Environmental history in southern Mozambique
Reconstruction of flooding events, hydroclimate and sea-level dynamics since mid-Holocene
Sandra Raúl Sitoe

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Abstract
The aim of this thesis has been to reconstruct paleoenvironment, paleohydrology and paleoclimate in coastal southern Mozambique, with emphasis on tracing past flooding events on the lower Limpopo River floodplain. In order to extend flood chronologies beyond periods covered by instrumental data, sediments from lakes on the floodplain were studied (Lake Lungué, Coasane Oxbow, Lake Magandane and Lake Soane). Past sea-level variations and climate changes were deduced by analyzing sediments from coastal sites north of the floodplain area (Lake Chilau, Lake Nhauhache and Macassa Bay). To achieve the established objectives, a multi-proxy approach was applied on most of the retrieved sediment cores, involving analysis of mineral magnetic parameters, grain-size and organic carbon in combination with analysis of microfossils such as diatoms and/or phytoliths. Chronologies for the constructed time-series analysis were obtained by radiocarbon dating and age-depth modelling. The synthesized data from the sampled sites on the Limpopo River floodplain suggest that the area was affected by at least 16 flooding events of variable magnitudes during the studied period. These are dated to c. AD 940, 980, 1040, 1100, 1250, 1300, 1370, 1580, 1665, 1730, 1755, 1855, 1920, 1945, 1970 and 2000. In calibrated years BP these ages correspond to 1010, 970, 910, 850, 700, 650, 580, 370, 285, 220, 195, 95, 30, and 5 cal yrs BP. The two youngest are dated to 20 and 50 years AP (After Present being 1950). Proxy data further suggest that southern Africa was subject to two periods of sea-level highstands, at c. 5000–4200 BC (6950–6150 cal yrs BP) and AD 300–950 (1650–1000 cal yrs BP). The former represents the middle part of the postglacial climatic optimum. The wettest period in the Limpopo River floodplain was reported between AD 1360 and 1560 (590 and 390 cal yrs BP) in the Lake Lungué record, while Lake Chilau experienced wet conditions between AD 1200 and 1400 (750 and 550 cal yrs BP), then returning to drier conditions that prevailed until c. AD 1600. In Lake Nhauhache, however, drier conditions prevailed from c. AD 1200–1700 (750–250 cal yrs BP), shifting towards wetter at c. AD 1900 (50 cal yrs BP). The deviating signals between records can partly be explained by Lake Lungué basin being located on the Limpopo River floodplain, responding to flooding events associated with precipitation upstream the drainage area. Therefore, wet and dry periods in floodplain lakes (e.g. Lake Lungué) are not expected to correlate with precipitation changes on a local scale, as indicated by e.g. Lake Nhauhache. This is supported by a relatively weak agreement between Lake Lungué record and other nearby records (outside the floodplain), but a better correlation with records from the upper catchment, where a more regional climate signal is provided of the southern African summer rainfall region.

Keywords: Southern Africa, Limpopo River floodplain, flooding event, sea-level change, climate change, diatoms, phytoliths, mineral magnetics, grain-size, radiocarbon dating.

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Department of Physical Geography
Stockholm University, 106 91 Stockholm
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Sandra Raúl Sitone
Por ti meu anjo
Siyabonga Paolla Mucavele
The aim of this thesis has been to reconstruct paleoenvironment, paleohydrology and paleoclimate in coastal southern Mozambique, with emphasis on tracing past flooding events on the lower Limpopo River floodplain. In order to extend flood chronologies beyond periods covered by instrumental data, sediments from lakes on the floodplain were studied (Lake Lungué, Coassane Oxbow, Lake Magandane and Lake Soane). Past sea-level variations and climate changes were deduced by analyzing sediments from coastal sites north of the floodplain area (Lake Chilau, Lake Nhauhache and Macassa Bay). To achieve the established objectives, a multi-proxy approach was applied on most of the retrieved sediment cores, involving analysis of mineral magnetic parameters, grain-size and organic carbon in combination with analysis of microfossils such as diatoms and/or phytoliths. Chronologies for the constructed time-series analysis were obtained by radiocarbon dating and age-depth modelling. The synthesized data from the sampled sites on the Limpopo River floodplain suggest that the area was affected by at least 16 flooding events of variable magnitudes during the studied period. These are dated to c. AD 940, 980, 1040, 1100, 1250, 1300, 1370, 1580, 1665, 1730, 1755, 1855, 1920, 1945, 1970 and 2000. In calibrated years BP these ages correspond to 1010, 970, 910, 850, 700, 650, 580, 370, 285, 220, 195, 95, 30, and 5 cal yrs BP. The two youngest are dated to 20 and 50 years AP (After Present being 1950). Proxy data further suggest that southern Africa was subject to two periods of sea-level highstands, at c. 5000–4200 BC (6950–6150 cal yrs BP) and AD 300–950 (1650–1000 cal yrs BP). The former represents the middle part of the postglacial climatic optimum. The wettest period in the Limpopo River floodplain was reported between AD 1360 and 1560 (590 and 390 cal yrs BP) in the Lake Lungué record, while Lake Chilau experienced wet conditions between AD 1200 and 1400 (750 and 550 cal yrs BP), then returning to drier conditions that prevailed until c. AD 1600. In Lake Nhauhache, however, drier conditions prevailed from c. AD 1200–1700 (750–250 cal yrs BP), shifting towards wetter at c. AD 1900 (50 cal yrs BP). The deviating signals between records can partly be explained by Lake Lungué basin being located on the Limpopo River floodplain, responding to flooding events associated with precipitation upstream the drainage area. Therefore, wet and dry periods in floodplain lakes (e.g. Lake Lungué) are not expected to correlate with precipitation changes on a local scale, as indicated by e.g. Lake Nhauhache. This is supported by a relatively weak agreement between Lake Lungué record and other nearby records (outside the floodplain), but a better correlation with records from the upper catchment, where a more regional climate signal is provided of the southern African summer rainfall region.

Keywords: Southern Africa, Limpopo River floodplain, flooding event, sea-level change, climate change, diatoms, phytoliths, mineral magnetics, grain-size, radiocarbon dating.
Sammanfattning


Analys av diatoméer har visats vara värdefulla när det gäller översvämningshistorik, klimatförändringar och havsytevariationer. Sedimenten i den något till flodslättens nedre lopp perifert belägna sjön Lungué indikerar fuktiga förhållanden mellan AD 1360 och 1560 (590 till 390 kal år BP). Kombinerade fytolit- och diatoméanalyser av sedimenten i sjön Chilau indikerar fuktiga förhållanden från AD 1200 till 1400 (750 till 550 kal år BP), varefter torrare förhållanden rådde till ca AD 1600 (350 kal år BP). Diatoméanalyser av sedimenten i sjön Nhauhache indikerar generellt sett torrare förhållanden mellan AD 1200 och AD 1700 (750 till 250 kal år BP) då klimatet blev fuktigare. De fuktiga och torra förhållanden som dokumenterats i sjön Lungué och översvämningshistoriken korrelerar inte helt med lokala nederbördscorrimalden. Däremot stämmer erhållna data bättre med förhållanden i den övre delen av Limpopoflodens dräneringsområde. Även sjöar och fyllda meanderbågar på själva flodslätten verkar reagera tydligare på översvämningar orsakade av nederbörd i den övre delen av flodloppet.

Resumo

O presente projecto teve como objectivo a reconstrução do paleoambiente, paleohidrologia e paleoclima da costa Sul de Moçambique, com ênfase na identificação de vestígios de eventos de cheias que tenham, no passado, afectado a planície de inundação do Rio Limpopo, com vista a fazer a extensão das datações de cheias para o período anterior aos instrumentos de medição. Deste modo, foram estudados sedimentos recuperados através de testemunhos de sondagem em lagos dentro da planície de inundação (Lago Magandane, Lago Languê, Lago Soane e o canal abandonado Coassane). As variações do nível do mar e mudanças climáticas do passado foram deduzidas a partir da análise de sedimentos de áreas costeiras a norte da planície de inundação (Lago Chilau, Lago Nhauhache e a Baía de Macassa). Para o alcance destes objectivos, os sedimentos dos testemunhos de sondagem recuperados foram submetidos a várias análises laboratoriais que incluem propriedades de minerais magnéticos, granulometria, teor de matéria orgânica e de microfósseis (diatomáceas e fitólitos). Para o estabelecimento do modelo cronológico foram usadas datações pelo método 14C feitas em matéria orgânica, assim como conchas de gastrópodes e bivalves.

A combinação dos resultados obtidos para os pontos de amostragem localizados dentro da planície de inundação do Rio Limpopo, sugerem que esta área foi afectada por um mínimo de 16 eventos de cheias de variada magnitude nos últimos 1100 anos. As cheias de alta magnitude tiveram lugar nos anos 1250, 1370, 1580, 1855, 1920, 1970 e 2000. Por seu turno, as cheias de magnitude moderada ocorreram nos anos 940, 980, 1040, 1100, 1300, 1665, 1730, 1755 e 1945. Os anos a negrito são indicativos de eventos de cheias de alta magnitude. O número total de eventos identificados no presente estudo é um mínimo que poderá ter afectado a planície de inundação, tendo em consideração que fontes escritas reportam a ocorrência de pelo menos oito eventos nos últimos 62 anos, tendo o presente estudo revelado somente dois. Isto indica que apenas eventos de cheias intensos podem ser revelados pelos métodos aplicados nesta investigação. Adicionalmente, este estudo mostra a necessidade de aumentar o número de pontos de amostragem para permitir a identificação de mais eventos de cheias ocorridos no passado, devido à diferenciada resposta sedimentológica e geomagnética às cheias, a qual se encontra directamente relacionada à distância do rio meandrante.

As análises de microfósseis de diatomáceas permitiram reconstruir o paleoclima e as influências do nível do mar nas áreas de estudo deste projecto. Os registos de diatomáceas do Lago Languê indicam um período húmido entre AD 1360 e 1560. No Lago Chilau, dados de diatomáceas e fitólitos sugerem condições de umidade entre AD 1200 e 1400. Por seu turno, no Lago Nhauhache, condições de seca dominam entre AD 1200 e 1700. As condições de seca e umidade documentadas no Lago Languê e os eventos de cheias revelados pelos sedimentos analisados da planície de inundação do Rio Limpopo não mostram total correlação com períodos de baixa e alta precipitação a nível local, mas apresentam boa correlação com evidências a montante na área de drenagem do Rio Limpopo. Em geral, lagos activos ou preenchidos por sedimentos mostrarão ser mais susceptíveis a cheias com origem a montante do que a nível local.

As investigações conduzidas permitiram identificar dois períodos de alto nível do mar na região sul de Moçambique. A fase mais antiga teve lugar há cerca de 5000–4200 BC (6950–6150 anos do calendário BP), representando a fase mais recente do pós-glacial climático óptimo (postglacial climatic optimum, PCA). A fase recente é datada de AD 300–950 (1650–1000 anos do calendário BP), correspondendo a um período de temperaturas relativamente altas a nível global.
Thesis content

The doctoral dissertation consists of a summary and five appended papers, listed below:


Author’s contributions

The contributions from the authors listed for each article, are divided as follows:

I. My contribution: I designed and conceived the study, led the fieldwork and performed laboratory analyses. I was the main responsible for producing diagrams and figures and led the discussions as well as the writing process.

Others contributions: JR participated in the fieldwork, supervised the methodology and sample collection, discussed the results and co-edited the paper. EN contributed to later version of illustrations, results discussion and final editing. KH contributed to the results discussions and paper writing. IS contributed to the interpretations of mineral magnetic proprieties and ratios, results discussions and the overall language edition of the paper. MA and JM joined the fieldwork and contributed to paper writing.

II. My contribution: I designed and conceived the study, led the fieldwork and performed diatom laboratory analyses. I was the main responsible for producing diagrams and figures and led the discussions as well as the writing process.

Others contributions: JR supervised the methodology, participated in the fieldwork, discussed and co-edited the paper. EN contributed to the paper writing and construction of the age-depth model. L-OW participated in the fieldwork and contributed to discussion of the results and the overall language.

III. My contribution: I joined and contributed to fieldwork planning. I discussed the results and contributed to diatom interpretation and to the writing, particularly of the diatom sections.

Others contributions: EN performed phytolith and diatom analyses, wrote the first version of the paper and was main responsible for the illustrations. HÖ contributed to the diatom analysis and interpretation. AE contributed to data interpretation. L-OW contributed to discussions and paper editing. JR participated in the fieldwork, discussed the results and co-edited the paper.

IV. My contribution: I joined and contributed to fieldwork planning. I discussed the results and contributed to diatom interpretation and to the writing, particularly of the diatom sections.

Others contributions: EN performed stable carbon and nitrogen isotope analysis, wrote the first version of the paper and main responsible for the illustrations. JR participated in the fieldwork, supervised the methodology and sample collection, discussed the results and co-edited the later versions of the paper. HG participated in the fieldwork, performed diatom and magnetic susceptibility and Saturation Isothermal Remanent Magnetism analysis. KH contributed to results discussion and edition of later versions of the paper. IS contributed to results discussion and paper writing. JAM participated in the fieldwork, contributed to results discussion and later versions of the paper edition.

V. My contribution: I joined and contributed to fieldwork planning. I discussed the results and contributed to writing of later versions of the paper.

