.1. Principal Component Analysis

Ordination is a technique which is used in ecology to represent data points in a multi-dimensional space (Combrink, 2017), where all of the samples for this study were plotted against each other in three-dimensional space. The set of axes produced in the three-dimensional space, allowed for the variability in the dataset to be explored in one dimension. The first axis accounts for the greatest variance in the samples/species, and the next axis explains a smaller proportion of variance and so on. Different ordination methods are used for linear and unimodal data (Ter Braak & Prentice, 1988).

For this study, linear ordination was completed using Principal Component Analysis. Bi-plots were produced once the PCA was completed. In these plots the data points were in a two-dimensional space relative to the first and second principal components (Lepš & Šmilauer, 2003). The first principal component is the linear combination with the highest variance and principal component two is the linear combination with the highest variance at 90 degrees to principal component one, indicating no similarity between the linear combinations of data (Rencher & Christensen, 2003). The names of the different species were overlaid based on the species scores relative to the first and second components. This allowed for the visual exploration of the clustering of samples, enabling the species which are dominant in the clusters to be identified all at once (Rencher & Christensen, 2003).

#### 4.4.3.2. Clustering

Data can be grouped together or separated based on similarities in order to demonstrate periods of environmental change. Clustering is largely used in palaeoecological studies (Legendre & Birks, 2012a). There are several clustering methods which can be used, but for

the purpose of this research hierarchical agglomerative clustering was used. In this method, the individual samples are merged to form small groups and the smaller groups are then fused into larger groups (Legendre & Birks, 2012a).

The agglomerative clustering technique which was used for this study was CONISS (Constrained Incremental Sum of Squares). The data remained in the original order to reflect the depositional time series with the clusters then at the true depth of the samples (Birks et al., 2012). CONISS for this study was coupled with the Ward's minimum variance algorithm which was used to measure the distance between the samples (Fitchett, 2015). From the measurements, a silhouette plot was used to create all the possible group numbers (Legendre & Birks, 2012b). A silhouette plot with the values closest to one (1) is ideal, however, values below zero (negative values), are an indication that the samples included are in the incorrect cluster and 0 is an indication that the samples are between clusters (Birks et al., 2012). The results from clustering were graphically displayed on a dendrogram where the hierarchy of the sample groups is shown (Legendre & Birks, 2012b). The clusters were also colour coded to indicate statistically significant cluster structures.

#### 4.4.4. Visual representation

For the purpose of this research, diatom assemblage plots were produced using C2 software. This plots the counts of each diatom species against depth or age throughout the core (Juggins, 2007). The principal component scores from the first and second principal components are plotted in order to indicate periods of change in species composition, to show a distinct gradient of change (Mackay et al., 2013). The zones which appear on the graphs are determined by the CONISS cluster analysis for the diatoms (Finkelstein et al.,

2005; Fitchett, 2015). The stratigraphic diagrams produced using C2 also facilitated the comparisons and environmental associations between geographical regions.

## Chapter 5: Results

The results chapter presents and outlines the analyses (sediment and diatom) for the study. For the first study site, BLMA, 47 samples were analysed for sediment properties and the presence of diatoms, and for the second site, BLMB 76 samples were analysed for sediment properties only. Throughout the results chapter, diatom stratigraphic diagrams are presented with all the different diatom species and their relative abundances. CONISS cluster analysis was performed for the BLMA core diatoms to identify zones within the data. The PCA biplot for the BLMA core is colour coded according to the outputs acquired from CONISS, PCA was performed to identify the trends in relationships between the driver species vectors and the samples. The PC1 and PC2 are displayed with the zones determined by CONISS. Diatom and stratigraphic diagrams were generated using C2, with the zones determined by CONISS.

This chapter will therefore demonstrate the results as obtained in the various statistical analyses mentioned above. The interpretations of the results for this study will be discussed in the Discussion Chapter (Chapter 6), where all the results acquired will be utilised to reconstruct past climatic and environmental conditions.

### 5.2. Site BLMB

#### 5.2.1. BLMB: Chronology and accumulation of sediment

Seven AMS dates were measured for the BLMB site (Table 5.1). The samples dated were selected to span the length of the core that was extracted from the site. The sediments which were dated range from 40 cal. yr BP with an uncertainty of  $\pm 31$  years at a mean depth of 1 cm, and 1,710 cal. yr BP with an uncertainty of  $\pm 41$  years at a mean depth of 151cm

(Table 5.1). The dates for IT-C-2608 at mean depth of 121cm and for IT-C-2784 at mean depth of 129cm, are inconsistent with the rest of the dates. This is due to possible bioturbation or contamination which may have occurred. The dates for BLMB confirm that the transect falls within the Holocene.

Table 5.1: AMS radiocarbon dates acquired for the BLMB profile.

Laboratory ID	Sample name	Conventional Age (cal. yr BP)	1 $\sigma$ Uncertainty (yr)	Mean Depth	Sample thickness	d13C
IT-C-2623	BLMB1	40	$\pm 31$	1cm	2cm	-27.0
IT-C-2614	BLMB16	940	$\pm 36$	31cm	2cm	-23.9
IT-C-2787	BLMB32	1,090	$\pm 25$	63cm	2cm	-23.9
IT-C-2624	BLMB46	1,060	$\pm 27$	91cm	2cm	-23.7
IT-C-2608	BLMB65	550	$\pm 39$	121cm	2cm	-25.3
IT-C-2784	BLMB61	1,000	$\pm 30$	129cm	2cm	-23.9
IT-C-2622	BLMB76	1,710	$\pm 41$	151cm	2cm	-23.8

The BACON model estimated the mean sedimentation rate throughout the BLMB core to be 5 cm.yr. The BACON model further reveals a relatively steady accumulation of sediment for the first ~1000 cal. yr BP between the depths of ~0cm to ~100 cm (Figure 5.1). The two dates which are outliers may represent sediment that may have been displaced due to disturbances in the sediment, and the dates indicate that the stratigraphy may have been disturbed or these dates may indicate possible contamination. The BACON model also shows that there are uncertainties with the ages throughout the core, hence there are various interpolated ages for each depth. The points for the samples sent for AMS dating indicate uncertainty in the ages of the sediment. Broadly, from the radiocarbon dates, the core covered a period from 40 cal. yr BP  $\pm 31$  to 1,710 cal. yr BP  $\pm 41$ , demonstrates relatively consistent sediment accumulation at a steady rate. The BACON model excludes the topmost

date and regards it as an outlier (Figure 5.1), and therefore the date is not included in Figure 5.3.

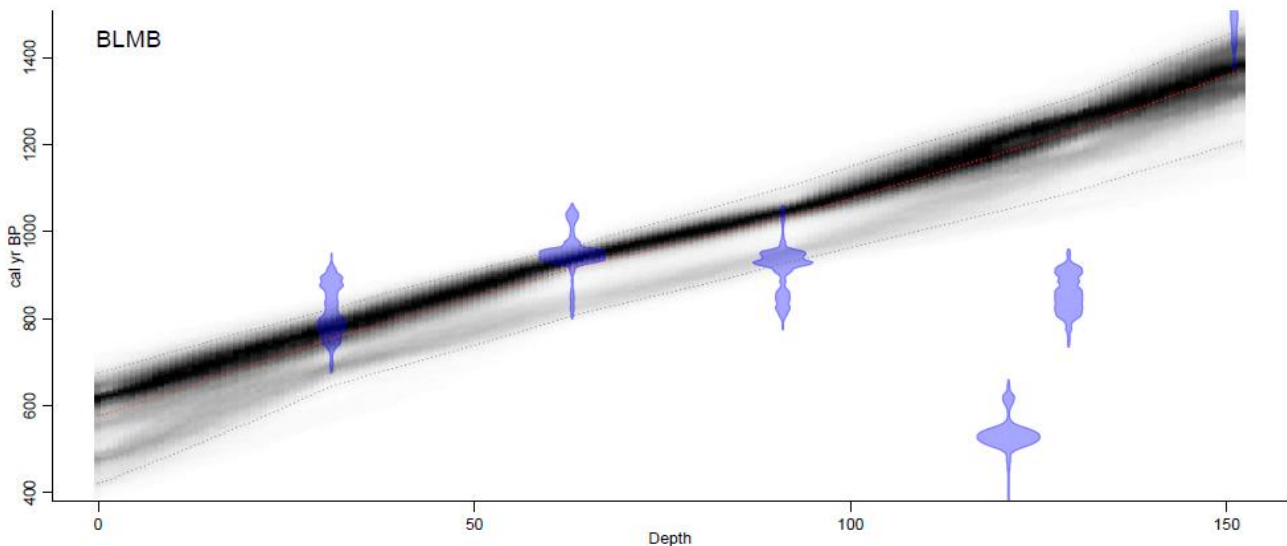


Figure 5.1: The BACON output for the BLMB profile showing interpolated ages for depth throughout the core.

#### 5.2.2. BLMB: Stratigraphy and sediment analysis of profile

For the BLMB, a total of 150 cm depth of sediment material was extracted from the study site, and from this profile a total of 76 samples were analysed at 2 cm intervals.

##### a) % organic content

The sediment analysis results for the BLMB site (Figure 5.12) revealed that the organic percentage range for the profile was 6-41 % (Figure 5.2), except for an outlier occurring at a depth of 52-54 cm, where organic material peaks at just over 80%. At the bottom of the core to ~1,250 cal yr BP the organic content percentage steadily increases. From ~1,230 cal yr BP up to ~940 cal yr BP the organic content in the sediment slightly decreases with the organic content not exceeding 20% (Figure 5.3).

b) Carbonate percentage

The carbonate content ( $\text{CO}_3\%$ ) in this profile is also relatively high, with content percentages ranging from 0% -20 %. The carbonate content in the profile is generally about 5% (Figure 5.2), however, three peaks occur at mean depth of about 29cm ( $\text{CO}_3 = 13\%$ ) and much lower in profile at about 95cm ( $\text{CO}_3 = 11\%$ ) and at 123cm where carbonate content is at its highest in the profile at ~20 %.

c) Particle size distributions

Between the depth of 0-74 cm there is no presence of granular-sized particles in the profile, however, much deeper in the profile, there are small proportions of granular-sized particles (not exceeding 4%). The upper part of the profile (0- 20 cm) has an abundance of silt-sized particle. As depth increases the sized-particles are generally lower but still higher than 60% (Figure 5.2). At the 52-54 cm, there is a decrease in silt-sized particles and an increase in the percentage of clay-sized sediment particles (Figure 5.2). The sand sized particles in this profile are broadly increasing for the profile until ~1,020 cal yr BP. Thereafter, from that point to the top of the profile, the sand sized particle percentage is very low (largely between 0 – 20%). The silt sized particles are generally very high throughout the profile, with an exception at ~900 cal yr BP, where there is no presence of these particles.

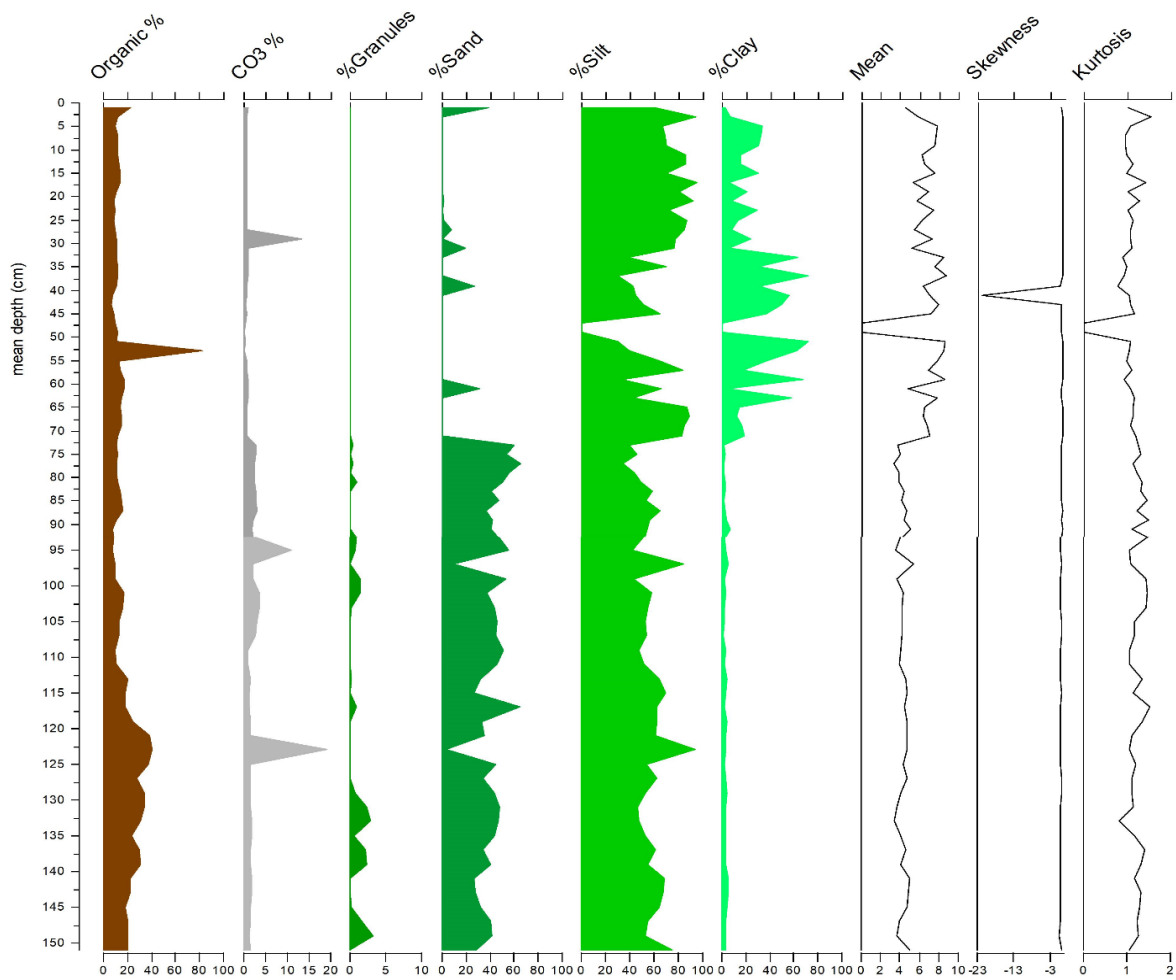


Figure 5.2: Changes in sediment properties throughout the BLMB profile with depth.

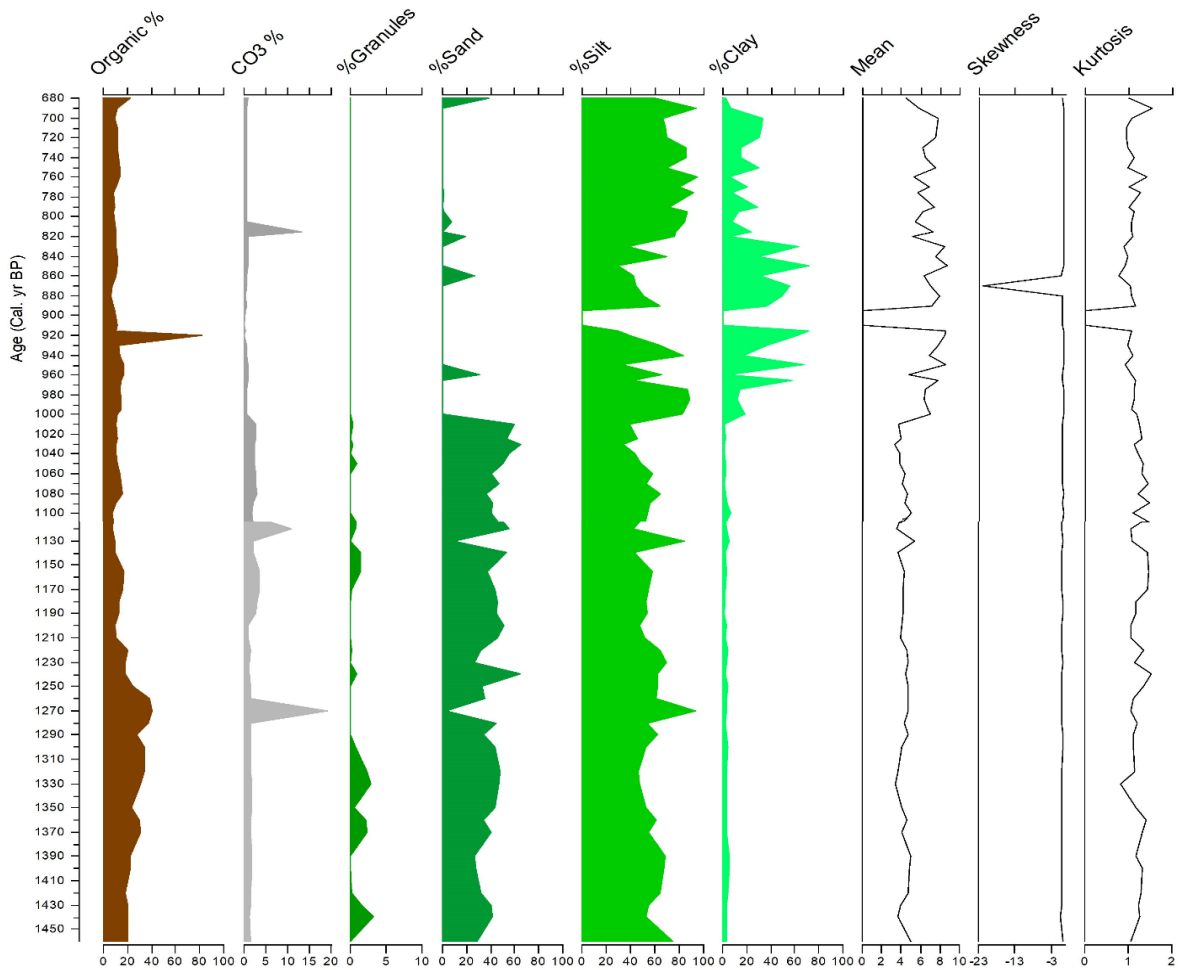


Figure 5.3: Changes in sediment properties throughout the BLMB profile over time.

d) Overall patterns in stratigraphy

The BLMB sequence contains relatively high organic content, with the period between ~1,460 to 1,250 cal. yr BP is characterized by higher organic content than the upper section of the core. Between the periods to 800 to ~680 cal. yr BP, ~ to 1,000 to 840 cal. yr BP, ~1,270 to 1,130 cal. yr BP and ~1,460 to 1,290 to cal. yr BP, the carbonate content for the BLMB sequence does not exceed 5% (Figure 5.2). At ~1,010 to 690 cal. yr BP, there is no presence of granular sized particles, although this is apparent during certain periods throughout the sequence, this is the longest period. Simultaneously, during this period (~ 1,010 to 690 cal. yr BP), the

percentage of silt sized particles is extremely high, and is relatively high throughout the sequence. The period is further characterised by low percentages of sand which increases thereafter. Clay percentages vary throughout the core, notably, between ~1,460 and 1,020 cal. yr BP clay in the sediment is much lower as compared to the periods prior, with clay percentages not exceeding 6% (Figure 5.3). Regarding skewness, the data for the sediment indicates a mostly positively skewed distribution between ~1,110 to 670 cal. yr BP, and between ~ 1,460 and 1,110 cal. yr BP the data indicates positive skewness and a normal distribution where skewness is zero (Figure 5.3). The data from the Mastersizer (Table 5.2) shows that the sediment particles are poorly sorted throughout the core. Texturally, the sediment from outside the wetland (site BLMB) wetland alternates between silt and silty loam in the uppermost part of the core (at 1cm to 43cm mean depth) and then the lower-most part of the core (at ~93cm to 151cm mean depth) has silty and sandy loam sediments. From the sediment composition and sediment properties, it can be concluded that the BLMB core is silty sediment.

Table 5.2: Sediment properties for BLMB Lesotho profile

Sample no	Mean depth	Mean	SD	Skewness	Kurtosis	Texture
BLMB1	1	Coarse Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silty loam
BLMB2	3	Medium Silt	Moderately Sorted	Fine Skewed	Very Leptokurtic	silt
BLMB3	5	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB4	7	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB5	9	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB6	11	Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silt
BLMB7	13	Fine Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	Silt
BLMB8	15	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB9	17	Medium Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	silt
BLMB10	19	Medium Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silt
BLMB11	21	Medium Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	silt
BLMB12	23	Very Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silty loam
BLMB13	25	Fine Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	Silt
BLMB14	27	Medium Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB15	29	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silt
BLMB16	31	Medium Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB17	33	Clay	Poorly Sorted	Fine Skewed	Platykurtic	silty loam
BLMB18	35	Very Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silty loam
BLMB19	37	Clay	Poorly Sorted	Fine Skewed	Mesokurtic	silty clay loam
BLMB20	39	Fine Silt	Poorly Sorted	Strongly Coarse Skewed	Platykurtic	silty loam
BLMB21	41	Very Fine Silt	Poorly Sorted	Coarse Skewed	Mesokurtic	silty loam
BLMB22	43	Very Fine Silt	Poorly Sorted	Coarse Skewed	Mesokurtic	silty loam
BLMB23	45	Very Fine Silt	Poorly Sorted	Coarse Skewed	Leptokurtic	silty loam
BLMB24	47			Insufficient sediment		
BLMB25	49			Insufficient sediment		
BLMB26	51	Clay	Poorly Sorted	Fine Skewed	Mesokurtic	silty loam
BLMB27	53	Clay	Moderately Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB28	55	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	silty loam
BLMB29	57	Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silt
BLMB30	59	Clay	Moderately Sorted	Fine Skewed	Mesokurtic	silty clay loam
BLMB31	61	Coarse Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silty loam
BLMB32	63	Very Fine Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB33	65	Fine Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silt
BLMB34	67	Fine Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silt
BLMB35	69	Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	silt
BLMB36	71	Very Fine Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	silt
BLMB37	73	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB38	75	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB39	77	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	loamy sand
BLMB40	79	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB41	81	Very Fine Grained	Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB42	83	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB43	85	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB44	87	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silty loam
BLMB45	89	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silty loam
BLMB46	91	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB47	93	Medium Silt	Poorly Sorted	Fine Skewed	Mesokurtic	sandy loam
BLMB48	95	Very Fine Grained	Poorly Sorted	Near Symmetrical	Mesokurtic	sandy loam
BLMB49	97	Medium Silt	Poorly Sorted	Near Symmetrical	Mesokurtic	silty loam
BLMB50	99	Very Fine Grained	Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB51	101	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB52	103	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB53	105	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	sandy loam
BLMB54	107	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	sandy loam
BLMB55	109	Coarse Silt	Poorly Sorted	Near Symmetrical	Mesokurtic	sandy loam
BLMB56	111	Very Fine Grained	Poorly Sorted	Near Symmetrical	Mesokurtic	sandy loam
BLMB57	113	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB58	115	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silty loam
BLMB59	117	Coarse Silt	Poorly Sorted	Near Symmetrical	Very Leptokurtic	silty loam
BLMB60	119	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB61	121	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB62	123	Coarse Silt	Poorly Sorted	Near Symmetrical	Mesokurtic	silty loam
BLMB63	125	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	sandy loam
BLMB64	127	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	silty loam
BLMB65	129	Coarse Silt	Very Poorly Sorted	Coarse Skewed	Leptokurtic	silty loam
BLMB66	131	Coarse Skewed	Very Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB67	133	Very Fine Grained	Very Poorly Sorted	Coarse Skewed	Platykurtic	sandy loam
BLMB68	135	Coarse Silt	Very Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB69	137	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB70	139	Coarse Silt	Very Poorly Sorted	Coarse Skewed	Leptokurtic	silty loam
BLMB71	141	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB72	143	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB73	144	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	silty loam
BLMB74	147	Very Fine Grained	Very Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB75	149	Very Fine Grained	Very Poorly Sorted	Coarse Skewed	Leptokurtic	sandy loam
BLMB76	151	Medium Silt	Poorly Sorted	Fine Skewed	Mesokurtic	sandy loam

For the BLMB sample, AMS dating, and sediment analysis were completed, from the data the profile is evidently characterised by sedimentary disturbances which may have resulted in the dates not being coherent. The data from the BACON model also revealed that there were several uncertainties with the dates for the sequence which may be attributed to bioturbation which may have occurred or other physical disturbances in the stratigraphy. For the BLMB core, the sequence, did show evidence for the presence of diatoms, however the diatoms were not analysed for the core. This is because of the hiatus in the stratigraphy which would possibly confound any interpretations of the diatom data.

### 5.3. Site BLMA

The BLMA sediment core was extracted from a wetland to a depth of 95 cm. The physical attributes of the sediment suggested high organic content due to the fine texture of the material and colour. During the preparation of the samples, several samples reacted with the hydrochloric acid (HCl), suggesting the presence of carbonates in the sediments.

#### 5.3.1. BLMA: Chronology and sediment analysis profile

Seven samples were sent for AMS dating for the BLMA profile, however, only six dates were obtained for the site (Table 5.2). The uppermost sample for the core had insufficient sediment material, and therefore AMS dating could not be carried out for that sample. The samples which were selected span the length of the core that was extracted from the site. The sediments date range was from 340 cal. yr BP with an uncertainty of  $\pm 26$  years at a mean depth of 17cm to 3,220 cal. yr BP with an uncertainty of  $\pm 27$  years at a mean depth of 93cm. The date ( $100 \pm 30$  cal. yr BP) for IT-C-2609 at mean depth of 31cm is inconsistent with the rest of the dates obtained for the core, and this may be largely due to

contamination in the lab, as the core indicated very little disturbances. From the AMS dates obtained (Table 5.1; 5.2), it is quite clear that the BLMA sequence is much older than the BLMB sequence although the BLMB sequence spanned at a greater depth than the BLMA sequence. The AMS dates confirm that the sediments were all deposited during the Holocene.

Table 5.3: AMS radiocarbon dates acquired for the BLMA profile.

Laboratory ID	Sample name	Conventional Age (cal. yr BP)	1 $\sigma$ Uncertainty (yr)	Mean Depth	Sample thickness	d13C
IT-C-2823	BLMA1	340	$\pm 26$	17cm	2cm	-26.7
IT-C-2609	BLMA9	100	$\pm 30$	31cm	2cm	-25.8
IT-C-2788	BLMA16	1,530	$\pm 26$	43cm	2cm	-25.5
IT-C-2607	BLMA22	2,970	$\pm 35$	61cm	2cm	-24.8
IT-C-2789	BLMA39	3,100	$\pm 32$	75cm	2cm	-25.3
IT-C-2790	BLMA47	3,220	$\pm 27$	93cm	2cm	-25.5

The BACON model estimated the mean accumulation rate throughout the BLMA core to be 50yr.cm . The date which is an outlier at the ~31 cm depth (Figure 5.4), possibly due to contamination or that the upper 31cm of the core are disturbed, this inconsistent date was excluded by the BACON model (Figure 5.4). The BACON model shows that there are uncertainties with the ages throughout the core, the model further shows that there is variation in the accumulation of sediment over time. Notably, between 1,530 cal yr BP to 2,970 cal yr BP and 340 cal yr BP to 1,530 cal yr BP periods of relatively slow deposition occurred, with an accumulation of 18cm and 14cm depth, respectively. The BACON model estimates that between 0-2cm (uppermost part of the sequence), is less than 100 years, ~85 cal yr BP to be precise. Relatively rapid sediment accumulation is prominent between ~85 cal yr BP to 340 cal yr BP with 17cm depth of sediment accumulation. Between 3,100 cal yr

BP to 3,220 cal yr BP was another period of relatively rapid accumulation, with an accumulation of 18cm depth.

