2017

A Palaeo-history of moisture and vegetation change in the Top-End, Australia: Variability in the Australian monsoon during the late Quaternary

William Gerard Reynolds
University of Wollongong
A Palaeo-history of moisture and vegetation change in the Top-End, Australia: Variability in the Australian monsoon during the late Quaternary

By William Gerard Reynolds

Supervisor:
Dr. Samuel Marx
Co-supervisor:
Dr Jan-Hendrik May

This thesis is presented as required for the completion of the degree:

Master of Philosophy (Science)

The University of Wollongong, Australia
School of Earth and Environmental Science

March 2017
STATMENT OF ORIGINALITY

I, William Reynolds, declare that this thesis, submitted in partial fulfilment of the requirements for the award of Master of Philosophy, in the School of Earth and Environmental Science, Faculty of Science, Medicine and Health, University of Wollongong, is solely my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

(William Reynolds)
March 2017
ACKNOWLEDGEMENTS

A great debt of gratitude is readily acknowledged for the support of many people and institutions without whose help this thesis would not have been possible. The patient and tolerant guidance of my primary supervisor Sam Marx was crucial to this project. The guidance of my secondary supervisor, Jan-Hendrik May helped shape the project and ensured academic rigour in the final result. It has been a privilege to work with these two inspiring supervisors as part a collaborative team. The project could not have been completed without the support of ANSTO under the guidance of Henk Heijnes and the help of ANSTO staff in performing ITRAX analysis (Patricia Gadd), radiocarbon dating (Fiona Bertuch, Alan Williams and Geraldine Jacobsen), and stable isotope and C/N analysis (Debashish Mazumda, Linda Barry). Patrick Moss (University of Queensland) provided pollen and charcoal analysis and assisted with interpretation of the results. Similarly Jessica Reeves (Federation University) performed the diatom analysis and advised on how to present and interpret the results. John Tibby (University of Adelaide) provided additional advice on diatom analysis. The support staff at University of Wollongong, Australia were consistently generous with their time and expertise, including help with geospatial analysis (Joseph Blackley-Stock, Heidi Brown and Raphael Carvelho) and with grain size analysis (Brian Jones and Jose Abranates). Laine Clark-Balzan performed the Bayesian analysis, which was vital to derivation of the age model. Alan Greig (University of Melbourne) provided Inductively Coupled Plasma Mass Spectrometry elemental analysis. Joshua Larsen provided valuable comments on an early draft of the hydrology chapter. This study was partly funded by an ARC Discovery Early Career Research Award (DP0987819) granted to Jan-Hendrik May. My wife, Kerry Banks takes credit for encouraging me to commence post-graduate research and for supporting my efforts despite the conversation-killing effects of my newfound predisposition to talk about dirt.
Abstract

The aim of this project was to establish the first long (LGM to present), high-resolution, monsoonal climate record, from terrestrial archives within the core monsoon region. This was achieved by developing a new record from Table Top Swamp (TTS) within Litchfield National Park, Northern Territory, Australia, a site where the Australian Summer Monsoon (ASM) dominates the climate.

As one of the dominant climate systems affecting Australia, understanding the operation of the monsoon is crucial for understanding Australian landscape dynamics, biological systems and human occupation history. In addition understanding past changes contributes to our ability to predict future changes, for example under climate change scenarios. Importantly it is unclear if the monsoon was active before and during the Last Glacial Maximum. There are two hypothesis of how the monsoon may have operated in response to cooling or warming; either, 1) the mean position of ASM may have changed resulting in the influence of the ASM becoming weaker or stronger at particular locations such as TTS, or 2) the ASM may have switched on or off in response to warming and cooling phases.

The existing palaeomonsoon record is problematic. Many of the records are of short duration or come from areas where factors additional to the monsoon contribute to the climate signal. The temporal resolution of the record is low due to a heavy reliance on geomorphic evidence.

A 1.2 m sediment core was extracted from Table Top swamp in Australia’s ‘Top End’ near Darwin. A variety of palaeo-environmental proxies were analysed through the core to reconstruct past conditions. These included grain size, stable N and C isotopes, pollen, diatoms and geochemistry (major and trace elements).
An age model was developed for the core by applying a Bayesian analysis to radiocarbon and OSL dates. A common problem associated with palaeoclimate research is isolating a climatic response from other possible causes of change. To overcome this problem novel hydrological modelling techniques were employed to verify that the changes recorded in the TTS archive are driven by climate. Modelling was also used to assess the likely hydrological response of the site to an inactive monsoon and to changes in sea level.

Results showed that the temperature minimum, recorded elsewhere during the Last Glacial Maximum, had no discernible effect on monsoon strength in Australia’s Top End. The monsoon was probably inactive until 26 ka when very gradual monsoon strengthening commenced, as evidenced by the stable isotope and organic matter preservation records. The rate of increase in monsoon activity increased after the LGM, but there is no discernable date when the monsoon “turned on”. The greatest shift to increased monsoon strength occurred between about 10 to 8.5 ka coinciding with flooding of the continental shelf. Maximum monsoon strength occurred at about 6 ka, broadly coincident the mid-Holocene sea level high stand and peak southern hemisphere insolation. Since then the ASM appears to have become more variable, although changes in hydrology caused by the progressive shallowing of the swamp may also explain the evidence of recent highly variable monsoon activity.
# Table of Contents

Statement of Originality ................................................................. ii

Acknowledgements ..................................................................... iii

Abstract ......................................................................................... iv

Table of Contents ........................................................................ vi

List of Tables ................................................................................ viii

List of Figures ................................................................................ ix

List of Abbreviations ..................................................................... xi

List of Appendices ......................................................................... xiii

1. Introduction ................................................................................... 14
   1.1. Research Objectives ................................................................. 16
   1.2. Thesis outline and scope ........................................................... 17

2. Site Description ............................................................................. 19
   2.1. Vegetation ............................................................................... 20
   2.2. Geology .............................................................................. 22
   2.3. Climate ................................................................................ 23

3. Operation of the Australian Summer Monsoon through time .......... 27
   3.1. Contemporary operation of the ASM ...................................... 27
   3.2. Palaeohistory of the ASM ...................................................... 31
   3.3. State of knowledge of past monsoon climate ......................... 42

4. Methods ....................................................................................... 49
   4.1. Sample collection ..................................................................... 49
   4.2. Dating ................................................................................. 49
   4.3. Loss on Ignition and Hurst Index .......................................... 52
   4.4. Grainsize ............................................................................ 53
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5.</td>
<td>Geochemistry</td>
<td>55</td>
</tr>
<tr>
<td>4.6.</td>
<td>Diatoms</td>
<td>56</td>
</tr>
<tr>
<td>4.7.</td>
<td>Stable Isotopes</td>
<td>57</td>
</tr>
<tr>
<td>4.8.</td>
<td>Pollen and Charcoal</td>
<td>58</td>
</tr>
<tr>
<td>5.</td>
<td>Results</td>
<td>60</td>
</tr>
<tr>
<td>5.1.</td>
<td>Core description</td>
<td>60</td>
</tr>
<tr>
<td>5.2.</td>
<td>Dating</td>
<td>64</td>
</tr>
<tr>
<td>5.3.</td>
<td>Loss on Ignition and Hurst Index</td>
<td>71</td>
</tr>
<tr>
<td>5.4.</td>
<td>Grainsize</td>
<td>72</td>
</tr>
<tr>
<td>5.5.</td>
<td>Geochemistry</td>
<td>76</td>
</tr>
<tr>
<td>5.6.</td>
<td>Diatoms</td>
<td>88</td>
</tr>
<tr>
<td>5.7.</td>
<td>Pollen and Charcoal</td>
<td>97</td>
</tr>
<tr>
<td>5.8.</td>
<td>Stable Isotopes</td>
<td>99</td>
</tr>
<tr>
<td>5.</td>
<td>Results</td>
<td>102</td>
</tr>
<tr>
<td>5.1.</td>
<td>Contemporary and past hydrology of TTS</td>
<td>102</td>
</tr>
<tr>
<td>5.2.</td>
<td>Introduction</td>
<td>102</td>
</tr>
<tr>
<td>5.3.</td>
<td>Method and Approach</td>
<td>103</td>
</tr>
<tr>
<td>5.4.</td>
<td>Model Parametrization and Sensitivity Analysis</td>
<td>110</td>
</tr>
<tr>
<td>5.5.</td>
<td>Results</td>
<td>119</td>
</tr>
<tr>
<td>5.6.</td>
<td>Contemporary Swamp Hydrology</td>
<td>119</td>
</tr>
<tr>
<td>5.7.</td>
<td>Sensitivity Analysis</td>
<td>125</td>
</tr>
<tr>
<td>5.8.</td>
<td>Palaeohydrology</td>
<td>125</td>
</tr>
<tr>
<td>5.</td>
<td>Summary and Discussion</td>
<td>129</td>
</tr>
<tr>
<td>5.1.</td>
<td>Sensitivity Analysis</td>
<td>129</td>
</tr>
<tr>
<td>5.2.</td>
<td>Palaeohydrology</td>
<td>133</td>
</tr>
<tr>
<td>5.3.</td>
<td>Implications of the Results</td>
<td>135</td>
</tr>
<tr>
<td>5.4.</td>
<td>Conclusion</td>
<td>135</td>
</tr>
<tr>
<td>6.</td>
<td>General Discussion</td>
<td>136</td>
</tr>
<tr>
<td>6.1.</td>
<td>Changes recorded in TTS</td>
<td>136</td>
</tr>
<tr>
<td>6.2.</td>
<td>Palaeoenvironmental and palaeoclimate conditions at TTS</td>
<td>138</td>
</tr>
<tr>
<td>6.3.</td>
<td>Provenance of Sediment</td>
<td>143</td>
</tr>
<tr>
<td>6.</td>
<td>General Conclusion</td>
<td>145</td>
</tr>
<tr>
<td>7.</td>
<td>References</td>
<td>150</td>
</tr>
<tr>
<td>8.</td>
<td>Appendices</td>
<td>161</td>
</tr>
</tbody>
</table>
## List of Tables

3.1. MIS3 (Pre 29 ka) monsoon activity ............................................................. 44  
3.2. MIS2 (29 – 12 ka) monsoon activity ......................................................... 45  
3.3. Pattern of wet events during MIS2 recorded at the Kimberly cave sites, Lynch’s Crater, and Liang Luar Cave, Flores ......................................................... 45  
3.4. Monsoon activity during MIS1 (after 12ka) .................................................... 47  
5.1. Radiocarbon ages ....................................................................................... 65  
5.2. Moisture content and calculated dose rates .............................................. 67  
5.3. Results from single-grain OSL dating ....................................................... 69  
5.4. Grain size at the periphery of the swamp ................................................... 75  
5.5. Diatom salinity classification .................................................................... 90  
5.6. Diatom nitrogen uptake metabolism classification .................................. 90  
5.7. Diatom oxygen requirements ..................................................................... 90  
5.8. Diatom saprobity index ............................................................................. 91  
5.9. Diatom trophic state .................................................................................. 91  
5.10. Diatom moisture index ............................................................................. 92  
5.11. Environmental indicator values of TTS diatoms according to Van Dam... 93  
5.12. Average environmental indicator values of TTS diatoms ....................... 94  
6.1. Distance from the shoreline to TTS during the last deglacial period .......... 107  
6.2. Average values of precipitation at various distances from theshore line ................................................................................................................ 107  
6.3. Calculated rates of precipitation at time slices identified byYokoyama et al............................................................... 108  
6.4. Volume of sediment and total swamp volume at 12 ka and 18 ka........... 114  
6.5. Hydrologic model input variables ................................................................ 118  
6.6. Parameters used to model hydrologic sensitivity of the swamp ............... 119  
6.7. Sensitivity analysis ..................................................................................... 125  
6.8. Modelled percentage of time TTS was empty at 12 ka and at 18 ka..... 128
List of Figures

1.1 Locations referred to in the text........................................................................................................16
2.1 Location of Table Top Swamp........................................................................................................19
2.2 Vegetation map of Table Top Plateau.................................................................................................20
2.3 Community S (Low woodland with a hummock grass understorey).................................................21
2.4 Melaleuca closed forest with Table Top Swamp wetland.................................................................22
2.5 Variability of average monthly rainfall at three sites........................................................................24
2.6 Darwin Airport Annual Rainfall.......................................................................................................25
2.7 Average Maximum Temperature at Darwin and at Batchelor.........................................................25
2.8 Darwin Airport Annual Mean Maximum Temperature.....................................................................26
3.1 Summary of the main factors affecting Australian monsoon climate..............................................28
4.1 Core TS423 with the location of sample depths..............................................................................54
5.1 Units, image and grain size of TS425 core.........................................................................................64
5.2 Summary of Radiocarbon and OSL data..........................................................................................66
5.3 Equivalent dose rates of TTS samples...............................................................................................68
5.4 Age-depth model of Table Top Swamp...........................................................................................71
5.5 Organic matter content and Hurst Index..........................................................................................72
5.6 Skewness of grain sizes of core TS-425..........................................................................................74
5.7 Kurtosis of grain sizes of core TS-425..............................................................................................75
5.8 Grainsize distribution of TTS sandstone..........................................................................................76
5.9 CONISS analysis of similarity in XRF data.......................................................................................77
5.10 Eigenvalue screeplot of Principal Components.............................................................................78
5.11 Principle Component Analysis of all XRF data below 238 mm depth.........................................79
5.12 K/Ti ratios through TTS425...........................................................................................................80
5.13 Y/Ho ratios of TTS sediment and parent materials.........................................................................81
5.14 Strontium counts through the TTS425 core....................................................................................82
5.15 Abundance of REE’s normalized to MUQ in soil and catchment rock.......................................83
5.16 Abundance of REE’s normalized to MUQ for sediment and catchment rock.................................84
5.17 Ti/Th ratio compared to the Zr/Hf ratio for TTS sediment (Cores) and possible parent materials...86
5.18. Th/Zr ratio compared to the Zr/Hf ratio for TTS sediment (Cores) and possible parent materials........................................................................................................87
5.19. Nb/Ta ratio compared to the Ti/Th ratio for TTS sediment and possible parent materials........................................................................................................88
5.20. Total diatom count versus depth.................................................................................................................................89
5.21. Planktic and non-planktic Diatom abundance against depth..........................................................................................96
5.22. Pollen diagram of TTS.......................................................................................................................................................98
5.23. Stable isotopes through the TTS core.............................................................................................................................100
6.1. Changes in shoreline near Table Top Swamp................................................................................................................106
6.2. Major seasonal rainfall zones of Australia........................................................................................................................110
6.3. Topographic profiles of Table Top Swamp.......................................................................................................................111
6.4. Elevation map of Table Top Swamp................................................................................................................................112
6.5. Average maximum temperature at Darwin and Batchelor...............................................................................................115
6.6. Average annual point potential evaporation.....................................................................................................................115
6.7. Variability of average monthly rainfall at three sites.........................................................................................................117
6.8. The mean onset date of the Australian monsoon.............................................................................................................120
6.9. Table Top swamp in late October 2014.............................................................................................................................121
6.10. Change in percentage of swamp capacity over time using Walkers Creek precipitation data...........................................122
6.11. Swamp filling using contemporary Walkers Creek rainfall data.......................................................................................122
6.12. Modelled lake level of TTS during 2007............................................................................................................................123
6.13. Modified normalised difference water index (MNDWI) for 2007...................................................................................124
6.14. Landsat images of Table Top Swamp...............................................................................................................................124
6.15. Modelled swamp filling at Daly Waters (18 ka)................................................................................................................126
6.16. Modelled swamp filling at Manton Dam (12 ka)................................................................................................................127
6.17. Comparison of drying at 18 ka and 12 ka..........................................................................................................................127
6.18. Modelled pattern of swamp filling simulating LGM conditions.........................................................................................129
6.19. Comparison of monsoonal and non-seasonal hydrology...............................................................................................129
6.20. Comparison of the three phases of hydrology................................................................................................................131
7.1. Schematic of hydrological phases ....................................................................................................................................138
List of Abbreviations

Ac  Catchment area
ANSTO  Australian Science and Technology Organisation
As  Swamp full area
ASM  Australian Summer Monsoon
BP  Before Present
CAM  Central Age Model
CPA  Chemical Proxy of Alteration
$\delta^{13}C$  Carbon isotope 13 depletion
DW  Dry Weight
ENSO  El Nino Southern Oscillation
EP  Effective Precipitation
HFSE  High Field Strength Element
IPWP  Indo Pacific Warm Pool
ITCZ  Intertropical Convergence Zone
ka  thousands of years ago
Lat  Laterite
LGM  Last Glacial Maximum
LOI  Loss on Ignition
m  meter
ma  million years ago
MAM  Minimum Age Model
MAP  Mean Annual Precipitation
MAT  Mean Annual Temperature
MIS  Marine Isotope Stage
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>millimetres</td>
</tr>
<tr>
<td>MNDWI</td>
<td>Modified Normalised Difference Water Index</td>
</tr>
<tr>
<td>OM</td>
<td>Organic Matter</td>
</tr>
<tr>
<td>OSL</td>
<td>Optically Stimulated Luminescence</td>
</tr>
<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>$P_{Vmax}$</td>
<td>Effective precipitation required to fill Table Top swamp</td>
</tr>
<tr>
<td>Rc</td>
<td>Runoff Coefficient</td>
</tr>
<tr>
<td>REE</td>
<td>Rare Earth Element</td>
</tr>
<tr>
<td>SS</td>
<td>Sandstone</td>
</tr>
<tr>
<td>TT</td>
<td>Table Top</td>
</tr>
<tr>
<td>TTS</td>
<td>Table Top Swamp</td>
</tr>
<tr>
<td>XRF</td>
<td>X Ray Fluorescence</td>
</tr>
</tbody>
</table>
List of Appendices

1. Average annual precipitation of locations approximately 75 km from the coast .................................................................................................................................................................................. 161
2. Average annual precipitation at locations approximately 135 km from the coast .................................................................................................................................................................................. 161
3. Average annual precipitation of locations approximately 393 km inland .................................................................................................................................................................................. 162
4. Modelled swamp filling at Pine Creek, a proxy for climate at 12 ka .................................................................................................................................................................................. 162
5. Modelled swamp filling at Jindari, a proxy for climate at 12 ka .................................................................................................................................................................................. 163
6. Modelled swamp filling at Larrimah, a proxy for climate 18 ka .................................................................................................................................................................................. 163
7. Modelled swamp filling at Mataranka Homestead, a proxy for 18 ka .................................................................................................................................................................................. 164
1. Introduction

The Australian Summer Monsoon (ASM) is the main driver of climate for one fifth of the Australian landmass, delivering eighty per cent of the Top End’s rain, yet our understanding of its operation is poor. The short historical record shows considerable interannual and interdecadal variation that is largely unexplained. However understanding the operation and variability of the monsoon is critical to Australian landscape dynamics, biological systems, water availability and human occupation history.

Despite the importance of the ASM to Australia’s climate, there are large gaps in our understanding of how the monsoon behaved during the last thirty five thousand years. Existing evidence suggests the monsoon was inactive during the last glacial maximum and reactivated at about 14 ka years ago (Fitzsimmons 2012; Wyrrwoll et al. 2001). There are two hypothesis how the monsoon may have operated in response to cooling or warming; either, 1) the mean position of ASM may have changed resulting in the influence of the ASM becoming weaker or stronger at particular locations, such as TTS (Abram et al. 2009; Griffiths et al. 2009; Haug et al. 2001; Marshall et al. 2008; Marx et al. 2009; McGregor et al. 2004; Shulmeister et al. 1995), or 2) the ASM may have switched on or off in response to warming and cooling phases (Bowler et al. 1976; Reeves et al. 2008; Spooner et al. 2005a; van der Kaars et al. 2002b; Wyrrwoll et al. 2001).

Understanding which of these hypotheses, i.e. shifting monsoon or diminishing monsoon intensity, is more likely has been hampered by limitations of the existing palaeoclimate archive. The relatively few existing palaeo-records from Northern Australia (see Fig. 1.1 for locations) are primarily based on fluvial sedimentation (Bowler 1986; Fitzsimmons 2012; Nanson et al. 2005; Nott et al. 1994, 1999; 1996a). As such they are complex to interpret and date. Furthermore they lack the resolution to derive finer (centennial to millennial scale) patterns in monsoon variability. Critically, most of the existing evidence for Australian monsoon activity comes from areas peripheral to the part of the Australian mainland directly
affected by the monsoon. While the contribution of this research is valuable it comes with qualifications associated with the non-monsoon climate signals captured alongside the monsoon signal. For example, speleothem records of ASM activity from the Kimberley are from an area at the current margins of ASM activity and provide a discontinuous record of monsoon activity, which is complicated by the influence of mid-latitude weather systems (Denniston et al. 2013b). Likewise, records from Indonesian speleothems (Denniston et al. 2013b; Lewis et al. 2011) show a sharp disconnect with the Australian monsoon after the establishment of modern sea-levels from about 9,500 years ago (McRobie et al. 2015). Similarly, records from Lake Eyre (Croke et al. 1996; Magee et al. 2004; Nanson et al. 2008) are confused by the potential contribution of moisture from mid-latitude weather systems, which currently contribute eighty per cent of the water received by the lake system (Cohen et al. 2011).

Perhaps the most directly relevant record of ASM activity comes from the Gulf of Carpentaria marine sediments (Devriendt 2011; Reeves et al. 2007; 2008; Torgersen 1985), however, the contribution of sediment from New Guinea to palaeo-Lake Carpentaria generates uncertainty in interpretation of the ASM record. Palaeoenvironmental records from Vanderlin (Prebble et al. 2005), Mua (Rowe 2008) and Groote (Shulmeister 1992; Shulmeister et al. 1995) islands is useful, but is of limited resolution and short duration, i.e. typically less than 8 ka. Records from tropical north Queensland (Haberle 2005; Kershaw 1983; Kershaw et al. 2007; Luly et al. 2006; Muller et al. 2008) may provide a record the ASM based on vegetation change, but they are again complicated by the potential influence of the trade winds on recorded changes. The need for a long continuous high resolution record of monsoon activity is a common theme of palaeoclimate research (e.g. (Bird et al. 2013)).

The timing of activation of monsoon conditions following the LGM has been variously put at 14 (Fitzsimmons 2012; Wyrwoll et al. 2001), 18 (Devriendt 2011; Reeves et al. 2008) and 21 (De Deckker et al. 2014) ka. This spread of ages may reflect a latitudinal gradient in the timing of changes in insolation. Alternatively they may be due to the crossing of tipping points inherent in the dynamics at
individual sites. In this study, the timing of invigoration of the monsoon at TTS was investigated to determine if there is a date at which the monsoon “switched on.”

1.1 Research objectives

In summary the key research objectives of this thesis are:

- To investigate the operation of the Australian Summer Monsoon during Marine Isotope Stage 2. Specifically to determine if the monsoon switch off, or whether it migrated north.
- To determine the date of re-establishment of the ASM after the LGM

1.2 Thesis outline and scope

Several problems associated with existing ASM research were overcome in this study by the careful selection of the study site. Table Top Swamp lies directly within the region currently affected by the Australian summer monsoon, which is largely driven by the seasonal shift in the position of the Intertropical Convergence Zone (ITCZ). During the last 35 ka the position of the ITCZ is thought to have varied between 10.5°S (currently and during the LGM) and 8°S (at 11 ka) (Marshall et al. 2008). At 13°S and 130°E the study site should have remained continuously in the region where the monsoon is the primary driver of climate. Consequently the problems encountered elsewhere of intermittent records and/or overprinting by non-monsoon climate signals are avoided at TTS.

Geospatial analysis and hydrological modelling were used to examine the sensitivity of the site to climate change and to model the likely hydrological response of the swamp to past conditions over the last 35 ka. A 1.1 m core was extracted from the deepest part of TTS. Chronology for the core was established by applying a Bayesian analysis to dates derived by Optically Stimulated Luminescence and radiocarbon techniques. A variety of analyses were performed on the core, including stable isotopes, grain size, major and trace elements, diatoms and pollen to develop a record of palaeo-environmental change in the swamp. These proxies were chosen to give a continuous record of monsoon variability that allowed internal crosschecking of results to ensure a robust palaeoclimate reconstruction was derived.

This thesis is divided into eight chapters. Chapter Two provides background information about the study site to allow understanding of the dynamics of the environment of TTS, including vegetation, geology and climate. In Chapter Three a review of our current understanding of monsoon dynamics is presented, followed by an assessment of the palaeomonsoon literature and a summary of the current state of knowledge. In Chapter Four the methods employed in this study to derive the palaeoclimate history and age model are outlined. Results of analysis are presented in Chapter Five. In order to allow subsequent discussion to focus on palaeoclimate interpretation the influence of post-depositional processes is dealt
with in this section. In Chapter Six the geospatial and hydrological analysis of the swamp are presented together with palaeohydrological reconstructions. Chapter Seven presents a discussion of the likely palaeohydrological changes in the swamp and the implications for past activity of the ASM. In the final chapter (Chapter Eight) conclusions derived from this research are presented, the limits of certainty attached to these conclusions are discussed and opportunities for future research are suggested.
2. Site Description

Table Top Swamp (TTS) is an ephemeral swamp located on the Table Top Plateau situated at -13.17815°S and 130.74585°E (Fig. 2.1). Measuring roughly 300 m by 250 m TTS lies in a small catchment of about 750,000 m². Because the maximum depth of the swamp is only about 2.6 m, it is most likely meromictic, that is, there is no temperature or salinity stratification in the water column. Organic productivity in the swamp is high and it can be considered mesotrophic. A shallow blanket (up to 230 mm in depth) of peat lines the substrate of the swamp. Below this are largely inorganic sediments to a depth of over 1,160 mm.

Figure 2.1. a) Location of Table Top Swamp and the Intertropical Convergence Zone. b) Aerial view of Table Top Swamp c) Table Top Swamp at the end of the dry season (April 2014) d) Table Top Swamp at the end of the dry season (November 2014).
2.1 Vegetation

The vegetation of the wet/dry tropics has generally been described as a mosaic of open woodland and Eucalypt forest. Using the structural classification system of Specht (1972), Kirkpatrick et al. (1987) defined eight types of vegetation community on the Litchfield National Park Plateau (Fig. 2.2.).

![Vegetation map of Table Top Plateau](image)

Figure 2.2. Vegetation map of Table Top Plateau. (Kirkpatrick et al. 1987 modified by Marx).
On the broadest scale, topography delimits the distribution of different vegetation communities. On the Plateau the distribution of five vegetation communities is edaphically delimited on the basis of fertility and the soil moisture regime.

Table Top Swamp is situated in a large tract of low woodland with a hummock grass understorey (Fig. 2.2.). This vegetation community occurs on shallow, well-drained sandy soil. Trees grow to 7 to 14 m tall; the dominant tree species is highly variable with *Callitris intratropica* (northern cypress pine) most prominent. The presence of the perennial grass *Triodia microstachya* (spinifex) and the annual grass *Eriachne ciliata* best characterises the community (Fig. 2.3.).

![Community S: Low woodland with a hummock grass understorey (after Kirkpatrick et al., 1987)](image)

*Figure 2.3. Community S: Low woodland with a hummock grass understorey (after Kirkpatrick et al., 1987) near Table Top Swamp.*
The survey of Kirkpatrick et al. (1987) did not include the aquatic environments of the Table Top Plateau, however, Bulrush (*Typha* sp.) is the dominant vegetation growing in the swamp (Fig. 2.4).