Others contributions: KH wrote the first version of the paper and was the main responsible for the illustrations. JR participated in the fieldwork, supervised the methodology and sample collection, discussed the results and co-edited the later versions of the paper. JF participated in the fieldwork and performed diatom analysis. EN produced some of the illustrations and co-edited the later versions of the paper. MA, AE, EN contributed to results discussion and co-edited the later versions of the paper. JM participated in the fieldwork, and co-edited the later versions of the paper.
Abbreviations

°C Degrees Celsius
¹²C Isotope 12 of carbon
¹³C Isotope 13 of carbon
¹⁴C Isotope 14 of carbon
AD Anno Domini (after Christ)
AMS Accelerator Mass Spectrometer
AP After present (1950)
ARM Anhysteretic Remanent Magnetization
BC Before Christ
BCal On-line Bayesian calibration tool
BP Before present (1950)
DNA Direcção Nacional de Águas (National Directorate of Water)
DNG Direcção Nacional de Geologia (National Directorate of Geology)
ENSO El Niño southern oscillation
HCl Hydrochloric acid
HIRM Hard isothermal remanent magnetization (High field isothermal remanence)
INGC Instituto Nacional de Gestão de Calamidades (National Institute for Disaster Management)
IPCC Intergovernmental Panel for Climate Change
ITCZ Intertropical Convergence Zone
LM Lake Magandane
LIA Little Ice Age
LOI Loss on ignition
LS Lake Soane
m a.s.l. Meters above sea-level
MCA Medieval Climate Anomaly
mT Milli-tesla
OC Organic content
ShCal04 Southern hemisphere calibration curve 2004
ShCal13 Southern hemisphere calibration curve 2013
SIDA Swedish International Development Agency
SIRM Saturation isothermal remanent magnetization
SSAG Swedish Society for Anthropology and Geography
T Tesla
δ¹³C Stable carbon isotope
δ¹⁵N Stable nitrogen isotope
χ Magnetic susceptibility
Ωm Ohm meter
1 Introduction

The Intergovernmental Panel for Climate Change (IPCC, 2014) projects in its synthesis report that southern Africa is likely to face significant changes in the climate system in the future. The region is predicted to experience a shortage of the total number of annual rainy days, although the frequency and intensity of extreme events, such as floods, is expected to increase (Trambauer et al., 2015). The Limpopo River floodplain in southern Mozambique is frequently affected by flooding events, leading to losses of human lives, severe damage of infrastructure and failure of crop production (INGC et al., 2003). The Limpopo River basin has received attention from the scientific community during the last decades, since it comprises a unique ecosystem in southern Africa, with large areas dedicated to fauna and flora preservation within the Great Limpopo Transfrontier Park (e.g. Ekblom & Gillson, 2010; Bhatasara et al., 2013; Cook et al., 2015). Presently, the Limpopo River Basin is densely inhabited and large areas are being dedicated to agriculture, hydrologically maintained mainly by mechanical irrigation in the upstream areas and rain-fed in the floodplain area (INGC et al., 2003). People show preference to live on the floodplain in order to reside nearby their crop fields, disregarding the risk of flooding. Thus, an increased frequency of intense flooding events is likely to have high societal and economic impact on communities situated on the floodplain. Furthermore, as a natural reserve presumes limited amount of changes in order to maintain the current fauna and flora, the predicted change in precipitation patterns constitute a challenge to current ecosystem services (IPCC, 2014).

The Limpopo floodplain is particularly sensitive to flooding considering the morphological features of the southern Mozambican coast (Figure 1). The narrow outlet of the river into the Indian Ocean combined with Pleistocene and coastal dunes acting as barriers cause a damming effect. Owing to these effects, a backward movement of river water is intensifying the impact of floods on communities and agricultural land on the floodplain. An example of such a scenario was observed during the AD 2000 (50 cal yrs AP) flooding event, when the Chilaulene Locality, situated on top of the dunes c. 10 km from the Limpopo River mouth, was completely isolated by flood waters (Spaliviero et al., 2014).

As there is a strong linkage between flooding and rainfall dynamics, an improved predictability of flooding events is dependent on in-depth knowledge of past climate variability. This can eventually aid the tuning of climate prediction models and lead to more accurate predictions of future hydro-climate conditions. Significant advances have been made in southern African paleoclimate and environmental research during the last decade. Available Holocene archives from south-eastern Africa cover a wide range of proxy records and provide paleo-data for several environmental parameters, including past precipitation patterns and temperatures (e.g. Nicholson & Kim, 1997; Sundqvist et al., 2013; Woodborne et al., 2015; 2016; Fitchett et al., 2017), flooding history (e.g. Pereira & Gonçalves, 2004; Spaliviero et al., 2014; Ekblom & Gillson 2017), sea-level changes (e.g. Strachan et al., 2014), past vegetation dynamics (e.g. Lotsch et al., 2003; Scott et al., 2012; Ekblom et al., 2012; McWethy et al., 2016; Scott, 2017), and anthropogenic influences on the environment (e.g. Hannaford & Nash, 2016 and references therein). From previous and recent climate research, a picture of Holocene climate variability in south-eastern Africa is emerging, although the underlying mechanisms are not always clear (Nash et al., 2016 and references therein; Burrough & Thomas, 2013 and references therein). Paleo-studies from Lesotho indicate that the early Holocene (c. 8050–5050 BC/10000–7000 cal yrs BP) was generally warm (Marker, 1994; Smith et al., 2002) and wet (Marker, 1994; Grab et al., 2005), which is supported by pollen records from lower lying areas along the Drakensberg escarpment in eastern Free State (Norström et al., 2014).
and in southwestern KwaZulu-Natal, South Africa (Neumann et al., 2014). The 8.2 ka cold event reported in northern hemisphere records at c. 6250 BC (8200 cal yrs BP; Thomas et al., 2007; Borzenkova et al. 2016), seems to have had an imprint also on the southern African climate (Smith et al., 2002; Grab et al., 2005). Indications of mid-Holocene climate (5050–50 BC/7000–2000 cal yrs BP) in southern Africa vary between sites; some report that it was warm and wet (Kutzbach et al., 1996; Lee-Thorp et al., 2001; Gil-Romera et al., 2006), while others suggest warm and dry conditions (Marker, 1994; Neumann et al., 2014; Norström et al., 2014). Indications of late Holocene climate (50 BC–present; 2000 cal yrs BP–present) are to some extent variable between available records. The consistency of the observations of the Medieval Climate Anomaly (MCA, c. AD 900–1300) in southern African records is debated, and the timing, and sometimes proxy-signals, varies between records. However, most of the available studies report a MCA characterized by warm and wet conditions, e.g. the pollen and diatom record from Lake Nhaucati in Mozambique (Ekblom & Stabell, 2008), tree ring isotope records from Mapungubwe and Pafuri, South Africa (Woodborne et al., 2015; 2016), pollen records from lower Limpopo Valley (Ekblom et al., 2012), a diatom record from Lake Sibaya in South Africa (Stager et al., 2013), and multi-proxy records from various sites in southern Africa (Tyson & Lindesay, 1992). Some studies report a more variable MCA climate (Kirsten & Meadows, 2016; Nash et al., 2016). The tentatively warm and wet conditions recorded during the MCA were interrupted by a period of cooler and drier conditions, named after the Northern Hemisphere Little Ice Age (LIA, c. AD 1400–1800). This phase is recorded at several sites in southern Africa, e.g. speleothem isotope records from Makapansgat Valley in South Africa (Sundqvist et al., 2013), microfossils in Lake Nhaucati in Mozambique (Ekblom & Stabell, 2008) and in Lake Sibaya in South Africa (Neumann et al., 2008; Stager et al., 2013).

Although our understanding of past climate variability in south-eastern Africa is progressing, the underlying mechanisms remain relatively unclear, mainly owing to sparse geographical coverage, discontinuity within sediment records and sometimes contradictory proxy signals between records and sites. In addition, dating uncertainties within individual records impede accurate inter-site and inter-regional comparisons. In order to improve knowledge on climate variability and thereby indirectly validate current models for future climate projection, a denser spatial coverage of well-dated, continuous paleoenvironmental records is required.

In low-lying coastal areas, climate and environmental conditions are affected by the sea, both on short-term (e.g. tidal effects) and long-term basis (e.g. sea-level change). Thus, in order to fully understand past climate processes, it is important to consider the long-term effects of particularly sea-level change on the environment. The Holocene sea-level variations along the southern African coastline are still relatively unclear owing to scarcity of data. However, available studies from some sites in South Africa and Mozambique indicate higher sea-levels than today at c. 4500 BC (6450 BP), 2500 BC (4450 BP) (Ramsay, 1995; Compton, 2001), 500 BC (2450 BP) (Compton, 2001) and AD 700 (1250 BP) (Compton, 2001; Strachan et al., 2014). In east Africa, however, information on sea-level changes are still a challenge to reveal (Woodroffe et al., 2015 a, b), although a study from the Rufiji Delta in Tanzania identified possible highstands at c. 3650 BC (1700 cal yrs BP) and 2700 BC (750 cal yrs BP) (Punwong et al., 2013).

The main purpose of this PhD thesis is to contribute to the understanding of paleoenvironment in southern Mozambique. Focus is given to the understanding of flooding events and their frequency, and the impact of climate and sea-level changes on the Limpopo River floodplain and beyond. The PhD project is part of the bilateral programme Environment and Climate Research, funded by Swedish International Development Agency (SIDA), and implemented in cooperation between the Department of Geology, Faculty of Sciences, Eduardo Mondlane University in Mozambique and the Department of Physical Geography, Faculty of Sciences, Stockholm University in Sweden.
1.1 Scope and objectives

The overall aim with this project is to improve the understanding of past environmental variability in southern coastal Mozambique, with emphasis on the Limpopo River floodplain. The specific objectives are to:

- Provide chronologies of flooding events in the Limpopo River floodplain, stretching beyond the instrumental records;
- Evaluate the applicability of selected methods for recording paleo-flooding events in the Limpopo River floodplain;
- Contribute to the understanding of middle- to late Holocene paleoclimatic variability and past hydrological changes in southern Mozambique;
- Contribute to the understanding of sea-level changes along the southern Mozambican coastline, and their tentative impacts on the Limpopo River floodplain;
- Investigate linkages between local environmental change observed within the floodplain area and more region-wide changes observed at other sites in southeastern Africa.

The methodological approach within the project, i.e. the parallel study of flooding events, climate dynamics, lake-hydrology and sea-level change, is an attempt to lead way for a process-orientated understanding of how paleoenvironments affected southern coastal Mozambique in the past, with emphasis on the Limpopo River floodplain area during late Holocene period.

Throughout the text, the following boundaries for the Holocene epoch are used: early to middle Holocene boundary at 8200 cal yrs BP and middle to late Holocene boundary at 4200 cal yrs BP (Walker et al., 2014).
2 Study areas

The present PhD thesis contains studies performed on sediment from sites located along the southern Mozambique coastal stretch, namely Lake Nhauhache, Macassa Bay, Lake Chilau, the Coassane Oxbow, Lake Lungué, Lake Magandane and Lake Soane (Figure 1). The latter four are located on the Limpopo River floodplain, while the other three are located within 300 km to the north-northeast. The large scale landforms along this stretch comprise sediments being brought by longshore currents from the south (Sætre & de Paula e Silva, 1979; Salma & Abdula, 1995; DNG & Consórcio GTK, 2006a-d). The coastal zone is characterized by consolidated internal dunes of Pliocene–Pleistocene age (Spaliviero et al., 2014), active and inactive coastal dunes of Holocene age, and beach deposits. The inland zone, which includes the Limpopo River floodplain, is made up by fluvial terraces and fluvial-lacustrine clayey deposits. Several interdunal lakes are present along the stretch between Xai-Xai and Vilankulos. These lakes are generally forming elongated shapes in the area northeast of Xai-Xai, and rounded shapes around Vilankulos.

The study areas belong to the summer rainfall zone and the precipitation pattern is largely controlled by the movement of the Intertropical Convergence Zone (ITCZ) (Tyson & Preston-Whyte, 2004). ITCZ brings warm and moist conditions into these areas between October and April when the majority of the precipitation falls. The northern study areas experience slightly longer rainy seasons than the southern. El Niño and its antithesis La Niña, controlled by the Walker circulation, represent the warm and cold stages of the El Niño Southern Oscillation (ENSO) cycles, which explain the interannual variability of precipitation that falls in the region (Richard et al., 2000; Tyson & Preston-Whyte, 2004, Li et al., 2013). In southern Africa, El Niño is commonly associated with dry conditions, while La Niña normally brings wet conditions (Nicholson & Kim, 1997; Hoell & Cheng, 2017). This pattern, however, seems to have varied over time, since a recent study of rainfall variations in South Africa based on tree rings displayed stronger correlation between El Niño conditions and higher rainfall for the periods AD 1301–1550 (649–400 cal yrs BP) and AD 1710–1970 (240 cal yrs BP – 20 cal yrs AP) (Woodborne et al., 2015). From AD 1970 (20 cal yrs AP), the record revealed correlation between higher rainfall and La Niña events.

2.1 Limpopo River floodplain (Paper I-II)

The Limpopo River basin is located in southern Mozambique and is one of the large transboundary river basins in southern Africa (Figure 1). It is shared by Botswana, South Africa, Zimbabwe and Mozambique. Upstream, the river flows over igneous and metamorphic rocks (Brandl, 2001). Before reaching the floodplain area, however, the river flows over Paleogene and Neogene sedimentary rocks, including arkosic sandstone from the Mazamba formation and limestone from the Mapai formation (DNG & Consórcio GTK, 2006e). The lower Limpopo floodplain is located in the Mozambican territory, stretching c. 100 km inland from the river mouth. The floodplain is delimited by a Pliocene–Pleistocene dune system to the east-northeast and west-southwest, and by Holocene dunes along the coast to the south (Figure 1). These Pliocene–Holocene dunes influence the outflow of the river, forming a narrow gap through which the river drains into the sea, thereby also affecting the upstream flow during high precipitation events. The floodplain sediments are mainly composed of alluvium, but also of sand and gravel in fluvial terraces (DNG & Consórcio GTK, 2006a, c). Five sites were investigated on the floodplain, two have been published, i.e. the Coassane Oxbow (Paper I, Figure 2) and
Lake Lungué (Paper II, Figure 3). In addition, two former meander bows from the Limpopo River, Lake Magandane and Lake Soane, were stratigraphically investigated and sampled (chapter 4.2). Presently, these lakes are shallow and partly overgrown by reeds. In order to retrieve information about deeper stratigraphic units, a resistivity profile was assembled in the southern part of the floodplain (Figure 1). A coring was performed at the central point of this profile.

Figure 2. Part of the Coassane Oxbow and enlarged view of the sediment in the pit. Note the light layer indicating higher proportion of clastic material accumulated during a flooding event. Photo: S.R. Sitoe, 2007.

Figure 3. View from east to west of Lake Lungué with the Limpopo River floodplain in the background. Photo: L.O. Westerberg, 2012.

According to INGC et al. (2003), oral sources and recent observations, the Limpopo floodplain has been affected by at least 10 flooding events, of varying magnitude and impact, since instrumental measurements started around AD 1950. The nature of flood-
ing events is normally associated with strong influences from La Niña on the southern African rainfall and shows positive correlation with periods of high rainfall in the region (Kruger, 1999; Nicholson & Selato, 2000). Tropical cyclone activities may exacerbate the impacts of flooding events, as was the case during the flooding in AD 2000 (Dyson & van Heerden, 2001; Reason & Keibel, 2004). This flooding, which co-occurred with the tropical cyclone Eline, was the most severe since instrumental measurements started and it was characterized by both direct rains on the floodplain and water flow from upstream areas (Reason & Keibel, 2004). Examples of the impact of flooding events in the floodplain are shown in Figure 4, for areas around Chokwé during the AD 2013 flood.

Figure 4. The red arrow on the house in Chokwé indicates the level of flooding water in 2013 and in enlarged view of cracks formed inside the house after the flooding event. Photo: S.R. Sitoe, 2013.