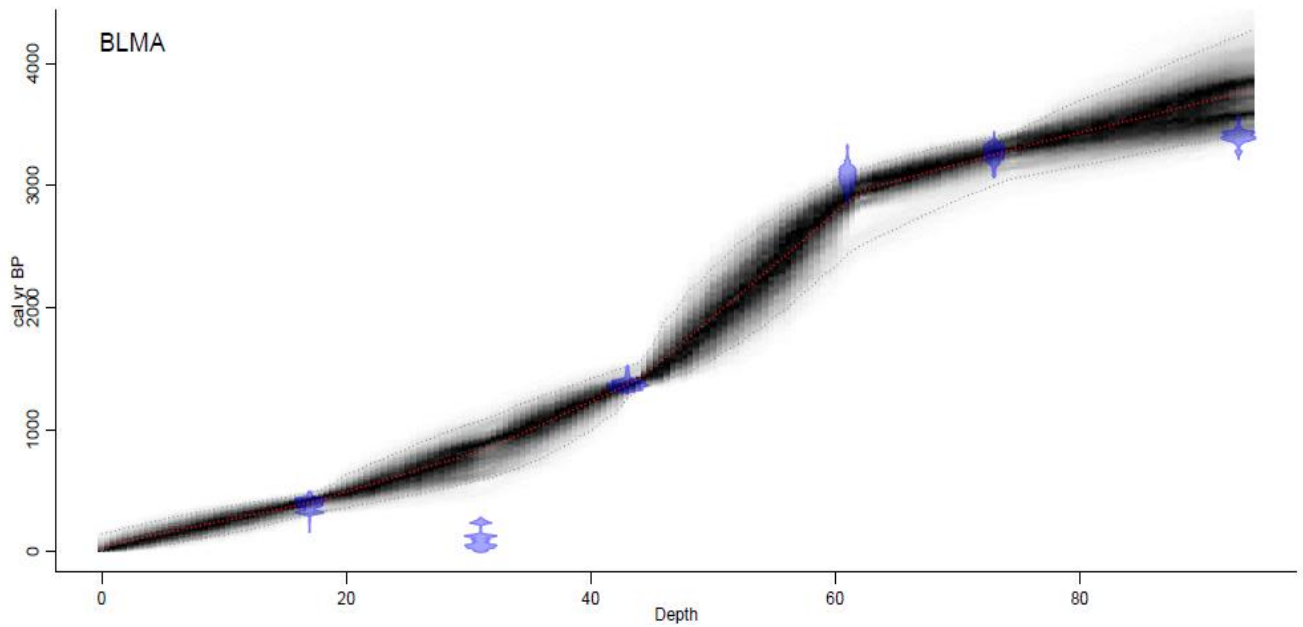


Figure 5.4: The BACON output for the BLMA profile showing interpolated ages for depths throughout the core.

### 5.3.2. BLMA: Stratigraphy and sediment properties of profile

For the BLMA core, a total of 95cm depth of sediment material was extracted from the site and from this a total of 47 samples were analysed at 2cm intervals.

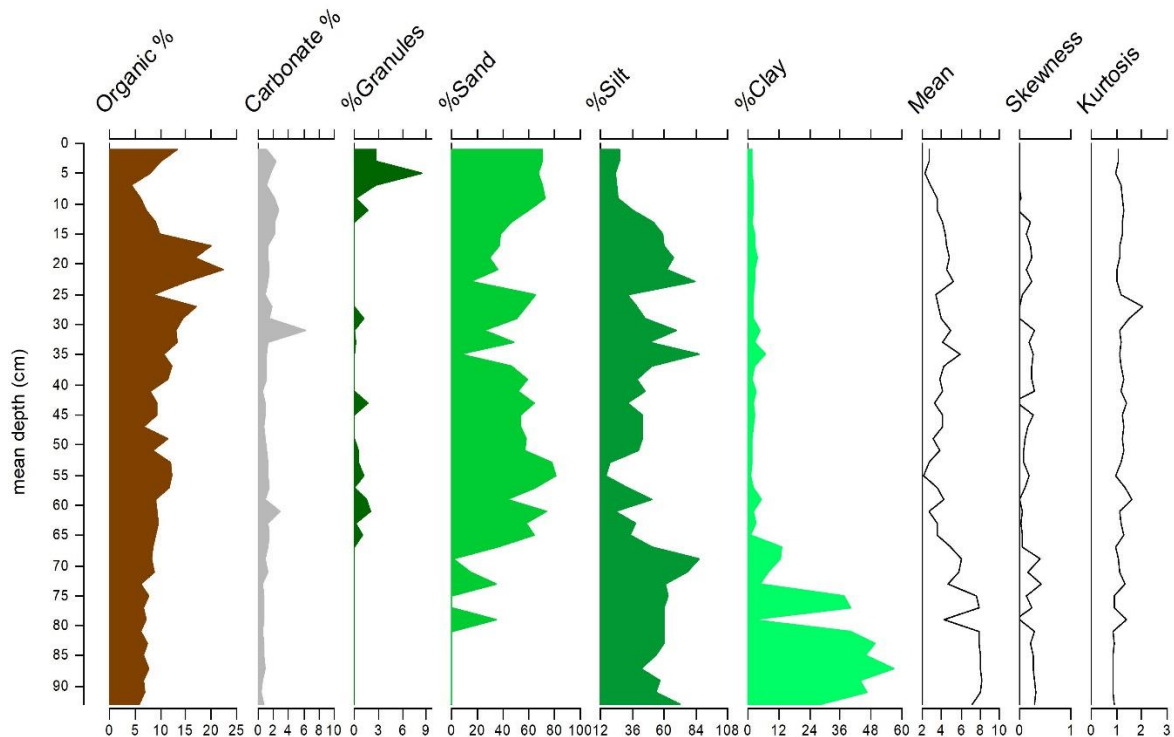


Figure 5.5: Changes in sedimentary properties throughout the BLMA profile with depth.

a) % Organic content

The sediment analysis results reveal that there is much lower organic content in the material throughout the profile than was expected, and this was due to the physical properties of the sediment which may have suggested much higher organic sediment was present. The organic percentage for this profile ranges from 4% - 23% (Figure 5.5). From the bottom of the core to the upper part of the core, the organic content percentage is broadly increasing (Figure 5.5). A peak is apparent in the profile for organic content (>20%), occurring at a depth of approximately 15 -25 cm (Figure 5.5) and in terms of age, that is between ~550 to 700 cal yr BP (Figure 5.6). During this period, the organic percentage is at its maximum for this profile.

a) Carbonate percentage

The carbonate content in the sequence is relatively low throughout the profile (Figure 5.5), with a peak in carbonate content (<6%) occurring between ~1,100 to 1,000 cal yr BP (Figure 5.6). The upper part of the core, ~1,000 to 200 cal yr BP is characterised by slight increases in carbonate percentages in the sediment. The carbonate percentage for the profile fluctuates with age, however, it does not exceed 7%.

b) *Particle size distributions*

Between ~1,000 to 1,100 cal yr BP, there is an increase in the silt-sized particles (86.95%) and an apparent decrease in clay, sand, and granules percentages. The BLMA sequence is mainly dominated by silt and sand sized particles, with granule sized particles not exceeding 9% (Figure 5.5). Between ~3,400 to 3,600 cal yr BP and ~3,800 to 4,200 cal yr BP there is a significant increase in clay sized particles during these periods while there is an absence of any sand-sized particle around the same time (Figure 5.6). During this period, the silt sized particle are also elevated. Between ~3,200 to 200 cal yr BP, the clay percentages are relatively low, however there are apparent increases in silt and sand percentages during the same period. (Figure 5.6).

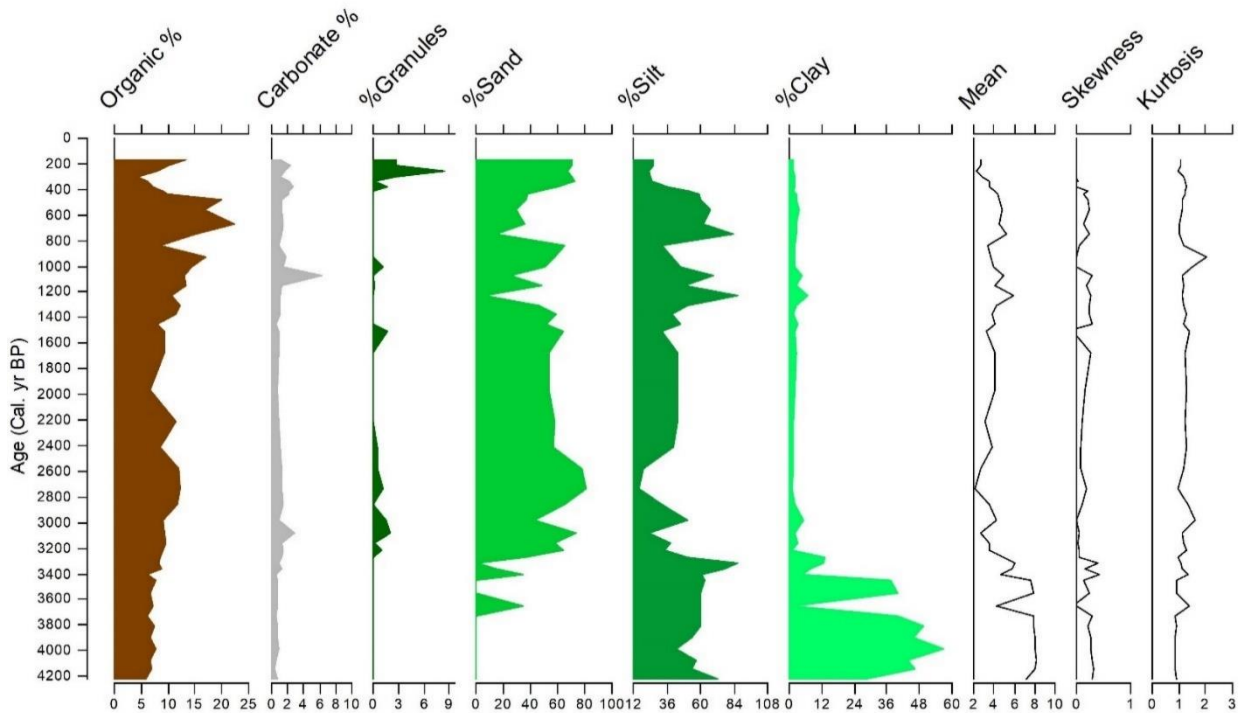


Figure 5.6: Change in sedimentary properties throughout BLMA profile with time (age).

c) Overall patterns in stratigraphy

The upper portion of the sequence is mainly dominated by high sand and silt percentages and is characterised by significantly low clay sized particles (Figure 5.5). Regarding skewness, the profile is broadly near symmetrical which is indicative of a positively skewed distribution throughout the core (Table 5.4). The data from the Mastersizer (Table 5.4) also shows that the profile is generally Leptokurtic. For this sequence, the fluctuations in the particle size percentages in sand, silt and clay show that changes have occurred in the sedimentation environment (Figure 5.5). These fluctuations in sediment particle sized also demonstrate changes in the general environment, particularly the shifts between dominance in sand to dominance in clay sized sediment particles. Texturally, the sediment from the upper section of the core is characterised by loamy sand and sandy loam (~1cm to 31cm; Figure 5.5) and the lower section of the core, is characterised by silty loam (~81cm to 93cm; Figure 5.5). The data analysed for the BLMA core indicates that the sediment

extracted from the site is peat. Although the organic content in this profile does not exceed 30%, the sediment can be defined as peat as it is consistent with Lesotho peats (*further discussed in Chapter 6*) but will not meet all international peat definitions.

Table 5.4: Sediment properties for BLMA Lesotho profile

Sample no	Mean depth	Age (cal yr BP)	Mean	SD	Skewness	Kurtosis	Texture
BLMA1	1	165	Fine Grained	Very Poorly Sorted	Near Symmetrical	Mesokurtic	Loamy Sand
BLMA2	3	210	Fine Grained	Very Poorly Sorted	Near Symmetrical	Mesokurtic	Loamy Sand
BLMA3	5	260	Fine Grained	Very Poorly Sorted	Near Symmetrical	Mesokurtic	Loamy Sand
BLMA4	7	300	Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Loamy Sand
BLMA5	9	340	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA6	11	380	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA7	13	410	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA8	15	440	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA9	17	480	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA10	19	560	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Silty Loam
BLMA11	21	670	Coarse Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam
BLMA12	23	750	Medium Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam
BLMA13	25	840	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Loamy Sand
BLMA14	27	930	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA15	29	1005	Very Fine Grained	Poorly Sorted	Near Symmetrical	Very Leptokurtic	Sandy Loam
BLMA16	31	1070	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Silty Loam
BLMA17	33	1145	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA18	35	1230	Medium Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Silt
BLMA19	37	1305	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA20	39	1370	Very Fine Grained	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA21	41	1450	Coarse Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	Sandy Loam
BLMA22	43	1510	Very Fine Grained	Poorly Sorted	Coarse Skewed	Leptokurtic	Loamy Sand
BLMA23	45	1680	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA24	47	1970	Coarse Silt	Poorly Sorted	Fine Skewed	Leptokurtic	Sandy Loam
BLMA25	49	2210	Very Fine Grained	Poorly Sorted	Fine Skewed	Leptokurtic	Loamy Sand
BLMA26	51	2410	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA27	53	2580	Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Loamy Sand
BLMA28	55	2730	Fine Grained	Poorly Sorted	Fine Skewed	Mesokurtic	Loamy sand
BLMA29	57	2860	Very Fine Grained	Poorly Sorted	Fine Skewed	Leptokurtic	Loamy Sand
BLMA30	59	2980	Coarse Silt	Poorly Sorted	Near Symmetrical	Very Leptokurtic	Sandy Loam
BLMA31	61	3080	Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Loamy Sand
BLMA32	63	3160	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA33	65	3220	Very Fine Grained	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA34	67	3270	Coarse Silt	Poorly Sorted	Near Symmetrical	Mesokurtic	Silty Loam
BLMA35	69	3320	Fine Silt	Poorly Sorted	Strongly Fine Skewed	Mesokurtic	Silt
BLMA36	71	3360	Medium Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam
BLMA37	73	3400	Coarse Silt	Poorly Sorted	Strongly Fine Skewed	Leptokurtic	Sandy Loam
BLMA38	75	3455	Very Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam
BLMA39	77	3550	Very Fine Silt	Poorly Sorted	Fine Skewed	Platykurtic	Silty Loam
BLMA40	79	3650	Coarse Silt	Poorly Sorted	Near Symmetrical	Leptokurtic	Sandy Loam
BLMA41	81	3730	Very Fine Silt	Poorly Sorted	Fine Skewed	Platykurtic	Silty Loam
BLMA42	83	3810	Very Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam
BLMA43	85	3900	Clay	Poorly Sorted	Fine Skewed	Platykurtic	Silty Loam
BLMA44	87	3980	Very Fine Silt	Poorly Sorted	Fine Skewed	Platykurtic	Silty Loam
BLMA45	89	4070	Clay	Poorly Sorted	Fine Skewed	Platykurtic	Silty Loam
BLMA46	91	4140	Clay	Poorly Sorted	Strongly Fine Skewed	Platykurtic	Silty Loam
BLMA47	93	4220	Very Fine Silt	Poorly Sorted	Fine Skewed	Mesokurtic	Silty Loam

### 5.3.3. BLMA: Diatoms

For the diatoms, *Fragilaria construens* and *Fragilaria pinnata* were combined to form one single group, '*Fragilaria construens*', this was done because accurately differentiating these two species posed a challenge when observed in girdle view. Moreover, these species have very similar ecological preferences, thus making the proportional differences between them insignificant.

The species diversity of diatoms occurring throughout the BLMA sequence is high. The 46 samples which were analysed for diatoms, revealed a total of 58 identifiable taxa (Table 5.5). A small group of taxa which were statistically insignificant could not be identified and were classified as 'unknown'. The samples for this core indicated a high average representative percentage for *Fragilaria construens* (10.5%, Table 5.5), and this species was widely distributed throughout the core, having a maximum representation percentage of 48.8% (Table 5.5) for sample BLMA 43 at 85cm depth.

Table 5.5: Diatom species of the BLMA profile with their respective average and maximum percentage representation.

Species	Average Representation (%) - Descending Order	Max Representation (%)	Sample -Max Representation
<i>Fragilaria construens</i>	10.50	48.75	BLMA43
<i>Eunotia minor</i>	7.62	27.75	BLMA25
<i>Pinnularia divergentissima</i>	5.57	16.50	BLMA1
<i>Cymbella microcephala</i>	4.70	16.24	BLMA11
<i>Eunotia praerupta</i>	4.52	33.73	BLMA46
<i>Achnanthes linearioides</i>	3.91	15.05	BLMA42
<i>Cymbella pusilla</i>	3.83	11.92	BLMA1
<i>Navicula confervacea</i>	3.22	21.51	BLMA42
<i>Pinnularia borealis</i>	3.12	13.98	BLMA42
<i>Aulacoseira granulata</i>	2.89	12.24	BLMA39
<i>Caloneis bacillum</i>	2.87	9.60	BLMA19
<i>Gomphonema gracile</i>	2.78	12.91	BLMA10
<i>Stauroneis producta</i>	2.67	8.94	BLMA21
<i>Eunotia bilunaris</i>	2.60	12.43	BLMA25
<i>Cymbella gracilis</i>	2.49	10.16	BLMA7
<i>Tabellaria flocculosa</i>	2.22	11.83	BLMA42
<i>Aulacoseira ambigua</i>	2.18	16.87	BLMA46
<i>Eunotia incisa</i>	1.93	11.08	BLMA13
<i>Nitzschia linearis</i>	1.92	11.22	BLMA14
<i>Aulacoseira subarctica</i>	1.87	9.68	BLMA42
<i>Eunotia rhomboidei</i>	1.57	10.61	BLMA22
<i>Eunotia exigua</i>	1.54	14.98	BLMA8
<i>Pinnularia viridis</i>	1.53	7.14	BLMA38
<i>Fragilaria brevistriata</i>	1.48	14.85	BLMA16
<i>Pinnularia viridiformis</i>	1.39	5.90	BLMA2
<i>Hantzschia amphioxys</i>	1.37	8.58	BLMA1
<i>Gomphonema parvulum</i>	1.37	8.00	BLMA15
<i>Fragilaria capucina</i>	1.25	13.25	BLMA19
<i>Achnantheidium minutissimum</i>	1.21	15.79	BLMA29
<i>Caloneis silicula</i>	1.20	7.59	BLMA45
<i>Cymbella minuta</i>	1.14	12.24	BLMA38
<i>Diploneis elliptica</i>	1.13	7.78	BLMA13
<i>Fragilaria nanana</i>	0.98	5.25	BLMA47
<i>Nitzschia themalis</i>	0.85	7.92	BLMA40
<i>Nitzschia elliptica</i>	0.81	14.29	BLMA38
<i>Stauroneis phoenicenteron</i>	0.62	6.62	BLMA17
<i>Cyclotella meneghiniana</i>	0.60	6.31	BLMA40
<i>Navicula trivialis</i>	0.57	9.60	BLMA3
<i>Diploneis oblongella</i>	0.57	7.50	BLMA43
<i>Achnanthes lanceolata</i>	0.54	7.31	BLMA40
<i>Fragilaria biceps</i>	0.44	4.65	BLMA40
<i>Cocconeis engelbrechtii</i>	0.40	4.92	BLMA32
<i>Navicula radiosa</i>	0.38	7.53	BLMA43
<i>Cymbella cesati</i>	0.32	4.95	BLMA45
<i>Amphora ovalis</i>	0.30	3.91	BLMA8
<i>Navicula zanonii</i>	0.27	3.95	BLMA23
<i>Achnanthes exigua</i>	0.26	3.08	BLMA15
<i>Mastrogloia dansei</i>	0.23	4.00	BLMA15
<i>Diploneis subovalis</i>	0.23	2.65	BLMA17
<i>Navicula capitatoradiata</i>	0.23	7.59	BLMA16
<i>Cymbella kappii</i>	0.23	2.95	BLMA26
<i>Navicula cincta</i>	0.23	4.98	BLMA30
<i>Navicula angusta</i>	0.20	2.65	BLMA17
<i>Nitzschia cofervacea</i>	0.18	5.96	BLMA27
<i>Amphora coffeaeformis</i>	0.18	4.29	BLMA45
<i>Amphora veneta</i>	0.13	2.65	BLMA27
<i>Navicula trivialis</i>	0.11	2.66	BLMA30
<i>Navicula subminuscula</i>	0.04	2.10	BLMA13

*Eunotia minor* (7.6%, Table 5.5), is also frequently and widely distributed throughout the core. Other species which were widely distributed throughout the core include; *Pinnularia divergentissima* (5.57%, Table 5.5), *Cymbella microcephala* (4.70%, Table 5.5), and *Eunotia praerupta* (4.52%, Table 5.5), having the highest representation percentages. These species (*Eunotia minor*, *Pinnularia divergentissima*, *Cymbella microcephala* and *Eunotia praerupta*) also had relatively high maximum percentages of 27.75%, 16.50%, 16.24% and 33.73%, respectively. From the data shown above (Table 5.5), it is evident that there is no relationship between average representation and maximum representation because species such as *Fragilaria brevistriata* (1.48%), *Fragilaria capucina* (1.25%), *Achnantheidium minutissimum* (1.21%) and *Nitzschia elliptica* (0.81%) have relatively low average representation percentages (Table 5.1), but relatively high maximum representation percentages, that is, 14.85%, 13.25%, 15.79% and 14.29%, respectively (Table 5.5).

The species mentioned above were relatively abundant at specific depths of the core, however, they were not evenly distributed throughout the core. The species with low average representative percentages and low maximum percentages include; *Nitzschia confervacea*, *Amphora coffeaeformis*, *Amphora veneta*, *Navicula trivialis* and *Navicula subminuscula* (Table 5.5). These species were not dominant in any of the samples and the species mentioned above were sparsely distributed throughout the core. It is important to note that species such as *Eunotia praerupta*, *Navicula confervacea*, *Fragilaria brevistriata*, *Aulacoseira ambigua*, *Eunotia exigua* and *Nitzschia elliptica* have maximum percentage contributions within an individual sample, which are considerably higher than the average percent occurrences within the core. This possibly suggests the existence of important

periods during the time period spanning the profile, this further indicates that the period was favourable for the species' concurrent growth.

The CONISS analysis for the BLMA sequence indicates that there are only two statistically significant clusters, as demonstrated on the dendrogram below (Figure 5.7). The first group includes samples from BLMA 1 to BLMA 21, and the second group has 26 samples, including sample BLMA 22 to BLMA 47. The two groups are an indication that there are two zones in the profile, named here as BA-1 and BA-2. The first zone, spans from a mean depth of 1cm to 41cm, accounting for the past ~1,450 cal. yr BP, the second zone, spans from a mean depth of 43cm to 93 cm, accounting for the period from 1,510 cal yr BP to 4,220 cal yr BP.

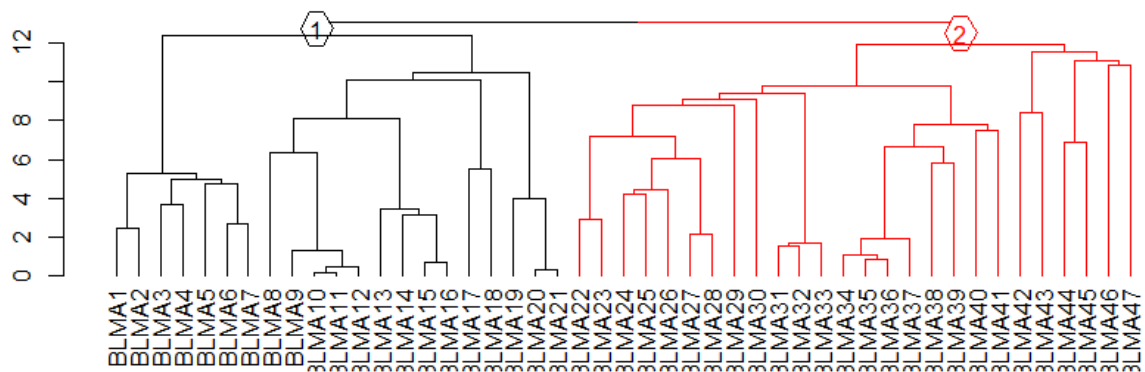


Figure 5.7: CONISS output showing the two separate zones within the Lesotho wetland profile, centred on the distribution of diatoms within the profile.

### 5.3.3.1. Principal Component Analysis

The principal component analysis reveals that the diatoms in this study can be grouped into only two significant groups (represented by points) for the diatom data that was analysed, and this aligns with the results presented in the dendrogram (Figure 5.7). The samples from the first zone (BA-1), largely lie in the 3<sup>rd</sup> quadrant, where PC1 values are negative and PC2 values are also negative, and, the rest of the samples for the first group lie in the third

quadrant where PC1 values are negative and PC2 values are positive (Figure 5.8). The second group consists of the majority of the samples which mostly lie in the first quadrant. This is where PC1 and PC2 are positive; second quadrant where PC1 is negative and PC2 is positive and fourth quadrant where PC1 is positive and PC2 is negative. PC1 separates species with negative values from the positive scores, specifically separating *Pinnularia divergentissima* (-0.75), *Eunotia praeurpta* (-0.68) and *Cymbella microcephala* (-0.60) from *Fragilaria construens* (0.93), *Aulacoseira subarctica* (0.67) and *Aulacoseira ambigua* (0.65). PC2 distinctly separates diatom species with negative scores and positive scores.