![Melaleuca closed forest with Table Top Swamp wetland dominated by Typha sp. in foreground.](image)

**Figure 2.4. Melaleuca closed forest with Table Top Swamp wetland dominated by Typha sp. in foreground.**

### 2.2 Geology

The plateau on which Table Top Swamp is situated is part of the Central Domain, one of the three geologic provinces composing the Pine Creek Orogen (Glass 2010). The surface lithology underlying Table Top Swamp is entirely within the Depot Creek Sandstone formation of the Tolmer Group which overlies the Pine Creek Geosyncline (Hollis et al. 2011). It is correlated with upper part of the Katherine River Group giving a depositional age of 1,720-1,700 Ma (Pietsch 1989). The Depot Creek sandstone consists of medium to very coarse grained, clean quartz sandstone with minor quartz pebble conglomerate beds and extensive laterisation (Pietsch et al. 1988). The laterite consists of ferruginous sandstone rubble up to boulder size in an iron oxide cement (Pietsch 1989).
The sandstone surface is usually indurated giving the rock a quartzite appearance and is friable where surface silification is absent. Quartz grains in the sandstone are clear in appearance, mainly subangular to rounded and usually comprise more than 85% of mineral mass of the Depot Creek Sandstone. Fine haematite coatings on the grain boundaries give the rock a pink appearance (Pietsch 1989).

2.3 Climate

The two nearest climate stations to Table Top Swamp are Walker Creek (station No 014279) and Batchelor Airport (Station No 014272). Walker Creek is twelve kilometers from Table Top Swamp while Batchelor Airport is 37 km away. Batchelor Airport offers a more complete record over the past although Walker Creek is closer to the site, its record is more sporadic over the past decade. Because these records are of relatively short duration (Walker Creek opened 1993, Batchelor Airport, 1992) the longer record (74 years) from Darwin Airport (Station No 014015) is also used to give an overview of the climate of the region around the study site.

Approximately 87% of annual rainfall at Darwin Airport occurs between November and March (Fig. 2.5.). Walker Creek, closest climate station to the study site receives slightly higher rainfall during these months (90% of annual precipitation). Rainfall at the study site therefore exceeds the 55% summer rainfall criterion for monsoon conditions (Wang et al. 2014). Wang and Ding’s (2008) other monsoon precipitation criterion, a 2 mm/day excess of average summer precipitation over winter precipitation, is also exceeded at the study site, that is average daily summer rainfall at Walker creek is 11.7 mm compared to average daily winter rainfall of only 0.9 mm giving a difference of 10.8 mm.

As a consequence of the monsoonal character of the climate at TTS the region has a positive moisture balance during the summer months and experiences a seasonal moisture deficit during the balance of the year.
On average Walker Creek receives more rain than Darwin, particularly in the month of February. This may be due to the altitude difference and related orographic effects. In comparison to Darwin Airport at 30 m altitude Walker Creek is much higher at 140 m. Table Top Swamp, at altitude 209 m is slightly higher then Walker Creek (altitude 140 m) and can be expected to receive higher rainfall. Therefore the Walker Creek rainfall record may somewhat underestimate rainfall at TTS.

Because of the short records of Walker Creek the longer-term rainfall patterns can only be examined from the Darwin airport climate station (note average annual rainfall at Walker creek is 1,961.3 mm while Darwin Airport’s average annual rainfall is 13% lower at 1,727 mm). Darwin Airport’s rainfall record shows considerable interannual variability, that is, rainfall can vary by approximately 1500 mm between years (e.g. between approximately 1000 mm/yr. and >2500 mm/yr.) (Fig. 2.6.). A shift to slightly wetter conditions after 1973 is indicative of recent increase in the activity of the ASM.
In contrast to the marked variability in rainfall, temperature shows a highly consistent pattern typical of tropical climates (Fig. 2.7.). The slightly lower summer temperatures experienced at Darwin compared to Batchelor, reflect a maritime influence, which does not operate throughout the rest of the year. Darwin’s average maximum temperature is 32°C, closely similar to Batchelor’s 33.7°C. The average minimum temperature of the coolest month at Batchelor Airport July is 17°C. The overall average temperature at Batchelor Airport is 27°C.

Figure 2.6. Darwin Airport Annual Rainfall (Bureau of Meteorology 2015).

Figure 2.7. Average Maximum Temperature at Darwin and at Batchelor. Note that temperature records are not available for Walker Creek (Bureau of Meteorology 2015).
There is also little interannual variability in temperature, with annual mean maximum temperature varying by 1.5°C. Note that temperatures show a steady rise of approximately 1°C since 1950 (Fig. 2.8.).

Figure 2.8. Darwin Airport Annual Mean Maximum Temperature (Bureau of Meteorology 2015).
3. Operation of the Australian Summer Monsoon through time

3.1. Contemporary operation of the ASM

The ASM is part of the global monsoon system (Wang et al. 2014). As such it shares the same basic dynamics as the world’s other monsoons, which occur in southern Asia, Central America and equatorial Africa (Beaufort et al. 2010; McRobie et al. 2015). As with the world’s other monsoons, the ASM is the result of the annual shift in the position of the ITCZ (Madden et al. 1994; Wang et al. 2014). During the austral summer the ITCZ shifts south resulting in a change of wind direction over northern Australia from easterly to north westerly. This is accompanied by elevated sea surface temperatures, increased evaporation and vigorous cloud formation, resulting in heavy rainfall (Holland 1986). Because precipitation is an important aspect of the monsoon system contemporary definitions of the monsoon include measures of the amount and seasonality of rainfall in their definition, as discussed in Chapter 2.

The ASM commences anywhere between mid-November and early January and finishes by mid-April. The rest of the year is dominated by easterly trade winds, which are depleted in moisture by the time they reach the study area. Consequently the easterly trade wind contributing less than 20% of annual rainfall (Bureau of Meteorology 2015).

The ASM region has been broadly defined as the area north of 18.5°S (Marshall et al. 2008), 20°S, (Gentilli 1995) or 25°S (Croke et al. 1999; Suppiah 1992). A useful distinction can be made between the true monsoon, the quasi-monsoon and the pseudo-monsoon. Gentilli (1995) argues that an essential feature of monsoon wind is its high moisture content derived as air masses pass over a long, direct fetch, of ocean. During summer, towards 25°S from the north, on the east coast of Australia, moist air is derived from easterly trade winds from the Pacific Ocean. These moist easterly trade winds are referred to as the quasi
monsoon and are not considered part of the true monsoon. Off the coast of northwestern Australia the summer northwesterly wind involves recycled moisture-depleted anticyclonic air, which originated as trade winds. This low-level trade wind is deflected to a south easterly direction by the Pilbara heat low. While this air mass fulfils the monsoon criteria in terms of season and direction it lacks the deep convection and high moisture content of a true monsoon. Gentilli (1971, 1995) refers to this as the pseudo monsoon. The true monsoon operates in the area between the quasi-monsoon and the pseudo-monsoon which includes Arnhem Land, Carpentaria and the Cape York Peninsular, at most between 130°E and 145°E. It occurs during the summertime development of northwesterly winds north of 20° and the associated broad region of convergence which develops as these moist winds interact with subtropical air masses. The green box (Fig. 1.1.) indicates the area where the true monsoon strongly influences the climate.

**Figure 3.1.** Summary diagram showing the main components of the Australian monsoon system. The broken yellow lines represent the approximate position of the Intertropical Convergence Zone during the austral summer (bottom line) and winter (top line). The broken blue line indicates southern boundary of the Indo Pacific Warm Pool. The red arrows indicate direction of the main currents of the Indonesian Throughflow.
Modern Climate Variability

In common with all monsoons, the ASM is driven by the seasonal interhemispheric shift of the ITCZ, which is driven by changing distribution of heat between the hemispheres. This seasonal change results in a reversal of wind direction resulting in heavy rain. Superimposed on this mechanism are a series of systems peculiar to the ASM that reflect the unique geography of the Australian region. These systems include the Indo-Pacific Warm Pool (IPWP), Indonesian Throughflow (IT), the Madden Julian Oscillation (MJO) and the Indian Ocean Dipole (IOD). While ENSO is not unique to the ASM its’ influence is particularly strong (Kershaw et al. 2003). A seasonal heat low centred over the Pilbara region and the Leeuwin current near the coast of Western Australia also influence monsoon strength. Cross-equatorial surges of cold air emanating from the Tibetan Plateau have been shown to play a role in monsoon onset though their influence is inconsistent and complicated by interactions with ENSO (Suppiah et al. 1992). Collectively these systems account for most of the variability in the ASM on an interannual scale.

Indo-Pacific Warm Pool

The Indo-Pacific Warm Pool (IPWP) is a surface layer of warm, buoyant water in the region between 10°N to 15°S and 90°E to 180°E the average temperature of which exceeds 28°C (Gagan et al 2004). Evaporation from this pool of warm water generates the warm, moist air, which drives the convective activity and precipitation characteristic of the ASM. Changes in the size and position of the IPWP lead to changes in the supply of warm, moist air which affect monsoon strength.

Indonesian Throughflow (IT) and El Nino Southern Oscillation (ENSO)

During El Nino phases of the Southern Oscillation relatively warm water in the east Pacific advects warm, moist air that drives upper atmosphere circulation from the east Pacific to the west Pacific (Trenberth 1976). During El Nino years cooler sea surface temperatures in the east Pacific reduce the gradient in sea surface temperatures between the east and west Pacific resulting in reversal of the El Nina wind pattern and reduced transport of heat and moisture from the east Pacific to
the west Pacific. The Indonesian Throughflow (IT) is a current of relatively fresh, warm water that flows from the west Pacific to the Indian Ocean. The IT, which varies in strength between 5 and 15 Sv is an important source of heat and moisture supply to the ASM (Susanto et al. 2012). Variability in IT has been linked to variations in ENSO with reduced flow during El Nino events (Gagan et al. 2004).

**Madden Julian Oscillation and the Indian Ocean Dipole**

The Madden Julian Oscillation (MJO) refers to eastward propagating cloud clusters originating in the western Indian Ocean occurring at an interval of forty to fifty days (Madden et al. 1994). Hendon et al. (1990) demonstrated the onset of 27 of the thirty monsoons prior to 1987 correlated with the arrival of an MJO cloud cluster. The MJO reflects the important contribution of heat and moisture from the Indian Ocean to the ASM.

The Indian Ocean Dipole is a measure of the variation in sea temperature between the western Indian Ocean and the relatively cool water off the coast of western Australia. This gradient in temperature influences the amount of heat and moisture advected by the MJO cloud clusters and consequently the strength of the ASM (Abram et al. 2007).

**Leeuwin Current**

The Leeuwin Current is a southward extension of the Indonesian Throughflow. It comprises a relatively strong southward flow (approximately 5 Sv or 5*10^6 m/s) of warm, low salinity tropical water along the western Australian coast extending to the Great Australian Bight (Smith et al. 1991; Wyrwoll et al. 2009). The Leeuwin Current is an important source of warm water for the ASM, especially in the Kimberley region, although it mainly operates outside the core region of the ASM. The strength of the current has been shown to be sensitive to ENSO. El Nino events are associated with a weakening of the current (Li et al. 2004).

**Pilbara and Carnarvon Heat Lows**

During summer the southern spatial extent of the monsoon is increased by the development of twin, semi-permanent heat lows, one over the Pilbara region in
Western Australia, the other over the Carnarvon region in Queensland (Suppiah 1992; Wyrwoll et al. 2001). Strong convection associated with these heat lows, especially the stronger Pilbara heat low, draws moisture from the surrounding area, serving to increase monsoon intensity.

### 3.2 Palaeohistory of the ASM

The palaeoclimate archive recovered from TTS spans the last 35 ka. This period encompasses Marine Isotope Stages (MIS) 1 and 2 entirely as well as part of stage 3 (the last 6 ka of MIS3 (20%)). Because the monsoon is by definition an annual event brought about by the seasonal change in the position of the Intertropical Convergence Zone the ideal monsoon record would have annual resolution. No palaeo ASM record to date has annual resolution, so a pure monsoon signal has not been recovered. However because all the selected records come from locations where moisture tends to be associated with the monsoon currently, it has been inferred that this was also the case in the past. Where records indicate wetter conditions this may be interpreted as indicating more intense monsoon conditions.

Changes in sea level can be expected to have exerted a profound effect on the dynamics of the Australian monsoon (Kershaw et al. 2003; Lambeck et al. 2001; McRobie et al. 2015; van der Kaars et al. 2006). Sea level fell approximately 120 - 130 m during the LGM (Murray-Wallace et al. 2014). As it rose following the LGM it flooded the wide continental shelf (Yokoyama et al. 2001b) including the flooding of Palaeo Lake Carpentaria, creating the present day Gulf of Carpentaria (Torgersen 1985). The re-flooding of the continental shelf had the effect of increasing the surface area of the ocean and simultaneously increasing moisture advection to the adjacent landmass (Griffiths et al. 2009) and increasing the strength of the Indonesian Throughflow (Ding et al. 2013; Spooner et al. 2005a). Because sea level is largely governed by northern hemisphere ice extent, which is related to high latitude insolation (Evans et al. 1977; Murray-Wallace et al. 2014), the strength of the Australian monsoon over glacial/interglacial time periods is presumed to be closely linked to insolation in high northern latitudes. However the
dominant sea level effect of northern hemisphere forcing is modulated by insolation changes in the tropics (Marshall et al. 2008; Wyrwoll et al. 2007) with increased local insolation associated with increased monsoon strength.

MIS3 (Before 29 ka)
Palaeo-ASM records from MIS3 come from lakes in northern Australia, speleothems from Indonesia and pollen records from the Queensland Tropics (Lynch’s Crater). See Figure 1.1 for locations.

During MIS3 sea level was lower than present (Murray-Wallace et al. 2014). The current Gulf of Carpentaria existed as Palaeo Lake Carpentaria, between Australia and New Guinea (Torgersen 1985). Based on the estimated volume and spatial extent of Palaeo Lake Carpentaria, as determined by the sedimentology in a series of cores from the Gulf, only one quarter of current average annual rainfall would be required produce the lake extent (Bowler 1986). This suggests effective precipitation was half that of present between 41 and 12 ka (Torgersen 1985). Despite this, it remains unclear whether the rainfall that maintained Palaeo-Lake Carpentaria was derived from the monsoon or from other sources, i.e. advection of moisture by easterly trade winds.

At 25° S Lake Gregory lies beyond the region currently directly influenced by the monsoon, which has been variously defined as being between 18.5°S and 25°S, (Croke et al. 1999; Gentilli 1995; Marshall et al. 2008; Suppiah 1992). Despite its position outside the current monsoon zone, palaeomonsoon activity has been examined within the Lake Gregory sedimentary record. Lake Gregory has been assumed to record an ASM signal due to the influence of infrequent monsoon-driven cyclonic events or during insolation-driven southward shifts of the Intertropical Convergence Zone at various times in the past. However, the southerly position of Lake Gregory means that it is under the complimentary influence of mid-latitude weather systems that could alternatively provide moisture to the lake; therefore periods of ASM activity interpreted from the Lake Gregory must be treated with caution.
Deposition of muddy sediments near Salt Pan Creek in the Lake Gregory basin have been interpreted as indicating wet (monsoonal) conditions from 52 ka to 30 ka (Veth et al. 2009). Intermittent linear dune building phases occurred between 35 and 11.5 ka at Lake Gregory. These have been interpreted to indicate dry conditions indicative of either a failure of ASM or failure of the monsoon to penetrate as far south as Lake Gregory (Fitzsimmons 2012). An underlying assumption of Fitzsimmons’ (2012) approach, however, is that dune mobilisation/building occurs under dry conditions when vegetation cover becomes sparse. However the factors governing the formation of dunes are complex and other reasons for dune formation are possible. For example an increase in fire frequency and/or intensity may remove the vegetation and allow dune formation without change in rainfall. Therefore it remains unclear, without additional evidence, as to whether records from Lake Gregory are providing a true record of the operation of the ASM.

In northern Queensland, reduced river discharge, inferred from reduced deposition of sand in the alluvial fan of the Gilbert River (Nanson et al. 2005) was used to infer relatively arid conditions, indicative of an inactive monsoon from 50 ka till after the Last Glacial Maximum (LGM). South east of Glibert River at Lynch’s Crater, in the Atherton Tablelands, Queensland, a continuous pollen record dating from 190 ka has been developed (Kershaw 1976; Kershaw et al. 2007). During late MIS3 and MIS2 sclerophyll forest replaced rainforest as the dominant vegetation between 38 and 27 ka and remained dominant until 12 ka. This was inferred to be a period of generally weak monsoon activity (Kershaw 1976; Turney et al. 2004). However, there may have been episodes of enhanced ASM activity during this period. Simultaneous high ash yields, high Si/Al ratios, high Cyperaceae/Poaceae ratios and heavier δ¹⁵N isotope values recorded at Lynch’s Crater between 29-30 ka were interpreted as an episode of enhanced precipitation which imperfectly correspond to Heinrich Stadal 3 (Muller et al. 2008). High Si/Al ratios were interpreted to reflect high rates of biogenic silica production and therefore serve as a proxy of biological productivity. The biological cause of the increase in Si/Al ratio was confirmed by the high percentage of opaline silica in the layers where the Si/Al ratio was highest. Similarly the record from Cape Range in Western Australia
indicates non-monsoonal dry conditions before the return of summer rains at 20.4 ka (van der Kaars et al. 2002a; van der Kaars et al. 2006).

Speleothems from Liang Luar cave in Flores indicate that monsoon strength closely aligns with Southern Hemisphere insolation during MIS3 (Ayliffe 2013). Consequently it was concluded that the monsoon was weakest at 30 ka and gradually strengthened through the latter stages of MIS3.

**MIS2 (29 ka to 12 ka)**

The number and types of ASM records expands dramatically in MIS2. All of the records referred to in the previous discussion of MIS3 ASM activity continue into MIS2. Additional records from MIS2 include fluvial sedimentation records in plunge pools near Darwin, lacustrine, fluvial and emu eggshell records from Lake Eyre in Central Australia, glacial activity from New Guinea, speleothem records from the Kimberley region, and pollen records from Lake Euramoo in Queensland (see Fig. 1.1. for locations). It is noteworthy that the Darwin plunge pool studies (Nott et al. 1994, 1999; Nott et al. 1996a) are the only locations within the core monsoon region. The remaining sites receive additional non-monsoon sourced rain from other weather systems, such as trade winds and mid-latitude westerly winds. This leads to uncertainty in interpretation of past monsoon conditions from these sites.

The overall record of MIS2 shows continuation of the dry conditions recorded in MIS3 into early MIS2. This was succeeded by a trend towards wetter conditions towards the end of this period. During early MIS2 the volume of water trapped in ice caps increased, causing sea level to fall. After the LGM (~23 - 19 ka) sea level rose as glacial ice melted although the most dramatic effects of sea level rise associated with the flooding of the continental shelf occurred after MIS2 (Murray-Wallace et al. 2014; Yokoyama et al. 2001b).

During MIS2, which is dominated by the Last Glacial Maximum (LGM), Palaeo Lake Carpentaria was shown to have contracted in area between 23-19 ka, as indicated by Ba/Na and Ba/Sr ratios in ostracods which imply that Australian terrestrial
river discharge into the lake was minimal (Devriendt 2011). This has been interpreted as indicating cessation of the monsoon, or at least contraction to the far north of the Gulf of Carpentaria, during this period (Devriendt 2011). A pronounced change to wet conditions occurred at around 18 ka. The trend to increasing moisture accelerated over the following 4 ka until flooding of the lake at 12.2 ka due to rising sea levels (Devriendt 2011).

Intermittent dune activity throughout MIS2 at Lake Gregory has been interpreted to imply largely arid conditions (Fitzsimmons 2012) persisted to the end of MIS2 at 12 ka. However dating of gastropod fossils derived from a muddy, sand lacustrine deposit at Gilwah Waterhole in the Lake Gregory catchment indicates a return to monsoon conditions shortly before 14 ka (Wyrwoll et al. 2001). This discrepancy between the fossil gastropod evidence of active monsoon conditions at the same time as dune formation indicates dry conditions in the same region may be explained by time lags in the response of dune formation processes, or dating errors. If so this underscores the uncertainties and coarse resolution inherent in dune formation as a proxy of dry conditions.

Intermittent fluvial and aeolian deposition in the western catchment of Lake Eyre was interpreted by Croke et al. (1996) as indicating active monsoon conditions prior to 23 ka and weak monsoon conditions between 23 and 12 ka, after which the monsoon strengthened. The trend towards monsoon reinvigoration commenced after 14 ka. A weak monsoon phase between 19 and 14 ka was corroborated by evidence from the north-east Lake Eyre catchments showed enhanced dust deflation at the same time (Magee et al. 1998). Weak monsoon conditions for the period 28 to 15 ka are also indicated by the record of dominance by drought tolerant C4 grasses preserved in the δ^{13}C signal recorded in the egg shells of emu (Dromaius novaehollandiae) and extinct giant emu (Genyornis newtoni) collected from the Lake Eyre region (Johnson et al. 1999). The same evidence indicates a gradual strengthening of the monsoon after 15 ka.

In the ‘Top End’ fluvial deposition of coarse sedimentary units above the current levels of plunge pools recoded at three different sites close to Darwin, including
within the study site catchment, has been argued to represent flood deposits (Nott et al. 1994, 1999; 1996a). These results were interpreted as indicating synchronous extreme flooding during the period 30 to 18 ka. Consequently it was concluded that the monsoon was likely more active than at present during this period. An hiatus in flooding associated with a weakened monsoon occurred between 18 ka to about 9 ka, after which time extreme floods resumed.

Recent hydrological analysis of the plunge pool at, Wangi Falls (Soper 2014) casts doubt on the extreme magnitude of the floods suggested by Nott et al., (1994). It was found that the dynamic character of the channel, which is influenced by successive episodes of aggradation and erosion with consequent changes in channel profile, is as an important influence on depth of floodwater. Rather than changes in precipitation causing flooding it is suggested temporary aggradation of sediment causing a channel blockage that may have led to high water levels and is a more likely explanation for the raised flood deposits. In addition, and notwithstanding the aggradation and scour of the plunge pools sites, a recent re-examination of the luminescence dating of the sediments deposited below the Wangi Falls site suggests the original dating undertaken by Nott et al. (1999), is likely to be erroneous and the age of deposition overestimated (May et al. 2015a). Consequently, this critical evidence from within the core monsoon region needs to be treated with caution.

Based on a hiatus in alluvial fan deposition in the Gilbert River catchment, northern Queensland, Nanson and Jones (2005) concluded that the monsoon switched off during MIS3 and remained inactive through MIS2 until after the LGM (~19 ka). On the evidence of the formation of channels incised into mud they suggest the monsoon was more active than at present from 19 – 6 ka, though less active than during MIS 3-4.

The most critical variable controlling the extent of tropical glaciers is temperature rather than precipitation (Brown 1990). Temperature is indirectly related to monsoon strength through its relationship to the advection of heat and moisture, which “fuel” the monsoon. Consequently glacial evidence from the island of New
Guinea has provided valuable information regarding one of the factors associated with fluctuations in monsoon strength, that is temperature. Equilibrium Line altitude calculations for several mountains in New Guinea suggest air temperature was 5-6°C lower than present when the glaciers were at their maximum extent at ~19.4 ka (Prentice et al. 2005). Ice retreat and temperature increase was rapid after that date. Differences between air temperature and sea surface temperature during the LGM have been noted. It has been suggested that air temperature is controlled by sea surface temperature (Gagan 1998). However the processes controlling air temperature are different to the processes controlling sea surface temperature, which means temperature differences are likely.

In the peat deposits of Lynch’s Crater, Muller et al. (2008) identified layers marked by “somewhat synchronous” episodes of high ash yield, high Si/Al ratios, high Cyperaceae/Poaceae ratios and heavier δ15N isotope values. These changes were argued to be the result of increased precipitation, which imperfectly correspond to Heinrich events at 23-24 ka, 14.5-16 ka and 12.5-13.5 ka. These episodes of wetter conditions, which also extended into MIS3, occurring during an otherwise dry (weak monsoon) climate indicating generally weak ASM conditions (Kershaw 1976, 1983). Muller et al., (2008) propose that Heinrich events cause a southward migration of the Intertropical Convergence Zone, driving a corresponding southward migration of the monsoon. Dominance of grass and woodland taxa at Lake Euramoo, which is located close to Lynch’s Crater, confirms the regional scale of the record of dry conditions in tropical northern Queensland until 16.8 ka (Haberle 2005). After 16.8 ka the Lake Euramoo record shows a trend to increasingly moist conditions indicated by an increase in rainforest angiosperms and a decrease in herbaceous taxa. A return to drier conditions at Lake Euramoo occurred after 12.6 ka (Haberle 2005). Both the Lynch’s crater and Lake Euramoo sites lie in a region that receives considerable influence from SE trade winds, which bring significant non-monsoon rainfall (Gentilli 1971; Kershaw et al. 2007). This means the changes recorded at these sites may not be a reflection of monsoon strength alone.
Application of a BIOCLIM analysis to pollen retrieved from a marine core collected 60 km off Northwest Cape, Western Australia (22°S) allowed construction of a climate record for a zone at the current spatial limit of ASM influence (van der Kaars et al. 2002b; van der Kaars et al. 2006). Indices of mean summer rainfall and the number of humid months estimated using BIOCLIM give a good approximation of monsoon activity. This suggests the return of summer rain at ~20.4 ka. Additional pollen analysis of the same core (De Deckker et al. 2014) shows a substantial shift in rainfall to much greater precipitation at 13 ka marking the onset of the Holocene.

**MIS 1 (0-12ka)**

With the exception of the New Guinea glacial record all the records discussed in relation to MIS 2 also extend into the Holocene. The generally wetter conditions during the Holocene, combined with sampling bias, mean there are significantly more records from this period (more widespread anoxic environments in lakes and wetlands, which allowed increased organic matter preservation across northern Australia). Formation of chenier plains near the estuaries of rivers across northern Australia (Lees 1992; Lees et al. 1987) and coral records from the periphery of the Indo Pacific Warm Pool (Beck et al. 1997; McGregor et al. 2004) provide additional information on the Holocene climate across northern Australia.

The increasing sea level that marked the end of MIS3 reached a critical threshold at about 12.2 ka with the flooding of the continental shelf across northern Australia (Yokoyama et al. 2001b). The effects of this event found full expression during MIS 1 (Griffiths et al. 2013; Marshall et al. 2006; Murray-Wallace et al. 2014; Yokoyama et al. 2001b).

Rising sea levels caused flooding of Palaeo Lake Carpentaria from about 12.2 ka. The accretion of coarse sands in the submerged lake after that time shows the monsoon persisted throughout the Holocene (Devriendt 2011; Reeves et al. 2007). At Lake Gregory, intermittent dune formation until 11.5 ka suggests a dry phase, after which dunes stabilized, indicating a return to wet conditions. A brief phase of
extreme aridity at 5 ka, however, was indicated by the rapid deposition of 2.5 m of sediment on Gidgee Dune (Fitzsimmons 2012).