2.2 Lake Chilau (Paper III)

Lake Chilau is located in Inhambane Province, c. 25 km SW from the Homoine Municipality, (23°57'52''S, 34°56'55''W) (Figure 1). The lake is situated in the southern part of the drainage system of the Nhalihave River; in-between dune formations of Pleistocene age (DNG & Consórcio GTK, 2006b). In addition, alluvial clayey sand is present in the Nhalihave River floodplain. The vegetation in the area is characterized by woodland and savanna (Figure 5). According to the National Population Census performed in 2005, the municipality of Homoine was inhabited by approximately 110,000 people with a majority dedicated to agriculture.
Macassa Bay (Figure 6) is located in Inhambane Province c. 25 km south from Vilanculos municipality (22°13′53.47″ S, 35°19′30.20″ E). The bay is delimited by active spit formation on its eastern side and Pleistocene dunes to the west. To the south the bay is delimited by alluvial sand, silt and clay. The northern part of the bay is open towards the Indian Ocean. The sediment within the bay consists of alluvial mud of fluvial and marine origin (DN&G & Consórcio GTK, 2006c). Presently, the bay constitutes a filled-in saline wetland in permanent contact with the sea, warranted by a tidal range of 4 m and a spring tide of 4.4 m. The bay, and adjacent mangrove forests, is currently affected by the sea via small water courses (Figure 6). Nearby the sampling site there is an artisanal brick factory, with clay as the main feedstock being extracted from the bay. The livelihood of the neighboring communities is normally dependent on agricultural activities.
2.4 Lake Nhauhache (Paper V)

Lake Nhauhache is located c. 3 km northwest from Vilankulos Municipality in Inhambane Province (21°58′50″ S, 35°17′39″E). This area is characterized by abundant lakes, established on top of Pleistocene dunes from the internal dune formation (DNG & Consórcio GTK, 2006d). Most of these lakes show poor nutrient contents, with almost no vegetation growing nearby or in the water surface. However, Lake Nhauhache displays a different pattern, with the surroundings being cultivated and with scattered plants in the water (Figure 7). Typical vegetation in this area is Miombo savanna (Meadows, 1999). The lake has no visible outlet, why it is assumed that the water surface represents the groundwater level.

Figure 7. The surface of Lake Nhauhache is directly related to the groundwater table. Therefore, lake level variations mirror changes in precipitation and evaporation. Photo: S.R. Sitoe, 2009.

2.5 Geological evolution of Limpopo River basin

The Limpopo River basin has been subject to significant geomorphological changes, traced at least back to the Permo–Carboniferous (Förster, 1975; Moore & Blenkinsop, 2002; Goudie, 2005; Spaliviero et al. 2014). These changes were mainly associated with tectonic activities linked to the breakup of the Gondwana supercontinent, e.g. rifting, mantle plume activity, intrusions and volcanism. The drainage system in southern Africa, including the Limpopo River basin, was rearranged owing to mantle plume activity associated with the opening of the Indian and Atlantic Oceans (Moore & Blenkinsop, 2002). Originally flowing westwards because of the uplift of the Karoo dome, Limpopo River reversed to an eastward flow as the Paraná mantle plume emerged in the early Cretaceous (Moore & Blenkinsop, 2002), probably entering the Mozambique coastal plain by following the corridor formed by the Botswana dyke swarm (Moore et al., 2007). At that time the Limpopo River also contained the catchments of Okavango, upper Zambezi and Cuando rivers (Moore, 1999; Moore & Larkin, 2001), and constituted the largest river in southern Africa (du Toit, 1933; Spaliviero et al. 2014). Owing to uplift of the Okavango-Kalahari-Zimbabwe Axis in the late Paleogene, the contact between Limpopo and Okavango/upper Zambezi/Cuando was severed (Salman & Abdula, 1995; Moore, 1999). Although currently disconnected, the former floodplain of this huge drainage system
constitutes an area that is prone to recurrent flooding in case on heavy or persistent rain (Spaliviero et al., 2014).

The Limpopo River floodplain contains sediment of Cretaceous, Paleogene, Neogene and Pleistocene age (du Toit, 1933). Huge amounts of sediment, resulting from the disruption of the Gondwana supercontinent, were transported by the river (Moore & Larkin, 2001), and contributed to the formation of the great sedimentary basins at the Mozambican plain next to the Save and Limpopo rivers. Parts of the sediment transported by Limpopo River were deposited in the form of a megafan or paleodelta (Figure 8) of Jurassic–Cretaceous age (Burke & Gunnel, 2008). The distal end of the paleodelta is today found some 80 km inland from the present mouth of the river. The delta front is marked by the watercourse of Changane River, a tributary that merge with Limpopo River close to Chibuto (Figure 8). Its path, following the delta front, is likely determined by the later formation of a series of Pliocene–Pleistocene coastal dunes (referred to as “marine terraces” by Spaliviero et al., 2014) of successively younger age shorewards, that today characterize the area east-northeast of Xai-Xai (Figure 8).

During the late Holocene, formation of coastal dunes has continued, and has contributed to the build-up of the barrier at the Limpopo outlet. When the records presented in this thesis were accumulated there were no evidences of tectonic movements in the Limpopo River floodplain (Vail, 1968; Chorowitz, 2005) and earthquakes are not commonly observed in the area (Fenton & Bommer, 2006; Raucoules et al., 2010). It is therefore assumed that the area investigated in this thesis has been relatively stable tectonically during the period of interest.

Figure 8. Map showing the Limpopo River paleodelta (adapted from Spaliviero et al., 2014).
3 Material and methods

To meet the above defined objectives, the following methods were applied: stratigraphical investigations, geophysical surveys, analysis of siliceous microfossils (diatoms and phytoliths), mineral magnetic parameters and ratios, radiocarbon dating, and analysis of grain-size, organic carbon and stable carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N) isotopes (Table 1).

### Table 1. Summary of the methods applied for papers and additional data.

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<td>x</td>
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<td>x</td>
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<td>Phytoliths</td>
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<td>x**</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Mineral magnetic ratios</td>
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<tr>
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<td>Organic carbon</td>
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<tr>
<td>Stable isotopes ($\delta^{13}$C, $\delta^{15}$N)</td>
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<td>x</td>
</tr>
</tbody>
</table>

*type identification **counting

3.1 Fieldwork (Paper I-V) and geophysical survey

Fieldwork campaigns were carried out between December 2006 and February 2016 in the Limpopo River floodplain in order to improve the knowledge about sediment types and to locate suitable places to collect representative sediment cores. During the first campaign, the potential of Limpopo River floodplain sediments to record flooding events was evaluated by studying present geomorphological features. It was concluded that the floodplain was appropriate to retrieve past flooding history and other environmental changes.

In the subsequent campaigns, local geomorphology was explored in order to identify suitable places for collecting longer sediment sequences. Furthermore, local inhabitants were interviewed regarding geographic distributions, flooding intensities and frequencies. In total, five sites were collected for detailed lithologic description in the field and in the laboratory (Table 2). These sites included both open and filled-in lakes on the Limpopo River floodplain. In the later fieldwork campaigns focus was given to open lakes located on the floodplain and/or lakes with temporary connection to the river during flooding events.

Sediment has been collected using a 1.2 m long gouge auger with an inner diameter of 60 mm and a piston corer with a length of 75 cm and an inner diameter of 50 mm, above and below the groundwater table, respectively (site 1). Open lakes and wetlands were sampled using a Multi-sampler (manufactured by Eijkelkamp) and a Russian coring device (sites 2–4, Table 2). The deep drilling at site 5 was carried out with the purpose to validate a geophysical model (described below). A percussion drilling equipment was used at the center point of the profile to validate the model (Figure 9). The equipment has a 1.5 meters recovering tube with a diameter of 60 mm. The equipment does not allow
the preservation of contiguous segments of sediment, and the sampled material was therefore used only for macroscopic descriptions.

Table 2. Location and length of sediment cores collected from the Limpopo River floodplain. The core lengths are based on depth from the sediment surface. Coring sites numbers can be found in Figure 1.

<table>
<thead>
<tr>
<th>Coring site</th>
<th>Core length (cm)</th>
<th>Latitude (south)</th>
<th>Longitude (east)</th>
<th>Type of analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Coassane Oxbow)</td>
<td>448</td>
<td>24°53’28.5”</td>
<td>33°38’28.2”</td>
<td>GS, OC, MMP, RD, DT, WC, (Paper I, Sitoe et al., 2015)</td>
</tr>
<tr>
<td>2 (Lake Magandane)</td>
<td>320</td>
<td>24°47’12.8”</td>
<td>33°37’09.2”</td>
<td>MMP, WC, OC, DT, RD</td>
</tr>
<tr>
<td>3 (Lake Soane)</td>
<td>379</td>
<td>24°54’28.3”</td>
<td>33°40’51.2”</td>
<td>MMP, WC, OC, on-going DT, RD</td>
</tr>
<tr>
<td>4 (Lake Lungué)</td>
<td>299</td>
<td>24°45’43.2”</td>
<td>33°38’08.9”</td>
<td>MMP, OC, DT, RD (Paper II, Sitoe et al., 2017)</td>
</tr>
<tr>
<td>5 (deep core)</td>
<td>5100</td>
<td>25°05’34.9”</td>
<td>33°34’38.8”</td>
<td>-</td>
</tr>
</tbody>
</table>

The type of analyses performed is shown by the following abbreviations: DT: diatoms, GS: grain-size, MMP: mineral magnetic parameters, OC: organic carbon, RD: radiocarbon dating and WC: water content.

In order to construct a model for sediment accumulation on the floodplain, a geophysical survey was conducted at site 5 (Figure 1) in September 2013, using an ABEM Terrameter System. This equipment determines the resistivity of layers reaching 75 m depth. Below this depth the accuracy is significantly reduced. Based on the resistivity it is possible to determine the density of each unit, which reflects the type of sediment. A section of c. 2500 m length in approximately E-W direction was surveyed at Chilaulene (Figure 1). Resistivity gauge points were separated by c. 100 m and the average elevation was 4
m a.s.l. The measurements were performed in 27 points located along a profile between 25°05’50.4”S, 33°33’55.6”E and 25°05’21.9”S, 33°35’22.8”E.

During a survey in the Vilankulos area, aiming to retrieve past environmental history, various lakes and a bay were visited in order to identify suitable sites to collect samples. Lake Nhauhache and Macassa Bay were selected owing to their geomorphic and sediment characteristics. Furthermore, Lake Nhauhache was selected since the water level is directly dependent of precipitation over time. The lake was first subject to a bathymetry survey using a hand-held echo-sounder, and a sediment core was then collected from the deepest part of the Lake. In Macassa Bay, six cores were sampled along a profile perpendicular to the present coastline, with the aim to investigate the stratigraphy. A 3 m long core was selected from the eastern end of the profile for laboratory analyses. Both Lake Nhauhache and Macassa Bay were sampled using a Russian corer (1 m long, 45 mm diameter). Lake Chilau was selected for sampling after a survey performed in several lakes located in the Homoine Municipality. The lake was sampled using a Russian coring device from a wood-based platform (Figure 5). The macroscopic stratigraphy description was performed in the field. The location of the three sites, including core lengths and analyses performed are indicated in Table 3.

Table 3. Location and length of the various sediment cores collected northeast of the Limpopo River flood-plain.

<table>
<thead>
<tr>
<th>Coring site</th>
<th>Core length (cm)</th>
<th>Latitude (south)</th>
<th>Longitude (east)</th>
<th>Type of analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Nhauhache</td>
<td>230</td>
<td>21°58’49.65”</td>
<td>35°17’37.80”</td>
<td>RD, SM</td>
</tr>
<tr>
<td>Macassa Bay</td>
<td>300</td>
<td>22°13’53.47”</td>
<td>35°19’33.20”</td>
<td>RD, SM, MMP, SI</td>
</tr>
<tr>
<td>Lake Chilau</td>
<td>88</td>
<td>23°57’52.45”</td>
<td>34°56’53.86”</td>
<td>RD, SM, OC, IC, MMP</td>
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</tbody>
</table>

The type of analyses performed is shown by the following abbreviations: GS: grain-size, IC: Inorganic carbon, MMP: mineral magnetic parameters, OC: organic carbon, RD: radiocarbon dating, SI: stable isotope, SM: siliceous microfossils and WC: water content.

3.2 Chronology (Paper I-V)

The radiocarbon dating technique is the most commonly used method for dating events occurring during the late Quaternary period, and constitutes support for many stratigraphical studies. It was developed by Willard Libby and his colleagues in 1949 (Arnold & Libby, 1949). The development of Accelerator Mass Spectrometer (AMS) technique by Bennett et al. (1977) and Nelson et al. (1977) allowed the dating of smaller samples, containing less than a milligram of carbon. The radiocarbon technique is applied to date all material that contain organic carbon and allows the determination of the ratio of \(^{14}\text{C}\) in relation to the stable isotopes of carbon (\(^{12}\text{C}\) or \(^{13}\text{C}\)) and the age is calculated by comparing this ratio with a known standard for the long-lived \(^{14}\text{C}\) concentration. The limit of measurement of the \(^{14}\text{C}\) activity is eight to ten half-lives, which gives a limit of measurement back in time to 50,000 years. Owing to long-term variability in the production of \(^{14}\text{C}\), the ages obtained from the AMS need to be calibrated (e.g. Stuiver & Reimer, 1993). The \(^{14}\text{C}\) calibration curve is based on high resolution tree-ring data, which were extended using data from laminated sediments and tropical corals, stretching back to 26,000 years BP (Bard et al., 2004). The \(^{14}\text{C}\) calibration curve was recently extended to cover the last 52,800 years BP (Bronk Ramsey et al., 2012).

A total number of 65 samples were submitted for AMS \(^{14}\text{C}\) dating to the Ångström Laboratory in Sweden and to the Poznan Radiocarbon Laboratory in Poland. These included bulk sediment, plant macrofossils, shells, and pieces of wood (Table 4). The shells dated in the Coassane Oxbow, Lake Lungué, Lake Magandane, Limpopo River floodplain surface and Lake Soane were found both as fragments and as complete frustules.
Since this project has been running over a 10-year period, a number of techniques and software were applied for calibration of individual dates as well as age-depth model construction (Table 4), such as Oxcal 4.2.3 (Bronk Ramsey & Lee, 2013), BCal on-line Bayesian calibration tool (Buck et al., 1999), Clam 2.2 (Blaauw, 2010) and Bacon (Blaauw & Christen, 2011). Southern hemisphere calibration curves were applied; initially the ShCal04 curve (McCormac et al., 2004) and in the more recent papers the ShCal13 curve (Hogg et al., 2013). Samples displaying modern ages (pmC) were calibrated using the bomb radiocarbon curve (Hua et al., 2013).

Table 4. Type of dated material and total number of dated samples for each studied area. For references see text. A manual age-depth model is not based on computerized calculations but on drawings by hand.