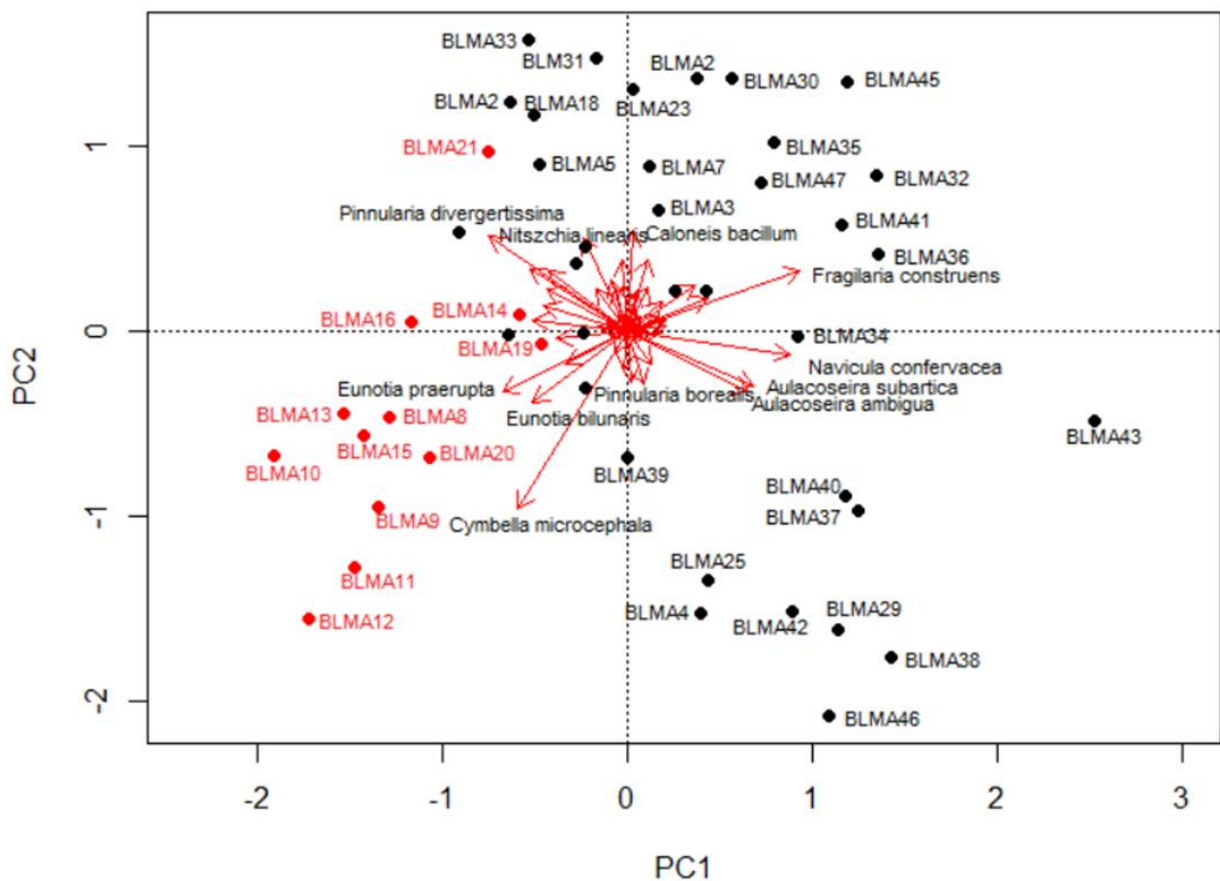


Figure 5.8: PCA bi plot for the Lesotho wetland profile, illustrating samples and taxa along the PC1 and PC2 gradient, with the explanatory power of the PCs 13.48% and 8%, respectively.

For the data presented, PC1 and PC2 combined account for 21.48% of the variability of the samples and diatoms present in the BLMA core. The arrows on the PCA bi-plot (Figure 5.8) represent the driver species which are present for each group, additionally the further the arrow is from the point of origin, the more influential the species is on PC. The similarity in samples for the first group, is driven and influenced by the following species; *Pinnularia divergentissima* (where PC1= -0.75, PC2=0.52) *Cymbella microcephala* (PC1= 0.59, PC2= -0.95), *Eunotia bilunaris* (PC1=-0.51, PC2= -0.38) and *Eunotia praeurupta* (PC1=-0.67, PC2=-0.33), however, the influence of *Cymbella microcephala* is highly predominant for this group (Figure 5.8). For the second group, the similarity in samples is mainly driven and influenced by several diatom species which; *Pinnularia divergentissima* (where PC1=-0.75, PC2=0.52), *Nitzschia linearis* (PC1=0.19, PC2= 0.07), *Fragilaria construens* (PC1=0.93, PC2=0.33). The less influential species for this group include; *Aulacoseira ambigua* (PC1=0.65, PC2=-0.33), *Aulacoseira subarctica* (PC1=0.68, PC2=-0.29) and *Navicula confervacea* (PC1=0.88, PC2= -0.12). Broadly, for the data presented in the bi-plot, *Fragilaria construens*, *Pinnularia divergentissima*, *Cymbella microcephala* and *Navicula confervacea* have the most influence on the Principal Components (Figure 5.8). The arrows reveal how the diatom species relate to each other depending on the angle between them. For example, an obtuse angle exists between *Fragilaria construens* and *Pinnularia divergentissima*, implying that the two species influence the different groups, however, the species have absolutely no influence on each other. *Caloneis bacillum* is at a 90 degree angle from PC 1, the arrow is close to zero (PC1= 0.03) for PC1, this indicates that the presence of of this species is not affected by Principal Component 1.

The CONISS analysis separates the sequence of the Lesotho wetlands into two primary zones that show statistically significant similarities tested through a silhouette plot (Figure 5.9). The first and second cluster has silhouette width values greater than zero (Figure 5.9). The first cluster consists of 21 samples and the second cluster consists of 26 samples. The first cluster group has a silhouette width value of 0.12, which is greater than the value of 0.02, of the second cluster (Figure 5.9). This indicates that most of the diatom species have been well-assigned to their relative cluster, while the second cluster may have various samples which may have not been well-assigned. The average width for the silhouette plot is relatively low, with a value of 0.06.

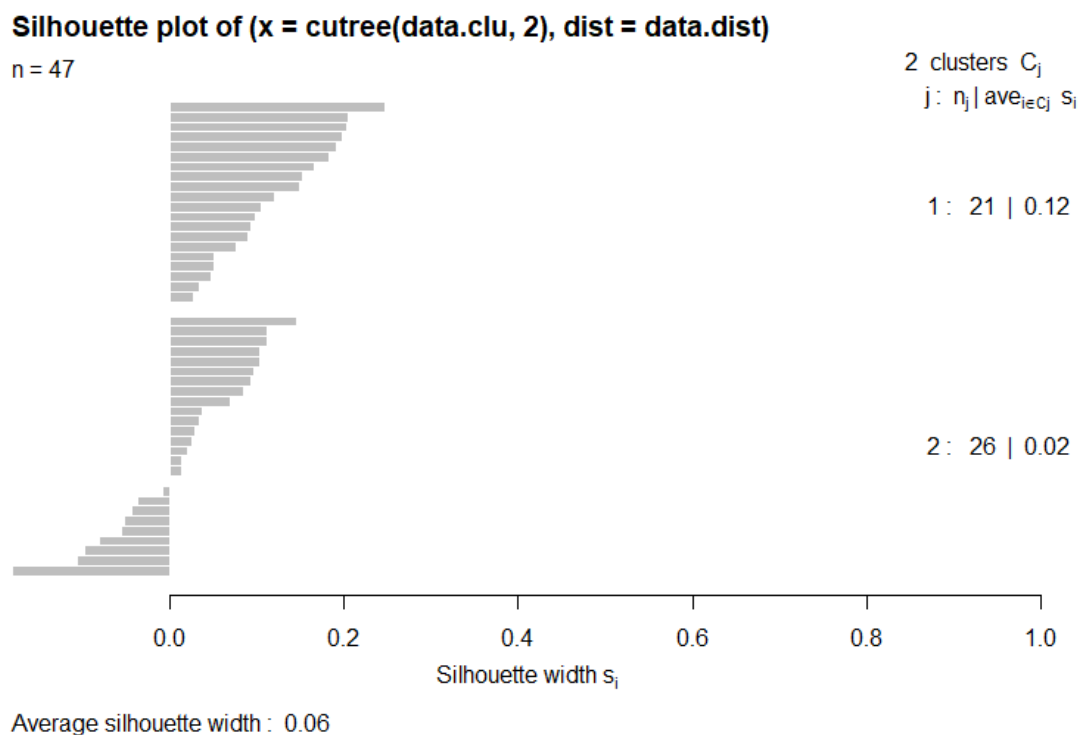


Figure 5.9: Silhouette plot for diatom samples in the BLMA profile.

#### 5.3.3.2. Environmental reconstruction

The composition and assemblages of diatom species is driven by a variety of environmental factors, and some factors include pH, moisture availability, temperature, conductivity and broadly the ecological conditions which their specific habitats provide (Stoermer & Smol, 2004; Falasco et al., 2019; Table 5.4). Interpretation of the composition of diatoms, and the changes which are apparent throughout the sequence enable the environmental and climatic inferences of the habitat based on the ecological similarities of co-existing diatoms (Stoermer & Smol, 2004). The diatom species which were identified in the sediment of BLMA sequence of Lesotho are representative of a wide range of habitats and environmental attributes (Table 5.4). A wide range of environmental attributes is essential in investigating changes in the environment, however, diatom communities change in response to varying interacting drivers (Juggins, 2013). Therefore, the preferred ecologies of diatoms and their specific characteristics are utilised only when necessary to explain the principal components observed during the Principle Component Analysis.

Table 5.6: Key species and their preferred ecologies.

Species	Ecologies
<i>Achnanthes exigua</i>	Oligotrophic, alkaline waters, unable to with stand shortages of dissolved oxygen (Schoeman, 1973:31). Weakly alkaline to neutral, optimum pH 8 (Cholnoky, 1968: 385), pH range 7.2-<9.0 (Jorgensen, 1948: 48). Temperature range 15- 30°C but up to 40°C (Taylor et al., 2007), found in swampy areas
<i>Achnanthes lanceolate</i>	pH indifferent according to Foged (1964), alkaliphilous (Hustedt, 1957) and calciphilous (Niessen, 1956), frequent at pH values of 7 to >9. Widely distributed in springs and streams. Good supply of dissolved oxygen (Cholnoky, 1968). Found in shallow streams with abundance of aquatic vegetation and unpolluted waters. Oligosaprobous (Hustedt, 1957). Ability to tolerate critically polluted conditions (Taylor et al., 2007).
<i>Achnanthes linearoides</i>	pH optimum lies between 6.5 and 6.8 (Cholnoky, 1968). Requires constant supply of oxygen for growth, favours oligotrophic waters (Cholnoky, 1968, Taylor et al., 2007). pH indifferent (Hustedt, 1957).
<i>Achnanthidium minutissimum</i>	Clean streams, low organic content. pH value of 6.7-8.4 but mostly above 7 (Schoeman, 1973). Found in swift flowing streams or rivers with enough supply of dissolved oxygen (Schoeman, 1973). Clean well-aerated waters, low nitrogen content, common in upland streams (Taylor et al., 2007).
<i>Amphora coffeaeformis</i>	Neutral to slightly alkaline waters (Cholnoky, 1957). pH optimum of above 8. Oxygen-deficient and polluted with nitrogenous organic compounds and pH indifferent. (Schoeman, 1973).
<i>Amphora ovalis</i>	Alkaliphilous, pH optimum above 8, described as an oligohalobe or salt-indifferent species (Kolbe, 1927). Widely distributed.
<i>Amphora veneta</i>	Inhabitant of strongly alkaline waters (Cholnoky, 1968), no tolerance to changes in osmotic pressure. pH optimum is 8.5. Hustedt, 1957 regards species as oligohalobic
<i>Aulacoseira ambigua</i>	Present in shallow and deep water, alkaline conditions (Siteo et al., 2015), eutrophic lakes and rivers (Taylor et al., 2007).
<i>Aulacoseira granulata</i>	Benthos and plankton eutrophic rivers & streams (Schoeman, 1973; Taylor et al., 2007), growth temperature 6–20 °C (Zhang et al., 2018).
<i>Aulacoseira subarctica</i>	Alkaline lakes and rivers, moderate electrolyte content (Taylor et al., 2007).
<i>Caloneis bacillum</i>	Found in neutral to weakly alkaline waters which are oligotrophic. Widely distributed in small streams (Hustedt, 1957).
<i>Caloneis silicula</i>	Alkaline waters, optimum pH is about 8.5. Benthic (Schoeman, 1973).
<i>Cocconeis engelbrechtii</i>	Inland waters, brackish waters (Taylor et al., 2007).
<i>Cyclotella meneghiniana</i>	Nitrogen rich waters, cosmopolitan distribution (Taylor et al., 2007).
<i>Cymbella cesatii</i>	Oxygen-rich waters, pH value of 6. Foged (1964) is pH indifferent. Moist environments (Schoeman, 1973).
<i>Cymbella gracilis</i>	Low electrolyte content, alkaline waters (Taylor et al., 2007).
<i>Cymbella kappii</i>	Oligotrophic, neutral to weakly alkaline waters. Oxygen-rich waters with pH of about 7.5-7.8 (Cholnoky, 1968)
<i>Cymbella microcephala</i>	Petersen (1943) salt indifferent while Hustedt (1937) say oligohalobus. Favours oxygen-rich waters and optimum pH of 7-7.2, widely distributed, tolerant of very slight acidity (Taylor et al., 2007).
<i>Cymbella minuta</i>	Freshwater and marine species, alkaline waters, low nutrient, low electrolyte content (Taylor et al., 2007).
<i>Cymbella pusilla</i>	Freshwater species, mostly found in rivers and lakes (Krammer, 2003), nutrient tolerant (Allanson et al., 2012; pg. 61)
<i>Diploneis elliptica</i>	Alkaline waters, cosmopolitan species found in standing waters, moderate electrolyte content, moist habitats (Taylor et al., 2007).
<i>Diploneis oblongella</i>	Freshwater species but able to survive slight osmotic pressure (Schoeman, 1973) Salt indifferent species, alkaline waters, optimum pH is 8 (Foged, 1964) Well-aerated waters, moderate electrolyte content (Taylor et al., 2007).
<i>Diploneis subovalis</i>	Freshwaters, alkaline environments, optimum pH of 7.3 to 8.0, tropical freshwaters, moderate to elevated electrolyte content.
<i>Eunotia bilunaris</i>	Epiphytic (Gasse & Van Campo, 2001) Freshwater, low electrolytes (Norström et al., 2012). Found in acidic waters (Taylor et al., 2007).
<i>Eunotia exigua</i>	Benthic, widely distributed in acidic, oligotrophic and oxygen rich waters. Optimum pH is 5.2-5.3. Moist environments. Acidic water (Harding & Taylor, 2011), electrolyte poor waters (Taylor et al., 2007), low conductivity (Flower et al., 2012), relatively low temperatures (Matlala, 2010; Gloschenko & Kulikovskiy, 2017).
<i>Eunotia incise</i>	Acidic waters upland streams, oligotrophic, electrolyte-poor waters (Taylor et al., 2007). Cosmopolitan (Flower et al., 2012), Acidic, oligotrophic/low nutrient and electrolyte poor waters (Taylor et al., 2007), low conductivity (Flower et al., 2012), low temperatures (Gloschenko & Kulikovskiy, 2017).
<i>Eunotia minor</i>	Circumneutral waters (Schoeman, 1973), Acidic to Circumneutral waters (Taylor et al., 2007), low temperatures (Patrick & Reimer, 1966), low conductivity (Flower et al., 2012).
<i>Eunotia praerupta</i>	Strongly acidic waters, pH even below 5.5 (Flower et al., 2012). Tolerates dry conditions (Cocquyt, 2007).
<i>Eunotia rhomboidea</i>	Widely distributed in acidic and oligotrophic waters (Taylor et al., 2007).

<i>Fragilaria biceps</i>	Cosmopolitan, found in the benthos of lakes and rivers, mesotrophic to eutrophic, weakly alkaline waters (Taylor et al., 2007).
<i>Fragilaria brevistriata</i>	Freshwaters, oligotrophic, oxygen-rich, slightly alkaline waters (Taylor et al., 2007).
<i>Fragilaria capucina</i>	Benthic cosmopolitan, circumneutral, oligo to mesotrophic waters, moderate electrolyte content (Taylor et al., 2007).
<i>Fragilaria construens</i>	Brackish or Freshwater species, Oligotrophic, oxygen-rich waters, optimum values of 7.7-7.8. Withstand changes in osmotic pressure (Cholnoky, 1968). Low Alkaline waters present in very cold waters, low temperature optimum, tolerates ice (Ohlendorf et al., 2000; Wang et al., 2013). Good quality water (Taylor et al., 2007). Moderate to high electrolyte (Lowe, 1974).
<i>Fragilaria nanana</i>	Cosmopolitan species, oligotrophic lakes (Taylor et al., 2007), 10–30 °C (Zhang et al., 2018).
<i>Gomphonema gracile</i>	Freshwaters, oligotrophic, neutral to slightly alkaline waters (Taylor et al., 2007), pH indifferent, may survive in weakly acidic waters ().
<i>Gomphonema parvulum</i>	Freshwater species, optimum pH 7.8-8.2, but able to tolerate fluctuations in pH. Widely distributed in polluted waters characterised by fluctuating organic nitrogen compounds (Walsh & Wepener, 2009). Common in high altitude, sponge area bogs (Schoeman, 1983).
<i>Hantzschia amphioxys</i>	Freshwater species tolerates pH fluctuations but has optimum pH value of 7.8-8.0. Common in cold clean waters in arctic regions and glacial streams. Tolerant of extreme drying (Schoeman, 1973; Taylor et al., 2007).
<i>Mastrogloia dansei</i>	Cosmopolitan Brackish waters and high pH optimum (Cholnoky, 1968).
<i>Navicula angusta</i>	Freshwater, oligotrophic and weakly acidic waters. Oligotrophic, clean, unpolluted, electrolyte poor waters.
<i>Navicula capitatoradiata</i>	Cosmopolitan, eutrophic waters, high electrolyte content as well as present in brackish waters, tolerant of critical pollution levels (Taylor et al., 2007).
<i>Navicula cincta</i>	Thrives in both fresh and brackish waters. Alkaliphilous, optimum pH above 8.0.
<i>Navicula confervacea</i>	Freshwater, alkaline waters, pH of 7- 8.0, found in polluted waters (Taylor et al., 2007).
<i>Navicula radiosa</i>	Freshwaters, weakly acidic conditions (Schoeman, 1973), sensitive to pollution, oligotrophic, electrolyte poor waters, strongly alkaline (Taylor et al., 2007).
<i>Navicula subminuscula</i>	Freshwater species, benthic, moist habitats (Taylor et al., 2007; Walsh & Wepener, 2009).
<i>Navicula trivialis</i>	Pollution tolerant, alkaline waters (Taylor et al., 2007).
<i>Navicula zanonii</i>	Autotrophic, freshwaters, alkaline waters pH 7.5-8. Tropical to sub-tropical waters (Taylor et al., 2007).
<i>Nitzschia cofervacea</i>	Freshwater and marine species (Harding & Taylor, 2011), pollution tolerant (Lowe, 1974)
<i>Nitzschia elliptica</i>	Brackish waters, able to tolerate low oxygen. (Taylor et al., 2007)
<i>Nitzschia linearis</i>	Mainly found in water but able to survive some exposure and drying. Autotrophic, freshwater species, oxygen rich waters, alkaline and oligotrophic waters.
<i>Nitzschia themalis</i>	Strongly eutrophic, oxygen deficient, alkaline waters pH of 8.4 (Schoeman, 1973; Taylor et al., 2007).
<i>Pinnularia borealis</i>	Acidic, below 6, cold waters (Cocquyt, 2007)
<i>Pinnularia divergentissima</i>	Acidic waters below pH 6.0, montane environments (Harding & Taylor, 2011)
<i>Pinnularia viridiformis</i>	Freshwater species, slight acidity, low temperatures (Walsh & Wepener, 2009)
<i>Pinnularia viridis</i>	Weakly to moderately acidic waters. Widely distributed (Harding & Taylor, 2011).
<i>Stauroneis phoenicenteron</i>	Weakly alkaline waters, pollution tolerant. Cosmopolitan, eutrophic waters (Harding & Taylor, 2011).
<i>Stauroneis product</i>	Freshwater, acidic (Schoeman et al., 1973).
<i>Tabellaria flocculosa</i>	Freshwater species, low oxygen intolerant (Schoeman, 1973). Circumneutral or slightly acidic electrolyte-poor waters (Taylor et al., 2007).

The analysis of the data from the principal components in conjunction to the literature reveals (Table 5.6) the environmental inferences which can be made through diatom assemblages and composition (Table 5.4). For the first principal component, the diatoms reveal that PC1 may be indicative of water depth, pH and water temperature. For the second principal component the diatoms indicate that PC2 possibly indicates conductivity and nutrient (pollution) tolerance. Therefore, the low PC1 scores and high PC1 scores are possibly separated by water depth, pH and water temperature. The low PC2 scores and high PC2 are separated possibly by salinity (conductivity) and pollution levels. (*Distinct environmental inferences for a PC1 and PC2 are made in Chapter 6*).

#### 5.3.3.3. Diatom and sediment analysis

The stratigraphic profile represents diatom species which were identified in the BLMA sequence and were statistically significant. For the stratigraphic diatom diagram (Figure 5.10) by diatom type, the relationship between the different groups and within the groups becomes more apparent. The diatom record is dominated by *Fragilaria construens*, *Eunotia minor*, *Pinnularia divergentissima*, *Cymbella microcephala* and *Eunotia praerupta*. The diatom species which were identified for the sequence are grouped according to their preferred habitats which was gathered from the literature (Table 5.6). The stratigraphic profile is divided into the two groups which were an output from CONISS. The BLMA profile is mainly dominated by benthic diatom species, which are species that are affiliated to more shallow habitats, and some of these species include *Cymbella pusilla*, *Eunotia incisa*, and *Fragilaria capucina*.

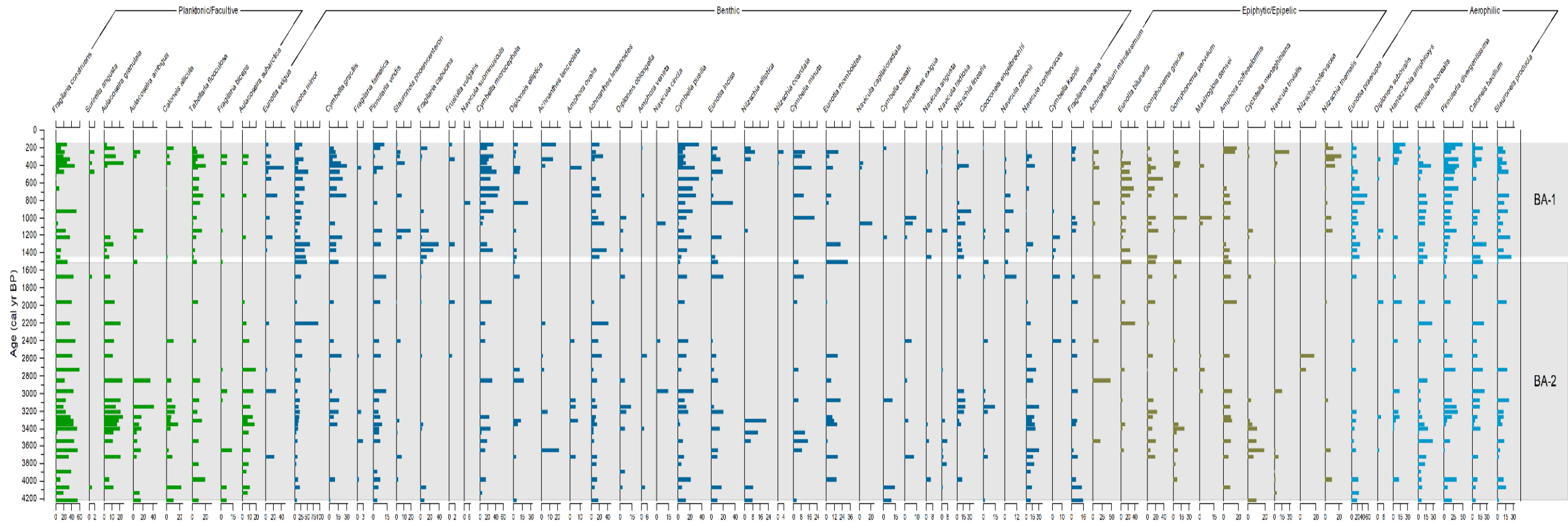


Figure 5.10: Stratigraphic diagram of the diatom results from the BLMA sequence, grouped according to specific habitats.

The BA-2, occurs between ~1,510 to 4,220 cal yr BP. In this zone the *Eunotia minor* species frequently occurs, however, the species is not as abundant as in the BA-1 (Figure 5.10). During the period between ~3,000 to 3,600 cal yr BP, a peak occurs for this species, concurrently, the species *Aulacoseira granulata* (41.01%) shows increases in abundance. Species that also commonly occur at the same age are *Aulacoseira subartica* (39.58%), *Eunotia minor* (10.70%), *Pinnularia divergentissima* (11.76%) and *Stauroneis producta* (11.98%). The *Caloneis silicula* diatoms reappears at ~3,080 to 3,400 cal yr BP and the reoccurrence accounts for 44.19% of this species in the core (Figure 5.7). Shortly after this period, there are distinct decreases in the occurrence of planktonic, benthic and aerophilic diatoms between 3,600 to 3,800 cal yr BP (Figure 5.11). During the same period increases occur in the percentages of Epipelagic/Epiphytic diatoms from about 7% to just over 20% (Figure 5.11). Broadly the BA-2 zone is characterized by fluctuating diatom species in terms of abundance and occurrence (Figure 5.10). In this zone there is a notable decrease in the occurrence of *Eunotia* species which frequently occur in the BA-1 zone, these include *Eunotia exigua*, *Eunotia praerupta* and *Eunotia bilunaris* (Figure 5.10).

The BA-1 occurs between ~150 to 1,450 cal yr BP, and is characterised by an abundance of *Eunotia minor*, which occurs throughout the zone (Figure 5.10). Notably, various *Eunotia* species are frequent throughout this zone which indicates that almost every sample in the BA-1 zone has the presence of one or more of the *Eunotia* species including *Eunotia minor*, *Eunotia exigua*, *Eunotia praerupta*, *Eunotia incisa*, *Eunotia bilunaris* and *Eunotia rhomboidea* (Figure 5.10). The frequent occurrence of this species may be indicative of slightly acidic conditions. The upper part of the zone, ~150 to 600 cal yr BP has increased numbers and frequency of *Cymbella gracilis* (41.14%), *Cymbella microcephala* (39.24%), *Pinnularia*

*divergentissima* (55.45%), *Stauroneis producta* (56.52%), *Hantzschia amphioxys* (46.45%) and *Fragilaria construens*, which is a well-known indicator species for cold conditions. Moreover, this portion of the zone also contains an increased number of planktonic diatom species (Figure 5.10). *Fragilaria construens* is common in this zone. At ~200 – 450 cal yr BP the *Fragilaria construens* diatoms are widely distributed, with the period accounting for 17.44% of the species, and this is a significant percentage considering that this species is widely distributed in the profile. Generally, the zone has fluctuating types of diatoms and notably at ~750 cal yr BP there is a peak in benthic and aerophilic diatoms (~25%), concurrently, a decrease occurred in the occurrence of planktonic/facultive diatoms (~ 5%; Figure 5.11).