The Holocene record from Lake Eyre contains an important contradiction. Croke et al. (1996) interpreted ephemeral fluvial activity and aeolian deposition at Lake Eyre as indicating active monsoon conditions similar to present from ~12 ka. This evidence is in agreement with the $\delta^{13}$C emu eggshell evidence collected from the same region, which showed a prevalence of moisture-dependant C3 plants (Johnson et al. 1999). By contrast Magee and Miller (1998) used the development of beach ridges and the deposition of lacustrine sediments in the Madigan Gulf (Magee et al. 2004) to deduce a lake phase of greatest runoff between 11-6 ka with relatively dry conditions before and after.

In contrast to the evidence from Lake Eyre, Nott and Price's (1999) plunge pool evidence indicates MIS1 commenced with a subdued or inactive monsoon which was invigorated after 9 ka when flooding resumed. At Wangi Falls, directly downstream of TTS they found large magnitude flooding occurred between 8 – 3.8 ka, with flood magnitude diminishing after 3.8 ka. The late timing suggested for reactivation of the monsoon at 9 ka is at odds with the 14 ka date inferred elsewhere (Reeves et al. 2008; Wyrrwoll et al. 2001). The discrepancy between Nott and Price's record and most other records may be due to the nature of the archives with which they worked. The sedimentary deposits they analysed were laid down during extreme rainfall events. Deposits laid down by smaller, intervening events were likely to be scoured out during subsequent extreme events erasing them from the archive. Consequently the plunge pool archives record only a small component of monsoon history and are unreliable as indicators of inactivity of the monsoon. Alternatively, as discussed earlier, both the dating and interpretation of these records has been recently questioned (May et al. 2015a; Soper 2014).

On the Gilbert River, Nanson and Jones (2005) found MIS1 commenced with the monsoon system more active than at present (greater sedimentation), which continued through to 6 ka. Accretion of the Gilbert River alluvial fan was
interpreted to imply diminished ASM activity, to current levels, after 6 ka when the contemporary ASM pattern was established.

Lees (1992) interpreted interruptions to the formation of dunes and cheniers at six beach sites across northern Australia as indicating periods of high fluvial discharge associated with strong monsoon conditions. On this basis he was able to identify intervals of increased monsoon strength between 3.5 and 2.8 ka and between 2.1 and 1.6 ka. Chenier formation during the intervening interval between 2.8 and 2.1 ka was enabled by weak river discharge. This was interpreted as indicating weak monsoon conditions at this time (Lees et al. 1987). This pattern aligns with the evidence of Gillieson et al. (1991) showing major flooding in the Lennard River, Kimberley region at 2.8 ka ended a preceding dry spell. A subsequent dry period ended in a series of large floods between 2.1 – 1.8 ka.

Pollen evidence of an increasing dominance of mesic species at Groote Eylandt in the Gulf of Carpentaria (Shulmeister 1992; Shulmeister et al. 1995) indicates an increasingly active monsoon from 10 ka. This continued until 3.7 ka, but was followed by a seven hundred period of weak monsoon activity from about 3.7 to 3 ka. Wetter, but more variable, conditions occurred after 3 ka. The same pattern was found at Vanderlin Island, which is situated about 200 km further south than Groote Eylandt in the Gulf of Carpentaria, though with slightly drier conditions (Prebble et al. 2005). The pollen record from Bentinck Island, further east in the Gulf of Carpentaria, indicates a dry early Holocene was followed by a trend to wetter conditions culminating in a mid-Holocene climatic optimum, i.e., increased climate variability and aridity after 5 ka with greatest variability between 2.5 ka and 1.7 ka (Moss 2015). Pollen and stratigraphy records from the King River region, eastern Kimberley (Proske et al. 2014) include a Holocene dry phase starting after 6.5 ka, which is significantly later than at the sites in the Gulf of Carpentaria. The timing of the return to wetter conditions at the King River is indeterminate due to a break in the sedimentary history between 6.5 and 1.9 ka. The most significant event recorded in pollen record from Mua Island in the Torres Strait was the mid-Holocene marine high stand at 6.4 ka, (Rowe 2008). Apart from that small exception the record showed a stable climate over the last 7,000 years.
Similarly, the pollen record of Luly et al. (2006) from Cape York found little Holocene variability and no evidence of a dry period, as was found in other records.

The Lynch’s Crater pollen record of increasing representation of rainforest taxa and diminishing inorganic component of sediment indicates a wet interval between 12.6 and 11.6 ka, after which dry conditions returned. Dominance of rainforest taxa established at 10.9 ka marked a return to wet conditions (Kershaw 1986; Turney et al. 2004). Also at Lynch’s crater Muller et al. (2008) identified a 400 year episode of enhanced precipitation centred at 8.5 ka. The Lake Euramoo pollen record parallels the Lynch’s Crater record with some variations. The 12.6-11.6 ka wet phase recorded at Lynch’s Crater is absent from the Lake Euramoo record and the establishment of rainforest at Lake Euramoo at 9.6 ka was delayed one thousand years compared to Lynch’s Crater. It has been suggested the Lynch’s Crater record is not truly monsoonal because monsoon rain is supplemented by precipitation generated by the Southeast Trade Winds (Gentilli 1971; Shulmeister et al. 1995; Turney et al. 2004). A similar caveat applies to the Lake Euramoo record, which is derived from a geographically similar location.

Monsoon driven changes in the rate of speleothem growth at Liang Luar cave, Indonesia align with changes recorded at Australian sites until the flooding of the continental shelf. With the flooding of the continental shelf across northern Australia the correlation between the Liang Luar record and the record from sites elsewhere breaks down and increasing ENSO dominance becomes evident (Denniston et al. 2013b; Griffiths et al. 2013; McRobie et al. 2015). Speleothems from Cave KNI51 in the Kimberley region indicates active monsoon conditions in the early to mid-Holocene culminated in greatest ASM strength between 7.5 and 4.5 ka. By 4 ka a drying trend commenced which was strongest 2-1.5 ka. Modern strong ASM conditions were established after 1.5 ka (Denniston et al. 2013b).

The analysis of Sr/Ca ratios in coral can provide information about sea surface temperature, which is related to the supply of advection moisture to the monsoon. Evidence from the margins of the IPWP indicates intervals that were 1-2°C cooler
prior to 6.8 ka and between 5.5 and 4.3 ka associated with a contraction of the IPWP (Gagan et al. 2004). The southern periphery of the IPWP has yielded records of warmer intervals from 6.6 ka to 6.3 ka and after 4.3 ka as well as evidence of lower salinity after 4 ka (Abram et al. 2009; Gagan 1998; Gagan et al. 2004). This has been interpreted this as indicative of increased monsoon strength at these times (Abram et al. 2009). The intensity and duration of ENSO events appears to have increased between 2,500 and 1,700 years ago (Gagan et al. 2004; McGregor et al. 2004; Moy 2002; Woodroffe 2003).

3.3. State of knowledge of past monsoon climate

The evidence of monsoon activity during MIS3 is mixed. Records from Palaeo Lake Carpentaria, Lake Gregory dunes, Gilbert River, Lynch’s Crater and Cape Range suggest the monsoon was inactive or weak (Table 3.1.). However, contra evidence showing an active monsoon is provided by geochemical evidence from Lynch’s Crater indicating a significant period wet conditions at 29-30 ka (Muller et al. 2008), muddy lacustrine deposits at Salt Pan Creek in the Lake Gregory catchment (Veth et al. 2009) and north of Australia at Liang Luar cave, Indonesia, where speleothems indicates an active and gradually strengthening monsoon (controlled by increasing Southern Hemisphere insolation) throughout MIS3 (Ayliffe 2013). In part these discrepancies may be explained by the resolution of the records. The Lynch’s Crater geochemical evidence records a brief phase of extreme rainfall in an otherwise dry period which may not have been recorded in other, less sensitive records. The position of Lynch’s Crater in an area subjected to easterly trade wind influence and therefore casts some doubt on the monsoon source of this high rainfall episode. Similarly the location of Salt Pan Creek at the southern margin of monsoon influence may indicate a mid-latitude westerly influence rather than the monsoon may be responsible for the precipitation that gave rise to the muddy lacustrine deposits. The relatively low southern hemisphere insolation at this time would have led to a northward migration of the Intertropical Convergence Zone and with it monsoon influence. Similarly the northerly location of Liang Luar Cave closer to the equator may explain why it remained under the influence of a monsoon system that had shifted northwards. It is noteworthy that none of the
sites from which MIS3 ASM records are derived are located in the core monsoon region. As such their archives of monsoon activity are overwritten by non-monsoon influences. The conflicting indications of monsoon activity show a clear need for a high-resolution record from the core monsoon area to confirm or disprove that the monsoon was active during MIS3.

During MIS2 evidence of either a reinvigoration or a return of the ASM is provided by studies from a wide variety of locations across northern and central Australia and from Indonesia. Despite this, there is a considerable range in the timing of the return of the monsoon and the degree of strength of the monsoon (see Table 3.2.). At Northwest Cape, Western Australia, summer rainfall attributed to the return of monsoon conditions was detected as early as 20.4 ka (van der Kaars et al. 2006), although the monsoon only became vigorous after 13 ka (van der Kaars et al. 2002a). At Gilbert River, Queensland, evidence suggests the monsoon was stronger than at present from 19 ka (Nanson et al. 2005). At Palaeo-Lake Carpentaria the transition to wet monsoon conditions at 18 ka was sudden and then accelerated with time (Devriendt 2011).

The western catchment of Lake Eyre showed persistently weak monsoon conditions throughout MIS2 (Croke et al. 1999) whereas the eastern catchment showed monsoon strengthening after 14 ka (Magee et al. 1998). A regional Lake Eyre Basin analysis of the egg shells of emu (Dromaius novaehollandiae) and extinct giant emu (Genyornis newtoni) showed the ASM strengthening from 15 ka (Johnson et al. 1999), while the monsoon was shown to be reactivated at Lake Gregory from 14 ka (Wyrwoll et al. 2001). In northern Queensland at Lynch’s Crater pollen evidence implies non-monsoonal conditions prevailed throughout MIS2 (Kershaw 1976, 1983), whereas there is evidence of monsoon reinvigoration at nearby Lake Euramoo at 16.8 ka (Haberle 2005). The Darwin plunge pool records indicate a hiatus in monsoon activity between 18 and 9 ka (Nott et al. 1999; Nott et al. 1996a).
Table 3.1. MIS3 (Pre 29 ka) monsoon activity.

<table>
<thead>
<tr>
<th>Archive</th>
<th>Reference</th>
<th>Monsoon Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lake Carpentaria</td>
<td>Bowler (1986)</td>
<td>Inactive</td>
</tr>
<tr>
<td></td>
<td>Torgersen (1985)</td>
<td></td>
</tr>
<tr>
<td>2. Lake Gregory Salt Pan Creek</td>
<td>Veth et al. (2009)</td>
<td>Active 52-30 ka</td>
</tr>
<tr>
<td>3. Lake Gregory dunes</td>
<td>Fitzsimmons (2012)</td>
<td>Inactive 35-11.5 ka</td>
</tr>
<tr>
<td>5. Darwin plunge pools</td>
<td>Nott et al. (1994, 1999; 1996a)</td>
<td>Active 30-18 ka</td>
</tr>
<tr>
<td>6. Lynch’s Crater geochemistry</td>
<td>Muller et al. (2008)</td>
<td>30-29 ka wet</td>
</tr>
<tr>
<td>7. Lynch’s Crater pollen</td>
<td>Kershaw (1976)</td>
<td>38-27 ka inactive</td>
</tr>
<tr>
<td>8. Cape Range pollen</td>
<td>Van der Kaars et al. (2002b; 2006)</td>
<td>Inactive</td>
</tr>
<tr>
<td></td>
<td>(Ayliffe 2013)</td>
<td></td>
</tr>
<tr>
<td>9. Liang Luar Cave</td>
<td></td>
<td>Weakest at 30 ka, strengthening towards LGM</td>
</tr>
</tbody>
</table>

Part of the problem of deciding when the ASM reinitiated after the LGM depends on deciding when the ASM can be considered active. For example, at Northwest Cape, pollen records indicate the earliest sign of ASM activity following the LGM occurs at 20.4 ka, however, that the monsoon only becomes vigorous after 13 ka. The qualitative nature of the record means the timing of reinvigoration of the monsoon is a window between 20.4 and 13 ka. A similar scenario applies to Palaeo Lake Carpentaria, where the first signs of monsoon influence were detected at 18 ka but maximum strength during MIS2 was not attained until the end of MIS2 at around 14 ka.

The absence of a MIS2 ASM signal in pollen records from Lynch’s Crater indicates the ASM did not affect the site during MIS2. Similarly the absence of a monsoon signal in the record from the western catchment of lake Eyre suggests the monsoon did not influence this site and its was only operating over the far north of the continent. The relevance of these two records to monsoon history is questionable.
Key studies from the Lake Eyre east Basin (Magee et al. 1998) and the Darwin plunge pools Nott et al. (1994, 1999; 1996a) rely on geomorphic processes to track ASM activity. Because of the intermittent nature of geomorphic processes and potential low preservation of geomorphic signals these records do not allow continuous ASM records during MIS2. Such factors may explain much of the variation between sites in timing of the return of monsoon conditions.

Despite the lack of an ASM signal during MIS2 in the pollen record at Lynch’s Crater, geochemical analysis indicates there are variations (episodes) in moisture recorded in MIS2 that may be related to ASM activity. These episodes are superimposed on the general pattern of monsoon strengthening during MIS2 indicated by other records at Lake Eyre Basin (Johnson et al. 1999), North West Cape (van der Kaars et al. 2002b; 2006) and Liang Luar cave (Ayliffe 2013) (Table 3.2.) These episodic wet periods have been interpreted as monsoonal in character, occurred at 24-23, 16-14.5 and 13.5-12.5 ka. They broadly align with wet intervals identified in the Kimberley caves and Liang Luar at 24, 17 and 13 ka. Both Kimberley cave records and Liang Luar Cave records also indicate a dry phase at 14 ka.

In summary the timing of reinvigoration of the monsoon during MIS2 remains unresolved. Many of the issues impeding the resolution of this question arise from the location of the study sites outside the core monsoon region and the complications in interpreting geomorphic data. The fragmented, contradictory nature of the MIS2 monsoon record demonstrates the need for a long, continuous record from the core monsoon region to derive a purely monsoonal record.

Table 3.2. MIS2 (29 – 12 ka) monsoon activity

<table>
<thead>
<tr>
<th>Archive</th>
<th>Reference</th>
<th>Monsoon Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Lake Carpentaria</strong></td>
<td>Devriendt (2011)</td>
<td>Inactive 23-19 ka, active by 18 ka</td>
</tr>
<tr>
<td><strong>2. Lake Gregory</strong></td>
<td>Fitzsimmons (2012)</td>
<td>Active after 14 ka</td>
</tr>
<tr>
<td></td>
<td>Wyrwoll et al. (2001)</td>
<td></td>
</tr>
<tr>
<td><strong>3. Lake Eyre west</strong></td>
<td>(Croke et al. 1996)</td>
<td>Weak 24-12 ka</td>
</tr>
</tbody>
</table>
Table 3.3. Pattern of wet events during MIS2 recorded at the Kimberley, Western Australia cave sites, Lynch’s Crater, North Queensland and Liang Luar cave, Flores

<table>
<thead>
<tr>
<th>Lynch’s Crater</th>
<th>Kimberley Caves</th>
<th>Liang Luar</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Age ka)</td>
<td>(Age ka)</td>
<td>(Age ka)</td>
</tr>
<tr>
<td>24-23</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>16-14.5</td>
<td>17</td>
<td>17.7 – 14.6</td>
</tr>
<tr>
<td>13.5-12.5</td>
<td>13</td>
<td>12.9 – 11.5</td>
</tr>
</tbody>
</table>

Most records indicate the monsoon was active at the beginning of the Holocene (Table 3.4.). However some records indicate a dry early Holocene with monsoon strengthening later. These include lake Gregory dunes at 11.5 ka (Fitzsimmons 2012), Lake Eyre fluvial evidence at 10 ka (Magee et al. 1998), Lake Euramoo pollen at 9.6 ka (Haberle 2005), Darwin plunge pools at 9 ka (Nott et al. 1994, 1999) and the mid-Holocene, Bentinck Island pollen (Moss 2015).
Relatively dry Holocene phases are evident in several records though there is divergence in the timing ranging from 6-4 ka and 2.4-1.3 ka in Kimberley mound springs (McGowan et al. 2012), 5 ka (Lake Gregory dunes, Fitzsimmons 2012), after 6.5 ka at Northwest Cape (Prosk et al. 2014), after 5 ka at Bentinck island (Moss 2015) and 3.7 – 3 ka at Groote Eylandt (Shulmeister et al. 1995). Denniston detected a dry phase at Cave KNI51 in the Kimberley at 2 – 1.5 ka (Denniston et al. 2013b) (Table 3.4).

Evidence of maximum moisture and monsoon strength during the Holocene were recorded in the speleothem record of Cave KNI51 in the Kimberley at 7.5-4.5 ka (Denniston et al. 2013b) which loosely agrees with coral evidence of elevated SST 6.6-6.3 ka and after 4.3 ka which were linked to increased monsoon intensity (Abram et al. 2009; Gagan 1998; Gagan et al. 2004) (Table 3.4). Chenier dune building associated with a strong monsoon at 3.5-2.8 ka and 2.1-1.6 ka (Lees 1992; Lees et al. 1987) closely agrees with Gillieson’s (1991) evidence of flooding at Lennard river 2.8 and 2.1-1.8 ka. Shulmeister (1992; 1995) and Prebble (2005) detected strong monsoon conditions after 3 ka in the pollen records of two islands in the Gulf of Carpentaria.

Table 3.4. Monsoon activity during MIS1 (after 12ka).

<table>
<thead>
<tr>
<th>Archive</th>
<th>Reference</th>
<th>Monsoon condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lake Carpentaria</td>
<td>Devriendt (2011)</td>
<td>Active</td>
</tr>
<tr>
<td></td>
<td>Reeves et al. (2007)</td>
<td></td>
</tr>
<tr>
<td>2. Lake Gregory dunes</td>
<td>Fitzsimmons (2012)</td>
<td>Dunes stabilized by active monsoon at 11.5 ka, brief arid phase at 5 ka</td>
</tr>
<tr>
<td>3. Lake Eyre fluvial</td>
<td>Croke et al. (1996)</td>
<td>Similar to present from 12 ka</td>
</tr>
<tr>
<td>4. Lake Eyre lake deposits</td>
<td>Magee et al. (1998)</td>
<td>Active 10-6 ka</td>
</tr>
<tr>
<td>5. Lake Eyre emu eggshells</td>
<td>Johnson et al. (1999)</td>
<td>Active throughout MIS1</td>
</tr>
<tr>
<td>6. Darwin plunge pools</td>
<td>Nott et al. (1994, 1999; 1996a)</td>
<td>Subdued or inactive till 9 ka, flood magnitude diminished after 3.8 ka</td>
</tr>
<tr>
<td>7. Gilbert River</td>
<td>Nanson et al. (2005)</td>
<td>More active than present before 6ka when current intensity established</td>
</tr>
<tr>
<td>8. Cheniers and</td>
<td>Lees (1992); (Lees et al.</td>
<td>Strong at 3.5-2.8 ka and</td>
</tr>
<tr>
<td><strong>dunes</strong></td>
<td>1987)</td>
<td>2.1-1.6 ka, weaker between</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>---------------------------</td>
</tr>
<tr>
<td><strong>9. Lennard River</strong></td>
<td>Gillieson et al. (1991)</td>
<td>Major flooding at 2.8 ka and 2.1-1.8 ka</td>
</tr>
<tr>
<td><strong>10. Groote Eylandt</strong></td>
<td>Shulmeister (1992)</td>
<td>Active from beginning of record at 10 ka; 700 yr. hiatus after 3.7 ka; stronger, more variable after 3 ka</td>
</tr>
<tr>
<td><strong>11. Vanderlin Island</strong></td>
<td>Prebble et al. (2005)</td>
<td>Same pattern as Groote Eylandt</td>
</tr>
<tr>
<td><strong>12. Bentinck Island</strong></td>
<td>Moss (2015)</td>
<td>Dry early Holocene, maximum moisture mid-Holocene; increased variability and aridity after 5ka; greatest variability 2.5-1.7 ka.</td>
</tr>
<tr>
<td><strong>14. ¾ Mile Lake, Cape York</strong></td>
<td>Luly et al. (2006)</td>
<td>No evidence of Holocene dry spell</td>
</tr>
<tr>
<td><strong>15. Kimberly Region</strong></td>
<td>Proske et al. (2014)</td>
<td>Holocene dry phase after 6.5 ka</td>
</tr>
<tr>
<td><strong>16. Kimberley mound spring</strong></td>
<td>McGowan et al. (2012)</td>
<td>Dry phases 6-4 ka, 2.4-1.3ka</td>
</tr>
<tr>
<td><strong>17. Lynch’s Crater</strong></td>
<td>Kershaw (1986)</td>
<td>Wet phases at 12.6-11.6 ka</td>
</tr>
<tr>
<td></td>
<td>Turney et al. (2004)</td>
<td>11.6-10.9 ka</td>
</tr>
<tr>
<td></td>
<td>Muller et al. (2008)</td>
<td>8.5 ka</td>
</tr>
<tr>
<td><strong>18. Lake Euramoo</strong></td>
<td>Haberle (2005)</td>
<td>Wet conditions from 9.6 ka</td>
</tr>
<tr>
<td><strong>19. IPWP coral</strong></td>
<td>Gagan (1998)</td>
<td>Elevated SST 6.6-6.3 ka and after 4.3 ka caused increased monsoon intensity</td>
</tr>
<tr>
<td></td>
<td>Gagan et al. (2004)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abram et al. (2009)</td>
<td></td>
</tr>
<tr>
<td><strong>20. Cave KNI51</strong></td>
<td>Denniston et al. (2013b)</td>
<td>Active monsoon peaked 7.5-4.5 ka, decreasing by 4 ka, weakest 2-1.5 ka</td>
</tr>
</tbody>
</table>

Overall, it is evident that there is considerable variability in the ASM activity recorded by various palaeo archives. To some extent this is explained by the broad geographic extent over which the monsoon operates. However there are several important discrepancies in ASM records, in particular the timing of ASM reactivation after the LGM. Resolution of these discrepancies is dependent upon finding a long, continuous archive in the core monsoon area, the key aim of this study.
4. Methods

4.1 Sample Collection

The master core (TS-425 at roughly -13.17815°S, 130.74585°E) was extracted manually using a vacuum-sealed aluminium tube, which was hammered into sediment in the deepest section of TTS. The resulting core was 1,164 mm in length.

After transport to a red-light laboratory the core was split in two. One half of the core was preserved for OSL dating and was placed in cool storage for later analysis. The other half was cut into 2 mm segments until to 402 mm depth, below which it was cut at 5 mm intervals. The higher resolution in the upper half of the core allowed for a high frequency of analysis in the more recent section of the core. The resulting 357 samples were dried at 45°C for 3 days.

A second 3 m core, (TS-423 at roughly -13.17814°S, 130.74586°E) was extracted from the periphery of the swamp using motor driven percussion corer. The coring location was approximately 60 m NE of TS425 and 1.3 m higher. Samples were retrieved from 35 mm, 50 mm and 2,950 mm depths. Samples of the two types of rock present in the TTS catchment, laterite and Depot creek sandstone were collected.

4.2. Dating

Radiocarbon Dating

Radiocarbon dating was undertaken on nine samples extracted from the top 775 mm of core TS-425. Samples were dated at either the Australian Nuclear Science and Technology Organisation (ANSTO) or at the Waikato Radiocarbon Laboratory by Accelerator Mass Spectrometry. Material for 14C dating was isolated using acid-base-acid treatment to remove carbonates, atmospheric CO₂ and fulvic and humic acids. Radiocarbon dating measurements were taken on the resulting insoluble organic fraction, which is referred to in the literature as either humins or bulk
organics. The term humins is used here. Pollen concentrate samples were separated using the procedure of Moss (2013).

After combustion and graphitisation, measurements were performed using the standard Accelerator Mass Spectrometry protocols of ANSTO and the Waikato Radiocarbon Laboratory (Fink et al. 2004; Hogg et al. 2013; Hua et al. 2001). The results were calibrated using SHCal13 calibration curve in the Oxcal programme.

Paired dates from the pollen and humin fractions were obtained at depths 118 and 246 mm. Additional humin fraction dates were obtained at depths 182 and 308 mm. The choice of sampling depth was informed by several competing criteria. The need to obtain a continuous record of age was balanced against the need to better constrain dates following initial dating and to investigate depths of special interest identified by the stratigraphy of the core. Radiocarbon dating was not attempted on lower depths in the core due to the low carbon content (~5%).

**Optically stimulated luminescence dating**

Samples for OSL dating were extracted from TS-425 at three depths (75, 92 and 108 cm) under red light conditions. Material surrounding each sample position was used for dose rate determination. Material for OSL dating was sieved between 180 and 212 µm, organic matter was removed by treatment with H₂O₂. Samples were etched using 40% HF, for one hour. Following this carbonates were removed by addition of 15% HCl.

Single-grain samples were loaded into microhole discs and were stimulated with green (532 nm) laser light for 2 s at 125 °C in a Risø DA20 TL/OSL reader (Bøtter-Jensen et al. 2003) at the University of Bern (Switzerland). Irradiations were given using a calibrated 90Sr/90Y beta source. The ultraviolet OSL emissions were measured using an Electron Tubes Ltd 9635Q photomultiplier tube fitted with a 7.5 mm Hoya U-340 transmission filter. Effects arising from potential non-uniformity in the spatial distribution of the dose (e.g. Thomsen et al. 2005) were avoided by individually calibrating each position on the single grain disc. Because of the identical source rock lithology in comparison with TTS, we applied the
Single Aliquot Regenerative Dose (SAR) protocol with specifications suggested for luminescence dating at nearby Wangi Falls, where dose recovery and preheat experiments as well as inter-laboratory comparisons showed that most preheat combinations are suitable for $D_e$ estimation (May et al. 2015). Therefore, for all measurements we used preheats of 230°C for 10 s and 180°C for 10 s preceding natural/regenerative and test dose measurements, respectively. 400 individual grains were measured. $D_e$ values were estimated by summing the first 0.17 s of signal and using the final 0.3 s as background. Standard rejection criteria such as natural test dose signals and errors, recycling ratios, a recuperation test (Murray et al. 2000; Wintle et al. 2006), and an OSL-IR depletion ratio (Duller 2003) were applied for single-grain measurements. Dose recovery tests were performed on sample TS-425-75 after bleaching in sunlight for 48 hours using a laboratory beta dose of 880 Bq and a test dose of 50 Bq. Given the possibility for contamination with partially bleached grains, or younger grains from above during the core extraction (e.g. Reimann et al. 2012) we excluded obvious outlier grains from further analysis. Mean $D_e$ values were finally calculated using the Central Age Model (CAM) and the Minimum Age Model (MAM) with an assumed overdispersion of 10% (Galbraith et al. 1999; May et al. 2015b).

**Dose rate determination**

Determination of dose rate relevant elements (K, Th, U) was carried out by high-resolution gamma spectrometry (cf. Preusser et al. 2001). Then, investigation for radioactive disequilibrium was done by using the activity determined for different isotopes of the uranium decay chain ($^{238}$U, $^{226}$Rn, $^{210}$Pb) (Zander et al. 2007). Present day depth and measured field water content (~8–40%) were used for the calculation of cosmic dose rate following Prescott and Hutton (1994).