<table>
<thead>
<tr>
<th>Study area</th>
<th>Dated material</th>
<th>Southern hemisphere calibration curve</th>
<th>Calibration software</th>
<th>Age-depth model</th>
</tr>
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<td>Shell</td>
<td>Wood</td>
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<td>6</td>
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<td>Oxbow (Paper I)</td>
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<td>surface (Paper I)</td>
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<tr>
<td>Lake Langué</td>
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<td>(Paper II)</td>
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<tr>
<td>Lake Chilau</td>
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<td>12</td>
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<td>(Paper III)</td>
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<td>(Paper IV)</td>
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<tr>
<td>Lake Magandane</td>
<td>7</td>
<td>7</td>
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<td>7</td>
</tr>
<tr>
<td>Lake Soane</td>
<td>6</td>
<td>1</td>
<td>7</td>
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</table>

* ShCal04 = Southern Hemisphere Calibration Curve 2004
** ShCal13 = Southern Hemisphere Calibration Curve 2013
3.3 Siliceous microfossils (Paper I-V)

Diatoms are unicellular algae surrounded by two valves with cell sizes varying between c. 2 μm and c. 2 mm (Krammer & Lange-Bertalot, 1986; Öberg et al., 2009). Identification to species level is granted by their shape and ornamentation. Diatoms are cosmopolitans growing in a variety of aqueous environments, ranging from strict planktonic preferences to growth attached to plants or different types of sediment, i.e. benthic. In the geological history they were observed from the late Cretaceous onwards (Davies & Kemp, 2015).

The history of diatom research began in the late 18th century; however, major developments took place during the 19th century with the improvements of microscopes. Baker (in 1753), Bory (in 1822), and Ehrenberg (in 1838; cf. Round et al., 1990) were some of the earliest researchers to observe diatoms under microscopes. The work performed during the 19th century was more focused on the description of diatom physiology, life cycles and their spatial and yearly distribution. During the beginning of the 19th century diatoms were classified as part of the animal kingdom. These ideas prevailed until 1844, when Kützing published a monograph where he described diatoms as plants; either unicellular or colonial and motile or non-motile (Kützing, 1844). In the first part of the 20th century research was focused on the systematization of various ecological parameters. In the later part of the 20th century diatoms have become more used as environmental and climate proxies. The use of scanning electron microscopes has allowed detailed descriptions of frustule ornamentation (e.g. Miller, 1969; Ktraktsiotis et al., 2015). This has increased the number of genera and species; *Fragilaria* has, for instance, been split into several new genera, e.g. *Staurosira*, *Staurosirella* (e.g. Williams & Round, 1987; Morales et al., 2013).

Diatoms may be used as indicators of various environmental and climatic parameters such as temperatures (e.g. Barron, 1973; Koizumi, 1994; Rioual et al., 2007), pH (e.g. Birks et al., 1990), light conditions (e.g. Jones et al., 2014), ice cover (e.g. Gersonde et al., 2003; Weckström et al., 2014), turbulence (e.g solot et al., 2016), nutrients (e.g. Dalu et al., 2016), moisture conditions (e.g. Pfister et al., 2015; Fitchett et al., 2017), sea-level variations (e.g. Ybert et al., 2003; Lamb et al., 2006; França et al., 2016), wet/dry periods in lakes (e.g. Gasse et al., 1997; Barker et al., 2000; Stone & Fritz, 2004; Ekblom & Stabell; 2008), salinity variations (e.g. Roberts et al., 2004), and pollution in lakes and rivers (e.g. Wu, 2012). In the present thesis, diatoms are used as indicators of changes in water sources, water level fluctuations in lakes and sea-level changes.

Analyses of siliceous microfossils, i.e. diatoms and phytoliths, were performed on samples from the Coassane Oxbow (Paper I), Lake Lungué (Paper II), Lake Chilau (Paper III), Macassa Bay (Paper IV) and Lake Nhauhache (Paper V). In addition, diatom data from Lake Magandane and Lake Soane, located on in the Limpopo River floodplain, is included. Extraction of siliceous microfossils followed the procedures compiled by Battarbee (1986). Carbonates were removed by reaction with 10% HCl, while organic matter was oxidized with 17% H₂O₂ and boiling over a water bath (100°C). Clay particles were removed by decanting from 100 ml beakers. This process was repeated in two hour intervals after refilling the beakers with distilled water allowing silt and sand sized particles to settle. Decanting continued until the samples was clean, i.e. the silt and sand fraction was accumulated at the bottom of the beakers. Coarser particles were removed after 5 s of sedimentation. The residue was mounted on a slide using Naphrax® and counting was performed under a light microscope with ×1000 magnification using immersion oil. For analyses of phytoliths residues were mounted in a liquid medium (water and/or Entella) to allow rotation for identification of different morphotypes.

Diatom species identification were mainly based on Cholnoky (1957), Giffen (1963; 1966a, b; 1970; 1971; 1973; 1975; 1976), Foged (1975), Gasse (1986), Krammer & Lange-Bertalot (1986, 1988, 1991a, b), Round et al. (1990) and Round & Basson (1997). The minimum number of diatoms counted per sample varies, mainly because of diatom availability. For Lake Lungué (Paper II) and Lake Nhauhache (Paper V) a basic sum of
at least 500 was considered, while in Lake Chilau (Paper III) the aim was to count at least 300 frustules. In Macassa Bay (Paper IV), the basic sums were variable owing to sparse diatom occurrence. In the Coassane Oxbow (Paper I), however, the occurrences of diatoms were scarce, constraining the basic sum to 100, although it was not possible to reach this number in all levels. The varying observations of diatoms can be attributed to taphonomic processes, i.e. physical and chemical factors influencing the frustules after death and deposition (Ryves et al., 2006, Christiansson, 2016). The results from the siliceous microfossil analyses are presented using Tilia (Grimm, 1993) and TG-view (Grimm, 2004). Zonation was established according to CONISS calculations (Grimm, 1987) and eye matching.

Phytoliths are microscopic opal and siliceous particles formed by plants by taking up dissolved silica from the soil water. These particles are deposited in and between the plant cells as amorphous silica (Madella et al., 2005; Piperno, 2006). Some of the particles are deposited in the sediment after the plant is dead and decayed. Owing to their minerogenic character, phytoliths are resilient and often well preserved in sediment, especially in arid, semi-arid, tropical and sub-tropical areas (Barboni et al., 2007; Finné et al., 2010). They are commonly classified based on their shape, texture and/or ornamentation and anatomical origin (Madella et al., 2005). Furthermore, they are grouped in different families and normally classification to sub-family level is possible (Twiss, 1992). Phytolith research began in the middle of the 19th century, although significant developments were made in the second half to the end of the 20th century (Piperno, 2006). The applicability of phytoliths in paleoenvironmental contexts (Fredlund & Tieszen, 1994; Alexandre et al., 1997; Barboni et al., 2007; Finné et al., 2010) and in other fields of science such as botany (Madella et al., 2005, Barboni & Bremond 2009), and archaeology (Albert et al., 2008; Power et al., 2014) is growing.

A minimum basic sum of 500 phytoliths was counted for each level on the samples from Lake Chilau (Paper III) and grouped according to their morphotypes. In Lake Nhauhache (Paper V), phytoliths were counted on the same transect as diatoms to allow the determination of phytolith/diatom ratio, which is applied as an indicator of terrestrial conditions.

3.4 Mineral magnetic parameters (Paper I- IV)

The use of mineral magnetic parameters in paleoenvironmental studies was developed during the end of the 1970s (e.g. Thompson et al., 1975; Thompson & Morton, 1979) and became established after the work “Environmental Magnetism” by Thompson & Oldfield (1986). Since then, various studies were carried out using mineral magnetic properties to understand environmental and climate variability. Examples include Pleistocene climate shifts in China, where loess deposits were studied regarding magnetic susceptibility and dated by comparison with oxygen isotope records (Kukla et al., 1988) and a reconstruction of palaeoclimate history in Kulna Cave (Šroubek et al., 2001). Furthermore, mineral magnetic parameters and ratios were used as indicators of variations in water energy fluxes in Spirálka Cave, Czech Republic (Šroubek et al., 2007). In the present PhD thesis mineral magnetic parameters and ratios are applied as proxies for past environmental and climate changes, which include sea-level and flooding events. Since several of these parameters are dependent on both grain-size and mineralogy it is assumed that they could record variations in sediment types transported during flooding events (Oliva et al., 2016) and within tidal flats (Wang et al., 2017).

Mineral magnetic parameters were measured for the sediment sequences retrieved from the Coassane Oxbow (Paper I), Lake Lungué (Paper II), Lake Chilau (Paper III), Macassa Bay (Paper IV), Lake Magandane and Lake Soane. Segments of sediment from these sites were contiguously sub-sampled in 1 cm intervals and kept in 2 × 2 × 2 cm plastic containers. These samples were submitted to mineral magnetic parameters in the
Paleomagnetic Laboratory from the Department of Geology, Lund University. Magnetic susceptibility (χ) measurements were performed in a Kappabridge KLY-2. Anhysteretic Remanent Magnetization (ARM) was acquired after the samples were magnetized to 10 mT in a Molspin Af Demagnetizer for DC bias field direction. To measure the Saturation Isothermal Remanent Magnetization (SIRM), samples were magnetized to 1 T in a Redcliffe Magnetometer 102D. Backfields were acquired using Redcliffe Magnetometer 102D to magnetize to 100 mT.

3.5 Organic carbon (Paper I- V)

Organic carbon and/or total organic matter was measured on samples dried at 105 °C overnight and homogenised. For the Coassane Oxbow (Paper I), 150–200 mg of each sample was measured on an Eltra CS 500 carbon-sulfur determinator (550 °C), while samples from Lake Lungué (Paper II), Lake Nhauhache (Paper V), Lake Magandane and Lake Soane, were run on Eltra Metalyt 80W carbon-sulphur determinator (550°C). The Lake Chilau samples (Paper III) were analysed for loss on ignition (LOI, 550 °C) to retain information on total organic matter. For Macassa Bay, samples were analysed for carbon and nitrogen content during massspectrometry, using a Finnigan Delta Plus mass spectrometer equipped with a Carlo Erba NC2500 and Conflo interface. Prior to this, Macassa samples were freeze dried and homogenized.

Sample resolution for analysis described above was applied as follows: Lake Nhauhache (each cm), Lake Magandane and Lake Soane (every second cm), Lake Chilau (every cm), Macassa Bay (every fifth cm), Lake Lungué (every fifth cm for Russian corer sequence, and every cm for Multi-sampler sequence).

3.6 Grain-size (Paper I)

Grain-size analyses were performed every second centimeter for the entire sequence of samples from the Coassane Oxbow (Paper I). Each sample of sediment (weighing c. 4 g) was wet-sieved through a 63 μm mesh with the aim to determine sand content, after spending one night in the shaker table with 0.05% Calgon® (Na₄PO₄) spread in 100 ml beakers. The fraction of sand was determined after weighing the dried sediment at 60°C overnight. Clay and silt content were measured using a Sedigraph 5100.
4 Results and interpretation

4.1 Summary of the papers

**Paper I**


The aim of this study was to reconstruct past environment and flooding history as recorded in a filled-in oxbow (in the thesis referred to as Coassane Oxbow) located on the Limpopo River floodplain. Furthermore, the potential of selected methods to mirror past environmental changes and flooding events were evaluated. Applied analyses included mineral magnetic properties, grain-size distribution, organic carbon and diatom assemblages. Ten AMS dates (six of bulk sediment, three of shells and one of wood) were used to establish an age-depth model, which indicated that the retrieved sediment sequence covers the last c. 800 years.

The site was interpreted to act as an active oxbow lake during the period AD 1200–1400 (750–550 cal yrs BP). During this phase, our record displays the highest percentages of diatoms, made up from a combination of freshwater, halophilous and brackish-marine taxa. A transition to terrestrial conditions was observed between AD 1400–1700 (550–250 cal yrs BP), marked by a decline of halophilous taxa. After this phase until present times, the record is characterized by low and scattered diatom content made up from brackish-marine taxa, indifferent taxa, freshwater taxa combined with aerophilous taxa.

Peaks in magnetic susceptibility (χ), saturation isothermal remanent magnetization (SIRM), hard isothermal remanent magnetization (HIRM) and sand content, combined with low contents of organic carbon (OC), were interpreted to be the result of four high magnitude flooding events. These events are dated to mid-1200s, late-1300s, mid-1500s and during the last century. Threshold values of $4 \times 10^{-6}$ m$^3$kg$^{-1}$ and $10 \times 10^{-3}$ Am$^2$kg$^{-1}$ for χ and SIRM, respectively, were interpreted to indicate flooding events at this site.

Conclusions from this study revealed that magnetic parameters and grain-size variations are useful proxies to record past flooding events, while diatom microfossil assemblages were important as proxies for past environmental change.

**Paper II**


The aim of this paper was to investigate the late Holocene climate evolution and sea-level changes in southern Mozambique. Analyses of diatoms, mineral magnetic parameters and organic carbon were combined to strengthen the past environment interpretation (Paper I). An age-depth model was established based on eleven radiocarbon dates from shells, and the use of the software Clam software (Blaauw, 2010). The age-depth model suggests that the core represents sedimentation since at least AD 740 (1210 cal yrs BP). It was not possible to determine an age of the lowermost sediment unit owing to lack of shells.
Diatoms are used as sea-level and climate proxies. Mineral magnetic parameters and organic carbon are used as complementary methods, and also as proxies for other environmental changes, e.g. erosional phases caused by climate changes and/or human impact. In order to facilitate comparison between the different proxies, the zonation established for the diatom stratigraphy, based on CONISS calculations (Grimm 1987), and was applied also for the other parameters. The results obtained from Lake Lungué were compared to nearby sites located within and outside the Limpopo River drainage area.

Diatom frustules were abundant and well preserved in the entire sequence except for the lower part of the sequence, which showed scattered occurrences and lower basic sums. The general pattern was a higher presence of brackish-marine taxa from AD 740–1130 (1210–820 cal yrs BP. The period AD 1130–1360 (820–590 cal yrs BP) is characterized by a massive decrease of the brackish-marine taxa, while the contribution from halophilous, indifferent and freshwater taxa increases. From AD 1360 (590 cal yrs BP) until present the brackish-marine taxa displayed the lowest percentages, while the input from halophilous, indifferent and freshwater taxa was more significant. Freshwater taxa report major influence on the assemblage between AD 1360 (590 cal yrs BP) and AD 1560 (390 cal yrs BP).