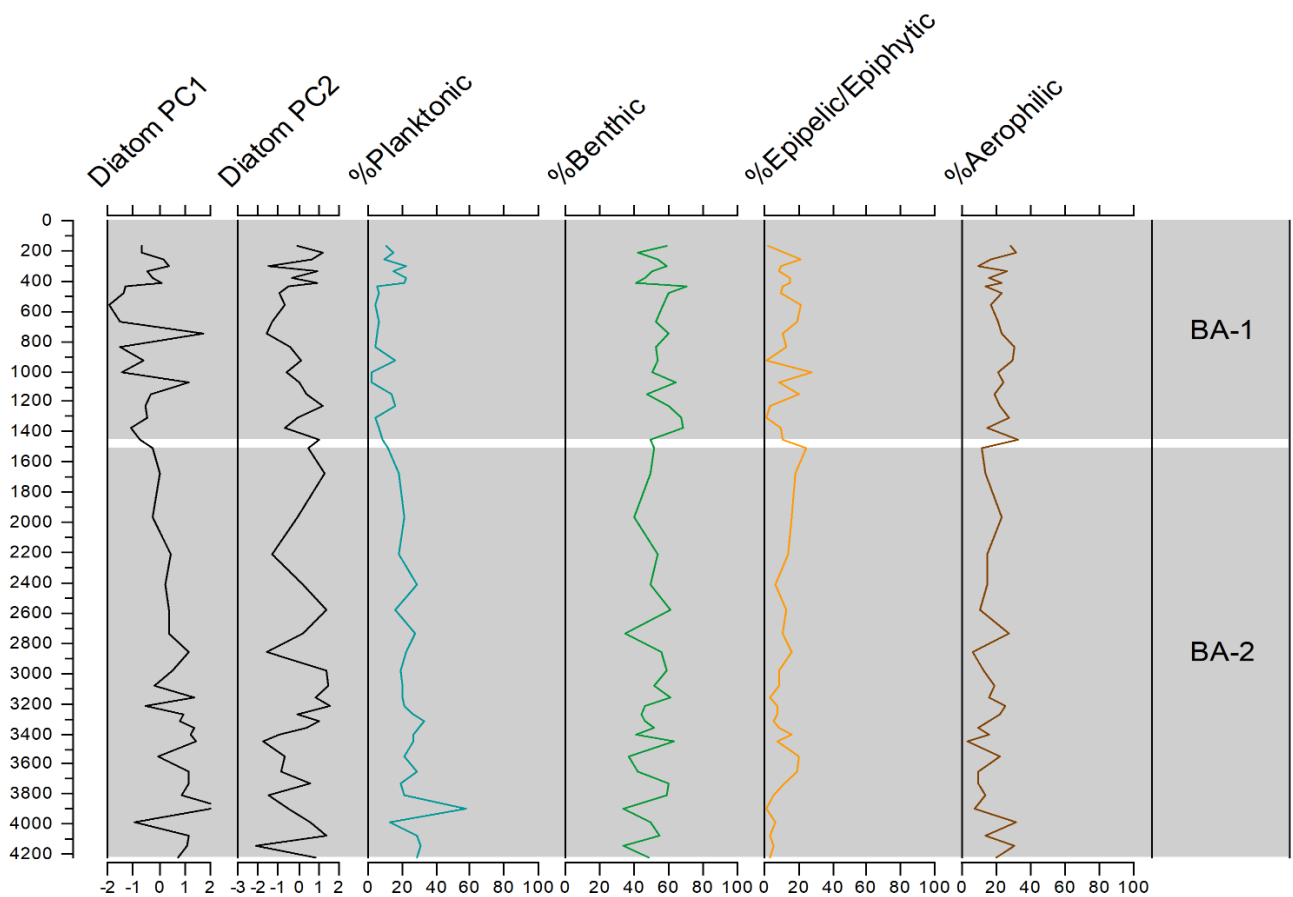


Figure 5.11: Stratigraphic diagram showing the total percentages of diatoms according to habitat.

The zone continues with fluctuating number of planktonic species, and a high number of benthic species and aerophilic species (Figure 5.11). Between ~600 to 800 cal yr BP, a peak in benthic (60%) and epipelagic/epiphytic (19%) organisms is apparent, concurrently there is also a peak in PC1 (~2) scores and a distinct decrease in PC2 scores at the same age. During this period, planktonic diatoms are very low, however, species such *Eunotia praeurpta*, *Pinnularia borealis*, *Pinnularia divergentisima* and *Stauroneis product* do occur (Figure 5.10; Figure 5.11). Throughout the BLMA sequence there are species which sparsely occur; however, these still show statistical significance, occurring at more than 2%, some of these diatom species include *Amphora ovalis*, *Navicula trivalis*, *Fragilaria capucina* and *Nitzschia elliptica* just to mention a few (Figure 5.10).

Fluctuations in sediment particle size, organic and carbonate percentages are apparent for most of the BLMA profile (Figure 5.12). The CONISS output dividing the BLMA profile based on the diatom sequence separates two zones.

The second zone, BA-2 spans from ~1,510 to 4,220 cal yr BP and is marked by a relative decrease in the organic percentage with age. The carbonate percentage in the second zone is also decreased, and gradually decreases with age and depth. Additionally, the zone contains a high percentage of clay sized sediment particles at ~3,730 to 4,220 cal yr. BP, and this coincides with the absence of sand sized particles at the same depth. Where clay percentage is low, sand sized particles are more prominent throughout the profile (Figure 5.12). In this zone the diatom PC1 scores and PC2 scores fluctuate rapidly throughout the zone, the upper part of the zone however, at ~1,680 to 2,730 cal yr BP shows a steadier increase in the diatom PC1 scores.

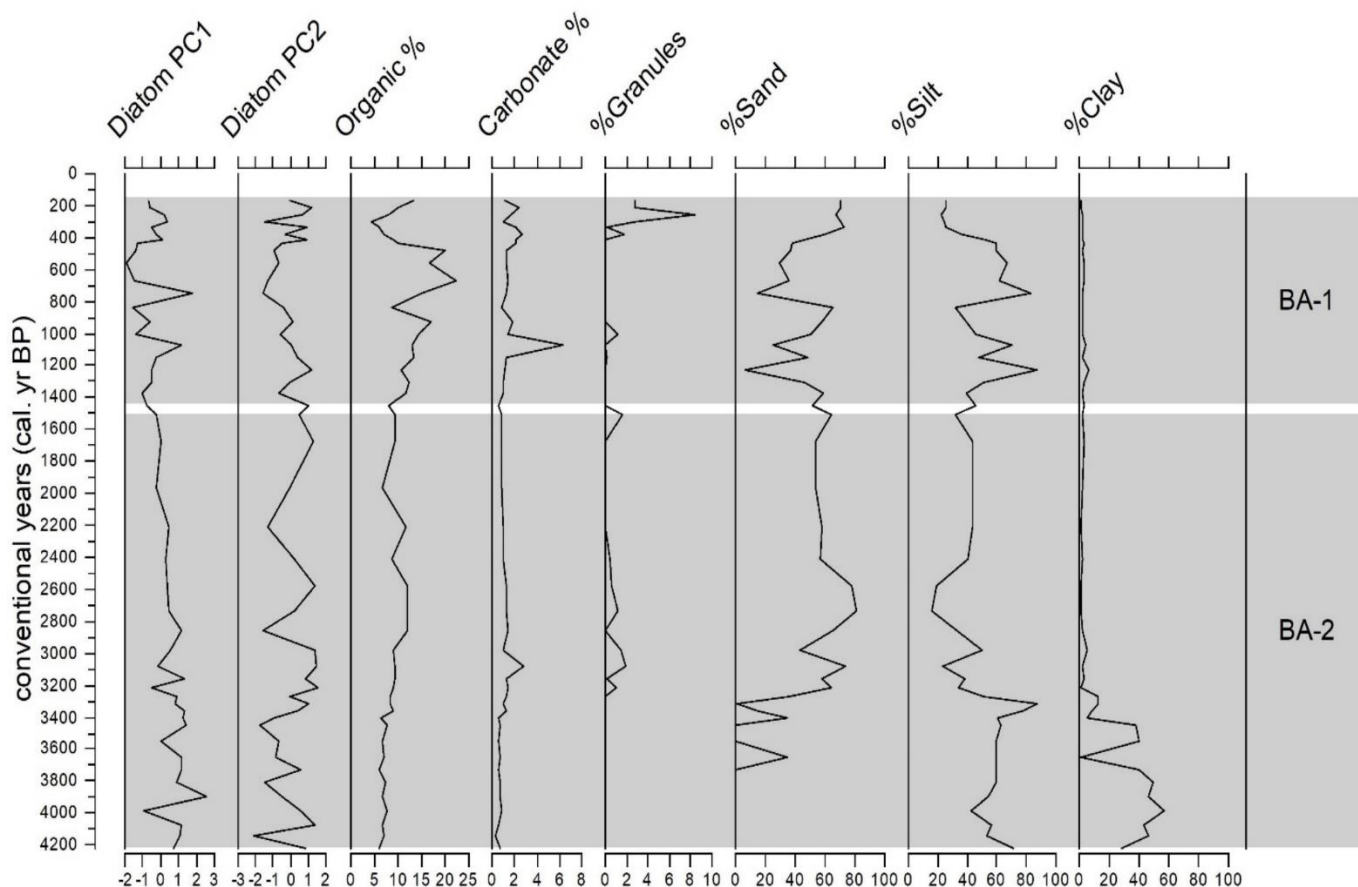


Figure 5.12: Diatom and sediment stratigraphic plot for BLMA sequence.

The first zone, BA-1, spanning from ~165 to 1,510 cal. yr BP is marked by fluctuating PC1 and PC2 scores, these fluctuations can most likely link to the disturbed stratigraphy shown by the AMS dates (Table 5.3). There is a distinct peak which occurs in diatom PC1 from ~670 to 750 cal. yr BP reflecting an increase in the abundance of *Fragilaria construens*, and concurrently a noticeable decrease in diatom PC2 scores is apparent at the same age (Figure 5.12). The BA-1 zone is characterized by relatively high organic percentages, with apparent decreases from ~165 to 300 cal yr BP, decreasing to approximately 5% at ~670 to 840 cal yr BP, decreasing to just over 6% (Figure 5.12). The zone is also characterized by relatively low clay sized particles not exceeding 12%. Worth of note is, throughout the zone, changes in the percentage of sand sized particles directly affects changes in silt sized particle percentage in that, where sand

percentage increases silt percentage decreases, and vice versa (Figure 5.10). At approximately 250 to 450 cal yr BP, there is a distinct increase in granule sized particles, at ~200 to 500 cal yr, BP the sequence is dominated by larger sized sediment particles, that is, granules and sand, possibly indicating drier conditions (Figure 5.12). The middle section of the zone at ~400 to 800 cal yr BP is characterized by a rapid increase in organic percentage and silt-sized particles with no occurrence of granule-sized particles possibly indicating wetter conditions or increased moisture availability than the previous period (Figure 5.12). The BLMA stratigraphy is characterized by fluctuations in diatom species as well as in the sedimentary composition at different periods, and it is distinct that granule sized particles are very low in the sequence and silt sized particles.

PC1 accounts for 13.48% of the variance in diatom species across the samples and principally segregated the two zones, BA-1 (~150 to 1450 cal yr BP) and BA-2 (~1,510 to 4,220 cal yr BP). The first zone shows strong affiliation with *Eunotia minor* and *Cymbella microcephala* (Figure 5.7). The PC1 sample score curve fluctuates between negative and positive scores for much of the profile, possibly influenced by the dominance of *Cymbella microcephala* at BA-1 and smaller amplitude peaks in the abundances of all the other diatom species (Figure 5.7). The peak occurring on the PC1 curve at ~700 -800 cal yr BP is possibly driven by sudden increase in the occurrence of *Eunotia praerupta* with just below 60 *Eunotia praerupta* diatoms counted at that depth (Figure 5.11). At ~3,200 to ~3,500 cal yr. BP, there is a slight peak in PC1 scores, simultaneously at that depth, it is apparent that peaks in diatoms species *Fragilaria construens* and *Aulacoseira granulata* result in the disappearance or decreased counts for several species, for example, *Eunotia minor* (Figure 5.11).

PC2 accounts for 8% of the variance in diatom species composition across the profile, there is minimal variance in species scores on the second principal component axis, separating *Pinnularia divergentissima* and *Cymbella microcephala* (Figure 5.8). The two species show similarities in their changes regarding their timing in the relative abundance, also mostly occurring in the first zone (Figure 5.10). The PC2 sample curve consists of fluctuating scores, generally, high positive scores are indicated by the slight increases in *Fragilaria construens* and *Aulacoseira granulata* (Figure 5.10).

## 6. Discussion

### 6.1 Introduction

The main aim of this research is to reconstruct the palaeoclimates and palaeoenvironments for the northern region of the Eastern Lesotho highlands. This research is valuable as it is the first study to be conducted in the far north of the Eastern Lesotho highlands. The results obtained from the two study sites are presented in palaeoreconstruction in the previous chapter, *Chapter 5 (Results)*. This chapter will explore, discuss, and develop a consolidated palaeoreconstruction for eastern Lesotho based on the analyses conducted for the diatoms and sediments. This chapter aims to develop a palaeoenvironmental reconstruction for each site, primarily based on inferences of the changes in the proxies (diatoms and sediment), as reflected in the results (*Chapter 5*). The discussion chapter explores the assumptions for climatic and environmental inferences made based on the results from the diatoms and sediments. This chapter will compare the results as well as the palaeoenvironmental inferences for the wetlands in the eastern Lesotho highlands to those of other sites in the same region. The purpose of these comparisons is to verify the synchrony of the climatic events, with specific attention to changes in moisture and temperature.

### 6.2. Palaeoenvironmental Reconstructions

The overall analysis of diatom composition through PCA (Figure 5.8) enables the inference of environmental conditions. A summary stratigraphic diagram is presented providing evidence for dry periods based on the aerophilic diatoms, percentage composition of gravel and sand sized particles (Figure 5.11). Evidence for wetter periods is on the basis of planktonic diatoms, the percentages of organic content, clay and slit sized particles in the sediment record (Figure 5.2, Figure 5.5, Figure 5.11, Table 6.1). The sediment extracted from the Lesotho wetlands,

for this study had relatively lower organic content composition than anticipated (Figure 5.2, Figure 5.5). Studies which have been conducted in the region (e.g. Marker, 1994; Fitchett et al., 2016a, b) have shown higher organic composition, this is attributed to the known occurrence of peat sediments within the wetlands of the region and in these studies the high organic content indicated high moisture within the environment (Meadows, 1988). As discussed in the previous chapters (*Chapter 3: Study site*), Lesotho consists of an enormous network of mires. This is because the environmental and climatic conditions are favourable for the formation of peat (Grab et al., 2005; Baker et al., 2014) and, according to Joosten & Clarke (2002) the term ‘peatland’ includes all mires.

Table 7.1: Summary of the keys strands of evidence for inferring wet and dry conditions.

Proxy		General conditions
Sediments	Organic content	High: increased moisture
	gravel	High: dry conditions
	Sand	High: dry conditions
	Silt & clay	High: moist & wet conditions
Diatoms	Benthic diatoms	High: wet conditions, increased surface water level.
	Planktonic diatoms	High: wet conditions
	Aerophilic	High: dry conditions
	<i>Fragilaria construens</i>	High: cold conditions

Sediments which contain high organic content, usually indicate environments which have a defined climatic profile of low temperatures and increased moisture, and therefore the lower the organic content in the sediment, the lower the moisture content and the higher the temperatures in the environment (Marker, 1994; Bell & Walker, 2013). With diatoms, increased species diversity is used to infer warm periods, the warmer periods characterised by increased temperatures create a tolerable environment for a wider range of diatom

species, activates growth, thus promoting species diversity (Savage et al., 2004). The cumulative percentage composition of *Fragilaria* diatoms >50, >60 and >70% can be used to infer colder periods (Fitchett, 2015), so, the higher the cumulative percentage composition of *Fragilaria diatoms*, the colder the period.

#### 6.2.1. Environmental variables

The diatom species which have been extracted and identified from the BLMA core represent a relatively wide range of habitat and environmental conditions (Figure 5.10). The diatom species which occur in abundance include *Fragilaria construens* (10.50%), *Eunotia minor* (7.62%), *Pinnularia divergentissima* (5.57%) and *Cymbella microcephala* (4.70%). These species are the main indicators of the general environmental conditions at the BLMA site. The cosmopolitan nature of diatom species limits the influence of temperature in the structuring of diatom species, although there are diatom species that are mainly limited to arctic and alpine environments, these species may still be widely distributed in other kinds of environmental habitats (Hartig & Wallen, 1986; Anderson, 2000). A good example to demonstrate this is the diatom species from the genera *Fragilaria*, because *Fragilaria* dominated assemblages have been identified in high altitudinal arctic and subarctic lakes (Smol et al., 1991; 1998; Laing et al., 1999; Schmidt et al., 2004). This diatom species (*Fragilaria*) was also found to dominate late-glacial assemblages (Haworth, 1976; Bradshaw et al., 2000; Robinson, 2004), shallow nutrient-rich lakes (Anderson & Odgaard, 1994; Hall et al., 1999) and in coastal environments (Stabell, 1985; Weckström & Juggin, 2005). Given the geographical variation of these environments one can conclude that the probability of temperature being the main controlling factor of the distribution of the diatoms is very minimal. According to Stoermer & Smol (2004), understanding the composition of diatoms

and the changes which occur in a specific habitat enable the environmental inferences using ecological similarities of co-existing diatoms.

On the basis of the habitat preferences and ecological characteristics of each diatom species present in the BLMA diatom sequence, PC1 separates species such as *Pinnularia divergentissima*, *Eunotia praeurupta* and *Eunotia bilunaris* from species such as *Aulacoseira subartica*, *Aulacoseira ambigua* and *Navicula confervacea* which have demonstrated a relatively high sensitivity to pH (Table 5.6; Taylor et al., 2007; Harding & Taylor, 2011). This is suggestive of a pH gradient, indicating a transition, which appears to reflect a shift in species which tolerate slight acidic, neutral to alkaline water. With increasing PC1 scores, the dominant diatom species identified in the BLMA sequence demonstrates an increase in alkalinity. PC2 separates diatom species with very negative scores from those with high positive scores (Figure 5.7), the second principal component is a variable that separates diatom species such as *Cymbella microcephala* and *Caloneis bacillum*. *Cymbella microcephala* is a species that exhibits strong affiliation to nutrients such as phosphate and nitrate (Matlala, 2010) and with increasing PC2 scores there is a transition from environments of nutrient rich/polluted waters to environments with cleaner and well oxygenated water, this is further indicated by the occurrence of *Fragilaria construens*, although commonly known as an r-strategist (van Dam, 1982; Weithoff, 2003; McGlynn et al., 2010), is a species that is affiliated with good quality water (Taylor et al., 2007).

There are apparent peaks in PC1, the first being ~580 cal yr BP, the second at ~800 cal yr BP and finally at ~4,000 cal yr BP (Figure 5.7). The peaks in PC1 indicate shifts to slightly acidic waters, which may be attributed to the slightly acidic to neutral soils which exist in the region (Carrol & Bawden, 1966; Ranthamane, 2005). Soils influence the pH of the water as it runs

off, the minerals such as sulphide and calcium minerals transform into alkalines or organic compounds, depending on the soil composition, thus influencing water pH levels (Hendershot et al., 1993). At ~750 cal yr BP, ~1,100 cal yr BP and ~3,900 cal yr BP there is an apparent shift to increases in alkalinity in the environment. For PC2, at ~ 250 cal yr BP, 2,400 cal yr BP and ~4,100 cal yr BP the PC2 scores indicate periods when the occurrence of nutrient/pollution tolerant diatoms had increased and thus indicating a shift from low nutrient/polluted water to nutrient-rich environments. The increased levels in alkalinity and pollution (nutrients) in the waters of eastern Lesotho during these periods, may possibly be attributed to farming activities such as livestock and other agricultural activities (Parker, 2011). The shifts that occur during this period are similar to those detected in the Sani valley profile (Fitchett, 2015), which were as a consequence of the introduction of livestock such as sheep into the mountainous regions of eastern Lesotho (Showers, 2005). The evidence for the introduction of livestock in the high mountains from historical records date back to AD 1890 (Van Zinderen Bakker, 1981; Showers, 2005), while in the Likoeng record (Parker et al., 2011) suggests this occurred around 1,070 cal yr BP. The BLMA profile shows that the introduction of livestock may have been much earlier than this, which implies that by around 1,100 cal yr BP there must have been an increased number of domestic livestock which promoted organic pollution and therefore influencing the water quality. Since the periods of higher pollution levels mainly occur only at ~ 250 cal yr BP, 2,400 cal yr BP and ~4,100 cal yr BP, it may indicate that the presence of large populations of livestock was on a seasonal basis.

#### 6.2.2. Multi-proxy environmental and climate reconstructions

From the sediments and diatom analyses the environment and climate of the northern region of eastern Lesotho is reconstructed. For the diatoms, inferences are made from the shifts in

the diatom communities which are based on the existing literature on diatom distribution and their preferred environments (Table 5.6). For the sediments, inferences are made from the changes in composition and particle size distribution throughout the core, these inferences are also based on existing literature on Lesotho (e.g. Marker, 1994).

With regards to the sediments from the BLMA profile, the organic content found in the sediment was relatively low (not exceeding 30%; Figure 5.4), however the sediment does 'qualify' to be identified as peat, this is because recent literature (e.g. Joosten & Clarke, 2002) reveals that peat definitions are not only limited to the accumulation of organic matter but physical characteristics as well (Grundling et al., 2015). In the Netherlands, for example, several peat-topped soils had organic content that range between 20 to 25% (Montanarella et al., 2005), which is similar to this profile. In this case the organic content percentages may have been decreased as a result of changes in land use and climate changes (Montanarella et al., 2005) as peatlands are known to be sensitive to climate change and anthropogenic pressures (Xu et al., 2019; Tanneberger et al., 2017). The peat from Lesotho is rare and therefore does not meet all international standards of peat (i.e. very high organic content). A more suitable definition in this context is one by Joosten & Clarke (2002) where they broadly define peat as material consisting of ~30% of organic material. Additionally, in other regions, peat has been defined as soils which either consist of at least 20% organic material or at least 18% of organic content if the soil have been saturated in water (Michéli et al., 2006). Taking all the unconventional definitions of peat into account, the sediment found Lesotho can be identified as peat. The occurrence of peat sediment in the site further indicates conditions of a stable and low-energy environment over prolonged periods (Grundling et al., 2015). Therefore, the presence of peat in the BLMA sequence suggests low energy hydrological regimes.

## **BA-2: ~4,200 to 1510 cal yr BP**

Zone BA-2 commences with a wet period at 4,200 cal yr BP, inferred from a progressive increase in the occurrence of planktonic diatoms (Willén, 1991; Morabito et al., 2003), such as *Aulacoseira granulata* and *Fragilaria construens* (Figure 5.10). A peak at ~3,850 cal yr BP occurs accounting for just over 60% of the diatom variation. The presence of *Fragilaria spp.* paired with a peak in epiphytic diatoms possibly suggests an extensive wetland area in the beginning of the zone (Figure 5.10). There are relatively low organic content percentages which slightly increase and peaks (~15%) at ~2,200 cal yr BP. The low carbonate content percentages which the zone commences with persist for much of the zone (<6%; Figure 5.11). The wet period probably began with slightly cooler temperatures indicated by progressive increases in *Fragilaria construens* (64.95%; Figure 5.10) and apparent decreases in the diversity of diatom species, meaning that the lowered temperatures could not support and enable the occurrence of a wider variety of species (Anderson, 2000)(Figure 5.10). This wet period terminated at ~3,200 cal yr BP.

At ~2,980 cal yr BP a dry period occurs, marked by a decrease in planktonic diatoms and a sharp increase in the relative abundance of aerophilic diatoms which are known to be suggestive of drier conditions in the environment (Shaw, 2010) (Figure 6.1). Decreases in planktonic diatoms also indicate decreased moisture levels in the environment (Willén, 1991; Morabito et al., 2003; Rioual et al., 2009). Additionally, there is an appearance of granule-sized particles and an abundance of sand-sized particles which further suggests the dry conditions (Marker, 1994) (Figure 5.2). The dry period linked with this zone was probably associated with much colder conditions, which is indicated by the slight increases in the presence of *Fragilaria construens*, and the tremendous decrease in benthic diatoms at ~2,750

cal yr BP. *Fragilaria construens* species is a good indicator for particularly cold conditions as the species is well adapted to cold temperatures as well as icy environments (Ohlendorf et al., 2000; Schmidt et al., 2004). The cumulative percentage for *Fragilaria construens* during this period is 76.25% and thus cold conditions are inferred for this period. Decreases in benthic diatom species also suggest a decrease in wetted area (standing water) (Lui et al., 2012). The occurrence of *Fragilaria construens* and the re-emergence facultative diatoms such as *Aulacoseira ambigua* is suggestive of the presence of ponds or surface water during the period (Yang, 2005)(Figure 5.10). The dry period was terminated at ~2,410 cal yr BP by a distinct decrease in aerophilic diatoms (Figure 5.10).

At ~2,400 cal yr BP another wet period is identified which is characterised by a progressive increase in planktonic diatoms (Willén, 1991). The wet conditions are more prolonged than the aforementioned wet period which occurred at the beginning of the zone. The increase in epiphytic diatoms marks an increase in moisture levels from ~1,650 cal yr BP to ~1,700 cal yr BP (Letáková et al., 2018) (Figure 6.1). The carbonate content percentage during this period is consistently low. The wet period is also indicated by high silt sized and clay sized particles with no presence of granule sized particles (Figure 5.2; Figure 5.11). There are frequent or large fluctuations in the appearance of benthic diatoms which may possibly indicate changes in the water levels in the wetland and surface water (Wolin & Stone, 2010). This wet period overlaps and forms a part of the BA-1 zone, with the period ending at ~1,145 cal yr BP.

#### **BA-1: ~1,450 to 160 cal yr BP**

The BA-1 zone spans for a much shorter period than the BA-2 zone (Figure 5.11). This zone is generally characterized by significantly low clay sized particles (<10%, Figure 5.11) and higher organic content percentages when compared to the BA-2 zone. The BA-1 zone

commences at 1,145 cal yr BP marking the occurrence of a wet period that is characterised by increases in planktonic diatoms. The abundance of benthic diatoms during this period indicate increases in wetted area (Wolin & Stone, 2010). The sediments from the BLMB profile indicate a wet period between ~1,300 cal yr BP and ~1,450 cal yr BP which may have consisted of wet climatic conditions (Figure 5.3) This wet period further extends to ~750 cal yr BP indicated by peaks in planktonic diatoms (Willén, 1991) and high percentages of silt sized particles (Marker, 1994). The wet conditions were possibly accompanied by much warmer temperatures marked by decreases in *Fragilaria construens* (Anderson, 2000)(Figure 5.10).

~700 cal yr BP to 450 cal yr BP is characterised by low planktonic diatoms and relative increases aerophilic diatom species (Figure 5.11). The ratio of the planktonic to aerophilic diatoms indicates that dry conditions were prominent during this time (Marker, 1994; Shaw, 2010). The increases in epiphytic diatoms suggest that some moisture was available in the environment (Pan & Stevenson, 1996). The increases in silt sized particles and increases in the organic content percentages further indicate moist conditions (Marker, 1994). It can be inferred that this was a dry period with fluctuating moisture availability in the environment (Figure 5.11). The sediments from the BLMB profile also suggest increased moisture during this period from ~650 cal yr BP to ~700 cal yr BP marked by high silt and clay content (Figure 5.3).

A more recent wet period is characterised by a relative increase in the percentages of planktonic diatoms from ~400 cal yr BP. The increase in planktonic diatoms is accompanied by progressive increases in benthic as well as epiphytic diatoms, and some of the prominent diatom species during this time include *Fragilaria construens*, *Aulacosiera granulate* and *Cymbella pussila*. The abundance of the benthic and planktonic diatoms suggests the

occurrence of a wet period (Willén, 1991; Pan & Stevenson, 1996; Wolin & Stone, 2010). The zone also begins with a high occurrence of *Fragilaria construens* indicating that the wet period was accompanied by a decrease in temperatures (Bigler et al., 2000; Rosén et al., 2000) (Figure 5.10).