**Additional luminescence measurements**

Further sediment samples of ~5 g were taken at 50 mm intervals through the TS-425 core in a red-light laboratory for Ln/Tn analysis to provide additional relative chronological information through the core (e.g. Sanderson et al. 2010). Organic material was removed from the selected samples by H$_2$O$_2$, prior to measurement. The natural luminescence signal (Ln) was measured from the bulk sediment for
three large (~4 mm) aliquots per sample with preheats of 230°C for 10 s and 180°C for 10 s on a Freiberg Instruments Lexsyg Smart reader (Richter et al. 2013) at the University of Freiburg. A test signal (Tn) was determined by applying a beta test dose of 99 Bs (~1.3Gy), then repeating the measurement.

In order to characterize the overall behaviour of the OSL signal with depth, and detect the presence of partial bleaching or potential erosional hiati, the normalized OSL signal (Ln/Tn with a test dose of 99 Bs) was calculated.

### 4.3 Loss on Ignition and Hurst Index

Loss on Ignition (LOI) was used to determine OM content through the core (TS425) because OM content is a proxy of biological productivity controlled by moisture availability and therefore monsoon strength (Winston et al. 2014). Subsamples of approximately one gram of dry sediment from each segment through the entire length of the core were combusted at 450°C overnight. Percentage LOI was calculated for the difference between dry weight and post-ignition weight as follows

$$\text{LOI \%} = \left(\frac{\text{DW}_{45} - \text{DW}_{450}}{\text{DW}_{45}}\right) \times 100 \quad (4.1)$$

Where DW<sub>45</sub> is the weight after drying at 45°C and DW<sub>450</sub> is the weight after combustion at 450°C.

The Hurst Index is a measure of the degree of redness of sediment. The degree of red colouration has been shown to be related to the amount of, and degree of oxidation of iron. Strong red colouration is associated with long periods of aerobic conditions allowing full oxidation (Hurst 1977; Nesbitt et al. 1989); Schaetzl et al. (2005). The Hurst Index was quantified in order to gain insights into the hydrology of the swamp and it’s variation over time. Colour was examined through the core by comparison to standard Munsell colour charts and was recorded following each colour change evident in the core.
Hurst Index values were calculated for each Munsell colour chart rating based on the formula below, which integrates the contribution of hue, chroma and value to arrive at a single value:

\[
\text{Hurst Index} = \frac{(H^*C)}{V} \quad (4.2)
\]

Where \( H = \) Hue, \( C = \) Chroma and \( V = \) Value.

### 4.4. Grain Size

Variations in the size of grains deposited in the swamp provide information about the depositional processes in relation to swamp hydrology. Because more energy is required to shift larger grains with greater mass the presence of larger grain sizes may be associated with larger water discharge events and episodes of vigorous monsoon activity.

A Malvern Mastersizer 2000 was used to measure grain sizes of the main core TS425, taken from the middle of the swamp, three samples from core TS423 which was taken from the periphery of the swamp (Fig. 4.1.) and 29 soil grab samples collected from Table Top plateau in the vicinity of TTS. Grain sizes were measured for all 357 segments of the main core, TS425.
Figure 4.1. Core TS423. The location of the subsamples analysed for grainsize are indicated on the photo (photo J-M May).

The Mastersizer determines particle size by the degree of diffraction of a laser as each particle passes across it, suspended in a liquid. Inspection of material prior to analysis showed cemented aggregate was not present. Ten seconds application of ultrasound by the ultrasonic probe attached to the Mastersizer allowed disaggregation of any aggregates not visible to the naked eye and dispersal of a few grains of sample sediment in one litre of ordinary tap water. Each sample grainsize measurement represented the average of five 20s measurement periods.

The grain size of catchment rock and surface soil were measured to allow comparison with swamp sediment. Grainsize of catchment rock was measured using an alternative method because sample preparation for the Malvern Mastersizer 2000 would have necessitated grinding the samples, which would have altered the size of grains. The grainsize distributions of samples of catchment sandstone were determined microscopically from thin sections. The microscope
Graticule was used to take 203 measurements taken in two transects across the slide. Grainsizes in the laterite were too fine to be measured by this technique.

### 4.5. Geochemistry

For this study geochemical analysis was used to investigate two questions: 1) to investigate the provenance of the sediment deposited in TTS and, 2) to reconstruct palaeoenvironmental changes recorded in the sediment of TTS. Establishing the provenance of sediment can provide important palaeoenvironmental information. For example, regional drying would be indicated by high aeolian inputs into TTS, while high catchment input would indicate enhanced runoff and wet conditions.

The TS425 core was scanned at 2 mm resolution using an ITRAX core scanner at the Australian Nuclear Science and Technology Organisation (ANSTO) by Patricia Gadd. The ITRAX is equipped with continuous XRF scanning (energy dispersive X-ray fluorescence radiation) which provides a semi-quantitative measure of the elemental abundance in the core, expressed on counts per second. Importantly, when scanning a non-homogenous core, such as the TTS mastercore analysed here, results can be affected by differences in core structure, such as moisture content, bulk density and organic content. A full description of the ITRAX core scanner is given by Croudace (2015). Elemental count data for Al, Si, P, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Br, Rb, Sr, Y, Zr, Mo, Pd, Ba, Hf, Ta, Tm, Er, Ho, Dy, Eu, Sm, Nd, Ce, La, W and Pb was collected using 2 mm steps at 30kV on one half of the split core. In addition to measuring variations in the relative abundance of elements the ITRAX also measures the Mo ratio, which is a proxy of organic carbon content. The ITRAX also produces a radiograph of the core and measures magnetic susceptibility (although the outputs of these are not discussed in this thesis).

Ultra-trace element analysis was performed by solution quadrupole ICP-MS on a Agilent 7700x instrument at the Department of Earth Sciences University of Melbourne, Australia, according the procedure of Eggins et al. (1997), with modifications according to Kamber (2009). These analyses provide highly accurate
and precise data with which to investigate the provenance of sediments deposited in the mastercore.

Samples for ultra-trace element analysis were extracted from the main core (TS425) at depths 150, 182, 600, 800 and 1,000 mm. Samples of potential sediment sources, local catchment sandstone and laterite were analysed. Samples were digested in 29 ml Teflon beakers on a hot plate at 150ºC in HF-NO₃ followed by conversion with HCl and NHO₃. Digested samples were inspected to ensure that complete fluoride conversion was achieved prior to analysis. A mixture of enriched isotopes (⁶Li, ²³⁵U) and pure elemental solutions (Rh,Re,Bi), covering the full mass range of elements analysed, were added to correct for internal drift, while repeat analyses of a reference solution every 5-8 samples was undertaken to correct for external drift. Oxide interferences were corrected using the approach of Ulrich et al. (2010). Rock standards BCR-2, AGV-2, BHVO-2, JA-2 and JA-3 were analysed as unknowns alongside the samples of this study.

The major element chemistry of two collected catchment rock samples was analysed using a hand-held XRF at the University of Wollongong. Six replicate measurements were taken from clean, flat surfaces on each sample using a runtime of 130 seconds/replicate. Data were averaged into elemental abundance for each sample.

4.6. Diatoms

Variations in the relative abundance of diatoms are related to changes in lake water quality, especially pH, salinity, moisture availability and nutrient abundance (Brugam 1983). Because changes in these parameters are often related to changes in climate (Battarbee 1986) variations in diatom abundance at TTS was investigated.

Samples from depths 97, 365 and 969 mm were analysed by Dr Jessica Reeves at Federation University. These sample depths allowed reconstruction of diatom
populations at three time slices representative of the three phases of swamp hydrology (Chapter 6 Contemporary and Past Hydrology of TTS): -

1) 969 mm depth (~30 ka) corresponding to Phase 1, Dry Dominated Ephemeral Phase.
2) 365 mm depth (~8.6 ka) corresponding to Phase 2, Permanent Lake Phase and
3) 97 mm depth (<1.3 ka) corresponds to Phase 3, Wet Dominated Ephemeral Phase.

Samples were weighed after drying at 105°C overnight. Approximately 0.5 g of each sample was added to 30 ml of 10% HCl which was simmered on a hotplate for one hour. The sample was then washed with distilled water three times. This process was then repeated with H2O2. The resulting solution was diluted to equalize the concentration of all three samples. One hundred μl of sample was applied to a microscope coverslip to which 300 μl of distilled water had been added to aid dispersal. After overnight drying the coverslip was mounted on a slide using two drops of NAPTHRAX mountant. Samples were then identified under a microscope, using appropriate keys (Gell et al. 1999; Sonneman et al. 2000). A minimum of 100 diatoms was counted per slide.

4.7. Stable Isotopes

Stable nitrogen (δ¹⁵N) and carbon (δ¹³C) isotopes were measured to obtain an indication of past biological productivity of the swamp and vegetation types (see Equation 5.1 for the method of calculating δ¹⁵N and δ¹³C). Because these isotopes are biologically fractionated, changes in isotope ratio reflect changes in biological productivity and vegetation assemblage that, in this context, are assumed to be most limited by moisture availability.

Twenty-three sediment samples were extracted from the core at regular intervals and placed in small sealed vials. Sediment samples were oven-dried at 60°C for 72 h. Dried sediment samples were acidified with 0.1 M hydrochloric acid for one hour, then gently rinsed with Milli-Q water, dried and ground to a fine powder.
with mortar and pestle for isotopic analysis (Mazumder et al. 2010). Isotopic analysis was performed at the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney, Australia. Powdered and homogenised sediment samples were loaded into tin capsules and analysed with a continuous flow stable isotope mass spectrometer (GV Instruments IsoPrime EA/IRMS). A two-point calibration was employed to normalise the data, using standards that bracket the samples being analysed. Two quality control references were also included in each run. Stable isotope values were reported in delta (δ) units in parts per thousand (‰) relative to the international standards (Pee Dee Belemnite limestone for δ¹³C and nitrogen in the air for δ¹⁵N):

\[ X(\%) = \left( \frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000 \]  

(4.3)

### 4.8. Pollen and Charcoal

Knowledge of the environmental constraints governing the occurrence of species identified by pollen analysis allows inference of the conditions prevailing at the time of pollen deposition. The abundance of charcoal is a broad measure of biological productivity (Power et al. 2008), which is partly controlled by climatic factors as well as fire regime. Pollen and charcoal analysis are well-established methods of reconstructing palaeoclimatic (Kershaw 1983; Kershaw et al. 2007; Moore et al. 1991).

Twenty-five samples were extracted from the TTS core at the depths indicated in Figure 5.21. Because the topmost 200 mm is rich in organic matter and therefore more likely to contain pollen and charcoal, samples were extracted roughly every 25 mm depth. Below 200 mm depth the interval between samples was increased to roughly 50 – 70 mm as pollen preservation was assumed to be lower. Previous use of sediment from the core for other analytical procedures limited the availability of sediment in some cases; therefore samples were taken from positions slightly above or below the initially selected depths. Patrick Moss at the
University of Queensland performed sample preparation and analysis. Samples were prepared for analysis using the technique developed by van der Kaars (1991) and refined by Moss et al. (2013; 2012). This involved dissolving exotic pollen marker tablets of *Lycopodium clavatum* in 10 ml distilled water to which sediment sample was added. The samples were disaggregated by grinding before dispersal of clay by addition of 30 ml of the deflocculant tetra-sodium pyrophosphate (10%) in 100 ml beakers. After heating for 40 minutes at 100°C samples were sieved through a 200 µm mesh to remove coarse material and through an 8 µm mesh to remove clay. The fraction between 8 and 200 µm was retained as containing pollen.

After siphoning off excess liquid samples were washed twice in 10 ml distilled water to remove excess tetra-sodium pyrophosphate. Unwanted inorganic material was separated by floating off the lighter organic fraction using 6 ml of sodium polytungstate (specific gravity 2.0). After washing and centrifuging the samples were subjected to acetolysis to darken the pollen grains and remove extraneous organic matter. Acetolysis involves addition of a mixture of 9 ml acetic anhydride and 1 ml sulphuric acid to each sample and heating for five minutes before centrifuging at 3,000 rpm for five minutes. Excess liquid was poured off before the samples were treated with two water washes. Excess water was removed by the addition of 10ml ethanol, centrifuging at 3,000 rpm and pouring off the excess liquid.

After mounting the pollen on microscope slides in glycerol, pollen identification and counting were performed using a x 400 magnification optical microscope. Charcoal analysis was performed by counting all black angular fragments greater than 5 mm diameter across three transects. Exotic *Lycopodium* spores of a known concentration were also counted to allow determination of the concentrations of both pollen and charcoal per cubic centimetre. Pollen diagrams were produced using TGView (Grimm 2004). The CONISS program was used to stratigraphically define zones of the pollen diagram within which variation from the mean is minimal (Grimm 1987). The dendrograph produced by CONISS analysis is agglomerative and hierarchical.
5. Results

5.1. Core Description

In this section variations in the core are described with the aim of identifying different phases of deposition reflecting varying environmental conditions. Some characteristics of the core reflect post-depositional processes rather than palaeoclimate variability. Post-depositional alteration of the core is discussed in this section in order to allow later discussion to focus on the key aims of the thesis, which is palaeoclimate interpretation.

Variations in colour, texture, organic matter content and geochemistry allowed identification of six distinct stratigraphic units (Fig. 5.1).

Unit 6 (1,110-1,164 mm depth) is characterised by a very high content of clay in a sandy loam, and distinctive orange (5YR 4/6) mottling in a brown (7.5YR 5/2) matrix colouration. Overall the texture is fine but variable with grain size dominated by clay and sand.

High clay content in Unit 6 likely represents an extended period of weathering under moist conditions that has allowed conversion of the silt and sand-size parent material to clay particle sizes. It is suggested the preponderance of clay particle sizes reflects a long period of post-depositional weathering, rather than the size of grains at the time of deposition. The alternative explanation of winnowing of particle sizes is untenable because Unit 6 is the earliest phase of sediment deposition and all grain sizes would be deposited at the bottom of a swamp empty of sediment. The development of this layer of relatively impermeable clay with small pore spaces that acts as a seal at the bottom of the swamp is likely an important component of the hydrology of the swamp. Without this clay layer groundwater loss to the underlying porous sandstone would be expected to be significant. The shift in chemistry, texture and colour indicates an unconformity exists between Unit 6 and Unit 5. The red colouration of this unit indicates the presence of iron oxides, which may be due to illuviation from higher in the profile.
**Unit 5** (800 – 1,100 mm depth) is characterized by a downprofile transition in colour from yellowish (7.5YR 5/2) to medium to very dark greyish (5YR 4/1). The bright yellow colour is likely to be characteristic of incompletely oxidized Fe (III) goethite minerals (Schaetzl et al. 2005; Torrent et al. 1983), present as coatings on sand grains. Alternatively the colour could be provided by presence of lepidocrocite, although lepidocrocite generally occurs as mottles or concretions associated with root growth.

Grain size follows a strong coarsening trend downprofile with sand content reaching >80% in the lowermost part of this unit. Silt content shows the opposite trend declining from 70% to 10% down through the unit. Clay contributes ~4-5% of the sediment volume throughout the unit except for a peak of 40% around 800-850 mm depth which coincides with the presence of mm-scale round and light grey patches (Fig. 5.1).

The predominance of sand-size particles (up to >80%) in Unit 5 indicates deposition under conditions characterized by high-energy water transport associated with large rainfall events. However accumulation of the soluble element K in this unit indicates flushing of the swamp, which would have led to loss of K, did not occur during the formation of this unit. The accumulation of K indicates low runoff and dry climatic conditions while the transport of sand indicates infrequent heavy rainfall events possibly at the beginning of the wet season (no winnowing effect). Gleying, evidenced by the grey colour of this unit has occurred subsequent to deposition under more recent persistently wet groundwater conditions that were established in a later period (see Chapter 6, Contemporary and past hydrology).

**Unit 4** (500–800 mm depth) The dark colour (5YR 4/1), which defines this unit, is due to the presence of oxidised Fe and Mn, rather than organic matter, which remains at the same low level (~5%), as in the adjacent units. Low Fe concentration in this layer may in part be due to vertical leaching (during seasonal
Post-depositional hydrological changes associated with shallowing of the water table have caused the alterations that have led to the formation of Unit 4. The dark colour that characterises this unit was formed through the reduction of Fe and Mn in anoxic conditions that occurred after the time of deposition.

Unit 3. (360–500 mm depth) is characterised by iron mottling in a brown matrix (mottles of 7.5YR 5/6 in a matrix of 5YR4/1). This is the region of the highest Fe concentration (assumed to be hematite) in the core, reflecting transport of soluble Fe (III) ions from Unit 4 to this layer and subsequent precipitation. This depth probably marks the limit of fluctuations in the water table, which causes vertical movement of dissolved elements and elements bound to clay. Sand content is at its lowest level in the deposit (~10-15%). Silt content is still >70% but there is an increase in clay content to ~10 – 15%. The slightly higher clay content of Unit 3 compared to Unit 2 leads to the classification of texture as silt loam.

Post-depositional hydrological processes dominate development of the stratigraphy of Unit 3. Seasonal fluctuations in the water table have caused a complicated pattern of simultaneous illuviation and eluviation most apparent in the accumulation of Fe in this unit. Mobile water-soluble Fe is illuviated from higher in the stratigraphy as the water table falls at the beginning of the dry season and subsequently precipitates as immobile iron oxide sand coatings under dry season oxidizing conditions. Additional mobile iron from lower in the deposit where anoxic conditions prevail, has been translocated upwards as the water table migrates during the wet season and precipitated as the water table falls during the subsequent dry season.
Unit 2. (180-360 mm depth) This unit is a transitional unit between the organic silty loam of unit 1 and the gley zone, unit 3 below. It is therefore characterised by a blue-grey colour (GLEY 1 3/10Y) typical of gleyed sediment. The increase in OM content from less than 5% at the bottom to 38% at the top of this unit suggests a change from dry conditions to wet conditions at the time of deposition. Alternatively the high organic matter content may be due to less advanced degradation in young material. Grain size shows little variability with sand content ranging between ~10-20% and silt content between ~70-80%. Clay content is slightly elevated in comparison to unit 1. The texture of this unit is silt.

Unit 2 records the shift in hydrology from dry, oxidising conditions to anoxic moist conditions. At the commencement of formation of this unit conditions were so dry that OM preservation was negligible (~5%). By the end of formation of this unit the hydrology had completely changed as evidenced by relatively high organic content (~40%) indicating anoxic conditions due to prolonged waterlogging.

Unit 1. (0-180 mm depth) is characterised by consistently high (38%) organic matter (OM) content to 165 mm depth (see Chapter 5.3 Loss on ignition and Hurst Index). OM declines steadily below 165 mm depth to 5% at 250 mm depth. The OM content is reflected in the black colour of the sediment (GLEY 2.5/5PB). Sand content is variable and up to 40% in the upper 100 mm but declines downprofile. Overall the texture can be characterised as a silty loam. The content of sand and silt is relatively variable. This occurs in contrast to clay content, which is consistently low. The high organic content indicates this unit is waterlogged and anoxic for prolonged periods allowing preservation of organics.

Preservation of organic matter in Unit 1 suggests a predominance of lake-full (i.e. “swamp-full”) conditions combined with biological productivity in the lake. The consistent iron content reflects subaerial exposure, and oxidation of the iron to form immobile iron oxides. These apparently contradictory trends, anoxic
conditions allowing OM preservation and oxic conditions allowing oxidation of iron are explained by seasonal drying of the swamp which allows alternation between the two states, wet/anoxic and dry/oxic. The high amplitude of fluctuations in sand and silt deposition is consistent with this scenario as they imply variations in the transport energy of runoff inputs or flow into a desiccated swamp.

The relatively plentiful supply of oxygen is sufficient to satisfy microbial demand leaving Fe bound in the clay fraction. Similarly most of the other elements remain bound in their mineral matrix suggesting mineral decomposition is not advanced in this relatively recently deposited unit.

![Figure 5.1. Units, image and grainsize of TS425 core.](image)

### 5.2 Dating

**Radiocarbon age determinations**

All ages are presented as ages in calibrated years (yrs. cal.). Above 550 mm depth the $^{14}$C dates within the core generally increase with depth (Table 5.1 and Fig. 5.2), although overlap occurred in the ages derived for 246 and 308 mm depth. Ages were in the range of modern (118 mm depth) to >11,000 yr. cal. BP (545...
mm depth). However a number of significant discrepancies in the age/depth relationship were evident. Paired dates derived from the pollen and humin fractions at depths 118 and 246 mm returned large age differences, i.e. 500 and 3,300 yrs. cal. BP, respectively. The two deepest dates, which were obtained on pollen concentrate, showed an inversion in the age/depth relationship. The sample from greater depth (10,300 ±120 yr. cal. BP at 775 mm depth) returned a younger age than the sample from lesser depth (11,200 ±210 yr. cal. BP at 545 mm). It is noteworthy that pollen concentration was low in the two lowest samples where organic matter content was ~5% and no whole pollen grains were detected in pollen analysis.

Table 5.1. Radiocarbon ages.

<table>
<thead>
<tr>
<th>Lab code</th>
<th>Fraction dated</th>
<th>Depth (mm)</th>
<th>F14C (%)</th>
<th>14C Age (Yrs. BP)</th>
<th>Age (Yrs. cal BP)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wk 39261</td>
<td>Pollen</td>
<td>118</td>
<td>100 +/- 0.3</td>
<td>100 +/- 0.3</td>
<td>Modern</td>
</tr>
<tr>
<td>Wk 39263</td>
<td>Humin</td>
<td>118</td>
<td>93.9 +/- 0.3</td>
<td>506 +/- 25</td>
<td>494 - 534</td>
</tr>
<tr>
<td>OZS 777</td>
<td>Humin</td>
<td>182</td>
<td>77.6 +/- 0.2</td>
<td>2035 +/- 25</td>
<td>1894 - 2004</td>
</tr>
<tr>
<td>Wk 39262</td>
<td>Pollen</td>
<td>246</td>
<td>58.2 +/- 0.2</td>
<td>4350 +/- 25</td>
<td>4833 - 4961</td>
</tr>
<tr>
<td>Wk 39264</td>
<td>Humin</td>
<td>246</td>
<td>39.6 +/- 0.2</td>
<td>7437 +/- 35</td>
<td>8056 - 8343</td>
</tr>
<tr>
<td>OZS 778</td>
<td>Humin</td>
<td>308</td>
<td>41.18 +/- 0.2</td>
<td>7125 +/- 50</td>
<td>7795 - 8004</td>
</tr>
<tr>
<td>OZS 780</td>
<td>Humin</td>
<td>398</td>
<td>36.44 +/- 0.2</td>
<td>8110 +/- 50</td>
<td>8724 - 9130</td>
</tr>
<tr>
<td>Wk 39265</td>
<td>Pollen</td>
<td>545</td>
<td>29.6 +/- 0.2</td>
<td>9778 +/- 51</td>
<td>10826-11251</td>
</tr>
<tr>
<td>Wk 39266</td>
<td>Pollen</td>
<td>775</td>
<td>31.6 +/- 0.2</td>
<td>9244 +/- 43</td>
<td>10239-10491</td>
</tr>
</tbody>
</table>

#Dates are, rounded according to Stuiver et al. (1977).
Optically stimulated luminescence age determinations
The dose rate varies between 1.32 Gy/ka (1,080 mm depth) and 1.84 Gy/ka (750 mm depth), and displays a diminishing trend downprofile (Table 5.2.). These values are high relative to the values recorded at nearby Wangi Falls which is downstream of TTS in the same catchment (May et al. 2015a), where the main component of sediment was identified as quartz-rich sandstone, which is depleted in radioactive elements. The relatively high dose rates recorded at TTS are due to the relatively high contribution of finer sediment in
TTS, likely derived from laterite and some dust input. For example, laterite on the Table Top Plateau is relatively rich in radioactive elements compared to sandstone. Ultra-trace element analysis performed by solution quadrupole ICP-MS showed uranium concentration of laterite is 15,368 ppb compared to 1,692 ppb of sandstone and concentration of thorium in laterite is 7,019 ppb compared to 316 ppb in sandstone. The dose rate of the lowest sample, TS425-108 was lower in comparison to the samples above it. This likely reflects the different sedimentary environment in this region of the core, with sediment produced by in situ weathering as well as deposition.

Table 5.2. Moisture content and calculated dose rates.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Depth (cm)</th>
<th>Moisture %</th>
<th>Gamma Dose Rate [Gy/ka]</th>
<th>Beta Dose Rate [Gy/ka]</th>
<th>Cosmic Dose Rate [Gy/ka]</th>
<th>Total Dose Rate [Gy/ka]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS425-75</td>
<td>75</td>
<td>42.8</td>
<td>0.94± 0.05</td>
<td>0.72 ± 0.06</td>
<td>0.15 ± 0.02</td>
<td>1.84 ± 0.13</td>
</tr>
<tr>
<td>TS425-95</td>
<td>92</td>
<td>28.7</td>
<td>0.86± 0.04</td>
<td>0.66 ± 0.05</td>
<td>0.16 ± 0.02</td>
<td>1.71 ± 0.12</td>
</tr>
<tr>
<td>TS425-108</td>
<td>108</td>
<td>15.8</td>
<td>0.62± 0.04</td>
<td>0.49 ± 0.04</td>
<td>0.18 ± 0.02</td>
<td>1.32 ± 0.10</td>
</tr>
</tbody>
</table>
Figure 5.3. Equivalent dose ($D_e$) rates of the TTS samples. Panel (a) shows radial plots of equivalent dose rates. The Central $D_e$ (Age) Model (CAM) is shown by grey shading and the Minimum $D_e$ (Age) Model (MAM) by yellow shading. In panel (b) age-rank (yellow curve) and kernel-density-estimate (KDE; grey curve) for the $D_e$ distributions are plotted.

Multi-grain measurement OSL dates were derived for two depths, 750 and 1,080 mm and expressed as CAM values. Single grain OSL measurements were derived for the same two depths and additionally at 950 mm.

The radial plots of the single grain equivalent dose rate ($D_e$) (Fig. 5.3 (a)) show there is some scatter in the $D_e$ signal, which was confirmed by high overdispersion values ranging from 26 % (950 mm depth) to 36.3 % (1,080 mm depth) (Table 5.3.). The results of single grain measurements were expressed as both CAM and
MAM values. The multi-grain CAM values were consistently older than the single grain values. Single grain CAM values were older than single grain MAM values (Fig. 5.1).