The observations stated in the paragraph above are interpreted as being the result of strong marine influences until AD 910 (1040 cal yrs BP). During the period AD 910–1130 (1040–820 cal yrs BP) there was no permanent connection with the sea. However, sporadic excursions of sea-water into Lake Lungué basin allowed the growth of typically brackish-marine taxa. The marine influence in the basin ceased sometime between AD 1130 (820 cal yrs BP) and AD 1360 (590 cal yrs BP). From this period until present the record is affected mainly by climate fluctuations, with the wettest period recognized between AD 1360 (590 cal yrs BP) and AD 1560 (390 cal yrs BP).

It is concluded that Lake Lungué was part of the Indian Ocean at least between AD 740 (1210 cal yrs BP) and AD 910 (1040 cal yrs BP). The highest lake level was observed at AD 1360–1560 (590–390 cal yrs BP), and after these dates lower levels were recorded. Furthermore, finds of *Gomphonema* spp revealed that livestock was established in the vicinity of Lake Lungué at c. AD 1300 (650 cal yrs BP). It was also concluded that precipitation pattern in Lake Lungué correlated relatively well with observations from other sites located upstream the Limpopo River floodplain, while the correlation is limited for more closely located sites (located outside the river basin).

**Paper III**


This paper aims to reconstruct past vegetation dynamics in the Miombo savanna biome in southern Mozambique during the Holocene. In addition, the study attempts to identify changes in the ecosystem and their possible connections with hydro-climate shifts, and also to evaluate whether the recognized link between vegetation and hydro-climate in Vilankulos area (Ekblom et al., 2014) is applicable at this more southerly located site, Lake Chilau. Applied methodology includes downcore phytolith and diatom analysis and measurements of mineral magnetic parameters. An age-depth model was established based on 12 AMS 14C dates on macrofossils and bulk organic matter. In combination with lithological indications, the 14C dates suggest discontinuous accumulation and several hiatuses. The periods for which sediment material is available include; late AD 1200 until present, the early MCA around AD 800 (1150 cal yrs BP) and middle-late Holocene at c. 3000–1000 BC (4950–2950 cal yrs BP) and 6000–4500 BC (7950–6450 cal yrs BP).
The phytolith analysis concluded that grasses from Panicoideae sub-family and other mesophytic types were abundant between AD 1200–1300 (750–650 cal yrs BP) and declined during the beginning of the LIA at c. AD 1400–1550 (550–400 cal yrs BP). The mesophytic grass communities were replaced by Chloridoideae grasses of more xerophytic affinity. This scenario is in accordance with the hydro-climatic changes observed in other regional records during this period, i.e. a transition from warm and wet towards more cool and dry conditions. The Chilau phytolith record furthermore reveals an increase in phytoliths associated with arboreal vegetation between AD 1400 and 1550 (550–400 cal yrs BP), suggesting that trees and shrubs, tentatively those associated with the Miombo forest component, were favoured by drier conditions. These findings support previous indications about Miombo savanna response to drought, derived from pollen analysis performed in the Vilankulos area.

**Paper IV**


Paper IV investigates changes in coastal paleoenvironment and sea-level fluctuations in Macassa Bay near Vilankulos. The methods applied are sediment stratigraphy, diatoms, mineral magnetic properties, stable carbon and nitrogen isotope composition as well as carbon and nitrogen content. Six AMS $^{14}$C dates indicate a basal sediment age of c. 4650 BC (6600 cal yrs BP). The results are put into broader perspective by comparison with other sea-level reconstructions from southern Africa.

The analysed sequence reveals shifts between marine and freshwater conditions at Macassa Bay since c. 4650 BC (6600 cal yrs BP) as a consequence of relative sea-level fluctuations. Two periods of high relative sea-levels were identified at c. 4650–4350 BC (6600–6300 cal yrs BP) and c. 2650 BC–AD 1050 (4600–1000 cal yrs BP). The former period coincides with the global sea-level transgression during the Holocene Climatic Optimum. In between these two periods, at c. 4350–2650 BC (6300–4600 cal yrs BP), the site was under influence of freshwater conditions, probably as a consequence of sea-level lowering. Terrestrial conditions were established during the last millennium as a result of sea-level lowering, sediment deposition and increase in organic productivity. The Macassa Bay record is in accordance with a relative sea-level reconstruction from SW African coastline (Compton, 2006), but shows less agreement with records from the NE coastline of South Africa (Ramsay & Cooper, 2002). The inconsistencies between records urge for additional studies focusing on sea-level variations, in order to provide a more robust sea-level reconstruction for the south-east African coast.

**Paper V**


In Paper V, diatoms and phytoliths were analysed to determine lake-level variations in Lake Nhauhache, located in the Vilankulos area. A 2.3 m long sediment core was dated by ten radiocarbon dates indicating a basal age of 350 BC (2300 cal yrs BP). Diatom identification and phytolith/diatom ratio were applied as hydro-climate proxies allowing the reconstruction of past lake level variations. The period between c. 300 BC and AD 850 (2250–1100 cal yrs BP) was dominated by benthic taxa with a significant contribu-
tion from aerophilous taxa, although around AD 800 the aerophilous taxa decline simultaneously with a peak in planktonic taxa. This phase was interpreted as indicative of generally humid conditions and a probable flood occurring c. AD 800. The period between AD 850 and 1180 (1100–770 cal yrs BP) is marked by a decline of aerophilous taxa, accompanied by a decline of planktonic and the halophilous taxa towards the top. This diatom composition probably represents a saline wetland or a small lake in relation to the previous period, indicating the initiation of a change towards drier conditions. The period AD 1180–1700 (770–250 cal yrs BP) is characterized by lower lake levels and drier conditions marked by the absence of planktonic taxa, abundant benthic taxa and a relatively high occurrence of phytoliths in relation to diatoms. Between c. AD 1700 and 1800 (150–250 cal yrs BP) wetter conditions are inferred by high abundance of planktonic taxa and low percentages of halophilous and benthic taxa. The lowest percentages of phytoliths in relation to diatoms suggest that this represents the wettest period of the record. There is a general agreement between Lake Nhauhache record and other climate archives from southern Africa, including those from the Limpopo floodplain.

4.2 Additional data
Besides the published material within this project, three sites in the Limpopo River floodplain were sampled, resulting in additional, however sporadic, litho-, bio- and chronostratigraphic information. These data were achieved by augering, drilling and a geophysical survey (resistivity measurements). Lake Soane (site 2) and Lake Magandane (site 3) are shallow lakes occupying abandoned meander bows. The geophysical survey was performed at site 5, which today represents a flat surface.

4.2.1 Lithology
The established resistivity model, combined with the complementary drilling at site 5 (Figure 1), indicates that the section is composed by five main units (Figure 10). The boundary of each unit is undulating, and the depths stated below should therefore be considered as averages.

Unit 1 (c. 75–54 m; not reached during drilling) displays resistivity values between 1.4 and 3.75 Ωm. These numbers are relatively low, probably as a result of deposition of clay in deep water under marine conditions (Adepelumi et al., 2009). Unit 2 (c. 54–46 m) shows resistivity values of 1.4–1.95 Ωm. Drilling in this unit indicate that it consists mainly of green clay supporting an interpretation similar as in Unit 1. The observed clay did not contain shells or organic matter. Unit 3 (c. 46–18 m) displays resistivity values of 1.0–3.75 Ωm. The drilling indicate that the lower part of this unit is made up from coarse to very coarse sand, which contains variable amount of shells and occasional heavy minerals. Unit 3 shows the lowest resistivity values throughout the sequence even though the material consists of coarse sand with fragments of shell. It is likely that this unit contains trapped saline groundwater causing these low values (Adepelumi et al., 2009). Unit 4 (c. 18–5 m) displays resistivity values of 3.75–14 Ωm. Drilling indicates that this unit consists of intercalated medium to coarse sand, with shell fragments at various depths and silt with scattered shells fragments in the upper 150 cm. The high resistivity values indicate a freshwater aquifer (Fukue et al., 1999). Units 3 and 4 could represent near-shore deposits, where the upper part has been eroded by the Limpopo River. Unit 5, between c. 5 m depth and ground surface, shows resistivity values between 1.95 and 3.75 Ωm. Drilling indicates that the lowermost 150 cm comprises fine sand while the uppermost part consists of silty clay. This unit again shows low values, which can be attributed to fine-grained fluvial sediment, i.e. Limpopo River sediment accumulated during flooding events.
Sediment from cores collected at Coassane Oxbow, Lake Magandane, Lake Soane and Lake Lungué mainly consists of clay and silty clay (Table 5), probably representing Limpopo River fine grained fluvial sediment. The core from Lake Soane shows 4 cm coarse sand at the bottom, which could represent near-shore accumulations, i.e. correlated with unit 3 and 4 in Figure 10.

Table 5. Litho-stratigraphy, based on field observations, of five cores collected in the Limpopo River floodplain. Core numbers refer to sites shown in Figure 1.

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (cm)</th>
<th>Lithology</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coassane Oxbow (Paper I)</td>
<td>000–113</td>
<td>Clay</td>
<td>Root remains in the upper 10 cm with Fe precipitation.</td>
</tr>
<tr>
<td></td>
<td>113–198</td>
<td>Silty clay</td>
<td>Mottled with Fe precipitation and <em>Corbicula fluminea</em> (Müller) at 190 cm depth</td>
</tr>
<tr>
<td></td>
<td>198–239</td>
<td>Silty sand</td>
<td><em>Corbicula fluminea</em> (Müller) at 233–239 cm depth</td>
</tr>
<tr>
<td></td>
<td>239–302</td>
<td>Clay</td>
<td>Scattered fragments of <em>Melanoides tuberculata</em> (Müller)</td>
</tr>
<tr>
<td>Lake Magandane</td>
<td>000–133</td>
<td>Clay</td>
<td>Roots of varying size. Complete shells were present between 37–50 cm depth and a mixture of fragments and complete shells between 83 and 133 cm depth</td>
</tr>
<tr>
<td></td>
<td>133–178</td>
<td>Clay</td>
<td>Compacted</td>
</tr>
<tr>
<td>Lake Soane</td>
<td>000–200</td>
<td>Clay</td>
<td>Fresh roots in the upper 21 cm. Shell were present between 38 and 40 cm in depth. Contained two complete shells below 100 cm depth and dispersed shells between 150 and 200 cm depth</td>
</tr>
<tr>
<td></td>
<td>200–375</td>
<td>Silty clay</td>
<td>Fine sand intercalations between 275–277, 291.5–295, 309–337.5, 345–348, 351–354 and 361–365 cm depth. Conglomerate with c. 2 cm diameter at 257 cm depth</td>
</tr>
<tr>
<td></td>
<td>375–379</td>
<td>Medium to coarse sand</td>
<td></td>
</tr>
<tr>
<td>Lake Lungué (Paper II)</td>
<td>000–231</td>
<td>Clay</td>
<td>Scattered complete and fragments shell</td>
</tr>
<tr>
<td></td>
<td>231–268</td>
<td>Silty clay</td>
<td>Scattered complete and fragments shell</td>
</tr>
<tr>
<td></td>
<td>268–299</td>
<td>Clay</td>
<td>Desiccated</td>
</tr>
<tr>
<td>Deep drilling</td>
<td>000–300</td>
<td>Silty clay</td>
<td>Scattered shell fragments</td>
</tr>
<tr>
<td></td>
<td>300–450</td>
<td>Fine sand</td>
<td>Scattered shell fragments</td>
</tr>
<tr>
<td></td>
<td>450–600</td>
<td>Silty</td>
<td>Scattered shell fragments</td>
</tr>
<tr>
<td></td>
<td>600–900</td>
<td>Medium sand</td>
<td>Scattered shell fragments</td>
</tr>
<tr>
<td></td>
<td>900–1500</td>
<td>Coarse sand</td>
<td>Variable amount of shell fragments at different levels</td>
</tr>
<tr>
<td></td>
<td>1500–1800</td>
<td>Medium sand</td>
<td>Shells fragments at the bottom</td>
</tr>
<tr>
<td></td>
<td>1800–4650</td>
<td>Coarse to very coarse sand</td>
<td>Some levels contained variable amount of shells fragments and there are also signs of heavy minerals</td>
</tr>
<tr>
<td></td>
<td>4650–5050</td>
<td>Clay</td>
<td>Green</td>
</tr>
</tbody>
</table>
4.2.2 Lake Soane chronology

The calibrated ages for Lake Soane are shown with one and two sigma standard deviations in Table 6 and Figure 11. The lowermost part of the sequence (287–389 cm) was not possible to date owing to lack of shells. The lowermost date, Poz-47816, reports a calibrated age of c.1150 BC. This date was performed on a piece of wood, possibly re-worked and, if so, does not represent its stratigraphic position. Furthermore, the laboratory reported low carbon content, which motivated removal from the age-depth model.

The date Poz-51547 showed two probable ages (AD 1958 or 1999) after the calibration performed using the Bomb curve (Hua et al., 2013). This sample was collected in the sediment surface in AD 2011, suggesting reservoir ages of either 53 or 12 years. Thus, an average reservoir age of 33 years was considered when establishing the age-depth model (Figure 11).