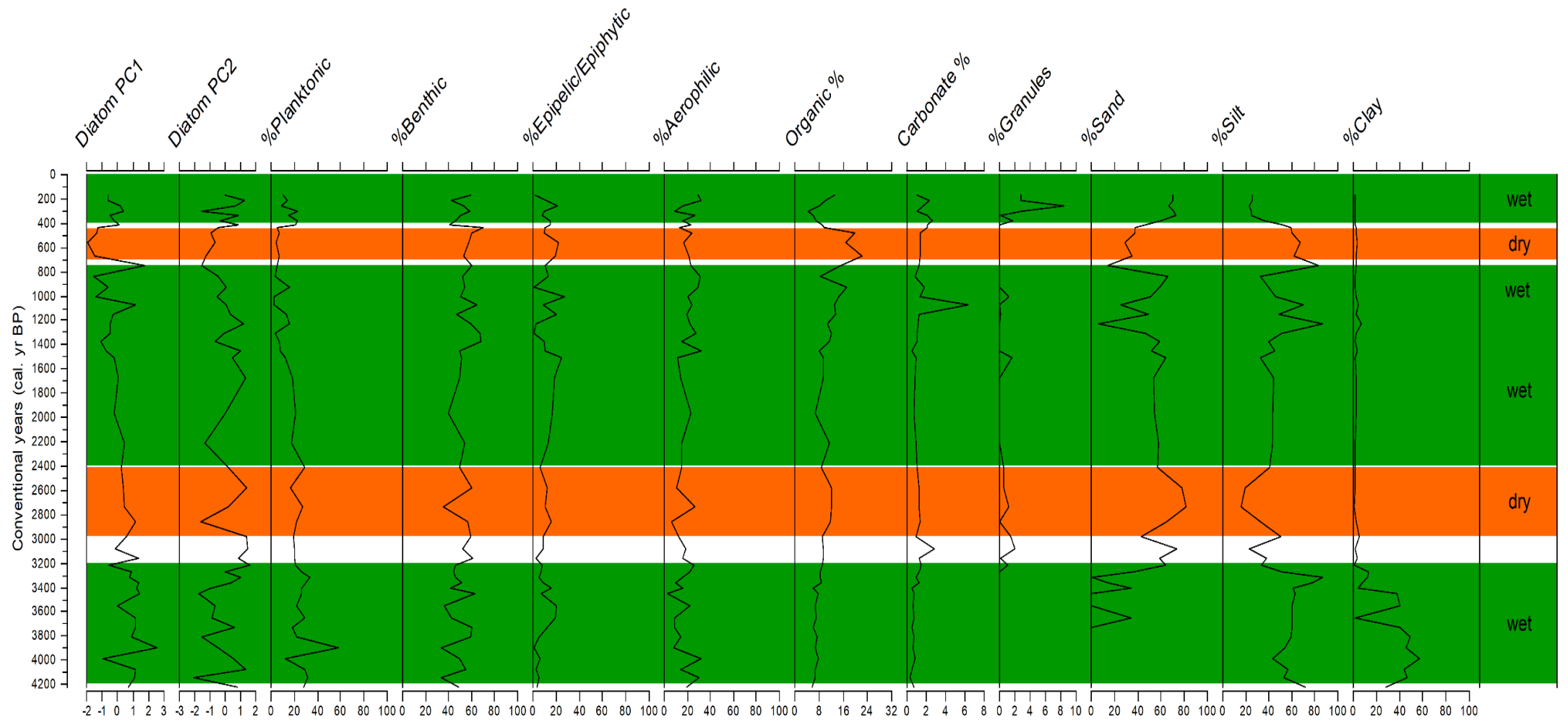


Figure 6.13: Stratigraphic diagram showing dry and wet periods throughout the BLMA sequence

### 6.3. Comparison of data to regional palaeoenvironmental sites.

There are a number of palaeoenvironmental sites that are suitable for comparing the data and inferences that have been made in this study, these include studies conducted in the region of Lesotho, including Mafadi (Fitchett et al., 2016a) and Sekhokong (Fitchett et al., 2016b) and those that form part of the Drakensberg-Maloti wetland sites which include Braamhoek (Norström et al., 2009; 2014; Finné et al., 2010), Mahwaqa Mountain (Neumann et al., 2014) and Ntsikeni wetland (Combrink, 2017)(Table 6.1). These sites will be discussed in terms of the time frame the profile for this study spans, the similarities between the proxies used and finally the possible influences resulting in the changes in the environment. The BLMA profile spans a period of ~4,200 cal yr BP to ~165 cal yr BP and is characterised by fluctuations between wet and dry periods. In the previous sections, the inferences separate the profile into five periods of alternating wet and cold conditions and therefore the comparisons of the palaeoenvironmental sites will be according to these periods: ~400-165 cal yr BP, ~700-450 cal yr BP, ~1,145- 750 cal yr BP, ~2,400-1,145 cal yr BP, ~2,980- 2,410 cal yr BP and ~4,200 -3,200 cal yr BP (Figure 6.1). The profiles from the aforementioned previous studies, all span a longer temporal period than that covered in this study.

The BLMA profile presents a wet, cool period between ~4,200 and 3,200 cal yr BP, indicated by the sediments and diatoms (Figure 6.1). The wet period identified in this region coincides with the Sekhokong record, where ~3,260 to 3,190 cal. yr BP and ~3,050 cal. yr BP were inferred to be wet periods indicated by the diatoms, sediment, and pollen data (Fitchett et al., 2016b). The pollen and diatoms from Africa's highest altitudinal wetland, Mafadi, indicate fluctuations between wet and dry conditions from even before ~4,200 cal yr BP until ~1,000 cal yr BP (Fitchett et al., 2016a). The phytoliths and diatoms from the Braamhoek wetland,

reflect a dry period from ~8,000 to 2,000 cal. yr BP (Finne et al., 2010), which overlaps with the wet period that is identified in the BLMA sequence (Figure 6.1). Norström et al. (2014) further investigated the Braamhoek wetland using mineral magnetic, pollen, charcoal and biomarkers, these proxies indicated the occurrence of a dry period around 4,200 to 3,200 cal. yr BP. Therefore, evidence from Braamhoek places the period in question as a period that was characterised by dry conditions (Finné et al., 2010). The pollen record at the Ntsikeni Wetland also suggest a dry period, which is terminated at ~4,200 cal yr BP and a wet period commenced for the region shortly after, from ~4,100 cal yr BP (Combrink, 2017), accompanied by short periods of dry climates. The pollen record further suggests a wet and warm period. Similarly, the pollen from the Mahwaqa Mountain record also suggest a wet and warm period from ~3,500 cal yr BP (Neumann et al., 2014). The wet conditions at this time are synchronous to those which would have occurred as indicated by the sediments and diatoms from the BLMA record.

~2,400 cal yr BP marks another wet period for the BLMA records and is mainly indicated by the progressive increase in the planktonic diatoms for that period in the BLMA profile from Lesotho (Figure 6.1). The progressive increase in planktonic diatoms further suggest that the water depth for this period was much deeper than what it is in present day (Holland, 1993). The return of wet conditions at 1,500 cal yr BP at Braamhoek (Finné et al., 2010) coincides with the wet conditions inferred for Lesotho. At ~2,000 cal yr BP the increased diatom concentration suggest increased moisture during this time, moreover, the presence of high planktonic and benthic diatoms from 2,000 cal yr BP suggest conditions were relatively moist and wet (Finné et al., 2010). The phytoliths from Braamhoek, however, contradicts this finding, suggesting far less moisture and dry conditions were prominent during this period (Finné et al., 2010). The pollen at the Ntsikeni wetland indicates that at ~2,400 cal yr BP the

region experienced a wet and warm period just until after ~1,000 cal yr BP (Combrink, 2017), these conditions directly coincide with the conditions suggested by the diatoms from the eastern Lesotho region, because wet and warm conditions were inferred for the region in the previous section for this period (*Section 6.3*). A wet and warm period also occurs in Mafadi at ~1,000 cal yr BP (Fitchett et al., 2016a). Similarly, the Mahwaqa Mountain record (Neumann et al., 2014) suggests wet and warm conditions at ~1,000 cal yr BP, however, in the Sekhokhong record (Fitchett et al., 2016b), ~2,690 cal yr BP up until ~1,380 cal yr BP is a dry period which coincides with the wet period inferred for the eastern Lesotho region (Figure 6.1).

The inferred dry period for ~750 cal yr BP which is terminated ~450 cal yr BP and is indicated by particularly high percentages of sand particles and aerophilic diatoms (Figure 6.1), is further characterised by warmer conditions indicated by the variation in diatom species for this period. The conditions for this period closely echo those which may have occurred during the MWP event which was characterised by several warm episodes (Tyson et al., 2000). During the MWP event, temperatures may have been 3-4°C higher than present day temperatures (Tyson et al., 2000). These conditions are similar to the conditions in the Mafadi wetland, however, the dry period is more prolonged in that profile from ~1,060 cal yr BP to present day (Fitchett et al., 2016a). At ~820 cal yr BP, however, there are apparent increases in *Fragilaria* species indicating a sudden transition to cold conditions (Bigler et al., 2000; Rosén et al., 2000) which align to the LIA. The pollen from Mafadi suggest the short strengthening of the Westerlies around 820 cal yr BP (Fitchett et al., 2016a). Similarly, at ~900 cal yr BP there is a marked, short-lived increase in the presence of *Fragilaria construens* (Figure 5.10) suggesting similar conditions in the two sites around this period. The distinct peak in the *Fragilaria construens* diatoms indicates abrupt cold conditions (Bigler et al. 2000; Rosén et

al., 2000). The Sekhokhong profile, does however show greater evidence for much wetter conditions during this period, with extremely high silt sized particles and relatively high organic content percentages (Fitchett et al., 2016b). What is interestingly similar between the BLMA site, Mafadi and Sekhokhong, is the presence of *Fragilaria spp.* before ~750 cal yr BP further suggesting the cold conditions (Fitchett et al., 2016a, b). In the BLMA site however, the *Fragilaria* species were decreasing suggesting a shift from the colder conditions to much warmer conditions than at Mafadi or Sekhokhong. The wet and cooler conditions in Sekhokhong suggest the strengthening of the westerly winds (Fitchett et al., 2016b).

The BLMA sequence suggests relatively wet conditions from ~450 cal yr BP to ~165 cal yr BP. The diatoms and pollen in the Mafadi sequence suggest much drier and cold conditions particularly around this period. The cold conditions indicated by significant increases in *Fragilaria construens* and the slight drop in temperature at ~200 cal yr BP are possibly an effect of the LIA event (Fitchett et al., 2016a). In Sekhokhong, there is also evidence that the decreased temperatures may coincide or signal the LIA (Fitchett et al., 2016b), both the records, Mafadi and Sekhokong indicate a dry period just until ~250 cal yr BP. On the contrary the two of the records for the Braamhoek wetland (Norström et al., 2014; Finné et al., 2010) suggest that a wet period occurred from ~1,000 cal yr BP to present day and indicate no occurrence of a dry event. This implies that even the period that is in question, ~400 cal yr BP – present day, is characterised by wet conditions at Braamhoek (Norström et al., 2009; 2014; Finné et al., 2010). The Mahwaqa Mountain record, as well as the Ntsikeni wetland record suggest wetter conditions with indications of anthropogenic influence ~650 cal yr BP (Neumann et al., 2014; Combrink, 2017). The differences in the inferred conditions during this period may be attributed to the site differences as well as the different proxies used to infer the conditions for a specific period. Evidence from the Mafadi and Sekhokhong records

suggest dry conditions around 450 cal yr BP to present. However, the proxies from Braamhoek, Mahwaqa Mountain and Ntsikeni wetland record suggest wetter conditions and thus aligning with inferred conditions from the BLMA record.

Table 8.2: Summary of comparison between regional sites.

Age (cal yr BP)	Eastern Lesotho (BLMA)	Mafadi Wetland (Fitchett, 2016a)	Sekhokhong (Fitchett et al., 2016b)	Braamhoek Wetland (Norström et al., 2014; Finné et al., 2010)	Ntsikeni Wetland (Combrink, 2017)	Global climatic events
~0 (present)	Wet & warm conditions	Fluctuations between wet & dry	Anthropogenic influence	Wet period	No data	
~500	dry					
~1,000	Wet <b>Increasing moisture</b>	Wet & warm	~1.380-wet <b>Fluctuations between wet &amp; dry</b>		Wet & dry period	<b>MWP</b>
~1,500						
~2,000		SRZ warm, dry			~2,800 – <b>decreased temperatures</b>	
		<b>Cooling post altithermal</b>	~2,690 – wet ~3,260-dry	Dry period		
~2,500	dry					
~3,000	wet					
~3,500						
~4,000				~4,100 - <b>decreased temperatures</b>		
~4,500		Dry period			Generally wet & warm	<b>4.2 kyr cold event</b>

#### 6.4. Comparison of site to global climatic events

According to Chase & Meadows (2007), a considerable regional variation exists for southern Africa and the Southern Hemisphere at large with regards to the palaeoenvironmental records. This variation is greatly influenced by several factors such as altitude, climate, and the present environmental conditions (Scott, 2002). The regional variation is also apparent in the previous section (*Section 6.4*) between the different palaeoenvironmental study sites. To date, the climatic events which have occurred are well documented in the Northern Hemisphere (e.g. Bakker & Mercer, 1986; Zhou et al., 1999; Tyson et al., 2000; Holmgren et al., 2003; Mayewski et al., 2004; Li et al., 2020). Following the palaeoenvironmental reconstruction and the comparison of data to regional palaeoenvironmental sites in this research, it is necessary to assess whether the climatic events inferred in the diatom and sediment record for this study reflect any of the global climatic events (Table 6.3).

It is important to determine whether these events are detected in the proxy records of eastern Lesotho to investigate the synchrony of the Northern and Southern Hemispheres (Fitchett, 2015) and further facilitate the understanding of the palaeoenvironmental history of southern Africa.

The record for this study commences at ~4,200 al yr BP and therefore the record excludes most of the climatic events (Table 6.3) such as the LGM at ~24,000-17,000 cal. yr BP (Carr et al., 2006; Chase & Meadows, 2007; Mills et al., 2012), and the Younger Dryas, which is an event that occurred as a result of cooler temperatures following the LGM warming event of the Younger Dryas at ~13,000 – 11,500 cal. yr BP (Mayewski et al., 1996). The occurrence of the YD is supported in the context of southern Africa with evidence from isotope records (Chase et al., 2015). Another well-documented event in the Northern Hemisphere is the '8.2

kyr' which resulted in cooler conditions (Ehlers & Gibbard, 2004) and according to Alley & Ágústsdóttir (2005), this period resulted in changes in the North Atlantic thermohaline circulation thus reducing northward heat transport in the Atlantic and triggering significant North Atlantic cooling. The evidence for the '8.2 kyr' event can also not be determined in this record, however, based on the speleothem record at Makapansgat, evidence of this event does exist for southern Africa (Holmgren et al., 2003). Finally, the Altithermal in the Mid-Holocene occurred from ~7,500-6,500 cal. yr BP which is a period of warming connected to deglaciation (Truc et al., 2013; Wanner et al., 2015). Evidence for this event is shown in the pollen record from the Ntiskeni wetland indicated by an increase in Poaceae and Crassulaceae pollen from ~7,000-5,500 cal. yr BP (Combrink, 2017).

Table 9.3: A summary of global climatic events (Chronological order- oldest to present).

Climatic Event	Age	Climate Conditions: Southern Africa	Reference
Heinrich-2 (H-2)	26,000-24,000 cal. yr BP		Hemming, 2004; Wang et al., 2006
Heinrich-1 (H-1)	17,500-16,500 cal. yr BP		
Daansgaard Oeschger cycles (D-O)		<b>Warm, dry in Northern Hemisphere, wetter in Southern Hemisphere</b>	Bond et al., 1992; Wagner et al., 2010
Last Glacial Maximum (LGM)	Still debated – broadly 24,000-17,000 cal. yr BP	<b>Glaciation</b>	Carr et al., 2006; Chase & Meadows, 2007; Thackeray & Scott, 2007; Mills et al., 2012; Nörtsrom et al., 2014; Neumann et al., 2014
Younger Dryas	~13,000 – 11,500 cal. yr BP	<b>Cooling after LGM warming event</b>	Holmgren et al., 2003; Thackeray & Scott, 2006; Truc et al., 2013
African Humid Period	~14,800 – 5,500 cal. yr BP	<b>Increased moisture</b>	Chase et al., 2009; Burrough & Thomas, 2013
4.2 kyr Cold Event		<b>Cooler temperatures</b>	Mayewski et al., 2004; Wanner et al., 2015
2.8 kyr Cold Event		<b>Cold Event Cooler temperatures</b>	Mayewski et al., 2004; Wanner et al., 2015
Altithermal	Mid-Holocene	<b>reduced seasonality of precipitation</b>	Avery, 2003
Hypsithermal	Early to mid-Holocene		Davis, 1984
Maunder Minimum	AD 1645-1719	<b>Most cold period during LIA</b>	Eddy, 1976
Little Ice Age (LIA)	1500 – 1900 A.D (Northern Hemisphere) AD 1300-1800 (South Africa)	<b>Climatic conditions unclear, WRZ wet, SRZ dry</b>	Brook et al., 1999; Tyson et al., 2000; Holmgren et al., 2003
Medieval Warming Period	AD 800–1500	<b>Global temperatures warmer than present.</b>	Lamb, 1965, Tyson et al., 2000
Neoglacial	5ka-AD 900	<b>Increased precipitation and moisture.</b>	Porter & Denton, 1967
Holocene Stage	11.5 ka to present		

The '4.2 kyr' event is a global-scale neoglacial or cold climatic event which coincides with the commencement of the eastern Lesotho profile (BLMA) which spans a period of ~4,200 cal yr BP (Figure 6.1). The event was described as cold and dry period (Wanner et al., 2015) and a period of abrupt climate change (Bond et al., 2001). Evidence of this event in southern Africa is minimal, however the event is well documented in the Mediterranean (Bini et al., 2019) and in the Middle East (Arz et al., 2006) as a "widespread drought" which contributed to societal change (Scropton et al., 2020). In a recent study, evidence from stalagmites from caves in Madagascar indicate dry conditions around 4,200 cal yr BP possibly linked to the occurrence of this event (Scropton et al., 2020). For South Africa, the Ntsikeni record demonstrates strong evidence for the event, marked by a short cold event indicated by peaks in Caryophyllaceae pollen and low pollen diversity ~4000 cal yr BP (Combrink, 2017). The record from the eastern Lesotho wetlands (BLMA) displays a short cold event which is characterised by a low species diversity (Figure 5.11). Although 4,200 cal yr BP to 3,980 cal yr BP has been inferred to be a generally wet period, at ~4,000 cal yr BP dry conditions do occur which coincide with the occurrence or present the 4.2 kyr event. The dry conditions are indicated by significant decrease in planktonic and benthic diatoms and an increase in aerophilic diatoms such as *Pinnularia divergentissima*, particularly at ~4000 cal yr BP (Figure 5.10). The cold and dry conditions during this time may be attributed to the 4.2 kyr event.

The '2.8 kyr' event is another cold event which occurred during the Holocene (Wanner et al., 2015). For the Southern Hemisphere, very little evidence exists for this event, and speculation exists as to whether the 2.8 kyr cold event did even occur in southern Africa. However, pollen evidence from the Ntsikeni wetland appears to emulate this global climatic event (Combrink, 2017). This was indicated by increases in *Caryophyllaceae* pollen and low species diversity which suggest a decrease in temperatures and therefore may signal the occurrence of the

cold event in the region (Combrink, 2017). For the BLMA sequence a dry period occurs at ~2,800 cal yr BP, shortly after this period, ~3,000 cal yr BP an increase in the *Fragilaria construens* diatoms occurs, suggesting that cold conditions were prevalent around this time. The evidence in the eastern Lesotho record emulate the conditions of this cold global event and potentially proves that a cold event did occur during this time.

The LIA event was a period of cooling, it is suggested that temperatures decreased by about 1°C for southern African regions (Tyson et al., 2000). Strong evidence exists for this climatic event in the Makapansgat stalagmite record (Tyson et al., 2000; Holmgren et al., 2003) proving that the event did occur in South Africa. The evidence of the maximum cooling at the 17<sup>th</sup> century seen at Makapansgat appears in the tree-ring reconstructions in Canada (Luckman et al., 1997), the oxygen isotope record in Greenland (Johnsen et al., 1972), the  $\delta^{18}\text{O}$  values recorded from the Galapagos Island corals (Dunbar et al., 1994). The diatoms from the eastern Lesotho record (BLMA) do show some evidence for the LIA, which is a very short cold period (Tyson et al., 2000; Wanner et al., 2008). For the BLMA record, a short-lived peak in the occurrence of *Fragilaria construens* occurs ~850 cal yr BP and this possibly suggests that a strength of the Westerlies and cooler conditions which are readily tolerated by these species (Fitchett, 2015). The diatom evidence for this cold period is broadly synchronous with the commencement of the LIA in southern Africa (Tyson et al., 2000). The slightly cold conditions ~200 cal yr BP possibly provides evidence for local cooling, however, the temporal resolution is rather coarse and therefore the evidence provided in this record cannot be used to confirm an overlap with the LIA (Wanner et al., 2008). This is very similar to the Mafadi record, where the resolution of the pollen and diatom data was too low facilitate the accurate identification of a cold period at ~820 and ~150 cal yr BP and associate it with the LIA event (Fitchett et al., 2016a).

The MWP event is a period which occurred from before 1,000 cal yr BP, in recent research, it is commonly referred to as the MCA (Mann et al., 2009). This period is a distinctive feature of the climate in the last millennium (Tyson et al., 2000), and has been hypothesised to be stronger in certain regions in the Northern Hemisphere (Diaz et al., 2011). Evidence of this period suggests that much of the Northern Hemisphere experienced a prolonged interval of warmth from about AD 800 to 1500 (Hughes & Diaz, 1994). High resolution evidence for the MWP for southern Africa is derived from the speleothem isotope records (Tyson et al., 2000; Holmgren et al., 2003). For the Mafadi and Sani Valley wetland records, the increases in pollen taxa diversity and the significant decrease in the presence of *Fragilaria* species suggests warm conditions between AD 800–1500. For the BLMA record ~800 cal yr BP is marked by a decrease in *Fragilaria construens* and *Fragilaria famelica* (Figure 5.10) accompanied by the diversity in diatom taxa further presents possible evidence for the MWP for this region. The period in which the MWP occurs, is inferred as a wet period for the BLMA record (Figure 6.1) and this indicates fluctuations in precipitation may have occurred throughout the period. The possible fluctuating precipitation during this period contradicts the findings by Burrough & Thomas (2013), which indicate stable precipitation for southern Africa, however, evidence for fluctuations in precipitation is supported at a global scale (e.g. Wanner et al., 2008). The eastern Lesotho records do present some form of evidence for the global MWP event and evidence of the MWP seems to echo conditions that were prominent in the northern hemisphere.

## 6.5. Limitations

There are various limitations which are experienced when undertaking palaeoreconstruction research, this section of this chapter focuses on the limitations which were encountered while carrying out this study.

### 6.6.1. Dating of samples

Regarding the dating of samples, time and financial constraints results in a limited number of samples for which dates could be attained for and therefore the specific samples were selected for dating, these were evenly spaced throughout the two cores which were extracted at the wetlands. The gaps which exist between the samples in each core may influence the robustness of the dates (Cubizolle et al., 2007). For this study, there were dates which indicated possible contamination of the samples sent for dating, the erroneous dates create a gap in the data, and this may have possibly influenced the statistical analysis (Cubizolle et al., 2007). The sediment accumulation rates presented by the Bayesian age-depth model are also affected by the gaps in the AMS dates, and thus creating much greater variation in the accumulation rates (Blaauw et al., 2018). A limiting factor is that the variance in the data may result to generalized or over simplified data as well as the simplification of inferred conditions for climatic and environmental change in this study (Blaauw et al., 2018).

### 6.6.2. Diatoms as a proxy

Working with diatoms, or any other proxy comes with various limitations, diatom analysis has several assumptions which require consideration.

#### 6.6.2.1 Burial/preservation

Prior to burial, the transportation and mixing of frustules may cause misinterpretation and imprecise shifts in the diatom assemblages and thus leading to inaccurate environmental or

climatic reconstructions (Desianti, 2019). Materials which have been transported may represent diatom species which have not existed simultaneously in space or time (Bradbury, 1999). Processes of dissolution or diagenesis may have an impact on the diatom record, in that, these processes promote the selective removal of certain taxa from the record and therefore potentially influencing the results (Denys & de Wolf, 1999). Additionally, where different kinds of diatom habitats occur in close proximity, parautochthonous assemblages may be established, that is, assemblages of intermediate or mixed characteristics (Kirsten 2008; 2014). Parautochthonous assemblages may have occurred in the BLMA sequence as there is a presence of a river in the vicinity of the wetland which was sampled. To curb or restrict the misrepresentation of the results when reconstructing past climates of Lesotho, the various life forms as well as the ecology of the different diatom species is considered. Denys & de Wolf (1999) stated that the small displacements of diatoms may provide important information regarding the environmental and sometimes, climatic conditions during certain time periods.

#### 6.6.2.2. Identification

The total number of diatom species on earth is approximately 200,000, however, only about 12% has been ecologically described and classified taxonomically (Cooper et al., 2010). Some of the classified diatom species may have not been identified correctly, this is because identification of diatoms species is not definite but rather relative, to a certain extent (Harding & Taylor, 2007). The identification process of these microorganisms is mainly dependent on physical characteristics and traits, these include length and breadth of the diatom valve, presence of raphe, the type of striae, etc. (Taylor et al., 2007). The limitation is that some of the diatom species have very similar traits. Diatoms which have similar physical characteristics but belong to a different class, this may cause confusion and thus possibly distort the results.

For this research, the presence of species identified was verified against diatoms which have been found in Lesotho and therefore limiting the possibility of incorrect species being included in the data. The diatom guide used in this study (Taylor et al., 2007) has specified the length and breadth of the valves for each diatom species, however, the microscope did not have a measurement instrument, this may have possibly decreased the accuracy in the identification of diatoms as one could not distinctly estimate the dimensions of the microorganisms.

Finally, there are several diatom-based studies conducted in Lesotho (e.g., Schoeman, 1970, 1973; Fitchett et al., 2016a, b) however, this is the first to be conducted in the far north-eastern region of Lesotho, although the diatom species can be verified and evaluated through these studies, species may differ. It is important to note that in the previous chapters it is evident that diatoms are excellent indicators for past environmental and climatic changes, although all the limitations of this proxy have been discussed and outlined, they do not take precedence or priority over the value of these microorganisms as a palaeoenvironmental tool. The diatoms along with the quantitative assessments and assemblage statistics produce valuable information.