For samples of the same lithology at the neighbouring Wangi Falls site, May et al. (2015a) demonstrated issues related to micro-dosimetry. Based on theoretical considerations and comparison with independent age data (i.e. 14C) these authors suggested the use of the MAM model on single grain De values as the most accurate age estimate. Consequently, only MAM values of palaeodose were chosen to most accurately reflect the true palaeodose (Table 5.3.). The ages associated with these doses were determined according to equation 5.1.

\[ \text{Age} = \frac{\text{Palaeodose}}{\text{dose rate}} \] (5.1)

Table 5.3. Results of single-grain OSL analysis.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TS425-75</td>
<td>165/400</td>
<td>28.4</td>
<td>63.82± 1.51</td>
<td>34.69± 2.51</td>
<td>45.40± 3.13</td>
<td>1</td>
<td>24.67± 2.40</td>
</tr>
<tr>
<td>TS425-95</td>
<td>105/400</td>
<td>26.0</td>
<td>77.49± 2.14</td>
<td>45.28± 3.44</td>
<td>54.87± 4.74</td>
<td>0</td>
<td>32.06± 3.59</td>
</tr>
<tr>
<td>TS425-108</td>
<td>117/400</td>
<td>36.3</td>
<td>63.18± 2.21</td>
<td>47.86± 4.07</td>
<td>40.68± 3.75</td>
<td>2</td>
<td>30.82± 3.71</td>
</tr>
</tbody>
</table>

Overall the Ln/Tn value increases with depth. However a reversal in values occurs at the bottom of the core below 900 mm depth and above 200 mm depth the curve is steep with consistently low values of approximately one. Between 200 and 900 mm the Ln/Tn value increases fairly consistently from one to six (Fig. 5.1).

**Establishment of the age model**

Cracking to 10 cm depth evident in the surface of TTS during the dry season of 2014 (Fig. 6.9.) suggests vertical mixing of sediment is likely. In addition the thick mat of *Typha* vegetation that currently blankets most of the swamp surface suggests the further complications of bioturbation and introduction of young carbon from roots to lower sediment is likely. As a result of vertical mixing the ability to date at high resolution is diminished. Consequently the precision of interpretations of sedimentary proxy records is also diminished. Comparison of
the radiocarbon dates on humins and pollen also showed discrepancies. At 246 mm depth pollen concentrate returned a calibrated radiocarbon age of 4,830 – 4,960 years ago while the equivalent age from humins was 8,050 – 8,340 years ago. The difference of about three thousand years suggests either pollen or humins has been moved from its initial point of deposition. This means either the pollen dates or the humin dates are wrong.

The pattern of the normalized natural OSL signal (Ln/Tn) indicates a relatively smooth, continuous increase in signal with depth (Fig. 5.2). This implies that sediment age increases with depth. If there had been either episodes of aeolian deflation during dry periods, or hiatuses in sedimentation, this would have likely been evident as step changes in the Ln/Tn signal because the Ln/Tn signal increases with age since burial. The general trend of the normalized natural OSL signal matches that of the humins better than that of the pollen suggesting the humins are less mobile than the pollen.

Further support for the reliability of the humin dates rather than the pollen dates was provided by the OSL ages and the discrepancy between the pollen dates at 545 and 775 mm depths. The large discrepancy between the pollen radiocarbon date for 775 mm depth (9.2 – 10.5 ka) and the OSL MAM age at depth 750 mm (24.7 ± 2.4 ka) indicates one of these figures is wrong. Confirmation that the 750 mm pollen date is probably incorrect is provided by the discrepancy between it and the pollen radiocarbon date recovered for 545 mm depth (10.8 – 11.2 ka) which is older despite deposition 205 mm higher in the deposit. When a Bayesian analysis that allowed identification of outliers was applied to the overall radiocarbon and OSL data the pollen age at 775 mm was identified as an outlier.

Finally, a Bayesian age model for the core (TS425) was developed using the radiocarbon age determinations, MAM OSL dates and Ln/Tn data (Fig. 5.4.). Despite the effects of vertical movement of carbon inherent in the dynamics of TTS an age model that provides relatively high resolution has been derived. Notably the age-depth relationship above 200 mm depth does not preserve the original stratigraphic
integrity, probably as a result of vertical mixing. Consequently ages less than 5 ka cannot be determined with any confidence.

Figure 5.4. Age-depth model of TTS derived using a Bayesian model (OxCal v4.2.4) based on MAM OSL ages excluding the outlier at 775 mm depth the pollen radiocarbon.

5.3 Loss on Ignition and Hurst Index

The results of LOI are assumed to approximate organic matter content through the master core. The organic matter (OM) content is low, averaging 5-10% by weight, in the lower part of the core below 224 mm depth corresponding closely to Units 6 to 3 (Fig. 5.5). There is a rapid increase in OM content to 38% between 224 and
162 mm depth (roughly corresponding to Unit 2). Above 162 mm (Unit 1) the organic content remains around 40%.

The Hurst Index shows values less than 61 are recorded below 540 mm depth (Units 4 – 6)(Fig. 5.5). The darkest red colour (Hurst Index 80) occurs between 330 mm and 540 mm depth, roughly corresponding to Unit 3. Above 330 mm depth (Units 1 and 2) red colouration is not evident and the Hurst Index diminishes to zero.

![Organic Content Percent and Hurst Index graph](image)

*Figure 5.5. Organic Matter Content (%) (five point average) and Hurst Index against depth (mm).*

### 5.4. Grain Size

High silt concentrations occurring in the topmost 200 mm of the main core (TS425) show significant fluctuations, between 55 and 85%. After 200 mm depth the variability in silt concentration diminishes while the proportion of silt
gradually declines so that by 800 mm depth the proportion of silt has halved, to 24% close to the bottom of the core.

Sand content in the main core (TS425) is high and fluctuates between 10% and 40% by volume in the top 200 mm of the deposit. Below this depth sand concentration plateaus at 18%. Minor concentration peaks occur, centred at 300 and 600 mm depth. Below 600 mm depth sand content increases steeply peaking at 81% at 1,106 mm depth before diminishing rapidly at the bottom of the core.

From the surface to 142 mm depth clay content is low (~4%) in the main core (TS425). It then peaks at 13.5% at 200 mm depth before reducing until around 8%, which is maintained to 400 mm depth. From this level it rises steadily to 14.5% by 451 mm depth, after which it declines to about 11% by 530 mm depth. This concentration is maintained to about 1,000 mm depth with the exception of a sharp spike centred at 811 mm depth. A steady decline in clay concentration follows to 4% by 1,071 mm depth. The bottom of the deposit is marked by a dramatic increase in clay deposition to over 40%.

The size of grains in the swamp sediment (core TS425) is dominated by silt in the upper part of the core (above approximately 800 mm depth, Units 1 to 6) while in the lower half of the core sand tends to dominate (Fig. 5.1.). There is a general inverse relationship between sand and silt concentrations in the core. The difference in grainsize concentration in the upper and lower halves of the core implies a significant change in either the depositional environment or the source/supply of sediment or both. Clay deposition shows an independent pattern.

Skewness statistics of the distribution of grain size provide measures of the distribution of grain size relative to a normal distribution. Values of skewness greater than zero indicate a disproportionately large representation of large grain sizes. Conversely skewness values less than zero indicate a large representation of small particle sizes. Analysis of the skewness values of sediment from TS-425 shows that below 1,000 mm depth skewness values are high indicating the grainsize distribution is dominated by sand. Grain sizes are biased to negative
skewness values between depths 1,000 and 300 mm indicating small grain sizes are highly represented. Above 300 mm depth grain size distribution varies around zero indicating relatively normal distribution of grain sizes (Fig. 5.6).

Figure 5.6. Skewness of grain size distributions within core TS-425.

Kurtosis grain size statistics provide a measure of the breadth of distribution of grain size. High kurtosis values indicate a high percentage of grain sizes are at, or close to the mean. Low values indicate a relatively even distribution of grain sizes. Below 900 mm depth relatively low kurtosis values, around 0.8 indicate a broad range of grain sizes are present. Between 900 and 400 mm depth kurtosis values become progressively higher indicating particle sizes are more closely clustered around the mean. Kurtosis values diminish slightly between 400 and 200 mm depth before stabilizing above 200 mm depth.
Grain size analysis conducted on core TS-423 that was taken from the periphery of the swamp showed it was mostly composed of medium to coarse sand which accounted for 85% of grainsizes on average (Table 5.4.).

Table 5.4. Grainsize at the periphery of Table Top Swamp.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Depth (mm)</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD-35</td>
<td>35</td>
<td>86</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>CD-50</td>
<td>50</td>
<td>95</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>CD-III95</td>
<td>95</td>
<td>75</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>Average %</td>
<td></td>
<td>85</td>
<td>13</td>
<td>1</td>
</tr>
</tbody>
</table>
The average grainsize concentration of twenty-nine surface sediment grab samples collected from various geomorphic settings (e.g. hill slopes, channel banks etc.) within the Wangi Creek catchment, within which Table Top Swamp is located, again demonstrates sand is overwhelmingly dominate at 96%. By comparison silt concentration is below 5% and clay below 1%. This implies there is very little production of silt or clay within Wangi Creek catchment.

Grain sizes were counted within a thin section of sandstone collected with the catchment of Table Top swamp using a microscope graticule (Fig. 5.8.). Silt accounted for 10 % of volume of grains in the rock while sand made up the balance (90 %). Note it is not possible to determine clay concentration by this method.

![Grainsize distribution in catchment sandstone at Table Top Swamp](image)

**Figure 5.8. Grainsize distribution in catchment sandstone at Table Top Swamp.**

### 5.5 Geochemistry

**Overview of TTS Chemistry**

The statistical significance of the relationships between element variations in the ITRAX data was investigated using a CONISS analysis. CONISS is a computer program used to stratigraphically define zones within which variation from the
mean is minimal (Grimm 1987). The dendrograph produced by CONISS analysis is
agglomerative and hierarchical.

The CONISS analysis shown at the right of Figure 5.9 defined two zones. The upper
zone (above 238 mm depth) is characterized by high Mo values indicating
enrichment in organic matter that was also observed in the Loss on Ignition
analysis. In this zone relatively low XRF counts are recorded for minerals not
associated with organic matter indicating their count values are diluted by the
relatively high abundance of organic matter.

![Figure 5.9. CONISS analysis of similarity in TS425.](image)

Principle component analysis was use to define statistically significant similarities
in the data. Each factor contributing to variability in the data is called a Principle
Component. Eigenvalues indicate the percentage of variation contributed by each
Principle Component. The Eigenvalue screeplot (Fig. 5.10.) shows the amount of
variance explained by each Principle Component. Principle components one (PC1)
and Principal Component two (PC2) are the two variables that explain most of the
variance in the geochemistry. PC1 explains 30% of the total variance while PC2
explains an additional 15%. When Eigenvalues were calculated for the data below
238 mm depth, that is excluding the organic component of unit 1 of the core, the amount of variability explained by the eigenvalues diminished markedly, e.g., the Eigenvalue of PC1 explained only 16% of variance. This suggests the presence of organic matter explains most of the variability in the core and that there is no other strong driver of variations in element abundance.

Figure 5.10. Eigenvalue screeplot for all data showing the contribution to explanation of variance by each Eigenvalue.

It is known that grainsize sorting can have a strong affect on the abundance of many elements. For example, elements, such as Zr, which is primarily hosted by zirconium, which has approximately double the density of quartz, can be enriched or depleted in certain sedimentary environments. As already discussed in relation to the grain size results, changes in grain size in the core are likely to be influenced by changing hydrological conditions at TTS. This may have an effect on element abundance, i.e., elemental abundance may reflect hydrological conditions.

To investigate the grainsize/element abundance relationship, a Principal Component Analysis (PCA) was conducted on the section of the core with low (<6%) carbon content, that is the sections of the core below unit 1, i.e. below 238 mm depth (Fig. 5.11.). Despite silt being the dominant grain size in TTS425 there was no significant correlation between silt concentration and elemental abundance, except in the case of Ca (co-variance coefficient 0.66). Similarly, no elements correlate with clay. This includes Al, which is typically concentrated in
aluminium silicates clays. There is, however, a reasonably strong correlation between sand and the conservative trace elements Ti (co-variance coefficient 0.68) and Zn, presumably due to the presence of these minerals in rutile, ilmenite and zircon. There is an unexpected correlation between sand percentage and several mobile elements, such as Rb, Ce, V (co-variance coefficient 0.63), K (co-variance coefficient 0.75).

*Figure 5.11. Principle Component Analysis of grainsize variability and ITRAX element count. Note data from the highly organic unit 1 was excluded from this analysis.*

**Weathering indices in TS425 sediments**

A simplified measure of weathering, i.e., using K/Ti ratio (Wei et al. 2012) generated from ITRAX data, showed that zones of higher chemical alteration occurred in the core. After peaking at ~1,050 mm depth the K/Ti ratio steadily diminishes to 400 mm depth. Above 200 mm depth there is a marked increase in the amplitude of variation (Fig. 5.12.).
In contrast to other isovalent chemical twins the Y/Ho ratio is not solely determined by parent rock in the sedimentary environment. Variations in the ratio of Y to Ho can indicate chemical weathering, whereby Y is preferentially mobilized over Ho. Fractionation of these elements becomes most extreme in marine environment where Y is concentrated over Ho due to its higher solubility (Lawrence et al. 2006). High (low) Y/Ho ratios indicate enrichment (depletion) of Y brought about by mobilization and lateral or vertical transport during weathering (Babechuk et al. 2015; Thompson et al. 2013).

The Y/Ho ratio of samples and source rocks in TTS catchment measured by ICP-MS are shown in Figure 5.13. The values for local catchment rock (laterite=21 and sandstone=22) are lower than average values for Upper Continental Crust (MUQ=26.2) (Kamber et al. 2005). Y/Ho ratios within TTS range between 24.3 and 25.7, and therefore more closely match upper continental crust. The low amplitude
of variation in sediment Y/Ho (blue bars) indicates the rate of chemical weathering has not varied significantly over time. The small degree of enrichment shown by the swamp sediments (blue bars) relative to the local catchment sandstone and laterite (first two green bars) indicates only slight chemical weathering has occurred post deposition. The sand deposited at the periphery of the swamp (red bar) shows less Y enrichment than the other sediment ratios indicting it has experienced less chemical weathering. It can be concluded the rate of chemical weathering has not varied appreciably over time.

Figure 5.13. Yttrium/Holmium ratios in sediments from TTS425, in rock samples (Sstone and Laterite) and soils (TT423) in TTS catchment, sandstone, laterite and crustal average based on absolute values. MUQ is an estimate of the average composition of continental crust plotted for comparison.

**Geochemical indicators of palaeo-environmental conditions**

Strontium abundance through the core may serve as a measure of hydrological conditions because of its propensity to substitute for Ca in carbonates and salts. High Sr abundance may therefore indicate more endorheric phases of swamp development when evaporation dominates.
High strontium ITRAX counts of ~500 are recorded at the base of the core. Strontium count values decline sharply to less than 200 by 1,100 mm depth before rising to peak values of ~600 between 950 and 700 mm depth. A steady decline in values to ~100 is recorded above depth 700 mm (Fig. 5.14).

Unfortunately, other elements, such as Ca, S and Cl, which are also commonly associated with salts or carbonate precipitates, were poorly resolved by the ITRAX core scanner therefore their abundance was not able to be investigated.

![Graph showing strontium counts through TTS425 core](image)

*Figure 5.14. Strontium counts through the TTS425 core. The blue shaded box shows the region of peak Sr counts between 700 and 950 mm depths.*

**Provenance of TTS sediment**

Two complimentary methods were used to assess the provenance of TTS sediment, REE analysis and HFSE analysis.
The Evidence of Rare Earth Element analysis

Because mineral and chemical sorting generally does not affect REE’s they retain the pattern of their parent material. Counts of the REE’s of TTS sediment and catchment material were normalized to MUQ, a proxy of continental crust, to allow comparison. The laterite and sandstone of the local catchment as well as the soil collected from the periphery of the swamp were depleted in REE’s compared to MUQ (Fig. 5.15.). TTS values for catchment rock ranging between 0.04 and 0.35 indicating REE’s were 4 – 35% of the abundance in average continental crust. Laterite shows relative enrichment in the lightest REE’s and enrichment in heavy REE’s while sandstone is enriched in light and medium REE’s and depleted in heavy REE’s. While not an exact replica of the pattern of sandstone the pattern of soil from the periphery of the swamp shows close similarity to sandstone.

Figure 5.15. Abundance of REE’s normalized to MUQ in soil from the periphery of the swamp (TT423) and catchment laterite (TT Lat) and sandstone (TT SS).

A comparison of the MUQ-normalised abundance of REE’s of catchment rocks and sediment shows varying degrees of enrichment with sediment at all depths enriched in comparison to laterite and sandstone (Fig. 5.16.). With the exception of the pattern of sediment from 600 mm depth the overall pattern of greater light
REE enrichment than heavy REE enrichment shows greater similarity to the enrichment pattern of sandstone rather than laterite.

Sediment from the two shallowest depths, 150 and 182 mm show enrichment in all elements in comparison to MUQ with values ranging between 1.2 and 2. Light and medium REE's at these depths show greater enrichment than heavy REE's.

At 800 and 1,000 mm depth the sediment shows very similar patterns of enrichment in light REE's and depletion in medium and heavy REE's relative to MUQ and a pattern that closely follows the sandstone pattern. Compared to sandstone there is a negative Ce anomaly at both 800 and 1,000 mm depth. The sediment at 1,000 mm depth is more depleted compared to the sediment at 800 mm depth.

At 600 mm depth, light, medium and heavy REE's show similar rates of depletion relative to MUQ and an overall pattern closely similar to laterite. The difference between catchment rock and sediment is smallest at 600 mm depth.

Figure 5.16. Abundance of REE's normalized to MUQ for sediment at various depths and catchment laterite (TT Lat) and sandstone (TT SS).
High Field Strength Elements

The source material from which TTS sediment was derived was investigated through the use of isovalent chemical twins. The ratios of three pairs of HFSE chemical twins were plotted for sediment, possible sources of allochthonous dust, and catchment sandstone and laterite (Figs. 5.17 – 5.19.). Several proxies of dust were considered because the actual source of dust is unknown. MUQ is an Australian estimate of the composition of continental crust based on a variety of Queensland sediments. UCC (Upper Continental Crust) from McLennan (2001) is an estimate of the abundance of each element in the earth's crust and a dust average composite from central Australia (data from Marx et al., 2009).

The results of plotting the Ti/Th ratio to the Zr/Hf ratio (Fig. 5.17.) show a clear distinction between the ratios characteristic of the catchment rock (indicated by the red circle) and TTS sediment (denoted as Cores). The values of the sediment do not align with either the potential dust sources (MUQ, UCC and Dust average) or the catchment rock (sandstone and laterite), but plot in a position intermediate between these potential sources of sediment. The coarse grained soil taken from the periphery of the swamp shares the same Zr/Hf value as the average dust, MUQ and sandstone, suggesting it is derived from any one or a mixture of these sources.
Figure 5.17. Ti/Th ratio compared to the Zr/Hf ratio for TTS sediment (Cores), catchment rock indicated by red circle (Sandstone and Laterite), sediment from the swamp edge (soil) and possible sources of allochthonous dust (MUQ, UCC and dust average).

The plot of Th/Zr against Zr/Hf shows the values for average dust and MUQ are closely similar to the value for sandstone, which makes it impossible to distinguish between the contribution of sandstone and dust to the sediment ratio (Fig. 5.18.). Nevertheless it can be seen that the sediment ratios lie between the ratio of laterite and the ratio for sandstone and two of the dust proxies. The ratios of soil are closely similar to the ratios of sandstone, and dust and dissimilar to laterite.
Figure 5.18. Th/Zr ratio compared to the Zr/Hf ratio for TTS sediment (Cores), catchment rock (Sandstone and Laterite), sediment from the swamp edge (soil) and possible sources of allochthonous dust (MUQ, UCC and dust average).

Plotting Nb/Ta versus Ti/Th shows values for sediment plot between the values of dust and the value of laterite (Fig. 5.19.). The value of sandstone is very different to the values of the other possible sources of sediment, however the Ti/Th value of sandstone is closely similar to laterite indicating it may also play a role in determining the sediment values. The value for soil is nearly identical to the value for average continental crust.
5.19. Nb/Ta ratio compared to the Ti/Th ratio for TTS sediment (Cores), catchment rock (Sandstone and Laterite), sediment from the swamp edge (soil) and possible sources of allochthonous dust (MUQ, UCC denoted series 6 and dust average).

5.6 Diatoms

A total of 1,892 diatoms representing forty taxa were counted. Achnanthidium minutissimum was the most abundant diatom species accounting for 22% of the total count. Achanthes sp. was the second most abundant group accounting for 11% of the total. Total diatom count increased up core, from 500 diatoms per slide at 969 mm depth to 750 diatoms per slide at 97 mm depth (Fig. 5.20.). Because diatoms are composed of SiO$_2$ the rate of preservation is unlikely to be affected by post-depositional oxidation, however dissolution of Si is possible. Post mortem dissolution of silicone occurs when the concentration of dissolved silicone is low. Because the sediment parent material is sandstone and laterite, which have 85% quartz content (Pietsch et al. 1988), the supply of silicone was likely not limiting. The high level of sponge spicule preservation identified in the pollen analysis provides further evidence of abundant supply of SiO$_2$. It can be concluded that due
to an ample supply of dissolved silicone, biological silicone recycling does not take place. Post-deposition dissolution of diatoms is unlikely and the diatom count is probably reflects quantities at the time of deposition.

Figure 5.20. Diatom count against Depth (mm)

Using the approach of Van Dam et al. (1994) numerical values for each of the environmental variables considered most important in limiting diatom distribution were assigned to each taxa (Table 5.11).

Indicator Values
The classification system developed by Van Dam et al. (1994) for salinity, nitrogen uptake metabolism, oxygen requirements, saprobity (the degree to which organic matter decomposition occurs), trophic state and moisture availability was applied to the diatoms of TTS. Only diatoms that account for at least 0.25% of diatom abundance for at least one depth were included in this analysis. The classification system for each of these parameters is shown in tables 5.5 to 5.10.
Table 5.5. Diatom salinity classification.

<table>
<thead>
<tr>
<th>H value</th>
<th>Description</th>
<th>Salinity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>fresh</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>2</td>
<td>fresh brackish</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>3</td>
<td>brackish fresh</td>
<td>0.8 – 1.8</td>
</tr>
<tr>
<td>4</td>
<td>brackish</td>
<td>1.8 – 9.0</td>
</tr>
</tbody>
</table>

Table 5.6. Diatom nitrogen uptake metabolism classification.

<table>
<thead>
<tr>
<th>N value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>nitrogen autotrophic taxa, tolerating very small concentrations of organically bound nitrogen</td>
</tr>
<tr>
<td>2</td>
<td>nitrogen-autotrophic taxa, tolerating elevated levels of organically bound nitrogen</td>
</tr>
<tr>
<td>3</td>
<td>facultatively nitrogen-heterotrophic taxa, needing periodically elevated concentrations of organically bound nitrogen</td>
</tr>
<tr>
<td>4</td>
<td>obligately nitrogen-heterotrophic taxa, needing continuously elevated concentrations of organically bound nitrogen</td>
</tr>
</tbody>
</table>

Table 5.7. Diatom oxygen requirements

<table>
<thead>
<tr>
<th>O value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>continuously high (about 100% concentration)</td>
</tr>
<tr>
<td>2</td>
<td>fairly high (above 75% saturation)</td>
</tr>
<tr>
<td>3</td>
<td>moderate (above 50% saturation)</td>
</tr>
<tr>
<td>4</td>
<td>low (above 30% saturation)</td>
</tr>
<tr>
<td>5</td>
<td>very low (about 10% concentration)</td>
</tr>
</tbody>
</table>

Saprobity is a measure of available organic carbon and oxygen level. In most studies it is used as a measure of the level of organic pollution.
Table 5.8. Diatom saprobity index.

<table>
<thead>
<tr>
<th>S value</th>
<th>Saprobity</th>
<th>Oxygen saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>oligiosaprobous</td>
<td>&gt;85</td>
</tr>
<tr>
<td>2</td>
<td>β- mesosaprobous</td>
<td>70 - 85</td>
</tr>
<tr>
<td>3</td>
<td>α- mesosaprobous</td>
<td>25 - 70</td>
</tr>
<tr>
<td>4</td>
<td>α- meso-/polysaprobous</td>
<td>10 - 25</td>
</tr>
<tr>
<td>5</td>
<td>polysaprobous</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Trophic state is a measure of the availability of nutrients important to diatom metabolism. Nutrients important to diatoms include inorganic phosphorus, nitrogen, oxygen, carbon and silica. The T values presented in Table 5.9 are a qualitative representation of the collective availability of these nutrients. The term traphentic, which is not widely accepted in English literature, roughly translates as trophic. T value one corresponds to oligiotrophic, T value three corresponds to mesotrophic and T value 5 corresponds to eutrophic. The remaining T values correspond to intermediate trophic states.

Table 5.9. Diatom trophic state.

<table>
<thead>
<tr>
<th>T value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>oligotraphentic</td>
</tr>
<tr>
<td>2</td>
<td>oligio-mestraphentic</td>
</tr>
<tr>
<td>3</td>
<td>mesotraphentic</td>
</tr>
<tr>
<td>4</td>
<td>meso-eutraphentic</td>
</tr>
<tr>
<td>5</td>
<td>eutraphentic</td>
</tr>
<tr>
<td>6</td>
<td>hypereutratraphentic</td>
</tr>
<tr>
<td>7</td>
<td>oligio - eutraphentic</td>
</tr>
</tbody>
</table>
Table 5.10. Diatom moisture index.

<table>
<thead>
<tr>
<th>M value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very rarely occurring outside water bodies</td>
</tr>
<tr>
<td>2</td>
<td>Mainly occurring in water bodies, sometimes on wet places</td>
</tr>
<tr>
<td>3</td>
<td>Occurring in water bodies as well as on wet or moist places</td>
</tr>
<tr>
<td>4</td>
<td>Mainly occurring on wet or moist or temporarily dry places</td>
</tr>
<tr>
<td>5</td>
<td>Nearly exclusively occurring outside water bodies</td>
</tr>
</tbody>
</table>

Note that names of some species have changed since the work of Van Dam et al. Consequently Van Dam et al.’s values for *Eunotia praerupta* (*Eunotia bigibba*), *Cymbella gracile* (*Encyonema gracile*), *Fragilaria construens* (*Staurosira construens*), *Staurosirella elliptica*, (*Staurosirella pinnata*) and *Navicula pupula* (*Sellaphora pupula*) have been assigned to their renamed equivalents (indicated in brackets).

The precision of this analysis is limited by several factors. For the six species identified only to the genus level, mean values for the genus derived by Van Dam et al. were employed. The standard deviation was large in comparison to the mean in some instances (e.g. the value of mean oxygen requirement of *Navicula* is 1.9 and the standard deviation is 1.1). Consequently the inclusion of genus mean indicator values reduced the precision of this analysis. Another taxonomic source of error is the existence of several subspecies of many diatoms, each with slightly varying indicator values. None of the TTS diatoms has been identified beyond species level. In instances where Van Dam et al. provide indicator values of several subspecies the mode of these values was applied. Sub-specific variations were less than one indicator value unit so this source of error is small. Possible variations from the indicator values recorded by Van Dam et al. also add uncertainty. Within Europe Van Dam et al. (1994) noted small geographical variations in indicator values. The contrasting climates of Europe and tropical Australia ensure that some variations from the European values are likely (Telford et al. 2006). However due to the absence of data on the autecological requirements of tropical Australian diatoms the data of Van Dam et al. has been used. As a result of these several sources of error the overall precision of this dataset is unknowable. However it can be
expected that actual values are unlikely to vary by more than one unit from the tabulated value.

Table 5.11. Environmental indicator values of TTS diatoms using the approach of Van Dam et al. (1994).