Table 6. Calendar age conversion was performed using OxCal 4.3 (Bronk Ramsey, 2009) and the calibration curve for the southern hemisphere (Hogg et al., 2013).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Lab code</th>
<th>¹⁴C yrs BP (33 yrs reservoir age)</th>
<th>Calibrated age BC/AD (68.2% probability)</th>
<th>Calibrated age BC/AD (95.4% probability)</th>
<th>Dated material</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Poz-51547</td>
<td>105.72 ± 0.32</td>
<td>1703–1721 (9.7%)</td>
<td>1958 or 1999</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td>39-40</td>
<td>Poz-47779</td>
<td>165 ± 30 132 ± 30</td>
<td>1690–1728 (17.5%)</td>
<td>1805–… (77.9%)</td>
<td>Shell (bivalve and gastropods)</td>
</tr>
<tr>
<td>86</td>
<td>Poz-47780</td>
<td>150 ± 50 117 ± 50</td>
<td>1674–1740 (21.9%)</td>
<td>1797–… (73.5%)</td>
<td>Shell</td>
</tr>
<tr>
<td>107</td>
<td>Poz-47775</td>
<td>305 ± 30 272 ± 30</td>
<td>1635–1671 (49.6%)</td>
<td>1513–1545 (4.9%)</td>
<td>Shell (bivalve)</td>
</tr>
<tr>
<td>169</td>
<td>Poz-47776</td>
<td>550 ± 25 517 ± 25</td>
<td>1425–1447 (68.2%)</td>
<td>1411–1454 (95.4%)</td>
<td>Shell (bivalve)</td>
</tr>
<tr>
<td>227</td>
<td>Poz-47777</td>
<td>1050 ± 30 1017 ± 30</td>
<td>1025–1047 (22.2%)</td>
<td>1019–1151 (95.4%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td>287</td>
<td>Poz-47816</td>
<td>3020 ± 35 2937 ± 35</td>
<td>1154–1149 (2.0%)</td>
<td>1212–974 (93.5%)</td>
<td>Wood fragments</td>
</tr>
</tbody>
</table>
4.2.3 Lake Magandane chronology

The calibrated ages for Lake Magandane are shown with one and two sigma standard deviations in Table 7 and Figure 12. All ages are in stratigraphic order. Owing to the lack of shells in the lower part of the sequence, i.e. between 275 and 320 cm depth, this unit is dated by extrapolation assuming a similar average accumulation rate as for the dated sequence between 178 and 275 cm depth. This procedure seems acceptable since the lithology is similar and there are no indications of hiatuses. This approach indicates that sediment at bottom of the sequence accumulated c. AD 885 (1065 cal yrs BP).
Table 7. Calendar age conversion was performed using OxCal 4.3 (Bronk Ramsey, 2009) and the calibration curve for the southern hemisphere calibration curve (Hogg et al., 2013) for Lake Magandane. From the laboratory ages, 33 years of reservoir effect were subtracted (cf. Paper II).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Lab code</th>
<th>$^{14}$C yrs BP</th>
<th>$^{14}$C yrs BP (33 yrs reservoir age)</th>
<th>Calibrated age AD (68.2% probability)</th>
<th>Calibrated age AD (95.4% probability)</th>
<th>Dated material</th>
</tr>
</thead>
<tbody>
<tr>
<td>46-48</td>
<td>Poz-47773</td>
<td>250 ± 25</td>
<td>217 ± 25</td>
<td>1668–1677 (8.3%)</td>
<td>1651–1699 (22.9%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1734–1799 (59.9%)</td>
<td>1723–1809 (70.9%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1838–1843 (0.5%)</td>
<td>1868–1877 (1.0%)</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>Poz-47766</td>
<td>280 ± 25</td>
<td>247 ± 25</td>
<td>1652–1672 (28.1%)</td>
<td>1645–1679 (33.5%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1744–1759 (17.7%)</td>
<td>1732–1800 (61.9%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1780–1797 (22.4%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>181</td>
<td>Poz-47767</td>
<td>720 ± 30</td>
<td>687 ± 30</td>
<td>1300–1320 (25.6%)</td>
<td>1291–1392 (95.4%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1350–1386 (42.6%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>196</td>
<td>Poz-47769</td>
<td>785 ± 30</td>
<td>752 ± 30</td>
<td>1273–1302 (57.5%)</td>
<td>1231–1248 (3.7%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1365–1375 (10.7%)</td>
<td>1262–1319 (70.0%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1352–1385 (21.7%)</td>
<td></td>
</tr>
<tr>
<td>216</td>
<td>Poz-47770</td>
<td>940 ± 40</td>
<td>907 ± 40</td>
<td>1150–1224 (68.2%)</td>
<td>1046–1090 (12.5%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1108–1122 (1.8%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1129–1268 (81.1%)</td>
<td></td>
</tr>
<tr>
<td>257</td>
<td>Poz-47771</td>
<td>1060 ± 30</td>
<td>1027 ± 30</td>
<td>1021–1047 (27.1%)</td>
<td>995–1150 (95.4%)</td>
<td>Shell (gastropods)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1085–1135 (41.1%)</td>
<td></td>
</tr>
<tr>
<td>275</td>
<td>Poz-47772</td>
<td>1090 ± 30</td>
<td>1057 ± 30</td>
<td>990–1024 (68.2%)</td>
<td>985–1051 (73.2%)</td>
<td>Shell (bivalve and gastropods)</td>
</tr>
</tbody>
</table>

Figure 12. Age-depth model and lithology for Lake Magandane sediment core, established using Clam 2.2 software. The ages in the lowermost part of the sequence (dashed line) were extrapolated considering the average accumulation rate for the dated part.
4.2.4 Mineral magnetic properties for Lake Soane

The results from the analysis of mineral magnetic parameters (χ, ARM and SIRM), organic carbon (OC) and water content for Lake Soane are illustrated in Figure 13. Five zones were identified based on variations in magnetic susceptibility and SIRM.

Zone LS01 (379–328 cm) shows high values for χ, ARM and SIRM; however, the latter decreases upwards. OC and water content values fluctuate with low numbers. The fluctuations observed are likely the result of sediment accumulation during recurrent flooding events in the area.

In zone LS02 (328–205 cm), χ and SIRM values display a decreasing trend towards the upper part. ARM is stable with low number. OC and water content show an increasing trend towards the upper part of the zone. The characteristics displayed in this zone indicate sediment accumulation in a calm environment. Zone LS03 (205–161 cm) is characterized by high values of χ that decrease towards the top. SIRM values show two peaks, although the background values are lower in relation to the previous zone, and they decrease in the upper part. ARM values are low in the lower part, but fluctuate with higher values in the upper part. OC show a decreasing trend toward the top, while water content is increasing. The peaks displayed by SIRM values following the peaks in χ suggest that flooding events affected Lake Soane during this period. Zone LS04 (161–67 cm) displays low values for χ and SIRM. ARM shows low, increasing and fluctuating values towards the top. OC shows low values in the lower part and higher at the top. Water content shows an increase towards the top. The increasing values of ARM suggest more active pedogenic processes towards the top. This is also supported by an increase in OC towards the upper part. In zone LS05 (67–0 cm), χ, ARM and SIRM show high and fluctuating values. OC and water content show an increase towards the top. These characteristics are interpreted as being the result of sediment accumulation during flooding events, as indicated by the high values of χ and SIRM. The high ARM values suggest that in between these flooding events soil formation processes were active, possibly with formation of goethite (Lyons et al., 2014). This is supported by the high values of OC in the upper part.

Figure 13. Magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), organic carbon (OC) and water content for Lake Soane sediment core. The zones LS01–LS05 are based χ and SIRM.
4.2.5 Mineral magnetic properties for Lake Magandane

The results from the analysis of mineral magnetic parameters (χ, ARM and SIRM), organic carbon (OC) and water content for Lake Magandane are shown in Figure 14. Based on the variations in magnetic susceptibility and SIRM five zones were identified.

Zone LM01 (320–238 cm) shows predominantly low values, although fluctuations are observed for χ, ARM, SIRM, OC and water content. These are interpreted to be the result of sediment accumulation during recurrent flooding events. Zone LM02 (238–163 cm) displays relatively higher and fluctuating values in relation to previous zone for χ, ARM and SIRM. OC and water content display higher and stable values. This pattern suggests continuous sediment accumulation in the lake, possibly with less intensive flooding events.

Zone LM03 (163–125 cm) shows low values for χ and SIRM. ARM also displays low values with a fluctuating pattern, while OC and water content values are higher and stable. The high ARM values are interpreted to be the result of soil formation processes, i.e. high concentrations of fine grained pedogenic ferromagnetic particle (Lyons et al., 2010). In this period there are fewer flooding events as suggested by the low values of χ and SIRM. In zone LM04 (125–38 cm), χ, ARM and SIRM show a fluctuating pattern. These fluctuations are also observed in the water content curve, although it peaks towards lower values. The OC curve shows generally low values. This characteristic indicates a highly dynamic environment representing flooding events. High values of ARM, however, suggest active soil formation in-between the floods. Zone LM05 (38–0 cm) displays low values of χ and SIRM. ARM, OC and water content show higher values in comparison to the previous zone. This period is likely to represent a dominance of soil formation processes as indicated by high ARM and OC.

4.2.6 Lake Soane (preliminary diatom analysis)

Preliminary results on diatom analyses from Lake Soane are shown in Figure 15. A general feature of this diagram is mass occurrences of diatoms in the upper part of the sequence and low diatom concentrations in the lower part. Based on their salinity preferences the species found belong to brackish-marine taxa, halophilous taxa, indifferent taxa.

Figure 14. Magnetic susceptibility (χ), Anhysteretic Remanent Magnetization (ARM), saturation isothermal remanent magnetization (SIRM), organic carbon (OC) and water content for Lake Magandane sediment core. The zones LM01- LM05 are based on χ and SIRM.

Figure 15. Mass occurrences of diatoms in the upper part of the sequence and low diatom concentrations in the lower part. Based on their salinity preferences the species found belong to brackish-marine taxa, halophilous taxa, indifferent taxa.
and freshwater taxa. The most common taxon is the halophilous and euplanktonic *Cyclotella meneghiniana*, which is present in all samples indicating high evaporative conditions in the lake (Gasse, 2002) and relatively deep water (Stone et al., 2011). An interesting feature is the occurrences of brackish-marine taxa. The lowermost samples contain *Nitzschia scalaris* and *Rhopalodia gibba*, which could be a result from high tide influences (Zalat, 2005). The upper occurrences of *Nitzschia levidensis* are tentatively the result from reworking from an unknown source.

Figure 16 illustrate some typical diatoms, common in the sediment in Lake Lungué. Apart from the brackish-marine taxa illustrated most of them also occur in the sediment core collected in Lake Soane.
Figure 15. Selected diatoms of Lake Soane sediment core, grouped according to their salinity preferences.

<table>
<thead>
<tr>
<th>Age (AD)</th>
<th>Depth (cm)</th>
<th>Lithology</th>
<th>Halophilous taxa</th>
<th>Brackish-marine taxa</th>
<th>Indifferent taxa</th>
<th>Freshwater taxa</th>
<th>Unknown ecology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nitzschia levidensis</td>
<td>Rhopalodia gibberula</td>
<td>Cycladenella menamphibiana</td>
<td>Epithemia adnata</td>
<td>Nitzschia trophica</td>
</tr>
<tr>
<td>1900</td>
<td>1840</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1840</td>
<td>1835</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1835</td>
<td>1735</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1735</td>
<td>1610</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1610</td>
<td>1510</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1510</td>
<td>1400</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1400</td>
<td>1245</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1245</td>
<td>1188</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1188</td>
<td>623</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>623</td>
<td>300</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>300</td>
<td>118</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>118</td>
<td>75</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>12</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>48</td>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Basic sum:
- Halophilous taxa: 1041
- Brackish-marine taxa: 928
- Indifferent taxa: 1188
- Freshwater taxa: 623
- Unknown ecology: 300
- Total: 118

Maps show:
- Clay
- Silt Clay
Figure 16. Examples of diatoms identified in Lake Lungué samples, which have major relevance for environmental interpretations. Brackish-marine taxa (A-F), halophilous taxa (G-J), indifferent taxa (K-M), freshwater taxa (N-O).
5 Discussion

5.1 Geomorphological evolution

Previous studies suggest that during the Paleogene and Neogene, the Limpopo River formed a huge deltaic system emptying northwest to north from its current outlet (Figure 8) (Spaliviero et al., 2014 and references therein). The large amount of sediment accumulated in this area might have led to deviation of the river course to the south sometime during the Neogene and/or early Quaternary. Repeated marine regressions connected to glaciations during the Pleistocene, combined with sediment transport, caused a movement of the Limpopo River mouth towards its present position. In parallel, marine terraces were formed northeast from the current position of the river mouth by seasonal longshore drift (Sætre & de Paula e Silva, 1979), especially during interglacial periods. On top of the marine terraces, dunes were formed creating the undulating surface observed today. These geomorphological features seem to be present along the coastal stretch from Xai-Xai to Vilankulos (Paper III-V).

The deep drilling of core 5 (Figure 10, Table 5) allowed the observation of 50.5 m of sediment that supports the above described evolution of the lower stretch of the Limpopo River. This core displayed green clay at the bottom (unit 1-2), interpreted to represent deposition in deep water marine conditions (Maloney et al., 1989). Greenish, fine grained sediment have also been associated with mangrove accumulations (e.g. Limaye et al., 2014). This type of sediment, however, is often characterized by sand lenses and shell fragments, which was not the case in core 5. Hence, a marine deposition environment is more likely in this case. The above units 3 and 4 represent near-shore coastal sediments and unit 5 fluvial deposits. The fine-grained sediment representing the latter unit is likely the result from the meandering processes and/or flooding events.

During the late Holocene, the Limpopo River floodplain was a highly dynamic environment with marine influences reaching further inland and being frequently affected by flooding events of variable magnitudes (Muianga, 2004; Asante et al., 2007; Spaliviero et al., 2014). In the recent past, there is evidence that the floodplain has been in contact with the coastal area/Indian Ocean at c. AD 740 (1210 cal yrs BP) or prior to this age, as suggested by the lower and undated unit in the record from Lake Lungué. The sea-level highstand is evidenced by the presence of typical marine taxa in Lake Lungué (*Diploneis suborbicularis* and *Navicula yarrensis*), and is supported by other records (Compton, 2001; Strachan et al., 2014). Further evidence of marine influences in the floodplain is the observation of *Terpsinoë americana* (although in minor occurrences) in the record from the Coassane Oxbow. This species is considered to be a coastal living taxon and it has been observed at a number of coastal sites around the world (Alhonen et al., 1984; Tynni, 1986).

The studied lakes are affected in different ways by flooding events, related to their location (Figure 1). In Lake Lungué, sediments may only be accumulated during high magnitude flooding events, since it is located c. 10 km east of the current river channel and behind a threshold that acts as a barrier. In the Coassane Oxbow, however, sediment might also be accumulated during low magnitude flooding events, since it is located only c. 2 km east of the river channel. In addition, owing to the geomorphic characteristic of the Limpopo River, the water flow into the Coassane Oxbow might enter simultaneously from both south and north. Lake Magandane and Lake Soane are located at intermediate positions; therefore, these sites are likely to receive sediments in case of medium and high magnitude flooding events.

Depending on the flood intensity, the size of the particles transported and location of deposition vary (Kaase & Kupfer, 2016). Larger grains are expected to accumulate in the vicinity of the main river channel, while finer grains are likely to be transported longer...
distances (Asselman & Middelkoop, 1995). Therefore, the indications of flooding events in the Limpopo River floodplain is expected to vary with distance from the contemporary channel (Kaase & Kupfer, 2016). In turn, this will lead to deposition of coarser grains displaying high $\chi$ and SIRM values near the main channel, and fine-grained particles displaying lower $\chi$ and SIRM far from the channel. Lake Lungué displays low values of $\chi$ and SIRM, which is likely the result from its location away from the present river channel and behind a threshold that leads to accumulation of fine grained particles only in case of high magnitude flooding. This is further supported by the low accumulation rate determined for Lake Lungué in relation to the other sites investigated within the floodplain (see chapter 5.1). An aspect to consider in recent times is the abundant constructions of dams further upstream, which will hamper the meandering abilities for the river and affect the processes of flooding, erosion and deposition of sediments.