#### 6.6.3. Contamination of samples

Firstly, the laboratory which was used to prepare the diatoms was not used by any other diatomist around the same time that the samples for the Lesotho wetlands were prepared, this meant there was very limited cross contamination from other samples (Taylor, 2007). Any minor contamination which may have occurred in the laboratory or at the study sites, through sediment, will be nullified by the removal of diatom abundances which are less than 2% (MacKay et al., 2012). The possibility of contamination should not have a significant influence

on the high abundance species, however, for the low abundance species, this may have potentially influenced the results.

During the extraction of the cores, possible contamination of the sediment may have occurred which could influence or produce misleading results. The BLMB core specifically, proved to be challenging to extract and thus the sediments were extracted in unconventional ways (segmented extraction). Therefore, when the samples were collected at the wetlands, there is a possibility for contamination of the terminating end of the core by sediment from the uppermost part of the core. To limit contamination, the equipment which was shared between the sites were cleaned timeously and thus curbing the extent of contamination between the subsamples and the different cores (Renberg, 1990; Grab et al., 2005).

Very small sample sizes were utilized during AMS dating and therefore prohibiting the possibility of contamination is a difficult task, to ensure contamination was limited, thorough treatment of samples was required to ensure any contaminants in the samples are eliminated and thus no substantial errors during the process of dating carbon dating.

#### 6.6.4. Methods for preparation

Standard laboratory methods were used in preparing all samples required for this study. During diatom preparation, the valves could have been possibly destroyed in this process (Taylor, 2007). This may have impacted on the counts of the diatoms and therefore significantly influenced the results. Moreover, the presence of organic materials in the diatom samples, due to poor cleaning may have obscured the view and interfered with the identification process, there is no guarantee that all the unwanted material was removed completely from the slides (Harding et al., 2007).

## 7. Conclusion

The eastern Lesotho highlands are a valuable and significant region for palaeoenvironmental research, with the region comprising the highest altitudinal point in southern Africa (Grab & Linde, 2014; Grundling et al., 2015). Due to the extreme altitudes of the region, palaeoenvironmental work has great potential to further explore the responsive ecological boundaries and past climates of eastern Lesotho. The region is further characterised by a distinct climate which plays a vital role in sustaining the water supply for the interior regions of South Africa (Nüsser & Grab, 2002; Braun, 2020). Eastern Lesotho has a large dependence on subsistence farming thus increasing vulnerability to climate change. It is therefore important to further study the rates of climate change throughout the Holocene in order to better understand, respond and adapt to the present-day climate (Ziervogel & Calder, 2003; Fitchett et al., 2017; Chatanga & Sieben, 2019). Various studies have been conducted in Lesotho with the main purpose of reconstructing and understanding past climate using archaeological, geomorphological and palaeoenvironmental evidence. This research contributes to the body of work which already exists for the region and presents an addition to the past climates of Eastern Lesotho highlands as it is the first study conducted in the far north region of the Eastern Lesotho highlands. This work was undertaken using the analyses of sediment properties from the two sites (BLMA & BLMB), combined with the analysis from diatoms which were extracted from the BLMA study sites in the Eastern Lesotho highlands and the inferences made from the analyses.

The main aim of this study was to reconstruct the palaeoenvironments and palaeoclimates of the northern region of eastern Lesotho. The work was undertaken through the extraction of sediment cores in the vicinity of Afriski resort. This was followed by the examination of

sediment from the region, with fossil diatoms subsampled at regular intervals of 2cm throughout the sediment cores. The main aim of this study was accomplished through the following objectives: 1) To obtain two peat cores from a wetland in the vicinity at the border of the districts Leribe-Makhotlong Butha-Buthe, at >3,000 m.asl. 2) To count and identify the diatom assemblages throughout the cores, as well as explore the sedimentary properties. 3) To develop an age-depth profile for the cores using AMS radiocarbon dating. 4) To infer the palaeoenvironment and palaeoclimate from the diatom assemblages.

### 7.1. Achievement of objectives

**1. To obtain two peat cores from a wetland in the vicinity at the border of Leribe-Makhotlong Butha-Buthe, at >3,000 m.asl.**

The two study sites which were selected from this study were in the vicinity of the Afriski resort and were a few kilometres apart. The sites varied slightly in altitude, and the sites spanned different time periods. The first site that was sampled, BLMA, was a wetland lying at 3,108 m.asl and the second site, BLMB was a site that was just outside a wetland at an altitude of 2,996 m.asl. The BLMA profile spanned from 4,200 cal yr BP to present and the BLMB profile spanned a much shorter period from 1,450 cal yr BP to present. In terms of depth, for the BLMA site, 95 cm was cored from the site and for BLMB, 150cm was cored for the site. The BLMA wetland provides evidence for a larger portion of the Holocene and at a much higher resolution than the BLMB profile. The two sites consisted of several similarities, for example, the presence of hummocks, however, the BLMB site was eroded and evidently disturbed by possible bioturbation or other physical disturbance.

**2. To count and identify the diatom assemblages throughout the core, as well as explore the sedimentary properties.**

The sedimentary properties were explored using the Mastersizer and LOI, the results for the sediment analysis obtained for both the sites are presented in *Section 5.2.2.* for BLMB and *Section 5.3.2.* for BLMA. The results of the diatom analysis from the BLMA site are presented in *Section 5.3.3.*, the BLMA showed a great variety of diatoms species, however, the BLMB site was not analysed for diatoms due to the disturbed profile as they would not have added any significant value to the results. The sediment properties show that the two sites were similar as they had very low carbonate content and relatively low organic content. The sediment data analysed for the BLMA core indicates that the site is peat and that the BLMB site consists of silty sediment. The diatoms from the region showed a great variation and a total number of 58 different species were identified in the profile with species such as *Fragilaria construens* and *Eunotia minor* being the most frequently occurring species. The diatoms assemblages and the sediment properties from both sites broadly reflect pronounced shifts between wet and dry conditions.

### **3. To develop an age-depth profile for the cores using AMS radiocarbon dating.**

A total of 15 radiocarbon dates were obtained to temporally constrain the proxy and sediment results as well as to facilitate the palaeoreconstruction for this study. These dates included eight for the BLMA site, however, only six could be used as there was a problem with obtaining a date on one, and insufficient material on the other. Seven of these dates were for the BLMB. To calculate the accumulation rates of sediment for this study, and to determine the dates for the samples at depths between the AMS dates, the BACON model was used. Broadly, the accumulation rates are steady and relatively consistent for both the sites (Figure 5.1; Figure 5.4).

### **4. To infer the palaeoenvironment and palaeoclimate from the diatom assemblages.**

The diatom data from the laboratory analysis was statistically analysed using CONISS and the results are presented in *Chapter 5 (Section 5.3.3)*. The palaeoenvironmental reconstruction for the north-eastern region of the Lesotho highlands is presented in *the Discussion (Chapter 6)*, the reconstruction of the past environments is made through inferences on the basis of theory and literature. A synthesis of the inferred palaeoenvironmental reconstruction for the region is presented graphically in *Figure 6.1*. The record for the BLMA site commences with a wet, cool period from ~4,200 to 3,200 cal yr BP, this is followed by a dry period from ~2,980 to 2,410 cal yr BP which has much colder conditions than the wet period. ~2,400-1,145 cal yr BP marked a prolonged wet period characterised by increased moisture and warmer conditions, this is followed by a wet period from ~1,145- 750 cal yr BP with warm conditions substantiated by a wide diversity of diatoms. At ~700-450 cal yr BP another dry, moist period occurs. Finally, 400 cal yr BP to present is a wet period with relatively warm conditions.

## 7.2. Key Findings

The study analyses changes in diatom and sedimentary properties from subsampled sections of the sediment profiles that were extracted in the eastern Lesotho Highlands wetlands, located in the vicinity of the Afriski resort. The sediment profiles are temporally constrained by a set of 14 radiocarbon AMS dates. The palaeoenvironmental reconstruction of the site was based on the inferences relating to the changes that occur in the proxies used. The use of diatoms and sediment properties allow for the investigation of a wider range of environmental and climatic conditions. This study has demonstrated that there is a wealth of diatoms in the region of Lesotho (Table 5.5; Figure 5.11). For many decades, it has been hypothesised that eastern Lesotho wetlands favour diatom preservation (Schoeman, 1973; Mitchell, 1996) and this hypothesis is further confirmed in this study. The proxies in this study

show that the late Holocene for the eastern Lesotho highlands was characterised by fluctuations between dry and wet conditions for the region between 4,200 to 165 cal yr BP (*Figure 5.3; 5.6; 6.1*). The benthic diatoms also show that the wetland area has been altered over the years, possibly influenced by climate. The site in question for this research broadly shows close similarities with other sites in Lesotho such as Mafadi and Sekhokhong. This record also shows similarities with other regional site such as Braamhoek, Ntsikeni and Mahwaqa Mountain for specific time periods and certain conditions (*Section 6.3*). The eastern Lesotho wetland records demonstrated evidence for the '4.2 kyr' and '2.8 kyr' global cold event, a very weak signal for the occurrence of the LIA and evidence for the MWP (*Section 6.5*). There is not much evidence for the other global events which may have occurred as the record only spans for 4,200 cal yr BP.

### 7.3. Future Work

This study forms an important part of the palaeoenvironmental research in Lesotho. This study presents a palaeoenvironmental reconstruction for the far north-eastern Lesotho highlands region. This is the first study located in the northern region of eastern Lesotho, the advantage to conducting such a study is that one is presented with a wider selection of proxies and specific study sites than in a well-researched region. Since this is the first study in this region, a considerable body of work can be conducted in order to further verify the findings of this research and also increase the reliability of these results. A palaeoenvironmental reconstruction study of this kind can be conducted making use of a wider variety of proxies which have been previously used in the region such as pollen, phytoliths and isotopes. The use of other proxies can possibly better support the evidence which has been gathered for this research. To better understand and examine the past environments and climates of the

northern region of the Eastern Lesotho highlands, a core spanning a much longer period can be extracted and analysed , this would enable much more detailed comparisons of the data with global events. The analysis of more wetlands for the region would be valuable in understanding the shifts which may occur in the hydrological system and allow for better adaptation to those changes.

## References

- Acocks, J.P.H., 1953. Veld types of South Africa (Botanical Survey of South Africa Memoir No. 28), Pretoria: Government Printer.
- Allanson, B.R., Hart, R.C., O'keeffe, J.H. and Robarts, R.D., 2012. *Inland waters of Southern Africa: an ecological perspective*. Springer Science & Business Media. 6
- Alverson, K., Bradley, R., Briffa, K., Cole, J., Hughes, M., Larocque, I., Pedersen, T., Thompson, L. and Tudhope, S. 2001. A global palaeoclimate observing system. *Science*, 293(5527), 47-47.
- Andren, E., Clarke, A., Telford, R., Weckstrom, K., Vilbaste, K., Aigars, J., Conley, D., Johnsen, T., Juggins, S. and Korhola, A., 2007. Defining reference conditions for coastal areas in the Baltic Sea. *Nordic Council of Ministries: Copenhagen*.
- Anderson, N.J., 2000. Miniview: diatoms, temperature and climatic change. *European Journal of Phycology*, 35(4), 307-314.
- Anderson, N.J., Bugmann, H., Dearing, J.A. and Gaillard, M.J., 2006. Linking palaeoenvironmental data and models to understand the past and to predict the future. *Trends in Ecology & Evolution*, 21(12):696-704.
- Arz, H.W., Lamy, F. and Pätzold, J., 2006. A pronounced dry event recorded around 4.2 ka in brine sediments from the northern Red Sea. *Quaternary Research*, 66(3), 432-441.
- Avery, D.M., 1993. Last Interglacial and Holocene altithermal environments in South Africa and Namibia: micromammalian evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 101(3-4), 221-228.
- Bak, Y.S., Yoo, K.C., Yoon, H.I., Lee, J.D. and Yun, H. 2007. Diatom evidence for Holocene palaeoclimatic change in the South Scotia Sea, West Antarctica. *Geosciences Journal*, 11(1), 11-22.
- Ball, D.F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of Soil Science*, 15(1), 84-92.
- Barinova, S. and Stenina, A., 2013. Diatom diversity and ecological variables in the Arctic lakes of the Kostyanoi Nos Cape (Nenetsky Natural Reserve, Russian North). *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, 147(2), 397-410.
- Bard, E. and Rickaby, R.E., 2009. Migration of the subtropical front as a modulator of glacial climate. *Nature*, 460(7253), 380-383.

- Battarbee, R.W., Flower, R.J., Juggins, S., Patrick, S.T. and Stevenson, A.C., 1997. The relationship between diatoms and surface water quality in the Høylandet area of Nord-Trøndelag, Norway. *Hydrobiologia*, 348(1-3), 69-80.
- Battarbee, R.W., Jones, V.J. and Flower, R.J. 2001. Diatoms. Tracking Environmental Change Using Lake Sediments, Vol. 3: Terrestrial, Algal and Siliceous Indicators, eds Smol JP, Birks HJB, Last WM.
- Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L. and Juggins, S. 2001. Diatom analysis. In Smol, J.P., Birks, H.J.B. and Last, W.M. (eds.). *Tracking environmental change using lake sediments, volume 3: Terrestrial, algal and siliceous indicators*. Kluwer Academic Press: Dordrecht.
- Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L. and Juggins, S. 2002. Diatoms. In *Tracking environmental change using lake sediments*, 155-202. Springer, Dordrecht.
- Bell, M. and Walker, M.J.C. 2013. Late Quaternary environmental Change: Physical and human perspectives. *Routledge: Oxford*, 17-63.
- Bengtsson, L., 1986. Chemical analysis. Handbook of Holocene palaeoecology and palaeohydrology, 423-451.
- Bennion, H. and Battarbee, R. 2007. The European Union water framework directive: opportunities for palaeolimnology. *Journal of Palaeolimnology*, 38(2), 285-295.
- Bentley, L.K., Robertson, M.P. and Barker, N.P., 2019. Range contraction to a higher elevation: the likely future of the montane vegetation in South Africa and Lesotho. *Biodiversity and conservation*, 28(1), 131-153.
- Bergh, E., 2019. *Neogene to quaternary foraminifera from the western margin of southern Africa* (Doctoral dissertation, University of Cape Town).
- Bigler, C., 2001. *Diatoms as indicators of Holocene climate and environmental change in northern Sweden* (Doctoral dissertation, Umeå universitet).
- Bigler, C. and Hall, R.I., 2002. Diatoms as indicators of climatic and limnological change in Swedish Lapland: a 100-lake calibration set and its validation for palaeoecological reconstructions. *Journal of Palaeolimnology*, 27(1), 97-115.
- Bini, M., Zanchetta, G., Persoiu, A., Cartier, R., Català, A., Cacho, I., Dean, J.R., Di Rita, F., Drysdale, R.N., Finnè, M. and Isola, I., 2019. The 4.2 ka BP Event in the Mediterranean region: an overview. *Climate of the Past*, 15(2), 555-577.
- Birks, H.J.B., Mackay, A., Battarbee, R.W., Birks, J. and Oldfield, F. 2003. Quantitative palaeoenvironmental reconstructions from Holocene biological data. Global change in the Holocene, 107-123.

- Birks, H.J.B., 2012. Ecological palaeoecology and conservation biology: controversies, challenges, and compromises. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 8(4), 292-304.
- Birks, H.H., 2020. Bringing Palaeoecology alive. *Curious about Nature: A Passion for Fieldwork*, 146.
- Bisaro, A., Wolf, S. and Hinkel, J., 2010. Framing climate vulnerability and adaptation at multiple levels: addressing climate risks or institutional barriers in Lesotho?. *Climate and Development*, 2(2), 161-175.
- Bjune, A.E., Grytnes, J.A., Jenks, C.R., Telford, R.J. and Vandvik, V., 2015. Is palaeoecology a 'special branch' of ecology?. *The Holocene*, 25(1), 17-24.
- Blaauw, M. and Christen, J.A., 2011. Flexible palaeoclimate age-depth models using an autoregressive gamma process. *Bayesian analysis*, 6(3), 457-474.
- Blaauw, M., Christen, J.A. and Aquino-López, M.A., 2020. A Review of Statistics in Palaeoenvironmental Research. *Journal of Agricultural, Biological and Environmental Statistics*, 25(1), 17-31.
- Blaauw, M., Christen, J.A., Bennett, K.D. and Reimer, P.J., 2018. Double the dates and go for Bayes—Impacts of model choice, dating density and quality on chronologies. *Quaternary Science Reviews*, 188, 58-66.
- Boelhouwers, J., Holness, S., Meiklejohn, I. and Sumner, P. 2002. Observations on a blockstream in the vicinity of Sani Pass, Lesotho Highlands, southern Africa. *Permafrost and Periglacial Processes*, 13(4), 251-257.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science*, 294(5549), 2130-2136.
- Boutin, C. and Keddy, P.A., 1993. A functional classification of wetland plants. *Journal of Vegetation Science*, 4(5), 591-600.
- Bradley, R.S. and Jonest, P.D. 1993. 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene*, 3(4), 367-376.
- Bradshaw, E.G., Jones, V.J., Birks, H.J.B. and Birks, H.H., 2000. Diatom responses to late-glacial and early-Holocene environmental changes at Kråkenes, western Norway. *Journal of Paleolimnology*, 23(1), 21-34.
- Briggs, D. 1977. Sources and Methods in Geography: Sediments. Butterworths, London, 192
- Brown, S. and Fritz, S.C., 2018. Diatom-Inferred High-Resolution Mid-to Late-Holocene Climate Variability from Yellowstone Lake, Wyoming. *AGUFM, 2018*: PP11E-1294.

- Brown, E.T. and Johnson, T.C. 2005. Coherence between tropical East African and South American records of the little ice age. *Geochemistry, Geophysics, Geosystems*, 6(12).
- Caballero, R. and Huber, M., 2013. State-dependent climate sensitivity in past warm climates and its implications for future climate projections. *Proceedings of the National Academy of Sciences*, 110(35), 14162-14167.
- Calles, B. and Stålnacke, P. 2000. Modelling soil moisture fluxes and surface runoff on event basis. An experimental study from Lesotho. *Zeitschrift für Geomorphologie. Supplementband*, (122), 17-31.
- Carballeira, R. and Pontevedra-Pombal, X., 2020. Diatoms in palaeoenvironmental studies of peatlands. *Quaternary*, 3(2): 10.
- Carbutt, C. and Edwards, T.J., 2006. The endemic and near-endemic angiosperms of the Drakensberg Alpine Centre. *South African Journal of Botany*, 72(1), 105-132.
- Carrol, D.M. and Bascomb, C.L. 1967. Notes on the Soils of Lesotho, Tech. Bull, No. 1 Tolworth, U.K.: Land Resources Div., Overseas Surveys.
- Carter, P. 1976. The effects of climatic change on settlement in eastern Lesotho during the Middle and Later Stone Age. *World Archaeology*, 8, 197-206.
- Chase, B.M., Meadows, M.E., Scott, L., Thomas, D.S.G., Marais, E., Sealy, J. and Reimer, P.J., 2009. A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa. *Geology*, 37(8), 703-70.
- Chase, B.M. and Meadows, M.E. 2007. Late Quaternary dynamics of southern Africa's winter rainfall zone. *Earth-Science Reviews*, 84, 103-138.
- Chase, B.M., Meadows, M.E., Scott, L., Thomas, D.S.G., Marais, E., Sealy, J. and Reimer, P.J. 2009. A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa. *Geology*, 37, 703-706.
- Chase, B.M., Quick, L.J., Meadows, M.E., Scott, L., Thomas, D.S.G. and Reimer, P.J. 2011. Late glacial interhemispheric climate dynamics revealed in South African hyrax middens. *Geology*, 39(1), 19-22.
- Chase, B.M., Scott, L., Meadows, M.E., Gil-Romera, G., Boom, A., Carr, A.S., Reimer, P.J., Truc, L., Valsecchi, V. and Quick, L.J. 2012. Rock hyrax middens: A palaeoenvironmental archive for southern African drylands. *Quaternary Science Reviews*, 56, 107-125.  
291
- Chase, B.M., Boom, A., Carr, A.S., Meadows, M.E. and Reimer, P.J. 2013. Holocene climate change in southernmost South Africa: rock hyrax middens record shifts in southern Westerlies. *Quaternary Science Reviews*, 82, 199-205.

- Chatanga, P. and Sieben, E.J., 2019. Ecology of palustrine wetlands in Lesotho: Vegetation classification, description and environmental factors. *Koedoe*, 61(1), 1-16.
- Cholnoky, B.J., 1968. Die Ökologie der Diatomeen in Binnengewässer [Ecology of Diatoms in Inland Waters]. *J. Cramer in der Gebrüder Borntraeger Verlagsbuchhandlung*, 699.
- Chonova, T., Kurmayer, R., Rimet, F., Labanowski, J., Vasselon, V., Keck, F., Illmer, P. and Bouchez, A., 2019. Benthic diatom communities in an alpine river impacted by wastewater treatment effluents as revealed using DNA metabarcoding. *Frontiers in Microbiology*, 10, p.653.
- Clark, V.R., Barker, N.P. and Mucina, L., 2011. The Great Escarpment of southern Africa: a new frontier for biodiversity exploration. *Biodiversity and Conservation*, 20(12), p.2543.
- Cocquyt, C., 2007. Diatom diversity in Hausburg Tarn, a glacial lake on Mount Kenya, East Africa. *Diatom research*, 22(2), 255-285.
- Coetzee, J.A. 1967. Pollen analytical studies in East and Southern Africa. *Palaeoecology of Africa*, 3, 1-146.
- Combrink, M. 2017. *The Quaternary pollen of Ntsikeni Wetland, KwaZulu-Natal, South Africa* (Doctoral dissertation, University of the Witwatersrand).
- Combrink, M., Fitchett, J.M., Bamford, M.K. and Botha, G.A. 2020. A late quaternary palaeoenvironmental record from Ntsikeni Wetland, KwaZulu-Natal Maloti-Drakensberg, South Africa. *Quaternary International*.
- Crampton, J.S., Cody, R.D., Levy, R., Harwood, D., McKay, R. and Naish, T.R., 2016. Southern Ocean phytoplankton turnover in response to stepwise Antarctic cooling over the past 15 million years. *Proceedings of the National Academy of Sciences*, 113(25), 6868-6873.
- Cregan, P., 1981. The acid soil problem defined. In *Riverina Outlook Conference: [www.regional.org.au/au/roc/1981/roc198109.htm](http://www.regional.org.au/au/roc/1981/roc198109.htm)*. (Accessed: 03/11/20).
- Cubizolle, H., Bonnel, P., Oberlin, C., Tourman, A. and Porteret, J., 2007. Advantages and limits of radiocarbon dating applied to peat inception during the end of the Lateglacial and the Holocene: the example of mires in the Eastern Massif Central (France). *Quaternaire- Revue de l'Association française pour l'étude du Quaternaire*, 18(2), 187-208.
- Damane, M., Sekantsi, L.P. and Molapo, S.S. 2018. Testing the stability of money demand function in Lesotho. *International Journal of Sustainable Economy*, 10(4), 383-404.
- Dayaram, A., Powrie, L., Rebelo, T. and Skowno, A., 2017. Vegetation Map of South Africa, Lesotho and Swaziland 2009 and 2012: A description of changes from 2006. *Bothalia-African Biodiversity & Conservation*, 47(1), 1-10.

- DEA (Department of Environmental Affairs, South Africa). 2013. Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate Trends and Scenarios for South Africa. DEA, Pretoria.
- Dee, M. and Ramsey, C.B., 2000. Refinement of graphite target production at ORAU. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 172(1-4), 449-453.
- Denys, L., 1999. Diatoms as indicators of coastal paleoenvironments and relative sea-level change. *The diatoms: applications for the environmental and earth sciences*, 277-297.
- Deevey Jr, E.S., 1942. A Re-Examination of Thoreau's "Walden". *The Quarterly Review of Biology*, 17(1), 1-11.
- Desianti, N., Enache, M.D., Griffiths, M., Biskup, K., Degen, A., DaSilva, M., Millemann, D., Lippincott, L., Watson, E., Gray, A. and Nikitina, D., 2019. The Potential and Limitations of Diatoms as Environmental Indicators in Mid-Atlantic Coastal Wetlands. *Estuaries and Coasts*, 42(6), 1440-1458.
- Diaz, H.F., Trigo, R., Hughes, M.K., Mann, M.E., Xoplaki, E. and Barriopedro, D., 2011. Spatial and temporal characteristics of climate in medieval times revisited. *Bulletin of the American Meteorological Society*, 92(11), 1487-1500.
- Dincauze, D.F., 1987. Strategies for palaeoenvironmental reconstruction in archaeology. In *Advances in archaeological Method and Theory*. 255-336. Academic Press.
- Douglas, M.S. and Smol, J.P., 1995. Periphytic diatom assemblages from high arctic ponds. *Journal of Phycology*, 31(1), 60-69.
- Du Buf, H., 2002. Automatic diatom identification (Vol. 51). *World Scientific*.
- Dunbar, R.B., Wellington, G.M., Colgan, M.W. and Glynn, P.W., 1994. Eastern Pacific sea surface temperature since 1600 AD: The  $\delta^{18}\text{O}$  record of climate variability in Galápagos corals. *Paleoceanography*, 9(2), pp.291-315.
- Dupont, L.M., Kim, J.H., Schneider, R.R. and Shi, N. 2004. Southwest African climate independent of Atlantic sea surface temperatures during the Younger Dryas. *Quaternary Research*, 61(3), 318-324.
- Ehlers, Jürgen and Gibbard, Philip L. 2004. Quaternary Glaciations – Extent and Chronology. Part II: North America. Amsterdam: Elsevier. pp. 257–262. ISBN 978-0-444-51592-6.
- Engelbrecht, F.A., Marean, C.W., Cowling, R.M., Engelbrecht, C.J., Neumann, F.H., Scott, L., Nkoana, R., O'Neal, D., Fisher, E., Shook, E. and Franklin, J. 2019. Downscaling last glacial maximum climate over southern Africa. *Quaternary Science Reviews*, 226, 105879.