<table>
<thead>
<tr>
<th>Species Name</th>
<th>H Salinity</th>
<th>N Nitrogen uptake metabolism</th>
<th>O Oxygen requirement</th>
<th>S Saprobity</th>
<th>T Trophic State</th>
<th>M Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achnanthes Sp.</td>
<td>1.7</td>
<td>1.3</td>
<td>1.4</td>
<td>1.4</td>
<td>2</td>
<td>2.7</td>
</tr>
<tr>
<td>Achnanthisium minutissimium</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Amphora veneta</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Aulacoseira sp.</td>
<td>1.4</td>
<td>1.6</td>
<td>1.9</td>
<td>1.6</td>
<td>2.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Aulacoseira subarctica</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cyclotella comta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclotella bodanica</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cyclotella stelligera</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Eunotia bigibba</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Encyonema gracile</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Eunotia bilunaris</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Eunotia minor</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Eunotia monodon</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Eunotia pectinialis</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Eunotia sp.</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>Fragilaria sp.</td>
<td>2</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>3.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Melosira varians</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Navicula erifuga</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Navicula lanceolata</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Navicula radiosa</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Navicula sp.</td>
<td>2</td>
<td>1.7</td>
<td>1.9</td>
<td>2</td>
<td>3.8</td>
<td>3</td>
</tr>
<tr>
<td>Neidium affine</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Neidium sp.</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
<td>2.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Nitzschia sp.</td>
<td>2.6</td>
<td>2.2</td>
<td>2.2</td>
<td>2.4</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Nitzschia dubia</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Nitzschia recta</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Nitzschia tubicola</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Pinnularia sp.</td>
<td>1.3</td>
<td>1.4</td>
<td>1.8</td>
<td>1.4</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Pinnularia borealis</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Pinnularia parvulissima</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinnularia subcapitata</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Pinnularia subuiba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sellaphora pupula</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Staurosira construens</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Staurosirella pinnata</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>
The average score for each environmental indicator at each time slice is summarised in Table 5.12.

Table 5.12. Average environmental indicator values of TTS diatoms.

<table>
<thead>
<tr>
<th></th>
<th>97 mm (~1 ka)</th>
<th>365 mm (~8.6 ka)</th>
<th>969 mm (~30 ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (H)</td>
<td>2.0</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Nitrogen uptake</td>
<td>1.8</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>metabolism (N)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen requirement (O)</td>
<td>1.8</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Saprobity (S)</td>
<td>2.0</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Trophic state (T)</td>
<td>3.9</td>
<td>4.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Moisture requirement (M)</td>
<td>2.4</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Salinity values varied in a narrow range between 1.8 and 2.1 indicating fresh brackish conditions. Salinity less than 0.9% persisted throughout the record. Nitrogen uptake values varied within a narrow range between 1.7 and 1.9 indicating the presence of nitrogen autotrophic taxa that tolerate elevated concentrations of organically bound nitrogen. Oxygen requirement values between 1.8 and 2.1 indicate oxygen concentration values above 75% varied little over time. The oxygen requirement values are consistent with the saprobity values (1.9 – 2.2), which suggest oxygen saturation of 70 – 85%. Trophic state indicator values (3.7 – 4.6) indicate mesotrophic conditions. Moisture availability indicator values (2.3 – 2.5) suggest the swamp was mainly wet but dried occasionally.

Planktic species rely on the existence of a standing body of water to support their free-floating/swimming habit. By contrast benthic species, which are attached to a substrate, are able to exist in conditions were there is less water available. Benthic species are also reliant on relatively clear water conditions that allow light to penetrate to the lake bottom where they typically reside. Although planktic species abundance is low their presence suggests water was present at
all three sample depths. The predominance of benthic species (Fig. 5.21.) evident at TTS suggests relatively clear water conditions have persisted at all three sample depths.
Figure 5.21. Planktic and non-planktic Diatom abundance against depth.
5.7. Pollen and Charcoal

A total of 35 taxa were identified and divided into groups based on life form, specifically arboreal taxa, herbs, pteridophytes and aquatic taxa. Grass dominates the record accounting for around 60% of total pollen, while arboreal taxa comprises around 35% of pollen. Based on a CONISS classification (Fig. 5.22.) two pollen and charcoal zones were identified, TTP B between 330 and 183 mm depth and TTP C above 183 mm depth. A third zone, denoted TTP A, in which pollen is absent and charcoal is present in negligible quantities can be identified below TTPB. These zones are described below. Interestingly, the CONISS analysis indicated the record from 502 mm depth, which is dominated by *Ficus* pollen, was not considered to be statistically significant. Although analysis of sponge spicules is beyond the scope of this thesis their presence was noted in all samples including the sample from 1,065 mm depth, which is close to the base of the deposit.

**TTP A (1,164 to 330 mm).**

This zone encompasses depths below 330 mm and corresponds to stratigraphic units 3 to 6 and the lower half of unit 2. With the exception of 502 mm depth no pollen was recovered from the thirteen depths sampled in this zone. Zero or negligibly small amounts of charcoal were recovered from all depths and sponge spicules were present throughout this zone. 502 mm depth is characterized by a very low pollen count of approximately 100 grains dominated by arboreal taxa with *Ficus* at its greatest abundance in the record. Areceae, *Syzygium, Melaleuca, Eucalyptus* and *Callitris* are other arboreal taxa present while low levels of Poaceae represent the only herbaceous taxa present in this zone. Aquatic taxa present are *Cyperaceae* and *Typha.*
Figure 5.22. Pollen diagram for Table Top Swamp core TS425, showing relative frequency histograms for selected pollen and spore taxa, a summary diagram, concentration of charcoal and pollen and a CONISS analysis.
5.8. Stable Isotopes

Four major phases of stable isotope variation were identified through TTS425, (Fig. 5.23. panels (a) and (b)). They are:

1. $\delta^{13}$C Phase 1 (1,160 to 850 mm depth units 5-6): characterised by the highest $\delta^{13}$C depletion values in the core of approximately -18‰ and highest rates of $\delta^{15}$N enrichment of approximately +5‰.
2. $\delta^{13}$C Phase 2 (~850 to 300 mm depth broadly approximating units 3-4): characterised by a transition from C4 toward C3 ratios, i.e. the ratio becomes more depleted in $\delta^{13}$C relative to the standard changing from approximately -18 to -23‰ by 300 mm depth. $\delta^{15}$N enrichment ratios decrease from +5 to +4‰.
3. $\delta^{13}$C Phase 3 (~300 to 150 mm, approximating unit 2): records a rapid decrease in $\delta^{13}$C depletion values from -23 to -26‰ and a rapid decrease in $\delta^{15}$N enrichment ratios from +4 to +1‰.
4. $\delta^{13}$C Phase 4 (>150 mm, broadly approximating unit 1): modern $\delta^{13}$C levels (-26‰) and consistently low $\delta^{15}$N ratios of +1‰.

The C/N ratio through the core shows broadly the same pattern as $\delta^{15}$N and $\delta^{13}$C analyses (Fig. 5.23 panel (c)). However, phases 1 (1160-850 mm) and 2 of the stable isotope results appear as one phase of C/N variation while an additional phase, phase 4, occurs between depths 220 and 180 mm is apparent. The main C/N phases are therefore:

1. C/N Phase 1 (1160 to 400 mm depth): characterised by low C/N ratios averaging 5. Note that the C/N phase 1 includes phases 1 and 2 of stable isotope ratios.
2. C/N Phase 2 (~400 to 220 mm depth): a transition phase where the C/N ratio increases from ~5 to ~20. This phase corresponds to $\delta^{13}$C phase 3 but is offset temporally.
3. C/N Phase 3 (220-180 mm depth): a short period of relatively high C/N ratios (>17).
4. C/N Phase 4 (180 to 0 mm depth): characterised by slightly lower values ratios of ~16.

Figure 5.23. Stable isotopes through the TTS core; Panel (a) shows δ¹³C; panel (b) δ¹⁵N and panel (c) shows the C/N ratio. Error bars represent one standard deviation.
6. Contemporary and past hydrology of TTS

6.1. Introduction

Environments, like Table Top Swamp (TTS), which preserve a sedimentary record of past changes, underpin much of our understanding of palaeoclimate variations. A critical question, which is not commonly addressed in palaeo studies, is how sensitive is any specific palaeo archive to environmental change? That is, what is the magnitude of changes recorded in the sedimentary record? There are two ways this question can be addressed: 1) examining the sensitivity of the environment to current variability, and 2) examining whether expected past changes are recorded within the archive, i.e. what is the temporal resolution of the archive? In addition, the proxies used to derive palaeoclimate information are not always unequivocal and can be interpreted in different ways; understanding how palaeo archives may have responded to past conditions therefore aids in interpreting palaeoclimate.

Existing research on palaeo ASM activity has been summarised in Chapter 2. This review showed the climate across northern Australia varied considerably over the last 35 ka, the period recorded by the TTS archive (Magee et al. 2004; van der Kaars et al. 2006; Wyrwoll et al. 2001). A long-term drying trend commenced before 35 ka and culminated in coolest, driest conditions at the LGM (21 ±2 ka) when air temperature was approximately 5°C cooler than present (Hope et al. 2004). It is generally considered that the monsoon was inactive during and prior to the LGM (Fitzsimmons 2012; Johnson et al. 1999; Reeves et al. 2013; Reeves et al. 2007; Wyrwoll et al. 2001). A gradual trend to warmer and wetter conditions is thought to have occurred after 19 ka, with fully active monsoon conditions established by approximately 14 ka (Spooner et al. 2005b; Wyrwoll et al. 2001). The trend to stronger monsoon conditions is thought to have peaked at 8-5.5 ka (Griffiths et al. 2009). After 4.8 ka conditions became more variable as the influence of ENSO increased (Lees 1992; McGowan et al. 2012). Evidence suggests ENSO intensity increased from about ~3.5 to ~3 ka (Gagan et al. 2004; Magee et al. 2004) before diminishing approximately 900 years ago.
Current hydrological conditions at TTS are dominated by the ASM precipitation regime. TTS typically fills to its maximum depth (after which it overflows) during the wet season (December to March), with the exception of weak monsoon years, when the swamp may not fill to capacity. During the ensuing dry season (April to November) the high rate of evaporation (potential evaporation exceeds 2,200 mm/yr.) removes water from the swamp and occasionally, during drier years, when the monsoon is less active, this leads to complete drying of the swamp. As described in greater detail in Section 5.1 the uppermost sediment in TTS consists of organic rich material implying this material is deposited and preserved in the current regime, i.e. a monsoon dominated hydrologic regime. However, the deeper swamp sediment consists predominately of silt with a low organic content (<5%) implying a different depositional regime, namely drier conditions or diagenetically controlled downcore loss of organics over time.

Although the effects of variability in the activity of the Australian monsoon have been documented, i.e. changing moisture regimes, the actual response of the ASM to global patterns of cooling or warming remains uncertain. There are two hypotheses that can potentially explain how the monsoon may have operated in response to cooling or warming; either, 1) the mean position of ASM may have changed (Haug et al. 2001; Marx et al. 2009) resulting in the influence of the ASM becoming weaker or stronger at particular locations such as TTS, or 2) the ASM may have switched on or off in response to warming and cooling phases (Reeves et al. 2008). These hypotheses are not mutually exclusive, meaning the ASM may have responded differently at different times. Therefore two hydrological scenarios were modelled and compared. 1) The hydrological response of the swamp to a monsoonal rainfall regime hypothesized to reflect rainfall conditions at 18 ka was modelled and compared to 2) the modelled response to a non-seasonal rainfall distribution of similar amount.

This chapter examines the sensitivity of TTS to changes in its hydrological regime; namely changes in rainfall, runoff and evapotranspiration. This includes examining the current range of hydrological variability and its impact on TTS and examining the response of TTS to likely past climate conditions. In addition, it explores the
likely response of TTS to differing modes of operation of the ASM, i.e. the ASM switching on or off, or its north/south migration. This is achieved by using a hydrological model to examine current variability and past change. Understanding the sensitivity of Table Top swamp to hydro-climate changes aided interpretation the results of the geochemical and sediment analysis presented in Chapter 5.

6.2. Method and Approach

There are no data available for hydrological conditions in TTS; therefore the effects of current climate variability on the hydrologic regime can only be explored using a hydrological model. The same approach is then employed to examine the response of TTS to past hydroclimate conditions. This is of fundamental importance as it verifies the validity of interpreting the TTS archive as a record of climate. Modelling also allows an assessment of the relative importance of the various components of hydrology, that is run-off, evaporation, transpiration, precipitation and groundwater. This allowed a more complete understanding of the dynamics of TTS hydrology.

The hydrologic model

To examine the hydrologic regime of TTS a simple hydrologic mass balance model was used (Ladson 2008), where the effective precipitation (defined as the lake response to precipitation) required to fill the lake can be determined from Equation 6.1.

\[ P_{V_{\text{max}}} = \frac{V}{\left(\frac{As}{As+Ac}\right) + \left(\frac{Ac}{(As+Ac)}\right) \times Rc} \times (As+Ac) \]  

(6.1)

where \( P_{V_{\text{max}}} \) is effective precipitation, \( V \) is swamp water volume, \( As \) is swamp full area, \( Ac \) is catchment area and \( Rc \) is runoff coefficient. Note in this instance \( Rc \) is only applied to catchment area, as direct precipitation to lake does not result in runoff. Equation 6.1 represents a modified version of Ladson’s (2008) model, in which ground water is excluded as it is considered to make a minimal contribution to the hydrological budget of TTS (see section 4.3.1).
Equation 6.1 can be simplified to:

\[ P_{V_{\text{max}}} = \frac{V}{(A_s + (A_c R_c))} \]  \hspace{1cm} (6.2)

Determining annual effective precipitation and/or temporal variability in annual effective precipitation requires consideration of evaporation and evapotranspiration, as shown in equation 6.3:

\[ AEP = \frac{((A_s E_1) + (A_c E_{tc}) + V)}{(A_s + (A_c R_c))} \]  \hspace{1cm} (6.3)

where \( AEP \) is annual effective precipitation (m), \( E_1 \) is evaporation (m/yr.) and \( E_{tc} \) is evapotranspiration (applied to catchment only) (m/yr.).

The effect of variability in precipitation, runoff, evaporation or evapotranspiration on swamp volume can then be determined by rearranging equation 6.3 to:

\[ V = ((P - E_1) A_s) + (((P - E_{tc}) A_c) R_c) \]  \hspace{1cm} (6.4)

where \( P \) is precipitation (m).

Changing swamp water volume can then be determined from an iterative model that allows calculation of lake volume on a periodic basis as follows:

\[ V_n = ((P_{n-1} - E_{n-1}) A_s) + (((P_{n-1} - E_{tc}) A_c) R_{c_{n-1}}) \]  \hspace{1cm} (6.5)

Where the subscript \( n \) denotes the current period and the subscript \( n-1 \) denotes the previous period.

This modelling approach is based on a number of assumptions:

1. The geometry of the catchment has not changed over time.
2. The sill height has not changed over time, and therefore:
3. The maximum possible volume of TTS has not changed over time.
4. There is not a significant loss of swamp moisture to groundwater and there are no significant groundwater additions to the swamp.

5. The input data to the model accurately reflect the current and past hydrologic regime of TTS.

The likelihood of these assumptions is discussed in the following sections.

**The palaeo-hydroclimate modelling approach**

The ASM today influences the region north of approximately 25°S (Suppiah 1992) which includes TTS. The influence of the ASM declines with distance inland from the north Australian coastline. For example rainfall diminishes from 1,600 mm/year at coastal Darwin (13.5°S) to only 450 mm/year at Tennant Creek (19.5°S) 1,000 km inland at the southern limit of monsoon influence (Egan *et al.* 1996). The sea level history for Australia during the period represented by TTS, i.e. from 35 ka to present, indicates that sea level declined after 30 ka, reaching a minimum during the LGM, before sea level rose post LGM. At the height of the LGM sea level was approximately 120 m lower than present in Joseph Bonaparte Gulf, directly offshore of TTS, meaning the coastline was approximately 500 km from its present location. This change would have likely had a significant effect on moisture advection to TTS, i.e., similar to moving 500 km inland under current conditions where rainfall is half that recorded at TTS (see section 4.2.1).

Two hypotheses have been put forward for how the ASM in the past; either it migrates and as a result its influence on TTS changes through time, or the ASM has switched off in the past. This non-monsoon hydrological scenario was modelled by applying a non-seasonal temperate rainfall record to the model.

**Time/ Space Substitution for the Active ASM Scenario**

Changes in the position of the coastline in Joseph Bonaparte Gulf over the last 18 ka years were reconstructed by Yokoyama *et al.*, (2001b) using bathymetric data and glacio-hydro-eustatic modelling combined with previous geomorphic evidence and associated geochronology. From this they reproduced the coastline position at a series of time slices, 18, 16, 12, 9 and 6 ka over which the palaeo coastline moved.
closer to TTS (Fig. 6.1). The difference in position of the coastline would be expected to have a significant effect on moisture advection to TTS and therefore the hydrology of TTS. Potential northward migration of the ASM as suggested by Abram et al. (2009), Haug et al. (2001), Griffiths et al. (2009), Marshall et al. (2008), Marx et al. (2009), McGregor et al. (2004), Mohtadi et al. (2011) and Shulmeister et al. (1995) would have the effect of further reducing precipitation at the site. As a result, the outputs of this scenario can be considered the minimum of the potential hydrological changes experienced at TTS. The effect of changes in coastline position on swamp hydrology can be assessed by modelling the response of TTS to changing its moisture balance using a time/space substitution where current climate (rainfall and evapotranspiration) and hydrologic data (runoff) can be used to model likely past conditions at TTS. That is, current data from locations which are presently the same distance to the coastline as TTS would have been in the past can be substituted into equation 6.5.

Figure 6.1. Changes in shoreline reconstructed by Yokoyama et al. (2001). (a) Approximately 18,000 years ago, (b) 16,000 years ago, (c) 12,000 years ago, (d) 9,000 years ago and (e) 6,000 years ago. Bathymetry at 50 m intervals indicated by shading. The black line is the current coastline and green shading indicates land. The position of Table Top Swamp and scale in kilometres is indicated in image (e).
The changes in the shoreline reconstructed by Yokoyama et al. (2001a) allowed quantification of the distance inland of TTS at various times since the LGM (Table 6.1).

Table 6.1. Distance from the shoreline to TTS during the last deglacial period.

<table>
<thead>
<tr>
<th>Age (ka)</th>
<th>Distance from Coast (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>475</td>
</tr>
<tr>
<td>16</td>
<td>475</td>
</tr>
<tr>
<td>12</td>
<td>135</td>
</tr>
<tr>
<td>9</td>
<td>95</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
</tr>
</tbody>
</table>

Averaging the average annual rainfall of sites with average distance inland of 59, 205 and 393 km allowed quantification of the relationship between distance from the coast and precipitation, which is summarised in Table 6.2. Full details of the data used to calculate the values shown in Table 6.2 are given in Appendices 1-3. Note that no satisfactory modern analogue for the 18 – 16 ka scenario (locations 475 km inland) exists. Locations currently 475 km inland from the Indian Ocean are relatively close to the Gulf of Carpentaria and will receive moisture from that source. Therefore the rate of rainfall spatial lapse calculated for locations approximately 400 km inland was extrapolated to give an approximation of the likely rainfall at 475 km inland.

Table 6.2 Average values of annual precipitation at various distances from the shoreline

<table>
<thead>
<tr>
<th>Average Distance from Shoreline (km)</th>
<th>Average Annual Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>59</td>
<td>1595</td>
</tr>
<tr>
<td>205</td>
<td>1487</td>
</tr>
<tr>
<td>393</td>
<td>1015</td>
</tr>
</tbody>
</table>
Annual precipitation diminishes as distance from the modern coastline. For example, as average distance inland increases from 59 to 205 km average rainfall diminishes from 1,595 to 1,487 mm, i.e. by 0.74 mm per kilometre. At 393 km inland average rainfall is 36% lower than at the coast.

Calculated annual precipitation at the distances from the coast identified by Yokoyama et al. was derived based on the rate of precipitation decrease with distance inland (Table 6.3).

Table 6.3. Calculated average annual precipitation at time slices identified by Yokoyama et al.

<table>
<thead>
<tr>
<th>Time (Age ka)</th>
<th>Distance from coast (km)</th>
<th>Annual precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>475</td>
<td>685</td>
</tr>
<tr>
<td>12</td>
<td>135</td>
<td>1538</td>
</tr>
<tr>
<td>9</td>
<td>95</td>
<td>1568</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
<td>1583</td>
</tr>
</tbody>
</table>

At 6 ka the shoreline was likely to be slightly further inland than at present. Consequently, the effect of the coastline on rainfall advection would be minimal. As such, a space/time substitution of rainfall cannot be undertaken.

At 9 ka the shoreline was approximately twenty kilometres from its current position. The effect on precipitation advection of the more distant coastline at 9 ka would have only been about -1% or around -15 mm/year. This change is well within the range of contemporary inter-annual variability as shown by the Darwin Airport rainfall record (Fig.2.5.). Consequently, there was no appreciable effect of the difference in the position of the coastline on precipitation and therefore swamp hydrology at this time.

At 12 ka the shoreline was approximately 135 km from TTS. Rainfall stations approximately 135 km distant from the current coastline include Manton Dam (average annual precipitation = 1,522 mm/year), Pine creek, (average annual
precipitation = 1,492 mm/year) and Jindari (average annual precipitation = 1,462 mm/yr.). Precipitation from these stations can therefore be used to model the effects of changing coastline position on swamp hydrology at 12 ka. Each of these records included data gaps. Because the level of water in the swamp on any day is largely the result of antecedent water level, analysis was performed on segments of each record that were continuous.

At 18 ka the shoreline was approximately 475 km from TTS. Rainfall stations at 475 km from the current coastline include Larrimah, (average annual precipitation = 862 mm/year), Mataranka Homestead Resort (average annual precipitation = 859 mm/year) and Daly Waters (average annual precipitation = 673 mm./year). These sites were used to model swamp hydrology at 18 ka.

**Time/Space Substitution for the non-monsoon Scenario**

A number of studies have argued that the ASM was inactive for significant periods in the past, most notably the LGM (Bowler et al. 1976; Reeves et al. 2013; Spooner et al. 2005a; van der Kaars et al. 2002b; Wyrrwoll et al. 2001). This scenario was modelled using a non-seasonal rainfall record of similar amount to that hypothesized for TTS at 18 ka under monsoonal conditions (685 – 850 mm/year). Note that the rainfall at the LGM is likely to have been less than at 18 ka so that the 685 – 850 mm amount is likely to be the maximum probable rainfall at the LGM. A suitable rainfall record was selected using a map of average annual contemporary rainfall (Fig. 6.2.). The Oberon station (33.67°S, 149.83°E, Bureau of Meteorology Station No. 63063; average annual rainfall = 840 mm) in NSW was chosen to represent a rainfall scenario likely to have been experienced at TTS during the LGM. The average rainfall of Oberon it is closely similar to the average rainfall of the locations used to model the 18 ka scenario, Larrimah (857 mm) and Mataranka Homestead (859 mm) which allows a simple comparison of the active and inactive monsoon regimes.
Figure 6.2. Major seasonal rainfall zones of Australia. The green shaded areas experience non-seasonal rainfall. The rainfall record from Oberon with rainfall similar to that modelled for 18 ka was selected to model the non-monsoon scenario.

6.3. Model Parametrization and Sensitivity Analysis

In the following section the selection and generation of the input variables required for the model (Eqn. 6.5) are described. In addition the sensitivity of the swamp to changes in input variables is explored. The effect of changing each input variable by 10% and 15% was modelled to determine the resulting change in drying of the swamp.

Swamp and catchment morphology

Importantly the maximum extent (spatial area) and maximum volume of TTS are controlled by a sill (Fig. 6.3 and 6.4.) at the northern extent of swamp catchment. Once the water level in TTS reaches that of the sill at altitude ~209.6 m (Fig. 6.3.)
above sea level the swamp overflows with excess water draining to Wangi Creek. When the water level is below the sill height TTS can be considered endorheric.

Figure 6.3. Topographic profile of Table Top Swamp from RTK GPS data. Divide indicates the altitude of wetted perimeter of the swamp, determined as the terrestrial vegetation line. Blue circle indicates the height of the sill at which water overflows from the swamp. See Figure 6.4. for location of the transect.
Figure 6.4. Elevation map (AHAD) of TTS showing the maximum possible spatial extent of the lake (red line) and the swamp catchment. The location of the sill (overflow channel) is indicated as the yellow region to the top left of the swamp marked by the black arrow. The location of the Divide topographic survey is indicated on the figure. The lake topography elevation was established by an RTK GPS survey, the catchment derived from SRTM 1arc data.

The hydrological model required delineation of the area TTS and its catchment and the depth (volume capacity) of the swap (Eqn. 6.5). The catchment was derived for the swamp from the SRTM 1arc digital elevation model using the Spatial Analyst – Hydrology tool within the ArcMap software. A detailed topographic survey of the swamp was undertaken in late October 2014 using a Real Time Kinematic (RTK) differential GPS (Fig. 6.4.). Raw data was processed by Geoscience Australia through its AUSPOS GPS processing service to compute precise coordinates using the GDA94 datum. Topographic survey data were imported into ARCGis ARCMAP and a digital elevation model was constructed by interpolating between survey points. The ARCMAP profile tool allowed identification of the height of the sill (outflow channel) at which TTS overflows (209.6 m, Fig. 6.3.). The area of the
swamp (maximum wetted perimeter, $A_s$ in Eqns. 6.5) was defined as the area below the elevation of the sill (114,508 m$^2$). Swamp full volume ($V$ in Eqns. 6.5) was determined using the Polygon Volume tool in Geoprocessing below the elevation of the sill.

An assumption of the hydrologic modelling is that the elevation and area of the catchment has not changed significantly during at least the past 35 ka. Given the geological stability of the region and the low rate of erosion in this small sandstone catchment of low relief, this assumption is considered reasonable. For example, Nott et al. (1996b) calculated denudation rates for a similar sandstone plateau at Arnhem Land (due east of TTS) to be 1.7 to 4.8 mm/ka. Applying these erosion rates to the TTS catchment over the time period represented by the studied core imply erosion of 51-144 mm over 30 ka. This change is inconsequential in terms of swamp morphology.

In addition to changes in precipitation brought about by the position of TTS relative to the shoreline, accretion of sediment in the swamp (infilling) will have affected the water holding capacity of the swamp, which in turn affects its hydrology. The impact of these changes was incorporated into the modelled scenarios for the 12 and 18 ka time slices by making appropriate adjustments to the swamp volume based on the vertical mass of sediment accumulated since these time periods. Note the vertical mass of sediment was calculated from the age model presented in Chapter 5.2.

By assuming the swamp floor is a cone-shaped body the change in swamp volume was calculated from:

$$V = \frac{(A_s \times D)}{3}$$

(6.6)

Where $V$ is the volume of sediment, $A_s$ is the area of the swamp (114,508 m$^2$) and $D$ is the depth of sediment. The changing swamp volume at 12 and 18 ka is provided in Table 6.4.
Table 6.4. Volume of sediment and total swamp volume at 12 ka and 18 ka.