5.2 Age-depth models for the Limpopo River floodplain

All age-depth models were based on dating of the gastropod *Mellanoides tuberculata* (Müller), except in the Coassane Oxbow (Paper I), which also included dating of a bivalve and wood. Since *M. tuberculata* is known to grow well in silty sediments, where it can dig down a few centimeters, the accuracy of the dates can be questioned (Duggan, 2002). However, it is believed that these gastropods lived *in situ*, as they were found in colonies. Dates of shells found on the sediment surface delivered ages similar to AD 1998 or 1958, with an age difference of 13 or 53, i.e. an average of 33 years. Since the majority of the dates were performed on the same species it is assumed that the dates contain an equal error, which was considered during the calibration of ages and the construction of the age-depth models. Wood dates may be uncertain since wood can be re-worked from upstream sources and be incorporated quickly in the sediment during a flooding event. A comparison between dated shells and dated bulk sediment indicated that the bulk sediment dates display a reservoir effect of 500–1000 years (Paper I). Therefore, the option to establish age-depth models based on the gastropod *M. tuberculata* seems to be reasonable.

The age-depth models established for sites located on the Limpopo floodplain indicate that average accumulation rates vary substantially between different areas (Figure 17, Table 8). Lake Lungué displays the lowest rate (2.1 mm/yr), while the Coassane Oxbow has the highest accumulation rate (5.6 mm/yr). Lake Magandane and Lake Soane show intermediate values of 2.8 mm/yr and 3.4 mm/yr, respectively. These accumulation rates are similar to values reported from the Amazon River floodplain in Brazil (Moreira-Turcq et al., 2004), in the Mississippi River in USA (Davidson et al., 2004; Latuso et al., 2017) and Morava River in Czech Republic (Sedláček et al., 2016). The observed differences of accumulation rates are suggested to be associated with the distance to the contemporary Limpopo River channel (Omengo et al., 2016). In addition, local morphology at each site will lead to differences in sediment accumulation patterns (Kaase & Kupfer, 2016). For instance, compared with the other sites, Lake Lungué shows a low accumulation rate, which can be explained by its location behind a threshold currently located at c. 8 m a.s.l., i.e. c. 1-2 m higher than the nearby floodplain level. Lake Chilau and Lake Nhauhache display average accumulation rates of approximately 1.0 mm/yr. This is low compared to the majority of the sites on the floodplain. However, it is in line with the rate determined for Lake Lungué, which supports that Lake Lungué is not flooded on a regular basis.
Figure 17. Age-depth models for Lake Soane, Lake Magandane, Lake Lungué and Coassane Oxbow. The diagram includes only the dated part of each sediment sequence. The ages plotted are the best fit according to the age-depth model constructed based on Clam 2.2 (Blaauw, 2010). The Coassane Oxbow age-depth model was established by Sitoe et al. (2015). Since the radiocarbon dates are based mainly on gastropods and bivalves it is assumed that the models may match.

Table 8. Variation in accumulation rates for sediment cores in Lake Soane, Lake Magandane, Lake Lungué and the Coassane Oxbow according to the establish age-depth models. The calculation of accumulation rates takes into account only the dated parts of each sequence.

<table>
<thead>
<tr>
<th>Site</th>
<th>Core depth (mm)</th>
<th>Age at base (AD)</th>
<th>No. of years encompassed (years)</th>
<th>Average accumulation rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coassane Oxbow</td>
<td>4480</td>
<td>1204</td>
<td>796</td>
<td>5.6</td>
</tr>
<tr>
<td>Lake Lungué</td>
<td>2100</td>
<td>1020</td>
<td>980</td>
<td>2.1</td>
</tr>
<tr>
<td>Lake Magandane</td>
<td>2750</td>
<td>1037</td>
<td>967</td>
<td>2.8</td>
</tr>
<tr>
<td>Lake Soane</td>
<td>2870</td>
<td>1147</td>
<td>853</td>
<td>3.4</td>
</tr>
</tbody>
</table>

5.3 Mineral magnetic properties and flooding events in the Limpopo River floodplain

Magnetic Susceptibility (χ) and Saturation Isothermal Remanent Magnetization (SIRM) is plotted against age scale for the sites studied on the Limpopo River floodplain (Figures 18 and 19). Peaks in χ and SIRM are interpreted as the result of accumulation during high magnitude flooding events as suggested by the record in the Coassane Oxbow (Paper I). These events are dated to the mid-1200s, late-1300s, mid-1500s and the last century. Partly, these flooding events were identified in Lake Soane (mid-1200s, late-1300s and the last century) and Lake Magandane (mid-1200s, mid-1500s and the last century). In Lake Lungué, however, only the flooding event in the mid-1200s could be retrieved from the SIRM record. Revelation of the events dated to the last century was constrained owing to lack of data in the upper part of the record. The flooding events indicated by the Coassane Oxbow record display slightly different ages in comparison with Lake Magan-
dane and Lake Soane. Age calibration for the latter two sites took into account the reservoir effect (see chapters 4.2.2 and 4.2.3).

Figure 18. Magnetic susceptibility variations for Coassane Oxbow, Lake Lungué, Lake Magandane and Lake Soane over time. Grey areas represent flooding events identified in Coassane Oxbow. All data sets are in SI units (10^{-6} m^3 kg^{-1}). Numbers 1–16 represent the minimum number of flooding events that affected the floodplain during the last 1100 years. Data from Coassane Oxbow, Lake Magandane and Lake Lungué are on similar scale, while Lake Lungué data are plotted on different scale owing to visibility constraints. Vertical dashed lines indicate threshold values for flooding events established in Coassane Oxbow.

Higher values of magnetic susceptibility and SIRM were defined as an indicator of high magnitude flooding in the Limpopo floodplain (Paper I-II, plus additional data). Parallel analysis of grain sizes in the Coassane Oxbow acts as supporting evidence for mineral magnetic properties as a suitable flooding proxy in this area. Using the Coassane Oxbow as a reference site, threshold values were established, representing major magnitude flooding events; 4 \times 10^{-6} m^3 kg^{-1}, and 10 \times 10^{-3} Am^2 kg^{-1} for susceptibility and SIRM respectively. Based on the threshold value for SIRM in particular (Figure 19), and to some extent for susceptibility (which varied more between and within sites, Figure 18); at least 16 high magnitude flooding events were identified in the analysed proxy records during the last 1100 years (Table 9). Tentatively high magnitude flooding events, where both \chi and SIRM are above the threshold values, could be identified at AD 1250, 1370, 1580, 1855, 1920, 1970 and 2000 (Table 9). Combined peaks, which do not reach threshold values for both \chi and SIRM, are suggested to indicate less severe flooding events. The record of 16 identified events is considered to reflect the minimum number of flooding events that have affected the area during the studied period. Since the AD 1950s, the Limpopo River floodplain has been affected by at least eight flooding events, in AD 1955, 1967, 1972, 1977, 1981, 2000 and 2013 (DNA, 1996; INGC et al., 2003). Of these
documented events, only two or three were recorded in the studied sequences (Figure 18 and 19). Owing to various reasons (erosional processes, distance from river channel etc.), some floods are obviously not recorded by the studied proxies. The lack of proxy response to the more recent flooding events may also be a consequence of the coring procedure that sometimes may lead to loss or disturbance of the uppermost core section, particularly when sampling in lakes. A constraining factor is the number of available dates for each site. It is likely that sediment accumulation rates are high during flooding events. This could give a false impression of the duration of some flooding events. For example, flooding events 7 and 8 (Figure 18 and 19) in Coassane Oxbow seems to have durations of up to 100 years, which is not likely.

The above defined events are sometimes co-appearing between sites, but not always. This may to some extent be a result of age-model constraints that hamper inter-data comparison on this relatively high-resolution level. It may also be associated with the spatial distribution of sediment deposition in the Limpopo River floodplain during a flooding event, which is controlled by the location of precipitation (local or upstream), as well as by local topography and geomorphology. These factors, which are variable through time, will affect the flooding intensity and flow patterns on the floodplain during each event. For example, if the rain falls directly on the floodplain, the flooding event

Figure 19. 1Saturation Isothermal Remanent Magnetization (SIRM) variations for Coassane Oxbow, Lake Lungué, Lake Magandane and Lake Soane sediment cores over time. Grey areas represent flooding events identified in Coassane Oxbow. All data sets are in SI units (10^3 m²kg⁻¹). Numbers 1–16 represent the minimum number of flooding events that affected the floodplain during the last 1100 years. Data from Coassane Oxbow, Lake Magandane and Lake Lungué are on similar scale, while Lake Lungué data are plotted on different scale owing to visibility constraints. Vertical dashed lines indicate threshold values for flooding events established in Coassane Oxbow.
will start affecting sites located downstream, in the south. If increased rainfall is experienced on a more region-wide scale, with increasing intensity and duration, the impact of flooding will move continuously towards areas upstream. If intense rain falls only upstream (e.g. in the Olifant River catchment) and a huge volume of river water enters the floodplain, the water will flow over the levees before reaching the river mouth. This was exemplified in 2013, when northern areas were flooded first.

Table 9. List of flooding events that affected the Limpopo River floodplain during the last 1100 years. Bold numbers indicate when threshold values were reached, while underlined numbers indicate that there is no obvious peak. Remaining numbers indicate the presence of a peak although threshold values were not reached. Nd indicates portions of the cores without data. Lake Lungué is not included since the sediment displays too low concentrations of $\chi$ ($\times 10^{-6}$ m$^3$kg$^{-1}$) and SIRM ($\times 10^{-3}$ Am$^2$kg$^{-1}$). Note that magnitude classifications are relative.

<table>
<thead>
<tr>
<th>Flooding event</th>
<th>Age (AD)</th>
<th>Coassane Oxbow</th>
<th></th>
<th>Lake Magandane</th>
<th></th>
<th>Lake Soane</th>
<th></th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>940</td>
<td>Nd</td>
<td></td>
<td>Nd</td>
<td>12</td>
<td>Nd</td>
<td>Nd</td>
<td>Unclear</td>
</tr>
<tr>
<td>2</td>
<td>980</td>
<td>Nd</td>
<td></td>
<td>Nd</td>
<td>16</td>
<td>Nd</td>
<td>Nd</td>
<td>Unclear</td>
</tr>
<tr>
<td>3</td>
<td>1040</td>
<td>Nd</td>
<td></td>
<td>0.2</td>
<td>11</td>
<td>Nd</td>
<td>Nd</td>
<td>Unclear</td>
</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>Nd</td>
<td></td>
<td>0.25</td>
<td>8</td>
<td>0.35</td>
<td>30</td>
<td>Unclear</td>
</tr>
<tr>
<td>5</td>
<td>1250</td>
<td>0.8</td>
<td>17</td>
<td>0.27</td>
<td>8</td>
<td>0.3</td>
<td>7</td>
<td>Medium magnitude</td>
</tr>
<tr>
<td>6</td>
<td>1300</td>
<td>0.45</td>
<td>18</td>
<td>0.27</td>
<td>4</td>
<td>0.45</td>
<td>10</td>
<td>High magnitude</td>
</tr>
<tr>
<td>7</td>
<td>1370</td>
<td>0.85</td>
<td>15</td>
<td>0.15</td>
<td>23</td>
<td>0.43</td>
<td>10</td>
<td>Very high magnitude</td>
</tr>
<tr>
<td>8</td>
<td>1580</td>
<td>0.65</td>
<td>11</td>
<td>0.2</td>
<td>32</td>
<td>0.15</td>
<td>3</td>
<td>High magnitude</td>
</tr>
<tr>
<td>9</td>
<td>1665</td>
<td>0.42</td>
<td>9</td>
<td>0.15</td>
<td>35</td>
<td>0.17</td>
<td>4</td>
<td>Medium magnitude</td>
</tr>
<tr>
<td>10</td>
<td>1730</td>
<td>0.4</td>
<td>5</td>
<td>0.2</td>
<td>19</td>
<td>0.17</td>
<td>4</td>
<td>Medium magnitude</td>
</tr>
<tr>
<td>11</td>
<td>1755</td>
<td>0.38</td>
<td>5</td>
<td>0.18</td>
<td>3</td>
<td>0.17</td>
<td>4</td>
<td>Low magnitude</td>
</tr>
<tr>
<td>12</td>
<td>1855</td>
<td>0.42</td>
<td>6</td>
<td>0.05</td>
<td>5</td>
<td>0.6</td>
<td>70</td>
<td>High magnitude</td>
</tr>
<tr>
<td>13</td>
<td>1920</td>
<td>0.4</td>
<td>5</td>
<td>0.025</td>
<td>2</td>
<td>0.7</td>
<td>15</td>
<td>High magnitude</td>
</tr>
<tr>
<td>14</td>
<td>1945</td>
<td>0.23</td>
<td>5</td>
<td>0.025</td>
<td>2</td>
<td>0.2</td>
<td>30</td>
<td>Low magnitude</td>
</tr>
<tr>
<td>15</td>
<td>1970</td>
<td>0.2</td>
<td>5</td>
<td>0.05</td>
<td>2</td>
<td>0.5</td>
<td>38</td>
<td>Medium Magnitude</td>
</tr>
<tr>
<td>16</td>
<td>2000</td>
<td>0.75</td>
<td>13</td>
<td>Nd</td>
<td>0.05</td>
<td>10</td>
<td></td>
<td>High magnitude</td>
</tr>
</tbody>
</table>

5.3 Regional climate

The hydro-climate reconstructions presented in this thesis (Paper I-III and Paper V), result from proxy-responses in complex environments with various factors affecting the hydrology. The Coassane Oxbow and Lake Lungué are located in the highly dynamic floodplain system, where the diatom assemblage suggests that the former was developed from an open lake to soil formation stage, while Lake Lungué settled into a relatively
independent limnic system after c. AD 1350 (600 cal yrs BP). Sediment accumulation and lake levels at both these sites were probably driven by local effective precipitation, as well as sporadic impact from flooding events coupled with high rainfall in the upper Limpopo River drainage area. Thus, the diatoms living in the Coassane oxbow should have responded mainly to lake level variations from climate-related processes and occasional flooding of the Limpopo River. In Lake Lungué, wet conditions are evident at least since mid-AD 1300, continuing until c. mid-AD 1500. It is possible that the site was wetter even earlier, but marine influence until AD 1360 (590 cal yrs BP), as indicated by the diatom record, would have masked any climate signal before that.