- Engstrom, D.R., Fritz, S.C., Almendinger, J.E. and Juggins, S., 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. *Nature*, 408(6809), 161-166.
- Ertl, M. and Tomajka, J., 1973. Primary production of the periphyton in the littoral of the Danube. *Hydrobiologia*, 42(4), 429-444.
- Faegri, K., Kaland, P.E. and Krzywinski, K., 1989. *Textbook of pollen analysis* (No. Ed. 4). John Wiley & Sons Ltd.
- Falasco, E., Bona, F., Monauni, C., Zeni, A. and Piano, E., 2019. Environmental and spatial factors drive diatom species distribution in Alpine streams: Implications for biomonitoring. *Ecological Indicators*, 106, p.105441.
- Finch, J.M. and Hill, T.R., 2008. A late Quaternary pollen sequence from Mfabeni Peatland, South Africa: reconstructing forest history in Maputaland. *Quaternary Research*, 70(3), 442-450.
- Finlay, B.J., Monaghan, E.B. and Maberly, S.C., 2002. Hypothesis: the rate and scale of dispersal of freshwater diatom species is a function of their global abundance. *Protist*, 153(3), 261-273.
- Finné, M., Norström, E., Risberg, J. and Scott, L. 2010. Siliceous microfossils as late-Quaternary palaeo-environmental indicators at Braamhoek wetlands, South Africa. *The Holocene*, 20(5), 747-760.
- Fitchett, J.M., 2015. *Towards a multi-proxy Holocene palaeoenvironmental and palaeoclimatic reconstruction for Eastern Lesotho* (Doctoral dissertation, University of the Witwatersrand).
- Fitchett JM, Grab SW, Bamford MK et al. 2016a. A multidisciplinary review of late Quaternary palaeoclimates and environments for Lesotho. *South African Journal of Science*, 112(7–8), 1–9.
- Fitchett, J.M., Grab, S.W., Bamford, M.K. and Mackay, A.W., 2016b. A multi-proxy analysis of late Quaternary palaeoenvironments, Sekhokong Range, eastern Lesotho. *Journal of Quaternary Science*, 31(7), 788-798.
- Fitchett JM, Mackay AW, Grab SW et al. 2017. Holocene climatic variability indicated by a multi-proxy record from southern Africa's highest wetland. *The Holocene*, 27, 638–650.
- Fitchett, J.M. and Bamford, M.K., 2017. Research, Discussion and Debate in Southern African Quaternary Research in 2017. In 21st Biennial Conference of the South African Society of Quaternary Research, Johannesburg, 3–7 April 2017, 1993 (2003), 3.
- Fitchett, J.M., Mackay, A.W., Grab, S.W. and Bamford, M.K., 2017. Holocene climatic variability indicated by a multi-proxy record from southern Africa's highest wetland. *The Holocene*, 27(5), 638-650.

- Flower, R.J., 2005. A taxonomic and ecological study of diatoms from freshwater habitats in the Falkland Islands, South Atlantic. *Diatom research*, 20(1), 23-96.
- Foged, N., 1964. Freshwater diatoms from Spitsbergen. *Tromsø Museums Skrifter*, 11, 1-205.
- Foged, N., 1978. Diatoms in eastern Australia. *Bibliotheca Phycologica*, 41, 1-243.
- Fritz, S.C., Juggins, S. and Battarbee, R.W., 1993. Diatom assemblages and ionic characterization of lakes of the northern Great Plains, North America: a tool for reconstructing past salinity and climate fluctuations. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(9), 1844-1856.
- Fritz, S.C., Juggins, S., Battarbee, R.W. and Engstrum, D.R. 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. *Nature*, 352, 706-708.
- Franchini, W., 2013. The Collecting, Cleaning, and Mounting of Diatoms. "How To" Tutorial Series in Modern Microscopy Journal (art. 107). Available online: <https://www.mccrone.com/mm/the-collectingcleaning-and-mounting-of-diatoms/> (accessed on 14 August 2020).
- Gaiser, E. and Rühland, K., 2010. Diatoms as indicators of environmental change in wetlands and peatlands. *The diatoms: applications for the environmental and earth sciences*, (Ed. 2), 473-496.
- Gasse, F., Barker, P., Gell, P.A., Fritz, S.C. and Chalieu, F., 1997. Diatom-inferred salinity in palaeolakes: an indirect tracer of climate change. *Quaternary Science Reviews*, 16(6), 547-563.
- Gasse, F. and Van Campo, E., 2001. Late Quaternary environmental changes from a pollen and diatom record in the southern tropics (Lake Tritrivakely, Madagascar). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 167(3-4), 287-308.
- Glushchenko, A.M. and Kulikovskiy, M.S., 2017. *Amphipleura vavilovii*: a new diatom species of the family Amphipleuraceae from Laos. *Inland Water Biology*, 10(1), 17-21.
- Grab, S.W. and Knight, J., 2018. Southern African montane environments. In *Southern African Landscapes and Environmental Change*. Routledge, 153-180.
- Grab, S.W. and Linde, J.H., 2014. Mapping exposure to snow in a developing African context: implications for human and livestock vulnerability in Lesotho. *Natural Hazards*, 71(3), 1537-1560.
- Grab, S.W. and Nash, D.J., 2010. Documentary evidence of climate variability during cold seasons in Lesotho, southern Africa, 1833–1900. *Climate Dynamics*, 34(4), 473-499.

- Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & geosciences*, 13(1), 13-35.
- Grundling, P.L., Linström, A., Fokkema, W. and Grootjans, A., 2015. Mires in the Maluti mountains of Lesotho.
- Gwimbi, P. and Rakuoane, T.E., 2019. Impacts of dams on downstream riparian ecosystems' health and community livelihoods: A Case of the Lesotho Highlands Water Project. In *Agriculture and Ecosystem Resilience in Sub Saharan Africa*. Springer, Cham., 257-276
- Hall, R.I. and Smol, J.P., 1992. A weighted—averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. *Freshwater Biology*, 27(3), 417-434.
- Harding, W.R., Archibald, C.G.M. and Taylor, J.C., 2005. The relevance of diatoms for water quality assessment in South Africa: A position paper. *Water SA*, 31(1), 41-46.
- Haworth, E.Y., 1976. Two late-glacial (Late Devensian) diatom assemblage profiles from northern Scotland. *New Phytologist*, pp.227-256.
- Heiri, O., Lotter, A.F. and Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of palaeolimnology*, 25(1), 101-110.
- Hoag, C., 2019. “Water is a gift that destroys”: Making a national natural resource in Lesotho. *Economic Anthropology*, 6(2), 183-194.
- Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W. and Turney, C.S., 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon*, 55(4), 1889-1903.
- Holland, R.E., 1993. Changes in planktonic diatoms and water transparency in Hatchery Bay, Bass Island area, western Lake Erie since the establishment of the zebra mussel. *Journal of Great Lakes Research*, 19(3), 617-624.
- Hughes, D.A., 2016. Hydrological modelling, process understanding and uncertainty in a southern African context: lessons from the northern hemisphere. *Hydrological Processes*, 30(14), 2419-2431.
- Hughes, M.K. and Diaz, H.F., 1994. Was there a 'Medieval Warm Period', and if so, where and when?. *Climatic Change*, 26(2-3), 109-142.
- Hustedt, F., 1957. The diatom flora of the Weser river system in the area of the Hanseatic City of Bremen. *Treatises of the Natural Science Association in Bremen*. 34 ,181-440.

- Ilyashuk, E.A., Heiri, O., Ilyashuk, B.P., Koinig, K.A. and Psenner, R., 2019. The Little Ice Age signature in a 700-year high-resolution chironomid record of summer temperatures in the Central Eastern Alps. *Climate Dynamics*, 52(11), 6953-6967.
- Jalba, A.C., Wilkinson, M.H. and Roerdink, J.B., 2004. Automatic segmentation of diatom images for classification. *Microscopy research and technique*, 65(1-2), 72-85.
- Jenkins, G.T.H., Duller, G.A.T., Roberts, H.M., Chiverrell, R.C. and Glasser, N.F., 2018. A new approach for luminescence dating glaciofluvial deposits-High precision optical dating of cobbles. *Quaternary Science Reviews*, 192, 263-273.
- Jerardino, A., 1995. Late Holocene Neoglacial episodes in southern South America and southern Africa: a comparison. *The Holocene*, 5(3), 361-368.
- Johnsen, S.J., Dansgaard, W., Clausen, H.B. and Langway, C.C., 1972. Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature*, 235(5339), 429-434.
- Johnson, T.C., Brown, E.T., McManus, J., Barry, S., Barker, P. and Gasse, F., 2002. A high-resolution palaeoclimate record spanning the past 25,000 years in southern East Africa. *Science*, 296 (5565), 113-132.
- Jones, J., 1996. The diversity, distribution and ecology of diatoms from Antarctic inland waters. *Biodiversity & Conservation*, 5(11), 433-449.
- Joosten, H. and Clarke, D., 2002. Wise use of mires and peatlands. *International Mire Conservation Group and International Peat Society*, 304.
- Jorgensen, E.G., 1948. Diatom communities in some Danish lakes and ponds. *Det Kongelige Danske Videnskabernes Selskab Biologiske Skrifter*, 5(2),1-140.
- Juggins, S., 2013. Quantitative reconstructions in palaeolimnology: new paradigm or sick science?. *Quaternary Science Reviews*, 64, 20-32.
- Junk, W.J., An, S., Finlayson, C.M., Gopal, B., Květ, J., Mitchell, S.A. et al., 2013, 'Current state of knowledge regarding the world's wetlands and their future under global climate change: A synthesis', *Aquatic Sciences* 75(1), 151-167.
- Killick, D.J.B., 1978. Further data on the climate of the Alpine Vegetation Belt of eastern Lesotho. *Bothalia*, 12(3), 567-572.
- Knight, J. and Fitchett, J.M., 2019. Climate change during the Late Quaternary in South Africa. In *The Geography of South Africa*. Springer, Cham. 37-45.
- Knight, J. and Grab, S.W., 2018. Drainage network morphometry and evolution in the eastern Lesotho highlands, southern Africa. *Quaternary International*, 470, 4-17.

- Kolstrup, E., 2007. Lateglacial older and younger coversand in northwest Europe: chronology and relation to climate and vegetation. *Boreas*, 36(1), 65-75.
- Korhola, A., Weckström, J., Holmström, L. and Erästö, P., 2000. A quantitative Holocene climatic record from diatoms in northern Fennoscandia. *Quaternary research*, 54(2), 284-294.
- Krammer, K. and Lange-Bertalot, H., 1986. 1986–1991. Bacillariophyceae. Süßwasserflora von Mitteleuropa, 2(1).
- Krammer, K. and Lange-Bertalot, H., 1988. Bacillariophyceae, Teil 2. Epithemiaceae, Bacillariophyceae, Surirellaceae. Pascher A, Ettl, H., Gerloff, J., Heynig, H., & D. Mollenhauer, editors. Stuttgart, Germany: Gustav Fisher Verlag.
- Krammer, K. and Lange-Bertalot, H., 1991. 'Achnantheaceae', kritische Ergänzungen zu 'Navicula' ('Lineolatae') und 'Gomphonema': *Gesamtliteraturverzeichnis Teil 1-4*. Jena: G. Fischer.
- Krammer, K., 2003. Cymbopleura, Delicata, Navycymbula, Gomphocymbellopsis, Afrocybella. *Diatoms of Europe: Diatoms of the European inland waters and comparable habitats*, 4.
- Kruger, A.C. and Sekele, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, 33(3), 661-676.
- Kruger, A.C., Goliger, A.M., Retief, J.V. and Sekele, S.S., 2012. Clustering of extreme winds in the mixed climate of South Africa. *Wind and Structures*, 15(2), 87-109.
- Kylander ME, Holm M, Fitchett J, Grab S, Martinez Cortizas A, Norström E, et al. (2021) Late glacial (17,060–13,400 cal yr BP) sedimentary and paleoenvironmental evolution of the Sekhokong Range (Drakensberg), southern Africa. *PLoS ONE* 16(3): e0246821. doi:10.1371/journal.pone.0246821.
- Lawal, S., Lennard, C. and Hewitson, B., 2019. Response of southern African vegetation to climate change at 1.5 and 2.0° global warming above the pre-industrial level. *Climate Services*, 16, p.100134.
- Letáková, M., Fránková, M. and Poulíčková, A., 2018. Ecology and applications of freshwater epiphytic diatoms. *Cryptogamie, Algologie*, 39(1), 3-22.
- Letsie, M.M. and Grab, S.W., 2015. Assessment of social vulnerability to natural hazards in the mountain Kingdom of Lesotho. *Mountain Research and Development*, 35(2), 115-125.
- Lewis, C.A. and Illgner, P.M., 2001. Late Quaternary glaciation in southern Africa: moraine ridges and glacial deposits at Mount Enterprise in the Drakensberg of the Eastern Cape

- Province, South Africa. *Journal of Quaternary Science: Published for the Quaternary Research Association*, 16(4), 365-374.
- Liu, Q., Yang, X., Anderson, N.J., Liu, E. and Dong, X., 2012. Diatom ecological response to altered hydrological forcing of a shallow lake on the Yangtze floodplain, SE China. *Ecohydrology*, 5(3), 316-325.
- LMS, 2013. Lesotho's Second National Communication under the United Nations Framework Convention on Climate Change. Lesotho Meteorological Services, Lesotho.
- LMA, 2017. Lesotho's Nationally Determined Contribution under the United Nations Framework Convention on Climate Change. Ministry of Energy and Meteorology, Lesotho.
- Loftus, E., Pargeter, J., Mackay, A., Stewart, B.A. and Mitchell, P., 2019. Late Pleistocene human occupation in the Maloti-Drakensberg region of southern Africa: New radiocarbon dates from Rose Cottage Cave and inter-site comparisons. *Journal of Anthropological Archaeology*, 56, 101117.
- Low, A.B. and Rebelo, A.G., 1996. Vegetation of South Africa, Lesotho and Swaziland. *Department Environmental Affairs and Tourism, Pretoria*.
- Luckman, B.H., Briffa, K.R., Jones, P.D. and Schweingruber, F.H., 1997. Tree-ring based reconstruction of summer temperatures at the Columbia Icefield, Alberta, Canada, AD 1073-1983. *The Holocene*, 7(4), 375-389.
- Lugina, K.M., Groisman, P.Y., Vinnikov, K.Y., Koknaeva, V.V. and Speranskaya, N.A., 2005. Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881–2004. *Trends: A Compendium of Data on Global Change*.
- Mackay, A., Battarbee, R., Birks, J. and Oldfield, F., 2003. *Global change in the Holocene*.
- Mackay, A.W., 2007. The palaeoclimatology of Lake Baikal: a diatom synthesis and prospectus. *Earth-Science Reviews*, 82(3-4), 181-215.
- Magill, R.1., 1987. Musci Austro-Africana III. Alpine mosses of Lesotho. *Journal of Bryology*, 14(3), 527-530.
- Majara, N., 2005. *Land degradation in Lesotho: A synoptic perspective* (Doctoral dissertation, Stellenbosch: University of Stellenbosch).
- Mapfumo, P., Onyango, M., Honkponou, S.K., El Mzouri, E.H., Githeko, A., Rabeharisoa, L., Obando, J., Omolo, N., Majule, A., Denton, F. and Ayers, J., 2017. Pathways to transformational change in the face of climate impacts: an analytical framework. *Climate and Development*, 9(5), 439-451.

- Matero, I.S.O., Gregoire, L.J., Ivanovic, R.F., Tindall, J.C. and Haywood, A.M., 2017. The 8.2 ka cooling event caused by Laurentide ice saddle collapse. *Earth and Planetary Science Letters*, 473, 205-214.
- Matlala, M.D., 2010. The use of diatoms to indicate water quality in wetlands: A South African perspective (Doctoral dissertation, North-West University).
- Marker, M.E., 1994. Sedimentary sequences at Sani Top, Lesotho highlands, southern Africa. *The Holocene*, 4(4), 406-412.
- Maurya, S.K. and Letsie, M.M., 2017. Lesotho. In *The World Guide to Sustainable Enterprise*. Routledge, 102-108.
- McCarthy, T. and Rubidge, B.S., 2005. *Earth and Life*, 333.
- McVean, D.N., 1977. Nature conservation in Lesotho.
- Meadows, M.E. and Finch, J.M., 2016. The history and development of Quaternary Science in South Africa. *South African Geographical Journal*, 98(3), 472-482.
- Meadows, M.E., 1988. Late Quaternary peat accumulation in southern Africa. *Catena*, 15(5), 459-472.
- Meakins, R.H. and Duckett, J.D., 1993. Vanishing bogs of the Mountain Kingdom. *Veld and Flora*, 79(2), pp.49-51.
- Metcalf, S.E., O'Hara, S.L., Caballero, M. and Davies, S.J. 2000. Records of Late Pleistocene–Holocene climatic change in Mexico—a review. *Quaternary Science Reviews*, 19(7), 699-721.
- Michéli, E., Fuchs, M., Hegymegi, P. and Stefanovits, P., 2006. Classification of the major soils of Hungary and their correlation with the World Reference Base for Soil Resources (WRB). *Agrokémia és talajtan*, 55(1), 19-28.
- Mills, S.C., Grab, S.W. and Carr, S.J., 2009. Recognition and palaeoclimatic implications of late Quaternary niche glaciation in eastern Lesotho. *Journal of Quaternary Science*. 24(7), 647-663.
- Mills, S.C., Grab, S.W., Rea, B.R., Carr, S.J. and Farrow, A., 2012. Shifting Westerlies and precipitation patterns during the Late Pleistocene in southern Africa determined using glacier reconstruction and mass balance modelling. *Quaternary Science Reviews*, 55, 145-159.
- Mitchell, P., Parkington, J. and Wadley, L., 1998. A tale from three regions: The archaeology of the Pleistocene/Holocene transition in the Western Cape, the Caledon Valley and the Lesotho Highlands, Southern Africa. *Quaternary International*, 49, 105-115.

- Molaoa, T., 2016. Social resilience to climate change in Lesotho (Doctoral dissertation, University of the Free State).
- Montanarella, L., Jones, R.J. and Hiederer, R., 2006. The distribution of peatland in Europe.
- Morin, S., Gómez, N., Tornés, E., Licursi, M. and Rosebery, J., 2016. Benthic diatom monitoring and assessment of freshwater environments: standard methods and future challenges. *Aquatic Biofilms*, 111.
- Morabito, G., Oggioni, A. and Panzani, P., 2003. Phytoplankton assemblage at equilibrium in large and deep subalpine lakes: a case study from Lago Maggiore (N. Italy). *Hydrobiologia*, 502(1), pp.37-48.
- Morris, C.D., Taintoi, N.M. and Boleme, S., 1993. Classification of the eastern alpine vegetation of Lesotho. *African Journal of Range & Forage Science*, 10(1):47-53.
- Morris, C., 2017. Historical vegetation–environment patterns for assessing the impact of climatic change in the mountains of Lesotho. *African Journal of Range & Forage science*, 34(1), 45-51.
- Mpholo, M., Mathaba, T. and Letuma, M., 2012. Wind profile assessment at Masitise and Sani in Lesotho for potential off-grid electricity generation. *Energy Conversion and Management*, 53(1), 118-127.
- Mucina, L., Rutherford, M.C. and Powrie, L.W., 2006. Vegetation Atlas of South Africa, Lesotho and Swaziland. *The Vegetation of South Africa, Lesotho and Swaziland (Eds L. Mucina and M.C. Rutherford.)*, 748-789.
- Mulder, N. and Grab, S.W., 2009. Contemporary spatio-temporal patterns of snow cover over the Drakensberg. *South African Journal of Science*, 105, 228-233.
- Nel, W. and Summer, P., 2008. Rainfall and temperature attributes on the Lesotho-Drakensberg escarpment edge, Southern Africa. *Physical Geography*, 90, 97-108.
- Neumann, F.H., Stager, J.C., Scott, L., Venter, H.J. and Weyhenmeyer, C., 2008. Holocene vegetation and climate records from lake Sibaya, KwaZulu-Natal (South Africa). *Review of Palaeobotany and Palynology*, 152(3-4), 113-128.
- Nicolussi, K., Kaufmann, M., Melvin, T.M., Van Der Plicht, J., Schießling, P. and Thurner, A., 2009. A 9111 yearlong conifer tree-ring chronology for the European Alps: a base for environmental and climatic investigations. *The Holocene*, 19(6), 909-920.
- Niessen, H., 1956. Ökologische Untersuchungen über die Diatomeen und Desmidiaceen des Murnauer Moores. *Archiv für Hydrobiologie*, 51, 281-375
- Nipkow, F., 1920. Vorläufige Mitteilungen über Untersuchungen des Schlammabsatzes im Zürichsee. *Zeitschrift für Hydrologie*, 1(1-2), 100-122.

- Norström, E., Bringensparr, C., Fitchett, J.M., Grab, S.W., Rydberg, J. and Kylander, M., 2018. Late-Holocene climate and vegetation dynamics in eastern Lesotho highlands. *The Holocene*, 28(9), 1483-1494.
- Norström, E., Katrantsiotis, C., Smittenberg, R.H. and Kouli, K., 2017. Chemotaxonomy in some Mediterranean plants and implications for fossil biomarker records. *Geochimica et Cosmochimica Acta*, 219, 96-110.
- Norström, E., Neumann, F.H., Scott, L., Smittenberg, R.H., Holmstrand, H., Lundqvist, S., Snowball, I., Sundqvist, H.S., Risberg, J. and Bamford, M., 2014. Late Quaternary vegetation dynamics and hydro-climate in the Drakensberg, South Africa. *Quaternary Science Reviews*, 105, 48-65.
- Nthako, S. and Griffiths, A.L., 1997. Lesotho Highlands Water Project-Project Management. In *Proceedings of the Institution of Civil Engineers-Civil Engineering* (Vol. 120, No. 5: 3-13). Thomas Telford-ICE Virtual Library.
- Nusser, M. and Grab, S., 2002. Land degradation and soil erosion in the eastern Highlands of Lesotho, Southern Africa. *Erde-BERLIN-*, 133(3), 291-314.
- ORASECOM, 2015. Orange-Senqu River Commission 15 years 2000–2015, Orange-Senqu River Commission, Gauteng, 60 p.
- Palmer, A.J. and Abbott, W.H., 1986. Diatoms as indicators of sea-level change. In *Sea-Level Research*. Springer, Dordrecht, 457-487.
- Pan, Y. and Stevenson, R.J., 1996. Gradient analysis of diatom assemblages in western Kentucky wetlands. *Journal of Phycology*, 32(2), 222-232.
- Papry, R.I., Ishii, K., Al Mamun, M.A., Miah, S., Naito, K., Mashio, A.S., Maki, T. and Hasegawa, H., 2019. Arsenic biotransformation potential of six marine diatom species: effect of temperature and salinity. *Scientific reports*, 9(1), 1-16.
- Parnell, A.C., Buck, C.E. and Doan, T.K., 2011. A review of statistical chronology models for high-resolution, proxy-based Holocene palaeoenvironmental reconstruction. *Quaternary Science Reviews*, 30(21-22), 2948-2960.
- Patrick, R. and Reimer, C.W., 1966. The diatoms of the United States. *Academy of Natural Sciences*.
- Patrick, R. and Reimer, C.W., 1975. The Diatoms of the United States. Vol. 2, Part 1. Monograph No. 13. *Academy of Natural Sciences, Philadelphia*.
- Pennington, W., Tutin, M.T. and Tutin, T., 1943. Lake sediments: the bottom deposits of the north basin of Windermere, with special reference to the diatom succession. *New Phytologist*, 1-27.

- Pinseel, E., Van de Vijver, B., Kavan, J., Verleyen, E. and Kopalová, K., 2017. Diversity, ecology and community structure of the freshwater littoral diatom flora from Petuniabukta (Spitsbergen). *Polar Biology*, 40(3),533-551.
- Pla-Rabés, S. and Catalan, J., 2018. Diatom species variation between lake habitats: implications for interpretation of paleolimnological records. *Journal of Paleolimnology*, 60(2), 169-187.
- Plug, I., 1997. Late Pleistocene and Holocene hunter–gatherers in the Eastern Highlands of South Africa and Lesotho: a faunal interpretation. *Journal of Archaeological Science*, 24(8), 715-727.
- Preusser, F., Degering, D., Fuchs, M., Hilgers, A., Kadereit, A., Klasen, N., Krbetschek, M., Richter, D. and Spencer, J.Q., 2008. Luminescence dating: basics, methods and applications. *Quaternary Science Journal*, 57(1/2), 95-149.
- Pryor, J.W., 2018. Framework Integrating Climate Model, Hydrology, and Water Footprint to Measure the Impact of Climate Change on Water Scarcity in Lesotho, Africa.
- Quinlan, T. and Morris, C.D., 1994. Implications of changes to the transhumance system for conservation of the mountain catchments in eastern Lesotho. *African Journal of Range & Forage Science*, 11(3), 76-81.
- Ranthamane, M., 2005. Land and Water Management: Lesotho Country Situational Analysis. In Proceedings of the Workshop on Regional Situational Analysis: Land and Water Management in the SADC Region. Southern African Development Community.
- Ramaili, L.G., 2006. *Impact of the Lesotho Highlands Water Project in poverty alleviation in Lesotho* (Doctoral dissertation, Stellenbosch: Stellenbosch University).
- Reid, M.A., Tibby, J.C., Penny, D. and Gell, P.A., 1995. The use of diatoms to assess past and present water quality. *Australian Journal of Ecology*, 20(1), 57-64.
- Renberg, I., 1990. A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Palaeolimnology*, 4(1), 87-90.
- Rioual, P., Chu, G.Q., Li, D., Mingram, J., Han, J. and Liu, J., 2009. Climate-induced shifts in planktonic diatoms in lake Sihailongwan (North-East China): a study of the sediment trap and palaeolimnological records. In *11th International Paleolimnology Symposium* (p. 120).
- Roberts, P., Lee-Thorp, J.A., Mitchell, P.J. and Arthur, C., 2013. Stable carbon isotopic evidence for climate change across the late Pleistocene to early Holocene from Lesotho, southern Africa. *Journal of Quaternary Science*, 28(4), 360-369.
- Robinson, M., 2004. A Late glacial and Holocene diatom record from Clettnadal, Shetland Islands, northern Scotland. *Journal of Paleolimnology*, 31(3), 295-319.

- Rohling, E.J. and Pälike, H., 2005. Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature*, 434(7036), 975-979.
- Rott, E., Cantonati, M., Füreder, L. and Pfister, P., 2006. Benthic algae in high altitude streams of the Alps—a neglected component of the aquatic biota. *Hydrobiologia*, 562(1), 195-216.
- Round, F.E., 1991. Diatoms in river water-monitoring studies. *Journal of Applied Phycology*, 3(2), 129-145.
- Ruhland, K., Paterson, A.M. and Smol, J.P., 2008. Hemispheric-scale patterns of climate-related shifts in planktonic diatoms from North American and European lakes. *Global Change Biology*, 14(11), 2740-2754.
- Rullkötter, J., 2006. Organic matter: the driving force for early diagenesis. In *Marine geochemistry*. Springer, Berlin, Heidelberg, 125-168.
- Savage, V.M., Gillooly, J.F., Brown, J.H., West, G.B. and Charnov, E.L., 2004. Effects of body size and temperature on population growth. *The American Naturalist*, 163(3), 429-441.
- Schmitz, G. and Rooyani, F., 1987. *Lesotho geology, geomorphology, soils*. National University of Lesotho.
- Schunke, E., 1988. Earth hummocks. *Advances in periglacial geomorphology*, 231-245.
- Schwabe, C.A., 1995. Alpine mires of the eastern highlands of Lesotho. *Cowan, GI (Ed.)*.
- Schoeman, F.R., 1970. Diatoms from the Orange Free State (South Africa) and Lesotho. No. 3. *Botanica Marina*, 13(s1), 49-70.
- Schoeman, F.R., 1973. A systematic and ecological study of the diatom flora of Lesotho with special reference to the water quality, 365. *Biological indicators of water quality*, John Wiley and Sons, USA.
- Scott, L., 1982. A Late Quaternary pollen record from the Transvaal bushveld, South Africa. *Quaternary Research*, 17(3), 339-370.
- Scott, L., 1994. Palynology of Late Pleistocene hyrax middens, southwestern Cape Province, South Africa: a preliminary report. *Historical Biology*, 9(1-2), 71-81.
- Scott, L., 2002. Grassland development under glacial and interglacial conditions in southern Africa: review of pollen, phytolith and isotope evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 177(1-2), 47-57.
- Scott, L., Neumann, F.H., Brook, G.A., Bousman, C.B., Norström, E. and Metwally, A.A., 2012. Terrestrial fossil-pollen evidence of climate change during the last 26 thousand years in Southern Africa. *Quaternary Science Reviews*, 32, 100-118.