<table>
<thead>
<tr>
<th>Time Slice</th>
<th>Sediment volume m$^3$</th>
<th>Swamp volume m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12ka</td>
<td>16,795</td>
<td>108,670</td>
</tr>
<tr>
<td>18ka</td>
<td>23,283</td>
<td>115,158</td>
</tr>
</tbody>
</table>

**Runoff coefficients**

The runoff coefficients used in this analysis are based on a regional analysis by Petheram *et al.* (2012) and are not specific to the TTS site. However, importantly the region for which they were derived includes TTS. It is noteworthy that the range in regionally calculated runoff coefficients is narrow (0.31-0.35) meaning selecting differing runoff coefficients has little impact on the results.

**Evaporation and evapotranspiration**

Of the several measures of evaporation available point potential evaporation was chosen as the most appropriate measure of evaporation at TTS. Point potential evaporation can be defined as the evaporation that would occur with unlimited water supply, assuming the area of the water body is small enough that locally derived water vapour would not alter humidity (Bureau of Meteorology 2015). Locally derived vapour affects humidity when the area of a water body exceeds two hectares (Ladson 2008). Because the area of TTS is only one-hectare local humidity effects would be insignificant which means point potential evaporation is an appropriate measure.

The closest site to TTS from which point potential evaporation data is available (2,259 mm/yr.) is Darwin, 80 km north of TTS. The similarity of temperatures at Darwin and Batchelor (the closest climate station to the study site, 43 km to the east) (Fig. 6.5) implies evaporation at Darwin closely reflects that at TTS. A small negative bias in evaporation is, however, implied by higher spring/summer temperatures at Batchelor (up to 3°C). This difference is attributable to a relative reduction of sea breeze induced cooling at Batchelor (maritime effect).
Figure 6.5. Average maximum temperature at Darwin and Batchelor. The higher relative spring/summer temperatures at Batchelor are due to the absence of the maritime effect, which affects the coastal site of Darwin.

Changes in evapotranspiration influence the level of moisture loss from the catchment of TTS. The Bureau of Meteorology has integrated measurements of temperature, vapour pressure and global solar exposure to derive a broad scale map of evapotranspiration (Fig. 6.6):

Figure 6.6. Average annual point potential evaporation. (Bureau of Meteorology 2015)
Figure 6.6 shows the broadly latitudinal control of evapotranspiration is overprinted with an influence of distance from the coast. In the case of TTS it suggests the current rate of evapotranspiration lies between 2,800 and 2,600 mm/year. The Bureau points out these values should only be considered as a rough guide. Calculations of potential evapotranspiration by Montanari et al. (2006) for four weather stations near Katherine, (Katherine Aviation Museum, Douglas, Mango Farm and Wooliana) suggest a positive bias in the Bureau of Meteorology map. The four sites yielded average daily evapotranspiration rates between 2,256 and 2,431 mm/yr. For modelling purposes a value of 2,200 mm/year was chosen in line with the calculations of Montanari et al (2006).

**Precipitation**

There are a number of rainfall gauges located close to the study site including Walker Creek, 12 km to the northwest and Batchelor, 34 km to the east. Contemporary data from the Walker Creek rainfall gauge were decided to best represent precipitation at TTS because of the greater length of the Walkers Creek record which commenced in 1956 compared to the Batchelor Airport record which commenced in 1992 and because it is the closest available rainfall gauge to TTS (12 km northwest).

There is a 70 m altitude difference between Walkers Creek and TTS, which is expected to result in a negative bias due to orographic effects. Therefore the Walker Creek rainfall data is considered a minimum estimate for TTS (Note that there are no rain gauges on the tablelands in the vicinity of TTS). It is worth noting that all the rain gauge sites close to TTS display similar monthly average rainfall during the dry season, but show some divergence during the ASM (Fig. 6.7.), e.g. average February rainfall at Batchelor (34km east) is 335 mm compared to 482 mm at Walkers Creek.
Overall, although some bias/error occurs in the available contemporary climate data it is not considered significant enough to invalidate hydroclimate modelling, the purpose of which is to give a general indication of the changes in the swamp hydrology with respect to changing climatic conditions. The hydrological input variables are summarised in Table 6.5.
Table 6.5. Hydrologic model input variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swamp full area ( (A_s) )</td>
<td>114,508 m²</td>
<td></td>
</tr>
<tr>
<td>Catchment area ( (A_c) )</td>
<td>669,392 m²</td>
<td></td>
</tr>
<tr>
<td>Full swamp volume ( (V) ) current</td>
<td>91,875 m³</td>
<td></td>
</tr>
<tr>
<td>Full swamp volume ( (V_{12}) ) 12 ka</td>
<td>108,670 m³</td>
<td></td>
</tr>
<tr>
<td>Full swamp volume ( (V_{18}) ) 18 ka</td>
<td>115,158 m³</td>
<td></td>
</tr>
<tr>
<td>Runoff coefficient ( (R_c) )</td>
<td>0.31-0.35</td>
<td>Petheram et al. (2012)</td>
</tr>
<tr>
<td>Potential Evaporation ( (E_l) )</td>
<td>2.259 m/yr.</td>
<td>BOM. 2015</td>
</tr>
<tr>
<td>Catchment Evapotranspiration ( (E_c) )</td>
<td>2.20 m/yr.</td>
<td>(Montanari et al. 2006)</td>
</tr>
</tbody>
</table>

**Groundwater**

Groundwater is not expected to contribute significant water to TTS. This is due to the small size of the catchment, which means there is little capacity to store groundwater, combined with its elevated position in the landscape, which means groundwater cannot flow into the catchment from the surrounding landscape. However, the catchment lithology is comprised largely of sandstone, which is likely to be porous, so that a small groundwater contribution cannot be ruled out. Potentially more significantly the porous character of the catchment sandstone could also cause the swamp to lose water through seepage into the sandstone. However, if significant water is lost from TTS through seepage the water level in TTS will be lower than predicted due to evaporation alone, conversely, if TTS dries later than predicted, a groundwater contribution to lake water level may be inferred. In other words, if the swamp dries at a time different to that calculated by the model it could be inferred groundwater influence is significant.
As there are no water level records for Table Top Swamp to validate the model, satellite data was used to determine the actual time of drying and this was compared with the time of drying predicted by the model.

**Sensitivity Analysis**

Sensitivity analysis was conducted by adding ten per cent and fifteen per cent to each of the parameters used to model contemporary conditions at TTS using the Walker Creek rainfall record. This was done to assess the relative importance of each parameter in determining dryness of the swamp and to determine the possible impact of errors in the input parameters. The input parameters used in the sensitivity analysis are shown in Table 6.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Contemporary</th>
<th>10% increase</th>
<th>15% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swamp Full Volume</td>
<td>91,875 m³</td>
<td>101,062 m³</td>
<td>105,656 m³</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>669,392 m²</td>
<td>736,331 m²</td>
<td>769,801 m²</td>
</tr>
<tr>
<td>Runoff coefficient</td>
<td>0.31</td>
<td>0.341</td>
<td>0.356</td>
</tr>
<tr>
<td>Potential Evaporation</td>
<td>2.259 m</td>
<td>2.485 m</td>
<td>2.598 m</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>1.1 m</td>
<td>1.21 m</td>
<td>1.265 m</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Walker Creek</td>
<td>Walker Creek</td>
<td>Walker Creek</td>
</tr>
</tbody>
</table>

**6.4 Results**

**6.4.1. Contemporary Swamp Hydrology**

Using equation 6.2. (i.e. assuming no evaporation), 263 mm of effective precipitation is required to completely fill TTS. Mean annual rainfall is significantly higher at 1,977 mm than swamp capacity. Thus rainfall exceeds swamp capacity by 7.6 times. However, rainfall is highly seasonal in the Top End (Fig. 6.7.). At
Litchfield National Park 80% of average annual precipitation falls during the monsoon, the majority in January and February. By contrast, an average 367 mm of precipitation occurs during dry season (April to November). This means TTS experiences an extended annual period of low precipitation. Although the wet season officially lasts from December to March (Bureau of Meteorology 2015) there is considerable interannual variability in the actual start date of the monsoon season. The Bureau of Meteorology defines the onset date of the monsoon as the first date on which 50 mm of rain has accumulated since the beginning of September. This amount of rain is considered to be the amount required to stimulate plant growth after the dry season. For TTS the calculated median onset date is the end of October (Fig. 6.8.).

![Figure 6.8. The mean onset date of the Australian monsoon based on data for the period 1960 to 2009 (Bureau of Meteorology 2015).](image)

Importantly, potential annual evaporation (2,259 mm) exceeds rainfall (1,977 mm). This implies that TTS has a negative moisture balance, i.e. potential evaporation exceeds precipitation, meaning $EP$ (effective precipitation) is often not enough to maintain water in TTS throughout the year. Consequently, by the end of the dry season TTS is often dry. For example in 2014 when annual rainfall for Walkers Creek was 2,208 mm, well above average reflecting an especially active monsoon, TSS was dry by early August in the model and observed to be dry in late
October. As a result, 10 cm deep cracks present on the lake surface (Fig. 6.9.) and the water table was level with the lowest point of the swamp basin.

Figure 6.9. Table Top swamp in late October 2014. showing surface cracking. The dark staining on the lower portion of the trunks of the trees in the background reflect the depth of maximum inundation, approximately 2.5m.

Note that the dry-season rainfall of 2014 at 132 mm was well below the average of 368 mm, which according to equation 6.2 would be sufficient to maintain some water in the swamp throughout the year. The modelled pattern of filling and emptying of TTS under the current climate is illustrated in Figures 6.10. and 6.11. It can be seen that the swamp fills each wet season and becomes desiccated during the dry season with the result that the swamp is dry roughly 18 per cent of the time (Fig. 6.11.).
The validity of the model is predicated on a neutral influence by groundwater. In the absence of TTS water level data, satellite data was used to define the actual time of swamp drying for comparison with modelled time of drying. The Walker Creek 2007 precipitation record was chosen to test groundwater movement because dry season rainfall was very low that year, causing the swamp to completely dry. Only 16.7 mm of precipitation were received between April and September 2007 compared to the annual mean total of 112.6 mm. The result of applying the 2007 rainfall record to the model is shown below. Day 224 is the modelled day of drying.
Landsat data was analysed using the approach of Xu (2006) to generate modified normalised difference water index (MNDWI) values. Xu's method emphasises the contrast between radiation received in the green wavelength band and radiation received in the mid-infrared band. This approach allows best discrimination between areas of open water and moist vegetation, which is necessary in the TTS environment where vegetation covers much of the swamp. The results were calculated for a circular area including the swamp and its immediate surroundings (Fig. 6.13). The mean MNDWI averages all calculated MNDWI values in this area, while the maximum value gives an indication of the presence of open water as distinct from total desiccation. It can be seen that the mean value reaches a minimum at day 238 and does not decline further indicating the swamp has dried by this date. The max MNDWI suggests a small amount of surface water was still present up to day 270. It can be concluded that the satellite data indicates the swamp dried sometime between day 238 and day 270. Figure 6.14. gives a graphic indication of the changes in radiation emitted by TTS.

Figure 6.12. Modelled lake level of TTS during 2007 using Walkers Creek data showing day 224 as the modelled day of drying.
Figure 6.13. Modified normalised difference water index (MNDWI) of TTS for the year 2007 based on mid-infrared and green wavelengths of Landsat data. The mean value plateaus at day 238 while the maximum value reaches a minimum at day 270. The swamp dried out between day 238 and day 270.

(a) Day 120  
(b) Day 270

Figure 6.14. Landsat images of TTS for the year 2007. The red circles indicate the position of Table Top Swamp. The obvious decrease in the amount of green area in panel (b) compared to panel (a) indicates dry season desiccation of the landscape.
The modelled time of drying (day 224) is earlier than the date range suggested by the satellite data (day 238 – 270). The difference between the modelled drying and the drying indicated by satellite data is within the limits of model accuracy suggesting that neither groundwater input nor loss to the subsurface significantly impact the hydrology of the swamp. It can be concluded that changes in water level in the swamp are almost entirely due to factors other than groundwater.

6.4.2 Sensitivity Analysis

Sensitivity analysis shows the percentage of time the swamp would be dry as a result of a change in each input parameter of 10% and 15% (Table 6.7.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Contemporary % dry</th>
<th>Percentage of time dry with 10% increase</th>
<th>Percentage of time dry with 15% increase</th>
<th>Percentage of time change from contemporary with 15% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swamp Full Volume</td>
<td>18</td>
<td>14</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Runoff coefficient</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Potential Evaporation</td>
<td>18</td>
<td>22</td>
<td>24</td>
<td>29</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>18</td>
<td>19</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Precipitation</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>3</td>
</tr>
</tbody>
</table>

In addition to modelling the effects of 10 and 15% changes in other parameters the effect of a fifty per cent reduction in precipitation was modelled because the time/space substitution analysis suggested such large changes in precipitation may have occurred in the past. The result of halving precipitation is a modest reduction in the average volume of water held by the swamp from 54.3% to 48.5%.

6.4.3 Palaeohydrology

Palaeohydrology was modelled for active monsoon conditions at 12 and 18 ka and for an inactive monsoon at 18 ka.
1. Active Monsoon Scenario

18 ka

At 18 ka the swamp was 475 km inland and the swamp capacity was 25% greater than today due to the lower amount of accumulated sediment. In this analysis rainfall from locations currently 475 km inland was applied to the hydrological model with increased swamp capacity (Table 6.4.) to replicate conditions at TTS 18 ka. The results of modelling Daly Waters rainfall are shown below in Figures 6.15 and 6.17. The results of modelling rainfall of Larrimah and Mataranka Homestead, which are a similar distance inland, are very similar to the results of modelling Daly River hydrology and are shown in Appendices 6 and 7.

Modelling showed that at 18 ka the swamp would rarely fill completely, perhaps once in ten years, and in some years would be little more than a puddle (Fig. 6.15.). On average the swamp would be dry 35% of the time (Fig. 6.17.).

![Graph showing maximum swamp volume over years](image)

Figure 6.15. Modelled swamp filling at Daly Waters, a proxy for climate 18 ka.

12 ka

At 12 ka TTS would have been 135 km from the coast and the water holding capacity of the swamp would have been about 20% greater due to the lower amount of accumulated sediment. In this analysis rainfall from locations currently 135 km inland was applied to the hydrological model with increased swamp capacity as shown in Table 6.5. to replicate conditions at TTS 12 ka. The results of
modelling Manton Dam rainfall are shown below in Figures 6.16 and 6.17. The results of modelling Pine creek and Jindari are very similar to the results of modelling Manton Dam hydrology and as shown in Appendices 4 and 5.

Modelling showed that at 12 ka the swamp overflowed each wet season and was completely full for extended periods (Fig. 6.16). Complete drying was a very rare event in (Fig. 6.17.) occurring perhaps one year in one hundred.

Figure 6.16. Modelled swamp filling at Manton Dam, a proxy for climate at 12 ka.

Figure 6.17 shows the results of modelling the percentage of time the swamp was dry at 18 ka and at 12 ka.

Figure 6.17. Swamp moisture content at 18 ka (a), and 12 ka (b). The swamp was frequently dry at 18 ka but very rarely dry at 12 ka.
When the rainfall records of the other stations used to model the monsoon active scenarios were modelled, the pattern derived for Daly Waters and Manton Dam were repeated (Table 6.8). This indicates the results are not peculiar to Daly Waters and Manton Dam.

Table 6.8. Modelled percentage of time TTS was empty at 12 ka and at 18 ka for different rainfall stations.

<table>
<thead>
<tr>
<th>Rainfall station</th>
<th>Time Slice (Ka)</th>
<th>% of time empty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manton Dam</td>
<td>12</td>
<td>0.5</td>
</tr>
<tr>
<td>Pine Creek</td>
<td>12</td>
<td>1.2</td>
</tr>
<tr>
<td>Jindari</td>
<td>12</td>
<td>5.7</td>
</tr>
<tr>
<td>Daly Waters</td>
<td>18</td>
<td>38</td>
</tr>
<tr>
<td>Larrimah</td>
<td>18</td>
<td>33</td>
</tr>
<tr>
<td>Mataranka</td>
<td>18</td>
<td>35</td>
</tr>
</tbody>
</table>

2. Inactive Monsoon Scenario

The effects of failure of the monsoon were modelled using a non-monsoonal (aseasonal) rainfall record of similar amount to the monsoonal rain hypothesized for TTS at the LGM (Fig. 6.18 and 19.). Modelling suggests that under a non-monsoon regime the swamp is unlikely to reach maximum capacity and that the swamp was probably endorheric at almost all times. Modelling also indicates the more even distribution of rainfall under non-monsoon conditions halved swamp drying to 16% of the time compared to 35% under monsoonal conditions.
Figure 6.18. Modelled filling of TTS with rainfall of 840 mm per year, simulating LGM conditions with an inactive monsoon (Oberon rainfall).

(a) Non-monsoonal Rainfall  (b) Monsoonal rainfall

Figure 6.19. Swamp moisture conditions modelled with the non-monsoonal rainfall record of Oberon, NSW (a), and monsoonal rainfall of the same amount (Daly Waters record) (b). Both sites receive approximately 850 mm average annual rainfall.

6.5. Summary and Discussion

6.5.1. Sensitivity Analysis

Modelling the sensitivity of TTS to changes in each hydrological parameter illustrates some important points. The sensitivity analysis demonstrated that errors in calculation of swamp catchment area are unlikely to significantly affect the results of modelling. For example a fifteen per cent change in catchment area
only changes the drying of the swamp by about one per cent (Table 6.6). It was shown that 15% changes in runoff coefficient, evapotranspiration and catchment areas result in relatively minor changes in hydrology, less than four per cent. The effect of changes in precipitation are muted by the loss of water when the swamp overflows during the wet season. Modelling a fifteen per cent increase in precipitation caused only a 3% decrease in the time the swamp is dry and halving precipitation leads to average swamp volume declining by only 11%. Changes in evaporation have the greatest impact on swamp hydrology. A fifteen per cent change in evaporation leads to a 29% change in the time the swamp is dry.

In contrast to the minor changes identified above changes in swamp volume have a significant effect on the drying of the swamp. A fifteen per cent increase in swamp volume resulted in a disproportionate 28% decrease in drying. This is significant because the swamp has filled with sediment over time. Conservative estimates of past sediment volume were incorporated into parametrization of palaeohydrology.

6.5.2 Palaeohydrology

1. Active Monsoon Scenario

Palaeohydrological modelling of active monsoon conditions allowed identification of three distinct phases of hydrological development likely to have occurred in the past. They are:

Phase 1: Dry Dominated Ephemeral Phase. This reflects the likely conditions in the swamp around 18 ka and earlier, when the swamp was ~475 km inland from the coastline. The behaviour of hydrology of the swamp in this period is summarised in Figures 6.15. and 6.17. Modelling suggests the likely much lower precipitation level (~685 – 850 mm/year) was insufficient to fill the swamp, which rarely exceeded 60% of capacity. Modelling suggests the swamp became endorheric for extended periods, that seasonal desiccation occurred most years and that the swamp may have been dry 35% of the time.

Phase 2: Permanent Lake Phase. This reflects the likely conditions in the swamp around 12 ka. Swamp hydrology is summarised in Figures 6.16. and 6.17. In this phase the effects of lower monsoon precipitation compared to today (resulting
from an increased distance to the ocean) are more than offset by the increased water holding capacity of the swamp, which is deeper due to the smaller amount of sediment present. Modelling suggests the swamp may have been permanently wet and exorheric, experiencing seasonal flushing each year. Because the accumulation of sediment was a gradual process the timing of the end of this phase depends on when the balance between diminishing swamp capacity and evapotranspiration passed a tipping point which remains unknown.

**Phase 3: Wet Dominated Ephemeral Phase.** This reflects the likely conditions in the swamp from the present to 9 ka years ago when the swamp occupied its’ current position relative to the ocean. Swamp hydrology during this phase is summarised in Figures 6.10 and 6.11. In this phase excess, heavy monsoon rain ensures filling of the swamp in most years. As sediment gradually accumulated over time the capacity of the swamp to hold water progressively diminished and the percentage of time the swamp was dry gradually increased reflecting the dominance of evaporation in regional hydrology.

The contrast in modelled drying during these phases is illustrated in Figure 6.20 which shows the swamp dry 35% of the time at 18 ka, permanently wet at 12 ka and dry 18% of the time at 9 ka.

![Figure 6.20. The three modelled phases of swamp hydrology. Panel (a) Dry Dominated Ephemeral Phase hypothesized for 18 ka shows the lake dry 35% of time. Panel (b) Permanent Lake Phase hypothesized for 12 ka when increased rainfall in a relatively deep lake maintained water most of the time. Panel (c) Wet Dominated Ephemeral Phase hypothesized for 9 ka to present shows the shallow lake drying out more frequently due to its diminished water storage capacity.](image-url)
2. Inactive Monsoon Scenario

Because northward migration of the ASM has been suggested before and during the LGM (Bowler et al. 1976; Reeves et al. 2013; Spooner et al. 2005a; van der Kaars et al. 2002b; Wyrwoll et al. 2001) a, non-monsoonal rainfall pattern was modelled to test for differences in hydrology compared to an active monsoon scenario. It is not possible to know what the exact rainfall during this period was, however, an estimate of potential rainfall was made using the present day rainfall gradient across northern Australia to predict likely rainfall when TTS was further from the coast at lower sea levels.

Modelling indicated that hydrology would be markedly different at the LGM under non-monsoonal conditions by comparison to monsoonal conditions. In particular, under non-seasonal (monsoon) rainfall the swamp would have been likely to have experienced less desiccation (i.e. complete drying out of the swamp). For example modelling shows the LGM monsoonal rainfall patterns was likely to be dry 24% of the time, whereas the same amount of rain (840 mm) falling in a non-seasonal pattern (Oberon record) leads to drying of the swamp only 16% of the time on average. An additional difference is that much less discharge from the swamp is likely to have occurred if the monsoon was not operating. Under non-monsoon LGM conditions the swamp is predicted to have been endorheric with consequent accumulation of salts and possibly carbonates in the swamp. The likely result of such salt accumulation would be increased presence of salt in sediments and increasing prevalence of salt tolerant diatom and aquatic plant species. Conversely absence of these trends in the sedimentary archive would indicate continuing albeit infrequent outflow under monsoonal conditions throughout the LGM.

These model results are likely to underestimate dryness at the LGM. The rainfall records used here are based on distance from the coast and assume the monsoon penetrates as far south as it does currently. However it is widely considered the ITCZ, and consequently the monsoon, did not penetrate as far south in the past (e.g. Haug et al. (2001), Marshall et al. (2008), Marx et al. (2009), Mohtadi et al. (2011) and Shulmeister et al. (1995)). Therefore it is likely the modelled
paleohydrology presented here represents a scenario of maximum likely precipitation.

6.5.3 Implications of the Results
The simplicity of this approach to modelling the effects of sea-level change is acknowledged. The effects of change in sea level have been shown to be more complicated than the above results suggests. Modelling undertaken in other studies has shown that the increased area of land exposed by low sea levels leads to increased convection of sensible heat over land (Marshall et al. 2008; McRobie et al. 2015). This has the effect of intensifying monsoon strength which would lessen the drying of the swamp at 12 and at 18 ka. However a reduction of global sea cover of more than 2.5% is likely to have led to a reduction in the supply of available moisture which would more than offset the effects of increased convection, leading to an even greater reduction in precipitation (Marshall et al. 2008). Therefore our modelled paleohydrology of TTS is likely to overestimate precipitation and underestimate desiccation, especially for the 18 ka scenario. Comparison of climate proxies presented elsewhere in this thesis with the modelled hydrological scenarios may allow assessment of the relative importance of the change in rainfall associated with changes in proximity of TTS to the coast.

6.6. Conclusion

The hydrology of TTS was modelled for three reasons. Modelling was used to test the veracity of the TTS archive as a record of past changes in climate (i.e. that changes in swamp hydrology reflect past climate rather than something else). Modelling was used to gain an understanding of the hydrodynamics of the swamp, which informed interpretation of proxy records presented elsewhere. Modelling was also used to reconstruct paleohydrological changes likely to have occurred in response changes in sea level and failure of the monsoon.

The relative importance of each component of swamp hydrology was defined and it was established that changes in TTS hydrology are in large measure driven by climate. Contrasting hydrological regimes likely to have emerged as the swamp
evolved over time were identified and the unique hydrological signature of non-monsoonal conditions was defined.

A simple mass balance model was used which adds rainfall and runoff to the pre-existing water level and subtracts evapotranspiration to estimate the volume of water in the swamp. Parametrization of the model presented difficulties in estimating input data where actual measurements were unavailable. Sensitivity analysis defined the level of uncertainty inherent in input data estimates. Estimates of past climatic conditions are especially uncertain so that the results of modelling are considered broad indicators of past hydrology only.

It was established that changes in the hydrology of TTS are due to changes in climate and that groundwater gains or losses are insignificant. Sensitivity analysis has shown potential errors in measurements of the geometry of the TTS catchment are not critical to the performance of the model because these factors have a marginal impact on hydrology. Similarly uncertainties in runoff and evapotranspiration have a very small impact on swamp hydrology. Changes in swamp capacity, precipitation and especially evaporation exert most control swamp hydrology. The accumulation of sediment during the last 35 ka significantly changed the capacity of the swamp. Modelling suggests greater swamp capacity could have enabled the formation of a permanent lake around 12 ka, while at 18 ka the swamp would have dried each year because the effects of lower precipitation dominated the effects of increased swamp capacity. Consequently changes in climate proxies such as pollen, diatoms, stable isotopes, grain size and geochemistry described elsewhere are highly likely to reflect changes in climate, especially effective precipitation, rather than other factors.

Because penetration of the monsoon inland decreases markedly as distance from the shore increases, postglacial sea-level rise is likely to have significantly changed the hydrology of the swamp. Flooding of the wide, flat continental shelf over a very short time span approximately 9.5 ka can be expected to have caused a change from dry-dominated ephemeral conditions to a permanent lake.
The character of TTS under non-monsoonal LGM conditions would have been markedly different to under an active monsoon scenario. A non-seasonal distribution of rainfall would result in the swamp drying out significantly less on average than under monsoon conditions but it would fill much less often. These contrasting hydrological conditions would lead to markedly different and less variable conditions in the swamp. The infrequency of filling events in a non-monsoon scenario should lead to increased salt accumulation, which would probably be reflected in the sedimentary archives. Conversely, monsoonal conditions, which are characterised by strong rainfall events, would lead to transport and accumulation of larger grain-sizes compared to non-seasonal rainfall.

This modelling exercise has allowed derivation of useful insights into the relative importance of the various climatic parameters that determine changes in swamp hydrology over time. Palaeoclimate modelling has provided useful indications of the differences that can be expected in the swamp, which will provide a means for the distinction between monsoonal, and non-monsoonal climate signals in the sedimentary archives.
7. General Discussion

Two main research objectives were identified for this project. They are:

- To investigate the operation of the Australian Summer Monsoon during Marine Isotope Stage 2. Specifically to determine if the monsoon switched off, or whether it migrated north.
- To determine the date of re-establishment of the ASM after the LGM.

Before addressing these objectives it was necessary to gain a sound understanding of the hydrodynamics of TTS in order to make informed interpretations of any changes detected in the palaeorecord. To this end hydrological modelling was used to investigate swamp dynamics. The provenance of the sediment accumulated in TTS was also investigated in order to better understand processes in the swamp and to isolate changes which may be driven by processes external to the swamp and its’ catchment. An age model was developed to give context to the history of change observed and to allow comparison with the results of previous studies.