Several paleoclimate records are available for comparison, particularly from sites located within the upper drainage area of the Limpopo River (Figure 20); a speleothem from Makapansgat Cave (Lee-Thorp et al., 2001; Holmgren et al., 2003), trees from Northern Province (Woodborne et al., 2015; 2016; Norström et al., 2005) and sediments from Limpopo Valley (Ekblom et al., 2012). In both Makapansgat Cave and Limpopo Valley records, wetter conditions are reported from c. AD 1200 (750 cal yrs BP), continuing to around AD 1400 (550 cal yrs BP) at Limpopo valley (Ekblom et al., 2012) and to AD 1500 (450 cal yrs BP) at Makapansgat (Lee-Thorp et al., 2001; Holmgren et al., 2003). Baobab tree carbon isotopes also suggest high rainfall conditions during this period, with the wettest conditions at c. AD 1075 (875 cal yrs BP) and AD 1270 (680 cal yrs BP), and a shift towards drier conditions around AD 1600 (350 cal yrs BP) (Woodborne et al., 2015; 2016). The Lungué indications are thus relatively well paralleled with the signals from the upper catchment sites. The influence of distant source water on the floodplain lake is supported by the fact that the region-wide wet phase coincides with the occurrences of three high magnitude flooding events recorded in the Coassane Oxbow, Lake Magandane and Lake Soane at AD 1250 (700 cal yrs BP), AD 1300 (650 cal yrs BP) and AD 1370 (580 cal yrs BP). The former is coeval with a precipitation peak around AD 1270 (680 cal yrs BP) inferred by the high-resolution tree ring isotope record from northern South Africa (Woodborne et al., 2015).

Between late AD 1300s and late 1500s, there is a centennial long pause in flooding events traced from the sedimentological records. This pause is initiated simultaneous with a transition from wetter to drier conditions in many, but not all, of the paleoclimatic records. Although an obvious reason may be that less rainfall may lead to less flooding events, such rationale is weakened by the fact that flooding frequency increases again during the dry conditions of the 1600s and 1700s. This higher frequency of flooding events during generally dry conditions might be associated with increased intensity of single rain events during the extended period of droughts. Vegetation studies from southern Mozambique report that the arboreal cover has varied significantly during the last millennia, and both pollen and phytolith indicators suggest that the forest component of the Miombo savanna was favored by the dry conditions during the LIA (Ekblom et al., 2014; Paper III). The increase in forest cover between AD c. 1400–1600 (e.g. Paper III), may tentatively have led to a higher resilience of the land, despite the dry conditions, leading to less erosional impact from flooding events, and weaker flooding signals in the studied cores.
Figure 20. Wet and dry periods for sites included in this thesis (Paper I-III and Paper V) and other selected sites in southern Africa. The black circles represent flooding events recorded in the Coassane Oxbow (Paper I), Lake Soane and Lake Magandane.

From AD 1560 until present, the Lake Lungué record indicates a declining lake level. Right at the transition to this period, at AD 1580 (370 cal yrs BP), a third high-magnitude flooding event was recorded from Coassane Oxbow, Lake Magandane and Lake Soane, almost simultaneous with a peak in precipitation reported by tree ring isotopes c. AD 1580 (370 cal yrs BP) (Woodborne et al., 2016). The dry indications from Lake Lungué is generally concordant with similar conditions observed in upper catchment records (Lee-Thorp et al., 2001; Holmgren et al., 2003; Ekblom et al., 2012; Woodborne et al., 2016), although these sites display a return towards wetter conditions already around AD 1800 (150 cal yrs BP). Owing to low sample resolution in the Lungué core during the last 200 years (four samples) this signal may not have been picked up in our record. However, flooding events occurred in Coassane Oxbow, Lake Magandane and Lake Soane at c. AD 1855 (95 cal yrs BP), AD 1920 (30 cal yrs BP), AD 1945 (5 cal yrs BP), AD 1970 (20 cal yrs AP), AD 1985 (35 cal yrs AP) and AD 2000 (50 cal yrs AP) suggesting that this period was wet also in the Limpopo River floodplain.

Lake Chilau (Paper III), Lake Nhauhache (Paper V) and Lake Nhaucati (Ekblom & Stabell, 2008) belong to the same climate zone, the former located c. 200 km to the north of Limpopo floodplain, and the other two c. 400 km to the north (Figure 1). All these lakes are closed basins, located outside the Limpopo River drainage system, fed by direct precipitation and groundwater aquifers, and should thereby reflect local hydro-climate variability, i.e. evaporative effects in combination with precipitation amounts along the coastal stretch of southern Mozambique. The Lake Nhaucati record (Ekblom & Stabell, 2008) displays a wet signal AD 1050–1400 (900–550 cal yrs BP), which is in agreement with the Chilau record for the period AD 1200–1400 (750–550 cal yrs BP). However, the Lake Nhauhache record is in contrast, reporting dry conditions AD 1150–1700 (800–150 cal yrs BP). These indications are out of phase with the Lake Lungué transition from wetter to drier around AD 1560 (390 cal yrs BP), although the early part of the Lungué
dry period is concordant with dryness at Lake Chilau, Lake Nhauhache and Lake Nhau-
cati (Ekblom & Stabell, 2008). The latter two records report wetter conditions from AD 
1700 (250 cal yrs BP), which is not evident neither in Lake Lungué nor in the upper 
catchment sites (Lee-Thorp et al., 2001; Holmgren et al., 2003; Ekblom et al., 2012; 
Woodborne et al., 2016).

In modern times, El Niño events have been associated with higher rainfall amounts in 
Southern Africa, as a result from global teleconnections within the climate systems. 
Thus, one may hypothesize a connection between El Niño intensity on global scale, and 
flooding frequency in southern Africa, if assuming that high rainfall increases the risk of 
flooding. A comparison between a rainfall proxy for the summer rainfall region (Wood-
borne et al., 2015; 2016) and an El Niño Southern Oscillation (ENSO) proxy (Li et al., 2013), 
however, show weaker correlation between the two prior to AD 1650, but a 
stronger link after the Little Ice Age (post-AD 1750). Furthermore, the El Niño recon-
struction (Nino 3.4 index), which includes tree ring data from tropical to temperate areas 
in both hemispheres, indicate that ENSO was usually active in the 20th century compared 
to the past seven centuries (Li et al., 2013). This implies an ENSO response to global 
warming. It is likely that such a shift in ENSO activity would have impacted on flooding 
frequencies in southern Africa, and this may tentatively, or at least partly, explain the 
higher flooding frequency reflected in the Limpopo records during the last century. The 
flooding events recorded from the Limpopo River floodplain seem to occur both during 
periods of low (AD 1370, 1730, 1920 and 1970) and high ENSO activity (AD 1580, 
1665, 1755, 1855 and 1945), when compared with the reconstruction of ENSO modula-
tions (Li et al., 2013). The interruption in flooding events between late AD 1300 and late 
AD 1500 is however coinciding with a period of significantly lower ENSO activity on 
long-term basis (ca. AD 1300-1600, Li et al., 2013) suggesting that long-term changes in 
ENSO may explain at least partly the shifts in flooding frequency that affected Limpopo 
floodplain in the past. Furthermore, the period of low flooding frequency in Limpopo 
River may also support the suggestion of a weaker connection between El Niño and 
southern African rainfall before AD 1650 as suggested by Woodborne et al. (2015, 
2016).

5.4 Sea-level fluctuations

The periods of sea-level highstands recorded in Macassa Bay (Paper IV) and Lake Lun-
gué (Paper II) are compared with other records from south-eastern Africa (Figure 21), 
i.e. the Rufiji delta in Tanzania (Punwong et al., 2013), Mozambican coast (Jaritz et al., 1977), southeast African coast (Ramsay, 1995), Kariega Estuary in South Africa (Stra- 
chan et al., 2014), Groenvlei Lake in southern Cape coast in South Africa (Wündsch et 
al., 2016) and the Langebaan Lagoon salt marsh in South Africa (Compton, 2001). These 
investigations were performed using different research methodologies and span almost 
40 years of publication. This means that the accuracy of the applied methods has im-
proved continuously since the study by Jaritz et al. (1977) was published, and therefore, 
caution should be taken when comparing datasets. From these records, however, there 
seems to be two periods of mid- to late-Holocene sea-level highstands. These are shown 
as interval A (5000–4200 BC/6950–6150 cal yrs BP) and interval C (AD 300–950/1650– 
1000 cal yrs BP) in Figure 21.

Interval A is represented by sea-level highstands in Langebaan salt marsh, Mozambi-
can coast and Macassa Bay. Transgression maxima for these sites are relatively high, i.e. 
+3.5 m, +2.5 m and +1.5 m, respectively. These highstands seem to correspond to the 
later part of the postglacial climatic optimum showing elevated global temperatures 
(Marcott et al., 2013; Borzenkova et al., 2015; Wang et al., 2015). Interval B shows sev-
eral periods of sea-level highstands, i.e. in the records from Rufiji delta, Macassa Bay, 
southeast African coast, Groenvlei Lake and Langebaan lagoon. The transgression max-
ima are lower in relation to interval A, except in the southeast African coast record. These highstands display a scattered pattern, possibly depending on factors like various tidal influences and geomorphological differences between sites. Interval C displays contemporary sea-level highstands in Macassa Bay, Lake Lungué, Southeast African coast, Kariega estuary and Langebaan lagoon. Transgression maxima are, however, lower than sites represented in interval A (+0.5 m to +1.5 m), indicating a less pronounced transgression. On a global scale, this period shows slightly increasing temperatures in several areas (e.g. Dahl-Jensen et al., 1998; Holmgren et al., 2003; Masson-Delmotte et al., 2004; Moberg et al., 2005; Borzenkova et al., 2015), possibly resulting in just a slight increase in sea-level. It can be concluded that identifying sea-level changes along the African coast is problematic and hampered by a number of factors.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Sea-Level Reached (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rufiji delta</td>
<td>+2.5 m</td>
</tr>
<tr>
<td>Mozambican coast</td>
<td>+1.5 m</td>
</tr>
<tr>
<td>Macassa Bay</td>
<td>+1.0 m</td>
</tr>
<tr>
<td>Lake Lungué</td>
<td>+1.0 m</td>
</tr>
<tr>
<td>Southeast African coast</td>
<td>+1.5-3.5 m</td>
</tr>
<tr>
<td>Kariega estuary</td>
<td>+1.5 m</td>
</tr>
<tr>
<td>Groenvlei Lake</td>
<td>+1.0 m</td>
</tr>
<tr>
<td>Langebaan lagoon</td>
<td>+0.5 m</td>
</tr>
</tbody>
</table>

**Figure 21.** Summary of sea-level highstands in south-eastern Africa from middle Holocene onwards. The sites are arranged from north to south and numbers indicate mean sea-level reached. Absence of numbers indicates highstands; however, their transgression maxima could not be determined.
6 Conclusions

This project constitutes paleoenvironmental reconstructions from southern Mozambique, and it is the first study with focus on the Limpopo River floodplain. It contributes with past environmental history from the middle/late Holocene, including climate, flooding and sea-level history. The main findings are summarized below:

Mineral magnetic parameters are useful to retrieve past flooding events, particularly the magnetic susceptibility and Saturation Isothermal Remanent Magnetization (SIRM). In addition, the variations displayed from grain-size analysis provided a good support to recover past flooding history. Based on these methods, a minimum of 16 flooding events were identified in the Limpopo River floodplain during the last 1100 years. High magnitude flooding events were dated to AD 1250 (700 cal yrs BP), AD 1370 (580 cal yrs BP), AD 1580 (370 cal yrs BP), AD 1855 (95 cal yrs BP), AD 1920 (30 cal yrs BP), AD 1970 (20 cal yrs AP) and AD 2000 (50 cal yrs AP), where AP is after present being 1950. Less severe flooding events were dated to AD 940 (1010 cal yrs BP), AD 980 (970 cal yrs BP), AD 1040 (910 cal yrs BP), AD 1100 (850 cal yrs BP), AD 1300 (650 cal yrs BP), AD 1665 (285 cal yrs BP), AD 1730 (220 cal yrs BP), AD 1755 (195 cal yrs BP) and AD 1945 (5 cal yrs BP). Written sources indicate that at least eight flooding events affected this area during the last 62 years, while only two floods were identified in the proxy-records during this period. This suggests that only major events are picked up in the proxy-data. Furthermore, this study shows the necessity to apply a multi-core approach and to target several sites in order to identify as many paleo-flooding events as possible. This is because of the varying degree of sedimentological and geo-magnetic response to flooding, which is dependent on distance to the meandering river.

Diatom stratigraphy has been a valuable tool to reconstruct past climate and the influence of sea-level shifts at sites studied within this project. The Lake Lungué diatom record display wet conditions from AD 1360 to 1560 (590 to 390 cal yrs BP). In Lake Chilau, phytolith and diatom data suggest wet conditions between AD 1200 and 1400 (750–550 cal yrs BP), while drier conditions prevail until c. AD 1600 (350 cal yrs BP). Lake Nhauhache diatoms, however, indicates generally dry conditions from AD 1200 until AD 1700 (750–250 cal yrs BP) when wetter conditions dominate.

The wet and dry conditions documented in Lake Lungué and the flooding events revealed from the Limpopo floodplain cores do not entirely correlate to periods of high and low precipitation on a local scale, but show relatively good correlation to paleoclimatic indications from the upper drainage area of the Limpopo River. In general, filled-in lakes and active lakes on the lower floodplain have shown to be more susceptible to flooding events caused by upstream precipitation than local.

The research conducted allowed identification of two periods of sea-level highstands in southern Mozambique. An older phase is dated to c. 5000–4200 BC (6950–6150 cal yrs BP) representing the younger part of the postglacial climatic optimum. A younger phase is dated to AD 300–950 (1650–1000 cal yrs BP) corresponding to slightly higher temperatures on a global scale.
7 Suggestions for further studies

Although some progress has been made in the field of paleoenvironmental studies in southern Mozambique, particularly in the Limpopo River floodplain, there are still challenges to understand the past environmental evolution over time. Furthermore, the dynamics of sediment distribution, number of flooding events, wet/dry periods and impacts of sea-level shifts in the area still needs to be disclosed. Thus, the following activities could improve the current available results:

- Perform several density geophysical measurements across the floodplain, combined with deep drilling campaign, providing a transect stretching over the Limpopo River floodplain, in order to strengthen the present model of how sea-level affected the environment.
- Investigate further influences of the Indian Ocean into the Limpopo floodplain, through analyses of additional sediment sequences, e.g. from Lake Nhatsi, located c. 5 km NW of Lake Lungué.
- Retrieve longer and contiguous sediment cores, by combining deep drilling with OSL dating to reconstruct the evolution history of the floodplain based on local proxy records.
- Investigate and enlarge flood chronologies in the Limpopo River floodplain using magnetic susceptibility and saturation isothermal remanent magnetization in several sites, with emphasis on areas not covered by any of the four sites discussed in the present thesis.
- Apply additional proxies for hydro-climatic change, as some records (Chilau) suggest that diatom assemblages may be affected by lake bathymetry rather than lake level shifts, and thereby give misleading indications of paleoclimate, if not combined with other proxies.
- Investigate coastal lakes located in Chidenguele to strengthen paleoclimate and sea-level variations in southern Mozambique.
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