- Scott, L., 2016. Fluctuations of vegetation and climate over the last 75 000 years in the Savanna Biome, South Africa: Tswaing Crater and Wonderkrater pollen sequences reviewed. *Quaternary Science Reviews*, 145, 117-133.
- Scott, A.C. and Smith, D.G., 1977. What use are fossil plants?. *Hermathena*, 50-67.
- Scott, L., Steenkamp, M. and Beaumont, P.B., 1995. Palaeoenvironmental conditions in South Africa at the Pleistocene-Holocene transition. *Quaternary Science Reviews*, 14(9), 937-947.
- Scott, L. and, Vogel, J.C. 1978. Pollen analyses of the thermal spring deposit at Wonderkrater (Transvaal, South Africa).
- Scropton, N., Burns, S.J., McGee, D., Godfrey, L.R., Ranivoharimanana, L. and Faina, P., 2020. Possible expression of the 4.2 kyr event in Madagascar and the south-east African monsoon. *Climate of the Past Discussions*, 1-25.
- Serreze, M.C. and Barry, R.G., 2011. Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, 77(1-2), 85-96.
- Setty, M.G.A.P., 1966. Preparation and method of study of fossil diatoms. *Micropalaeontology*, 12(4), 511-514.
- Shi, G.R., 1993. Multivariate data analysis in palaeoecology and palaeobiogeography—a review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 105(3-4), 199-234.
- Shaw, P.A., 2010. The use of diatoms as palaeoenvironmental indicators in Botswana: A Review and Species Checklist. *Botswana Notes and Records*, 154-162.
- Showers, K. B. 1989. Soil erosion in the Kingdom of Lesotho: origins and colonial response, 1830s–1950s. *Journal of Southern African Studies*, 15, 263–286.
- Sieben, E.J.J., Kotze, D.C. and Morris, C.D. 2010. Floristic composition of wetlands of the South African section of the Maloti-Drakensberg Transfrontier Park. *Bothalia*, 40(1), 117-134.
- Sienkiewicz, E., Gąsiorowski, M. and Migala, K., 2017. Unusual reaction of diatom assemblage on climate changes during the last millennium: a record from Spitsbergen lake. *Journal of Palaeolimnology*, 58(1), 73-87.
- Sime, L.C., Kohfeld, K.E., Le Quéré, C., Wolff, E.W., de Boer, A.M., Graham, R.M. and Bopp, L., 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: model-data comparison. *Quaternary Science Reviews*, 64, 104-120.
- Sitoe, S.R., Risberg, J., Norström, E. and Westerberg, L.O., 2017. Late Holocene sea-level changes and palaeoclimate recorded in Lake Lungué, southern Mozambique. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 485, 305-315.

- Slingers, O., 2015. *An analysis of diatoms as biological indicators of water quality in rivers of the Western Cape* (Doctoral dissertation, University of Cape Town).
- Smith, J. 1997. Stable isotope analysis of fauna and soils from sites in the Eastern Free State and western Lesotho, Southern Africa : A palaeoenvironmental interpretation. (University of Cape Town).
- Smith, T.M. and Reynolds, R.W. 2005. A global merged land–air–sea surface temperature reconstruction based on historical observations (1880–1997). *Journal of Climate*, 18(12), 2021-2036.
- Smol, J.P., 1988. Palaeoclimate proxy data from freshwater arctic diatoms: With 2 figures and 1 table in the text. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, 23(2), 837-844.
- Smol, J.P. and Stoermer, E.F., 2010. *The diatoms: applications for the environmental and earth sciences*. Cambridge University Press.
- Sood, D. 2007. Environmental evaluations of a horticultural demonstration farm in Lesotho: A world bank funded study. Draft report E1534,. [www.wds.worldbank.org](http://www.wds.worldbank.org) (Accessed: 11/02/2020).
- Staples, R.R. and Hudson, W.K. 1938. An ecological survey of the mountain area of Basutoland. *An ecological survey of the mountain area of Basutoland*.
- Stewart, B.A., Dewar, G.I., Morley, M.W., Inglis, R.H., Wheeler, M., Jacobs, Z. and Roberts, R.G. 2012. Afromontane foragers of the Late Pleistocene: Site formation, chronology and occupational pulsing at Melikane Rockshelter, Lesotho. *Quaternary International*, 270, 40-60.
- Stockley, G.M. 1947. Report on the geology of Basutoland, Maseru. *Basutoland Govt*.
- Strachan, K.L., Finch, J.M., Hill, T. and Barnett, R.L. 2014. A late Holocene sea-level curve for the east coast of South Africa. *South African Journal of Science*, 110 (1/2), 1-9.
- Strachan, K.L., Finch, J.M., Hill, T.R., Barnett, R.L., Morris, C.D. and Frenzel, P., 2016. Environmental controls on the distribution of salt-marsh foraminifera from the southern coastline of South Africa. *Journal of Biogeography*, 43(5), 887-898.
- Tanneberger, F., Moen, A., Joosten, H. and Nilsen, N., 2017. The peatland map of Europe. *Mires and Peat*, 22(19), 1-17.
- Taylor, J.C., Harding, W.R. and Archibald, C.G.M. 2007. A methods manual for the collection, preparation and analysis of diatom samples. *Version*, 1, 60.
- Telford, R.J., Heegaard, E. and Birks, H.J. 2004. The intercept is a poor estimate of a calibrated radiocarbon age. *The Holocene*, 14(2), 296-298.

- Ter Braak, C.J.F. and Prentice, I.C. 1988. A Theory of Gradient Analysis. vol. 18 of Advances in Ecological Research.
- Tromp, L. 2006. May. Lesotho Highlands: the socio-economics of exporting water. In *Proceedings of the Institution of Civil Engineers-Civil Engineering* 159(5), 44-49.
- Truc, L., Chevalier, M., Favier, C., Cheddadi, R., Meadows, M.E., Scott, L., Carr, A.S., Smith, G.F. and Chase, B.M. 2013. Quantification of climate change for the last 20,000 years from Wonderkrater, South Africa: implications for the long-term dynamics of the Intertropical Convergence Zone. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 386, 575-587.
- Tuovinen, N., 2010. Past, present and future-assessing changes in aquatic environments using subfossil diatoms (Dissertation, University of Turku).
- Tyson, P.D. and Lindesay, J.A. 1992. The climate of the last 2000 years in southern Africa. *The Holocene*, 2: 271-278.
- Tyson, P.D., Karlén, W., Holmgren, K. and Heiss, G.A., 2000. The Little Ice Age and medieval warming in South Africa. *South African Journal of Science*, 96: 121-126.
- Valsecchi, V., Chase, B.M., Slingsby, J.A., Carr, A.S., Quick, L.J., Meadows, M.E., Cheddadi, R. and Reimer, P.J., 2013. A high resolution 15,600-year pollen and microcharcoal record from the Cederberg Mountains, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 387, 6-16.
- Van Dam, H., 1982. On the use of measures of structure and diversity in applied diatom ecology. *Nova Hedwigia*, 73, 97-115.
- Van Vliet-Lanoë, B., 1991. Differential frost heave, load casting and convection: converging mechanisms; a discussion of the origin of cryoturbations. *Permafrost and Periglacial Processes*, 2(2), 123-139.
- Van Vliet-Lanoë, B. and Seppala, M., 2002. Stratigraphy, age and formation of peaty earth hummocks (pounus), Finnish Lapland. *The Holocene*, 12(2), 187-199.
- Van Zinderen Bakker, E.M., 1955. *A preliminary survey of the peat bogs of the alpine belt of northern Basutoland*. Societas geographica Fenniae.
- Verschuren, D., Tibby, J., Sabbe, K. and Roberts, N. 2000. Effects of depth, salinity, and substrate on the invertebrate community of a fluctuating tropical lake. *Ecology*, 81(1), 164-182.
- Vyverman, W., Verleyen, E., Sabbe, K., Vanhoutte, K., Sterken, M., Hodgson, D.A., Mann, D.G., Juggins, S., Vijver, B.V.D., Jones, V. and Flower, R., 2007. Historical processes constrain patterns in global diatom diversity. *Ecology*, 88(8), 1924-1931.

- Wang, L.C., Behling, H., Lee, T.Q., Li, H.C., Huh, C.A., Shiau, L.J., Chen, S.H. and Wu, J.T., 2013. Increased precipitation during the Little Ice Age in northern Taiwan inferred from diatoms and geochemistry in a sediment core from a subalpine lake. *Journal of Palaeolimnology*, 49(4), 619-631.
- Warnock, J., Andrén, E., Juggins, S., Lewis, J., Ryves, D.B., Andrén, T. and Weckström, K., 2020. A high-resolution diatom-based Middle and Late Holocene environmental history of the Little Belt region, Baltic Sea. *Boreas*, 49(1), 1-16.
- Weithoff, G. 2003. The concepts of 'plant functional types' and 'functional diversity' in lake phytoplankton—a new understanding of phytoplankton ecology? *Freshwater Biology*, 48, 1669–1675.
- Willén, E., 1991. Planktonic diatoms-an ecological review. *Algological Studies*, 62, 69-106.
- Xu, J., Morris, P.J., Liu, J. and Holden, J., 2018. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, 160, pp.134-140.
- Yang, X.D., Dong, X.H., Gao, G., Pan, H.X. and Wu, J.L., 2005. Relationship between surface sediment diatoms and summer water quality in shallow lakes of the middle and lower reaches of the Yangtze River. *Journal of Integrative Plant Biology*, 47(2), 153-164.
- Zunckel, K., 2003. Managing and conserving southern African grasslands with high endemism. *Mountain Research and Development*, 23(2), 113-118.



BLMA3 7	73	0	0	0	15	7	0	3	27	0	0	21	18	7	0	5	0	0	0	21	0	12	0	11	3	0	20	0	0	0	0	0	11	0	0	15	0	0	6	0	0	0	0	0	16	0	6	0	0	0	23	0	0	0	0	0	0	4	0	0	53
BLMA3 8	75	0	0	0	8	7	0	0	5	0	2	12	8	0	14	0	0	9	0	7	0	0	0	0	0	3	0	0	0	12	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50		
BLMA3 9	77	16	8	0	12	8	0	0	20	0	0	11	9	0	6	0	0	0	22	0	0	22	0	10	0	11	30	0	0	0	15	0	10	0	3	0	0	0	7	0	0	10	13	0	0	0	0	0	0	0	0	0	4	0	3	0	0	0	47		
BLMA4 0	79	4	0	22	0	0	0	0	15	8	0	0	16	4	0	9	0	12	0	10	0	8	0	19	0	0	0	0	2	0	9	0	15	2	0	12	0	0	0	2	0	0	6	0	0	0	0	0	0	33	0	0	0	0	3	0	0	19	14	55	
BLMA4 1	81	0	11	0	13	0	5	0	0	0	8	22	7	10	0	0	0	0	0	20	0	7	0	0	16	23	6	0	0	6	0	8	18	11	0	0	15	0	0	7	3	0	0	13	0	0	0	4	0	18	8	0	0	0	9	0	0	0	0	33	
BLMA4 2	83	0	6	0	8	0	0	0	0	0	0	0	0	0	0	0	9	0	5	0	0	0	0	0	11	13	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	07				
BLMA4 3	85	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39					
BLMA4 4	87	34	22	0	14	8	0	13	17	10	3	7	0	0	0	0	11	0	0	8	0	0	14	0	0	20	7	0	0	0	0	0	26	2	16	0	0	0	16	0	0	0	12	0	0	12	0	0	0	0	0	0	6	7	1	0	0	0	13		
BLMA4 5	89	10	7	0	22	6	0	0	0	0	0	12	0	23	9	0	0	11	0	0	0	0	0	4	0	9	0	0	0	0	0	0	0	18	1	0	9	0	0	9	16	3	0	8	15	3	0	13	0	15	0	0	0	0	14	0	13	9	7	35	
BLMA4 6	91	0	0	0	0	0	0	0	7	0	0	0	14	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21				
BLMA4 7	93	22	14	0	9	5	6	0	0	0	0	0	16	12	8	0	2	0	0	0	0	0	10	0	11	7	0	2	0	3	0	20	0	0	11	0	0	18	0	0	0	3	0	0	8	10	0	0	1	0	13	0	0	0	0	16	0	9	6	7	56

## 9.2. BLMA sediment composition data

Sample Name	mean depth	Age	Organic %	Carbonate %	%Granules	%Sand	%Silt	%Clay	Mean	Skewness	Kurtosis
BLMA1	1	165	13.25536	1.060429	2.76	70.05	25.84	1.35	2.72	-0.09	1.05
BLMA2	3	210	10.04975	2.368159	2.76	70.05	25.84	1.35	2.72	-0.09	1.05
BLMA3	5	260	8.093126	1.658537	8.38	67.07	22.77	1.78	2.22	-0.05	0.94
BLMA4	7	300	4.354411	1.029913	2.75	70.63	24.5	2.12	2.88	-0.02	1.19
BLMA5	9	340	6.006121	2.081102	0.19	72.71	25.05	2.05	3.53	0.03	1.24
BLMA6	11	380	7.142857	2.629431	1.7	59.7	36.49	2.11	3.48	-0.05	1.26
BLMA7	13	410	9.003541	2.132524	0	46.43	51.77	1.8	4.16	0.21	1.23
BLMA8	15	440	9.842932	2.136126	0	38.04	59.09	2.87	4.37	0.12	1.24
BLMA9	17	480	19.86971	1.32899	0	37.31	60.06	2.63	4.48	0.22	1.15
BLMA10	19	560	16.68985	1.324061	0	29.09	67.36	3.53	4.77	0.23	1.11
BLMA11	21	670	22.33677	1.402062	0	35.35	61.91	2.74	4.56	0.14	1.04
BLMA12	23	750	15.13453	1.219731	0	14.29	83.13	2.58	5.23	0.23	1.04
BLMA13	25	840	8.550186	0.808922	0.05	65.72	32.33	1.9	3.37	0.04	1.16
BLMA14	27	930	17.0977	1.758621	0.01	58.4	39.62	1.97	3.66	0	2.06
BLMA15	29	1005	14.42125	1.419355	1.18	50.96	45.63	2.23	3.96	0.01	1.5
BLMA16	31	1070	12.98793	6.273953	0	25.63	69.7	4.67	4.91	0.29	1.13
BLMA17	33	1145	13.43066	1.290511	0.12	48.94	48.4	2.54	4.17	0.18	1.16
BLMA18	35	1230	10.61592	1.157737	0	6.36	86.95	6.69	5.92	0.27	1.13
BLMA19	37	1305	12.21757	1.024268	0	46.13	51.02	2.85	4.26	0.24	1.2
BLMA20	39	1370	11.52861	1.04526	0	58.7	39.52	1.78	3.87	0.23	1.27
BLMA21	41	1450	8.110883	0.558522	0	51.42	45.42	3.16	4.15	0.3	1.16
BLMA22	43	1510	9.384164	0.897361	1.61	64.07	32.41	1.9	3.27	-0.11	1.37
BLMA23	45	1680	9.438202	0.814981	0	53.3	44.03	2.67	4.17	0.25	1.23
BLMA24	47	1970	6.642599	0.78556	0	54.03	43.71	2.26	4.04	0.17	1.27
BLMA25	49	2210	11.55235	0.981949	0	57.92	43.5	1.42	3.14	0.1	1.23
BLMA26	51	2410	8.621554	1.022556	0.48	56.86	40.83	1.83	3.87	0.09	1.29
BLMA27	53	2580	11.99143	1.261956	0.55	78.35	19.56	1.54	2.69	0.07	1.19
BLMA28	55	2730	12.14431	1.313008	1.22	81.41	16.28	1.09	2.14	0.19	0.97
BLMA29	57	2860	11.83346	1.390796	0.01	65.09	32.64	2.26	3.56	0.11	1.36
BLMA30	59	2980	8.938011	0.980298	1.44	43.11	50.31	5.14	4.29	0.01	1.59
BLMA31	61	3080	9.280303	2.833333	1.97	73.25	22.9	1.88	2.74	0.04	1.14
BLMA32	63	3160	9.491525	1.306215	0.19	58.41	38.18	3.22	3.59	0.02	1.16
BLMA33	65	3220	9.054594	1.448735	1.03	63.87	34.04	1.06	3.51	0.05	1.28
BLMA34	67	3270	8.388038	1.239971	0	36.02	50.92	13.06	4.98	0.06	0.96
BLMA35	69	3320	8.324769	0.931826	0	0.79	86.83	12.38	6.02	0.39	1.07
BLMA36	71	3360	8.903021	1.243243	0	14.25	77.65	8.1	5.72	0.17	1.1
BLMA37	73	3400	6.198347	0.561983	0	34.56	60.66	4.78	4.64	0.43	1.32
BLMA38	75	3455	7.796014	0.717468	0	0	62.62	37.38	7.63	0.14	0.92
BLMA39	77	3550	6.725979	0.629181	0	0	59.96	40.04	7.83	0.23	0.89
BLMA40	79	3650	7.086365	0.68839	0	34.62	59.77	1.33	4.28	-0.03	1.37
BLMA41	81	3730	6.013802	0.536313	0	0	60.07	39.93	7.86	0.28	0.87
BLMA42	83	3810	7.344633	0.720339	0	0	59.58	49.42	7.84	0.22	0.9
BLMA43	85	3900	6.655711	0.670501	0	0	54.2	45.8	8.07	0.27	0.86
BLMA44	87	3980	7.670906	0.810811	0	0	43.01	56.99	7.98	0.27	0.88
BLMA45	89	4070	6.602604	0.548047	0	0	56.5	43.5	8.11	0.28	0.87

BLMA46	91	4140	6.853737	0.270176	0	0	53.51	46.49	8.03	0.31	0.85
BLMA47	93	4220	5.85262	0.687417	0	0	71.78	28.22	7.22	0.29	0.9

### 9.3. BLMB sediment composition data

Sample Name	mean depth	Age	Organic %	CO3 %	%Granules	%Sand	%Silt	%Clay	Mean	Skewness	Kurtosis
BLMB1	1	680	22.41992883	0.96797153	0	37.98	59.51	2.51	4.46	0.1	1
BLMB2	3	690	12.00923788	0.47113164	0	0	93.35	6.65	5.8	0.39	1.53
BLMB3	5	700	9.07063197	0.50557621	0	0	66.65	33.35	7.8	0.37	1.05
BLMB4	7	710	11.74055829	0.44663383	0	0	68.31	31.69	7.62	0.34	0.94
BLMB5	9	720	11.58707865	0.47752809	0	0	69.9	30.1	7.44	0.3	0.94
BLMB6	11	730	11.85667752	0.70879479	0	0.23	85.12	14.65	6.22	0.33	0.97
BLMB7	13	740	12.78140886	0.69135802	0	0	85.35	14.65	6.42	0.47	1.12
BLMB8	15	750	13.91585761	0.61618123	0	0	69.69	30.11	7.46	0.3	0.96
BLMB9	17	760	13.64829396	0.62467192	0	0	95.02	4.98	5.31	0.45	1.4
BLMB10	19	770	10.32578686	0.52567642	0	0	79.79	20.21	6.87	0.33	1.01
BLMB11	21	776	9.034907598	0.46543463	0	0.9	91.6	7.5	5.64	0.42	1.27
BLMB12	23	790	9.753160747	0.57314871	0	0	71.57	28.43	7.4	0.27	1
BLMB13	25	795	8.345323741	0.58705036	0	0.87	86.74	12.39	6.17	0.33	1.12
BLMB14	27	805	9.843606256	0.62557498	0	7.92	84.37	7.71	5.43	0.43	1.07
BLMB15	29	815	10.72410632	13.2135655	0	0	76.73	23.27	7.29	0.37	1.07
BLMB16	31	820	10.61528059	0.82758621	0	19.32	75.27	5.41	5.09	0.31	1.08
BLMB17	33	830	10.74540174	0.92158761	0	0	37.42	62.58	8.48	0.23	0.89
BLMB18	35	840	11.67597765	0.83575419	0	0	69.82	30.18	7.45	0.24	0.97
BLMB19	37	850	11.27744511	0.9500998	0	0	28.95	71.05	8.64	0.2	0.91
BLMB20	39	860	10.40358744	0.60986547	0	26.49	42.4	31.11	6.35	-0.38	0.76
BLMB21	41	870	7.644305772	0.63650546	0	0	44.6	55.4	7.02	-22	1.02
BLMB22	43	880	6.214689266	0.1920904	0	0	50.7	49.3	7.85	-0.13	1.06
BLMB23	45	890	8.2616179	0.46815835	0	0.03	63.81	36.16	7.14	-0.19	1.14
BLMB24	47	895	9.066666667	0.36266667	-	-	-	-	-	-	-
BLMB25	49	910	11.46496815	0	-	-	-	-	-	-	-
BLMB26	51	915	10.26392962	0.39882698	0	0	29.01	70.99	8.49	0.28	1.06
BLMB27	53	920	82.26324238	0.05457464	0	0	38.75	61.25	8.44	0.33	1.02
BLMB28	55	930	12.64367816	0.55829228	0	0	64.27	35.73	7.77	0.3	0.97
BLMB29	57	940	14.17050691	0.62672811	0	0	82.87	17.13	6.83	0.28	1.09
BLMB30	59	950	16.93950178	0.77437722	0	0	32.85	67.15	8.55	0.17	0.9
BLMB31	61	960	17.08683473	0.88888889	0	30.43	65.21	4.36	4.78	0.1	1.05
BLMB32	63	965	15.22346369	0.75977654	0	0	42.55	57.45	7.77	-0.04	1.16
BLMB33	65	975	13.95027624	0.56353591	0	0	86.64	13.36	6.49	0.25	1.13
BLMB34	67	985	14.58966565	0.68895643	0	0	88.34	11.66	6.29	0.2	1.12
BLMB35	69	995	15.34713764	0.66260658	0	0	84.16	15.84	6.7	0.23	1.06
BLMB36	71	1000	11.54219205	0.52764306	0	0	81.88	18.12	7.02	0.4	1.19
BLMB37	73	1010	10.98901099	2.61538462	0.29	59.32	39.42	1.26	3.66	-0.03	1.24
BLMB38	75	1025	11.23287671	2.60821918	0	53.53	44.74	1.73	3.89	0.01	1.28
BLMB39	77	1030	10.90909091	2.36969697	0.31	65.08	33.73	1.19	3.35	-0.07	1.13

BLMB40	79	1040	11.02292769	2.39858907	0	55.73	43.06	1.21	3.75	-0.04	1.22
BLMB41	81	1050	11.23363198	2.34321158	0.84	49.56	48.4	2.04	3.86	-0.12	1.32
BLMB42	83	1060	13.40996169	2.73563218	0	40.32	57.75	1.93	4.33	0.07	1.29
BLMB43	85	1070	14.53362256	2.65509761	0	46.71	52.14	1.15	4.13	0.02	1.43
BLMB44	87	1080	15.88486141	2.89978678	0	35.9	64.1	2.63	4.58	0.13	1.22
BLMB45	89	1090	10.13745704	2.10309278	0	41.19	56.05	2.76	4.28	-0.06	1.48
BLMB46	91	1100	7.489451477	1.79324895	0	40.9	53.24	5.86	5.02	0.24	1.08
BLMB47	93	1110	8.931698774	2.14360771	0.88	46.88	51.39	1.73	4.09	-0.08	1.5
BLMB48	95	1120	7.333333333	10.9706667	0.7	54.89	42.26	2.85	3.6	-0.07	1.05
BLMB49	97	1130	9.435364042	2.1218425	0	9.56	84.6	5.84	5.39	0.22	1.08
BLMB50	99	1140	10.10401189	2.15552254	1.42	53.68	43.19	1.71	3.74	-0.12	1.43
BLMB51	101	1155	16.80280047	3.38545313	1.47	36.84	58.38	3.31	4.4	-0.1	1.47
BLMB52	103	1170	15.62193928	3.52987267	0.18	43.17	54.68	1.97	4.19	-0.03	1.45
BLMB53	105	1180	12.60911736	2.90203686	0	45.44	52.72	1.84	4.2	0.13	1.17
BLMB54	107	1190	12.25510629	2.77782409	0	44.74	53.68	1.58	4.2	0.16	1.17
BLMB55	109	1200	9.948320413	0.87855297	0	51.37	47.75	3.62	4.07	0.06	1.05
BLMB56	111	1210	10.17811705	0.86513995	0	46.15	51.29	2.65	3.98	-0.09	1.05
BLMB57	113	1220	19.77715877	1.42061281	0.12	31.84	64.26	3.78	4.59	-0.09	1.35
BLMB58	115	1230	18.30177854	1.24842226	0	26.88	69.8	3.32	4.8	0.17	1.16
BLMB59	117	1240	18.30173124	1.23330585	0.93	65.04	61.88	2.23	4.44	-0.1	1.54
BLMB60	119	1250	24.32432432	1.38858859	0.07	33.43	62.58	3.92	4.68	-0.09	1.36
BLMB61	121	1260	38.59649123	1.34858886	0.08	35.2	61.14	3.58	4.7	0.06	1.11
BLMB62	123	1270	40.72632944	19.0505837	0	3.29	93.56	3.16	4.78	0.05	1.05
BLMB63	125	1280	36.77918425	1.33895921	0	44.23	53.4	2.37	4.32	0.06	1.21
BLMB64	127	1290	27.33260154	1.49286498	0	34.14	62.17	3.69	4.71	0.15	1.12
BLMB65	129	1300	33.8150289	1.49364162	0.71	43.56	52.53	3.91	4.13	0.14	1.13
BLMB66	131	1320	34.4182262	1.54922701	2.31	47.66	46.18	3.08	3.72	-0.14	1.15
BLMB67	133	1330	30.47272727	1.68145455	2.81	47.22	47.23	2.71	3.46	-0.2	0.82
BLMB68	135	1350	23.78716745	1.70266041	0.56	43.24	52.93	3.27	4.12	-0.13	1.19
BLMB69	137	1360	29.85957132	1.50776053	2.12	34.14	60.56	3.18	4.64	-0.1	1.4
BLMB70	139	1370	30.72983355	1.56722151	2.26	40.49	54.49	2.76	4.09	-0.22	1.31
BLMB71	141	1390	22.31491137	1.84358707	0	27	67.94	5.06	4.99	0.03	1.17
BLMB72	143	1400	22.01438849	1.85899281	0	27.66	67.03	5.31	4.92	-0.08	1.32
BLMB73	145	1420	18.44456122	1.35785602	0.15	31.76	64.03	4.06	4.72	0.02	1.3
BLMB74	147	1430	20.37292818	1.40883978	1.65	40.85	54.57	2.93	3.98	-0.2	1.23
BLMB75	149	1440	20.33036849	1.29606099	3.15	41.09	52.34	3.42	3.72	-0.26	1.26
BLMB76	151	1460	19.71496437	1.37292162	0	28.68	74.69	3.37	5.01	0.12	1.05

NB: There were insufficient sediments in BLMB24 and BLMB25