7.1. Changes recorded in TTS.

Hydrological modelling and sedimentological analysis allowed identification of three distinct hydrological phases reflecting the effects of sea level change and swamp infill (Fig. 7.1).

1. Dry Dominated Ephemeral Phase Between 1,100 and 576 mm depth (35 to ~17 ka) (Units 4 – 5) is interpreted to represent the early filling phase of the swamp. Deposition of sand size particles at the deepest part of the swamp (Fig. 5.1) is consistent with the time/space palaeohydrological reconstruction, which suggests frequent desiccation of the swamp under very dry conditions (Fig. 6.15). Over time the volume and surface area of sedimentation in the swamp increased, causing the slope of the swamp basin to decrease. As a consequence transport energy towards the centre decreased, so that sediment entering the swamp centre would have successively fined. Sand deposition progressively shifted further outwards as shown by the accumulation of sand at the periphery of the swamp (Table 5.4).
Accumulation of strontium between ~29 and 21 ka (Fig. 5.12) may indicate conditions were so dry the swamp was endorheric during this interval.

2. **Permanent Lake Phase** Between 576 mm and 200 mm depths (~17 to 5 ka) (Unit 3) very high rates of silt deposition indicate sorting of the coarser grain size to the periphery of the swamp as incoming suspended load was deposited into a relatively deep swamp (Fig. 5.1). Hydrological modelling of conditions at 12 ka showed that the swamp was likely to have remained wet for a longer period each year during this phase due to increased moisture availability associated with flooding of the continental shelf and because the swamp was deeper than present with the result that dry season evaporation took longer to empty the swamp (Fig. 6.16 and 6.17). The small amplitude of variation in abundance of all three grain sizes and the low contribution of sand confirm the scenario of deposition into a full lake (Fig. 5.1). Seasonal growth of waterlilies and reed beds at the shore of the lake would have made water flow within the lake difficult further reducing transport of large particle sizes to the middle of the lake. Very low rates of pollen (Fig. 5.21) and organic matter preservation (Fig. 5.5 and 5.22c) from this phase suggest a period of subsequent drying occurred which led to subsequent volatilization of organic matter.

3. **Wet Dominated Ephemeral Phase** Between 200 mm and 0 mm depth (5 ka to present) (Unit 1) there is a marked increase in the amplitude of variation of sand and silt inputs indicating greater variation in runoff (Fig. 5.1). High levels of sand input indicate hydrological conditions allowed transport of sand to the middle of the swamp. This scenario indicates sediment-laden water flowing into the middle of a shallow, dry swamp. This is consistent with hydrological modelling (Fig. 6.1) which showed that as sediment infill approached current levels the water-holding capacity of the swamp diminished significantly resulting in earlier seasonal drying. The pattern of sediment deposition in this phase may reflect early monsoon season rain flowing into a dry lakebed and/or a more pronounced monsoon onset.
7.2. Palaeoenvironmental and palaeoclimatic conditions at TTS.

In this section the likely implications of the results for palaeoenvironmental and palaeoclimatic are discussed. The discussion is presented divided into the MIS stages represented by TTS records (MIS3, 2 and 1).

MIS3 (35 to 29 ka)
Very high δ¹³C values probably reflect high rates of diagenetic loss of carbon occurred between 35 and 29 ka (Fig. 5.21a) (Wynn et al. 2005; Wynn et al. 2006). The C/N ratios during this phase are typically associated with phytoplankton or bacteria (Fig. 7.2.). This implies vascular plants are largely absent, which is not the case as shown by the δ¹³C evidence. A more likely explanation of the low C/N ratio is the effect of post-depositional volatilization of carbon in decaying organic
matter as indicated by the very low concentration of organic carbon, less than 6\% (Fig. 5.5).

The low preservation of organic matter shown by organic matter content less than 5\%, the C/N ratio of 5 and no pollen preservation suggests 35 to 29 ka was drier than any subsequent period. $\delta^{13}$C depletion ratios in the range -21 to -18 \%0 most likely reflect an extended period of diagenesis brought about by oxidising conditions in a very dry environment. High $\delta^{15}$N enrichment ratios may also be due to diagenetic overprinting (Fig.5.21) in an arid, oxidising environment supporting this conclusion that the monsoon was most likely inactive or, at most, extremely weak during MIS3.

The TTS evidence of monsoon failure during MIS3 confirms the evidence of most palaeomonsoon studies but contradicts the evidence from Liang Luar Cave (Ayliffe 2013; Griffiths et al. 2010), Indonesia, and Salt Pan Creek, Lake Gregory (Veth et al. 2009). There is also no evidence of the wet event at 30-29 ka recorded at Lynch’s Crater, Queensland (Muller et al. 2008). Lower southern hemisphere insolation and high northern hemisphere insolation during MIS3 is hypothesized to have caused movement of the Intertropical Convergence Zone and the Australian monsoon to a more northerly location than at present (Haug et al. 2001; Marshall et al. 2008; Wyrwoll et al. 2007). This northward migration of the Intertropical Convergence Zone and monsoon to a location north of TTS during MIS3 would explain the MIS3 pattern of TTS palaeoclimate archives. The Lynch’s Crater and Salt Pan Creek archives were south of monsoon influence during MIS3 while Liang Luar cave is sufficiently far north (8.5° S compared to TTS at 12° S) to remain under the influence of the monsoon even though it had contracted north. It might even be suggested the southern limit of the summer position of the ITCZ at 29 to 35 ka was between 8.5 and 12° S.

The diatom moisture availability index (5.12) suggests a standing body of water at 30 ka, which contrasts the evidence of stable isotope analysis (Fig. 5.21) that suggests very dry conditions in the TTS catchment at this time. This apparent contradiction is explained by the results of hydrological modelling (Chapter 6)
which showed how the greater storage capacity of the swamp at 30 ka relative to today allowed persistence of standing water despite low rainfall. Lowest diatom counts (Fig.5.19) and species diversity at 30 ka support the scenario of conditions being least favourable to diatoms (driest) at this time.

**MIS2 (29 to 12 ka)**

During MIS2 $\delta^{13}C$ values were between those of C3 and C4 plants, i.e. between -18 to -23 ‰ (Fig. 5.21a). In this section of the core $\delta^{13}C$ values become increasingly depleted through time. This is a reflection of age since deposition and diagenetic loss of carbon over time (Wynn et al. 2006). After 451 mm depth (12 ±1.7 ka) $\delta^{13}C$ values shifted to a definitely C3 signal. Early MIS2 dry conditions are also indicated by the poor preservation of organic matter shown by the pollen record (Fig. 5.20), and Loss on Ignition analysis (Fig. 5.5). The C/N ratio (Fig. 5.21c) remains low during MIS2 due to ongoing volatilisation (breakdown) of C in the aerobic environment of the seasonally dry swamp. Consequently the C/N ratio cannot be used to interpret past vegetation assemblages or climate in this unit of the core.

Importantly MIS2 incorporates the LGM, which has previously been observed in Australia as a significant climate event between ~23 and 18.5 ka characterized by low temperature and maximum dryness (Barrows et al. 2001; Moss et al. 2000; Petherick et al. 2008). The $\delta^{3}C$ values at TTS show no response to increasing dryness during the LGM, rather that time interval occurs as part of a long transition to wetter conditions which commenced at ~26 ka as evidenced by the gradual shift in $\delta^{3}C$ values to those associated with moisture-demanding C3 plants (Fig. 5.21a).

Geochemical analysis showed conditions favourable for the accumulation of strontium persisted from depth 950 (~29 ka) to 700 (~21 ka) mm and it is suggested endorheric conditions associated with a very low, probably non-monsoonal rainfall regime occurred during this interval (Fig. 5.12). This may indicated conditions in MIS3 were moister than during MIS2 when endorheric conditions are not indicated. The absence of a signal in the pattern of chlorine and
calcium accumulation may be due to the very small contribution of these elements from erosion in the TTS catchment, which is a consequence of the small size of the catchment.

The $\delta^{15}$N isotope record indicates the rate of the trend to increasing moisture increased around 15 ka (Fig. 5.21b). Increasing Hurst index values suggest moist conditions were established some time after 15 ka (Fig. 5.5). The pollen record preserved evidence of a brief moist phase at $\sim$14 ka (Fig. 5.20).

The date at which earliest evidence of monsoon strengthening was detected, 26 ±2 ka is considerably earlier than any other palaeoclimate archive, the earliest of which is 20.4 ka at Northwest Cape (van der Kaars et al. 2002b; van der Kaars et al. 2006). Like the Northwest Cape archive it is not suggested the monsoon was vigorous at this time, merely that its influence was detectable, albeit only in the stable isotope records. Subsequent monsoon strengthening during MIS2 was gradual. This indicates previous attempts to put a date on the initiation of the monsoon (e.g. Wyrwoll et al. (2001)) are spurious. The increase in the rate of monsoon strengthening recorded at about 18 to 17 ka agrees with the timing of similar strengthening recorded at Gilbert River (Nanson et al. 2005) and at Palaeo Lake Carpentaria (Devriendt 2011) indicating this was a regionally synchronous event. The contra indication of non-monsoon conditions at this time from the Darwin plunge pool sites (Nott et al. 1994, 1999) may be due to dating issues.

The roughly synchronous episodes of high monsoon intensity identified in the archives from Liang Luar Cave (Denniston et al. 2013c), Cave C126 (Denniston et al. 2013a) and Lynch’s crater (Kershaw 1986; Muller et al. 2008) at $\sim$24, 15 and 13 ka are not evident in the TTS archive.

**The Holocene (12 ka to present)**

The accelerated shift in $\delta^{13}$C values (from -23 to -26 %o) during the Holocene reflects a relative increase in C3 productivity associated with progressively increasing moisture availability (Fig. 5.21.). The increase in the C/N ratio from 5 to
20 is partly the result of increasing organic matter preservation that allowed greater sequestration of carbon.

By the early Holocene the monsoon was active as shown by the dominance of C3 plants indicated by the $\delta^{13}$C ratio. Increasing pollen and charcoal preservation suggests a shift to increasingly wet conditions occurred between 10 and 8.6 ka. This strong shift to wet conditions caused a change in swamp hydrology, specifically a rise in the water table, which allowed organic matter preservation as evidenced by the increasing C/N ratio, organic matter per cent, and concentrations of pollen and charcoal after 7 ka. Hydrological analysis showed this change to much stronger monsoon conditions is partly the result of the flooding of the continental shelf caused by rising sea levels, which occurred about this time. The difference in timing of the response to this change shown by the pollen concentration and C/N ratio illustrates the value of investigating multiple proxies rather than relying on one set of results and suggests there may be lags inherent in the response of the C/N ratio to climate change.

Increasing C/N values also shows a strong shift to values associated with vascular plants and maximum presence of vascular plants occurred at depths 180 – 200 mm (6 ka) indicating this was a period of maximum moisture availability (Fig. 5.21c). Maximum abundance of aquatic and herbaceous taxa and low levels of grass pollen at ~6 ka confirm this was a period of maximum moisture availability. High charcoal concentrations also occur at 6 ka indicating increased fire frequency and intensity (Fig. 5.20).

After 5 ka there is a shift towards $\delta^{13}$ values associated with drier conditions, that is higher $\delta^{13}$C values associated with drought tolerant C4 plants and higher C/N ratios associated with vascular plants (Fig. 5.21c). This indicates the current moisture regime was established after 5 ka. The consistent C/N ratio of 16 confirms stabilization of the relative contributions of terrestrial and aquatic plants commenced after 5 ka.
The contemporary climate regime was established sometime between 5 ka and 1.3 ka when the monsoon became relatively strong but with a high degree of variability as indicated by the increased amplitude of change in the Loss on Ignition and grain size signals. The K/Ti ratio (Fig. 5.10) indicates strongly fluctuating monsoon conditions after 4 ka. The Y/Ho weathering proxy shows little variation in weathering intensity (Fig. 5.11).

Hydrological modelling suggests part of the increased variability may be the result of changed hydrology rather than climate. The capacity of the swamp in the recent past has become so small that seasonal desiccation has become more frequent leading to more occasions where monsoonal rain enters a dry swamp allowing transport of coarse sediment to the middle of the swamp.

The TTS record of early Holocene strong monsoon conditions is in broad agreement with most of the palaeomonsoon evidence from elsewhere but with notable exceptions in the records from the Lynch's Crater (Kershaw 1983), Lake Euramoo (Haberle 2005), Lake Eyre (Croke et al. 1996; Magee et al. 1998) and Bentinck Island (Moss 2015). The wet mid-Holocene interval recorded at TTS is also present in the records from most other palaeomonsoon study sites although it is absent from the Kimberley mound spring record (McGowan et al. 2012), the Gilbert River (Nanson et al. 2005) record and Lake Gregory record (Fitzsimmons 2012).

7.3. Provenance of Sediment

Complimentary investigations using grain size and geochemical analysis were used to investigate whether there is an allochthonous component to sediment accumulating in TTS. Variations in the source of TTS sediments may serve as an indicator of palaeoenvironmental conditions, especially as the type of sediment input may vary over time. Increased presence of dust may indicate increased aridity and the position of TTS towards the end of a major dust transport trajectory means dust deposition may be expected (Marx et al. 2009). Comparison of the size of grains in the catchment of TTS with the sediment deposited in the swamp established that most of the sediment deposited in the middle of the
swamp is not derived from the local sandstone which constitutes the dominant lithology of the catchment (Fig. 5.1 and 5.6). It was shown that sand derived from erosion of local sandstone is deposited at the periphery of the swamp as water entering the swamp slows and deposits the coarse fraction of its suspended load. The dominance of silt size particles in the middle of the swamp where the core was taken is due to transport of the finer fraction of particles to the middle of the lake. No clay size particles were detected in the catchment sandstone (Fig. 5.6), which constitutes the majority of catchment lithology, and clay was less than one per cent of catchment soil, which suggests there is little clay in the catchment. The absence of clay in the catchment suggests the presence of this this particle size in swamp sediment may have been derived from an allochthonous source, although a contribution from laterite, which constitutes a secondary component of catchment lithology, is likely.

Further evidence of the role of laterite in the provenance of TTS sediment was provided by geochemical analysis. Comparison of the normalised HFSE ratios of swamp sediment with possible parent material candidates suggests laterite is the most significant contributor to the chemistry of TTS sediment. By contrast comparison of the REE patterns of TTS sediment to that of the chemistry of likely sediment sources demonstrated that catchment sandstone is more similar to TTS sediment than laterite. Therefore it is likely that the sediment in TTS contains a reasonable contribution from both these catchment lithologies.

Despite the similarities of the TTS sediment chemistry to both the catchment lithologies (sandstone and laterite) there are important aspects of the geochemistry that are seemingly not explained by either of these sources. Both the HFSE and REE signatures of the TTS sediment suggest an allochthonous component is present in TTS sediment. For example, a comparison of the Nb/Ta to the Ti/Th ratio (Fig. 5.18) suggests the chemistry of the TTS sediment was best explained as a mixture of laterite and dust input (as indicated by the average chemistry of dust producing areas from central Australia), i.e. a sediment source with a higher Ti concentration is required to explain TTS sediment chemistry. Similarly the ratio of Ti/Th to Zr/Hf (Fig. 5.16) supports this inference.
It was concluded that local catchment sandstone and laterite are the primary source of the sediment deposited in TTS. However a significant allochthonous component is also present in the swamp sediment. Normalized HFSE ratio analysis showed the different TTS samples were not significantly different from one another compared to the potential source samples (Fig. 5.16-8) so that it was not possible to identify regions of the core with significantly higher or lower dust input.

8. General Conclusion

Two key research objectives were addressed in this thesis. The findings presented here can be summarised in relation to these objectives as follows:

- To investigate the operation of the Australian Summer Monsoon during Marine Isotope Stage 2. Specifically to determine if the monsoon switched off, or whether it migrated north.

  Variations in the stable isotope signals and low organic matter preservation suggest moisture availability was very low and limiting to biological productivity during late MIS3 and early MIS2. Very slight increases in precipitation after 26 ka indicate weak monsoon activity commenced about this time. Although whether this is a true monsoon signal or whether it is simply increased precipitation could not be determined in this study, there is a continual trend of conditions indicative of increased moisture from this time, i.e. there are no reversals in this trend until the Holocene. Consequently, this suggests the beginning of this trend, at around 26 ka, does represent initial monsoon onset. This would suggest local climate forcing maintained monsoon operation, albeit at a very weak level, and the monsoon did not move to another location during the LGM.

- To determine the date of re-establishment of the ASM after the LGM.
Following evidence of early very minor monsoon activity at 26 ka, the monsoon consistently strengthened until around 19 k. After this, the rate of monsoon strengthening increased. Rising sea levels, causing the flooding of the continental about 9.5 ka, brought TTS much closer to the coastline and resulted in a substantial increase in moisture availability associated with increased monsoon rain. This large, sudden increase in monsoon strength was evidenced in the records of pollen and charcoal, organic matter preservation and stable isotopes which all show a marked trend to wetter conditions in the millennia immediately after 9.5 ka. Although flooding of the continental shelf is a clearly evident event that caused an increase in monsoon intensity at TTS this can be considered a local effect due to the position of TTS relative to the coast rather than a result of a change in monsoon strength. Overall it can be concluded that monsoon strengthening was gradual and the timing of more significant increases in monsoon strength are likely to be a reflection of local sea level hydrodynamics.

Limitations are imposed on the confidence that can be attached to any conclusions in this thesis by the limited scope of the study. Only one core from one site has been analyzed giving a sample size of one. No attempt has been made to measure the regional variability of monsoon activity and it is possible that further research at other sites in the core monsoon region could show that the results presented here are unrepresentative of the larger climate picture.

Limits in data availability constrain the validity of hydrological modeling. Approximations in parametrization reduced the accuracy and precision of the results of hydrological modeling limiting their value to broad conceptualization of how hydrology has changed over time. Nevertheless the three hydrological scenarios envisaged in the grain size and hydrological modeling probably reflect real world conditions in the past, though with a bias to moist conditions during MIS3 and 2.
Opportunities for Future Research

This research project was based on analysis of only one core. It is possible that changes recorded in this core reflect processes peculiar to its unique microenvironment rather than regional environmental processes. Therefore it would be valuable to test the validity of the palaeoenvironmental record captured in core TS425 by comparison with a similar analysis conducted on another core(s) from the same site.

The value of TTS as a site for palaeomonsoon study has been amply demonstrated by this thesis. To date this is the only record of past monsoon activity from the core monsoon zone with millennial scale resolution which records history beyond the Holocene. Our understanding of the dynamics of this site is perhaps better than for any other site where the monsoon has been studied. Therefore it makes sense to build on the solid base built by this thesis with further study at the TTS site. There are several opportunities for further palaeoclimate investigation at TTS. The exploratory investigation of diatoms at only three depths revealed a rich, well-preserved archive that merits further investigation. Diatom evidence of variation in the abundance of salt-tolerant taxa may allow further investigation of endorheric hydrological phases associated with failure of the monsoon during early MIS2.

The presence of freshwater sponge spicules throughout the core suggests this may provide another proxy of biological productivity worthy of investigation. However application of this technique in tropical Australia remains untried and basic research into gemmule identification and sponge ecology is a prerequisite. Stable oxygen isotope research was beyond the scope of the current project but investigation of the oxygen isotope record of TTS has since been initiated and should help elucidate the sensitivity of the ASM to changes in global ice volume and give insights into the continental effect on monsoon precipitation. Difficulties encountered in resolving the age profile of the last 5 ka may be resolvable by application of recently developed radiocarbon dating pre-treatment techniques developed for mound springs in the Kimberley region. A recalibration of the recent Holocene age record would allow finer resolution of the pollen and charcoal
records and may be important for understanding change in vegetation and in fire regime during the last 5 ka. Interest in pursuing this avenue of research has been expressed elsewhere. Analysis of the abundance of major elements, particularly K would allow application of conventional chemical weathering indices, which would provide an additional proxy of monsoon conditions valuable for cross-checking and refining the palaeoclimate history recorded here.

Further research into the origins of the allochthonous sediment component identified in geochemical analysis may allow reconstruction of past wind transport pathways. This research may give valuable insights into the timing of changes in wind patterns and the position of the Intertropical Convergence Zone which are crucial to understanding past climate patterns in both the temperate and tropical zones. This project will require preliminary research into the geochemical signature of potential dust sources as yet unidentified.

The application of hydrological modelling and geospatial analysis proved invaluable to understanding the dynamics of TTS and how its hydrology likely responded to changes in precipitation at various times in the past. The approach taken in the current project could be similarly useful to future climate research projects and there may be merit in applying the technique to previously studied locations.

While this project fulfilled the aims of deriving a long record from the core monsoon area the resolution of the record was, at best millennial and considerably less for the late Holocene. The aim of obtaining a high-resolution (centennial to decadal) record remains unfulfilled and demands further research. The problem of volatilization of carbon in the highly oxidising warm, wet tropical environment has so far limited the successful application of analytical tools such as radiocarbon dating and pollen and charcoal analysis. Similarly, complex hydrological conditions complicate the application of OSL dating techniques leading to loss of resolution. More research is needed to find a site that offers carbon preservation (anoxic conditions) beyond the Holocene together with simple hydrology. Discovery of
such a site provides the best hope of centennial to decadal resolution of the monsoon record and remains as the holy grail of Australian monsoon research.
9. References


Gillieson, D, Smith, DI, Greenaway, M & Ellaway, M 1991, ‘Flood history of the limestone ranges in the Kimberley region, Western Australia’, Applied geography (Sevenoaks), vol. 11, no. 2, pp. 105-23.


May, J-H, Preusser, F & Gliganic, LA 2015a, ‘Refining late Quaternary plunge pool chronologies in Australia’s monsoonal ’Top End’, *Quaternary geochronology*. 

154


Muller, J, Kylander, M, Martinez-Cortizas, A, Wüst, RAJ, Weiss, D, Blake, K, Coles, B & Garcia-Sanchez, R 2008, ‘The use of principle component analyses in
characterising trace and major elemental distribution in a 55 kyr peat deposit in tropical Australia: Implications to paleoclimate', *Geochimica et Cosmochimica Acta*, vol. 72, no. 2, pp. 449-63.


Nott, J & Roberts, RG 1996b, ‘Time and process rates over the past 100 m.y.: A case for dramatically increased landscape denudation rates during the late Quaternary in northern Australia’. *Geology*, vol. 24, no. 10, pp. 883-7.


Sanderson, DC & Murphy, S 2010, ‘Using simple portable OSL measurements and laboratory characterisation to help understand complex and heterogeneous sediment sequences for luminescence dating’, Quaternary Geochronology, vol. 5, no. 2, pp. 299-305.


Soper, AB 2014, ‘From past to present: hydrological and morphological characteristics of Wangi Creek, Northern Territory’, Bachelor of Science, Honours thesis, University of Wollongong.


Telford, RJ, Vandvik, V & Birks, HJB 2006, ‘Dispersal limitations matter for microbial morphospecies.’, *Science*, vol. 312, no. 5776], pp. 1015-.


van der Kaars, S, De Deckker, P & Gingele, FX 2006, ‘A 100 000 - year record of annual and seasonal rainfall and temperature for northwestern Australia based on a pollen record obtained offshore’, *Journal of Quaternary Science*, vol. 21, no. 8, pp. 879-89.


Wei, G, Xie, L, Sun, Y, Lu, Y & Liu, Y 2012, ‘Major and trace elements of a peat core from Yunnan, Southwest China: Implications for paleoclimatic proxies’, *Journal of Asian Earth Sciences*, vol. 58, no. 0, pp. 64-77.


10. Appendices

Appendix 1. Average annual precipitation of locations approximately 75 km from the coast.

<table>
<thead>
<tr>
<th>Location</th>
<th>Weather station No.</th>
<th>Distance from coast (km)</th>
<th>Average annual precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buley Rockhole</td>
<td>14021</td>
<td>60</td>
<td>1750</td>
</tr>
<tr>
<td>Lake Bennett</td>
<td>14240</td>
<td>60</td>
<td>1248</td>
</tr>
<tr>
<td>Batchelor Airport</td>
<td>14272</td>
<td>80</td>
<td>1492</td>
</tr>
<tr>
<td>Manton Dam</td>
<td>14035</td>
<td>50</td>
<td>1522</td>
</tr>
<tr>
<td>Walkers Creek</td>
<td>14279</td>
<td>50</td>
<td>1961</td>
</tr>
<tr>
<td>Middle Point Rangers Station</td>
<td>14090</td>
<td>60</td>
<td>1420</td>
</tr>
<tr>
<td>Mango Farm</td>
<td>14938</td>
<td>70</td>
<td>1417</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>59</td>
<td>1595</td>
</tr>
</tbody>
</table>

Appendix 2. Average annual precipitation at locations approximately 135km from the coast.

<table>
<thead>
<tr>
<th>Location</th>
<th>Weather Station No.</th>
<th>Distance from the coast (km)</th>
<th>Average annual precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emerald Springs</td>
<td>14205</td>
<td>160</td>
<td>1440</td>
</tr>
<tr>
<td>Douglas River</td>
<td>14905</td>
<td>135</td>
<td>1248</td>
</tr>
<tr>
<td>Pine Creek</td>
<td>14960</td>
<td>200</td>
<td>1492</td>
</tr>
<tr>
<td>Jindari</td>
<td>14917</td>
<td>180</td>
<td>1462</td>
</tr>
<tr>
<td>Burrell's Creek</td>
<td>14296</td>
<td>120</td>
<td>1919</td>
</tr>
<tr>
<td>Ban Ban Springs</td>
<td>14173</td>
<td>140</td>
<td>1363</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>205</td>
<td>1487</td>
</tr>
</tbody>
</table>
Appendix 3. Average annual precipitation of locations approximately 393 km inland.

<table>
<thead>
<tr>
<th>Location</th>
<th>Weather No.</th>
<th>Station No.</th>
<th>Distance from the coast (km)</th>
<th>Average annual precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mataranka Homestead Resort</td>
<td>14610</td>
<td>400</td>
<td>859</td>
<td></td>
</tr>
<tr>
<td>Mataranka Airstrip</td>
<td>14641</td>
<td>400</td>
<td>1040</td>
<td></td>
</tr>
<tr>
<td>Coodardie</td>
<td>14644</td>
<td>400</td>
<td>1002</td>
<td></td>
</tr>
<tr>
<td>Cave Creek</td>
<td>14650</td>
<td>400</td>
<td>1139</td>
<td></td>
</tr>
<tr>
<td>Maranboy Hill</td>
<td>14652</td>
<td>320</td>
<td>1110</td>
<td></td>
</tr>
<tr>
<td>Tyndall RAAF</td>
<td>14932</td>
<td>370</td>
<td>1066</td>
<td></td>
</tr>
<tr>
<td>Lakefield</td>
<td>14647</td>
<td>400</td>
<td>1046</td>
<td></td>
</tr>
<tr>
<td>Larrimah</td>
<td>14612</td>
<td>450</td>
<td>862</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>393</td>
<td>1015</td>
</tr>
</tbody>
</table>

Appendix 4. Modelled swamp filling at Pine Creek, a proxy for climate at 12 ka.
Appendix 5. Modelled swamp filling at Jindari, a proxy for climate at 12 ka.

Appendix 6. Modelled swamp filling at Larrimah, a proxy for climate 18 ka.
Appendix 7. Modelled swamp filling at Mataranka Homestead, a proxy for climate 18 ka.